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URBAN STORM RUNOFF INLET HYDROGRAPH STUDY

Vol. 1. Computer Analysis of Runoff from Urban Highway Watersheds under Time- and Space-Varying Rainstorms

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16. Abstract

The main objective of this study is to develop an accurate design method for computing inlet hydrographs of surface runoff, with average recurrence intervals of 10, 25, and 50 years, from typical urban highway by flood routing technique.

The most comprehensive mathematical model based on the method of characteristics was developed for computing the runoff inlet hydrograph. All flood routing methods were extensively reviewed and the most efficient and accurate technique was adopted for the formulation of a numerical (computer) model including all the rainfall-runoff processes on a highway watershed. Accuracy of the computer model was then examined by comparing the computed inlet hydrographs with field data obtained both from the Corps of Engineers airfield experiments and from typical highway cross-sections in the Salt Lake City area. A few exploratory computer experiments indicate that the development of a unified dimensionless inlet hydrograph or a family of such hydrographs for typical highway cross-sections seems possible.

This volume is the first in a series. The others in the series are:

Vol. No.	FHWA No.	Short Title	NTIS(PB) No. (if available)
2	76-117	Laboratory Studies of Sheet Flows	(not yet available)
3	76-118	Hydrologic Data for Highway Watersheds	(not yet available)
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PREFACE

The work described in this report was performed under contract DOT-FH-11-7806, entitled ''Urban Storm Runoff Inlet Hydrograph Study'' between the Federal Highway Administration and Utah State University. This research contract aimed at the development of an accurate design method for computing inlet hydrographs of surface runoff under intense rainstorms on urban highways. One of the major tasks in this research project was the development of the most accurate mathematical model for computing the runoff inlet hydrograph. All flood routing methods were extensively reviewed and the most efficient and accurate technique was adopted for the formulation of a computer model including all the rainfall-runoff processes on a highway watershed. Accuracy of the computer model was then checked by comparing the computed inlet hydrographs with field data obtained in the field phase of the research. The work reported herein is part of the analytical phase of the project.

The research was conducted under the general direction and supervision of Dr. Cheng-lung Chen, Professor of Civil and Environmental Engineering at Utah State University. During this study, Min-shoung Chu, Graduate Research Assistant, and Dr. George C. Shih, Research Engineer, at the Utah Water Research Laboratory, helped formulate the surface runoff computer model. The original computer program was written by Mr. Chu as part of his dissertation entitled ''Hydrodynamics of Runoff from Road Surfaces under Moving Rainstorms,'' submitted in 1973 in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Civil and Environmental Engineering, Utah State University, Logan, Utah. Subsequent modifications were made by Dr. Shih and mainly by the author in an attempt to correct inaccuracies found in the original program. The computer program was greatly expanded by the author to include the computation of the inlet hydrographs resulting from heavy storms under various drainage conditions in highway watersheds. Gratitude is due Dr. Shih for his assistance in the formulation of the drainage-area correction factor (Eq. 67) used in the computation of surface runoff on the curved roadway.

The contract was monitored by Dr. D. C. Woo, Contract Manager, Environmental Design and Control Division, Federal Highway Administration. The author is indebted to him for his idea to initiate this study and overall research plan, detailed discussions of research conduct of all phases, and critical reviews and comments of the results during the course of the work.

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A = cross-sectional area of flow; highway drainage area; infiltration model parameter

A_G = cross-sectional area of gutter flow

A_L = conjugate cross-sectional area of the discontinuity on region ''L''

A_o = cross-sectional area of the reference flow

A_P = cross-sectional area of flow at point P

A_R = conjugate cross-sectional area of the discontinuity on region ''R''

A_* = normalized cross-sectional area of flow

AMC = antecedent moisture condition

a = rainfall model parameter

B = total watershed area projected on the horizontal plane

b = rainfall model parameter

C = cross-sectional shape factor; a constant

c = concentration of raindrops; rainfall model parameter; runoff coefficient

C^+ = forward characterisitc

C_L^+ = forward characteristic on region ''L''

C_R^+ = forward characteristic on region ''R''

C^- = backward characteristic

C_L^- = backward characteristic on region ''L''

C_R^- = backward characteristic on region ''R''

CN = runoff curve number

D = hydraulic depth of flow

D_o	=	hydraulic depth of the reference flow
D_P	=	hydraulic depth of flow at point P
D_*	=	normalized hydraulic depth of flow
dA	=	change in cross-sectional area A
dds	=	change in length increment ds
dM_L	=	momentum influx due to lateral inflow
dM_r	=	momentum influx from rainfall in s-direction
ds	=	length increment in s-direction
dt	=	time interval
dV	=	change in velocity of flow V
e	=	superelevation of curved roadway
F	=	actual infiltration excluding the initial abstraction in inches
$\mathbf{F}$	=	Froude number
F_f	=	frictional force
F_g	=	force due to the weight of water
$\mathbf{F}_o$	=	reference Froude number
F_p	=	total resultant pressure force
f	=	Darcy-Weisbach friction coefficient; side friction (cornering ratio) between tires and road surface; infiltration capacity; initial abstraction coefficient
f_o	=	Darcy-Weisbach friction coefficient for the reference flow
g	=	acceleration of gravity; infiltration coefficient
h	=	depth of flow
$\bar{h}$	=	depth of the centroid of the whole cross-sectional area of flow
h_{ch}	=	channel depth
h_f	=	head loss due to friction
h_G	=	depth of gutter flow

h_{gs} = initial depth of gutter flow

h_L = conjugate depth of the discontinuity on region ''L''

$\bar{h}_L$ = conjugate $\bar{h}$ of the discontinuity on region ''L''

h_{min} = minimum depth below which the flow is assumed stationary

h_P = depth of flow at point P

h_R = conjugate depth of the discontinuity on region ''R''

$\bar{h}_R$ = conjugate $\bar{h}$ of the discontinuity on region ''R''

h_{rs} = initial depth of flow on the road surface

h^* = overpressure head due to raindrop impact

h_* = normalized depth of flow

$\bar{h}_{*L}$ = normalized conjugate $\bar{h}$ of the discontinuity on region ''L''

$\bar{h}_{*R}$ = normalized conjugate $\bar{h}$ of the discontinuity on region ''R''

h_*^* = normalized overpressure head

I_a = initial abstraction in inches

i = infiltration rate of the ground surface

$\bar{i}$ = average infiltration rate of the ground surface

i_* = normalized infiltration rate of the ground surface

K = index or counter of a grid point

k = roughness size of the ground surface texture

L_{ch} = gutter flow length

L_o = reference channel length

L_{rs} = overland flow length

M_t = momentum of the elementary volume of water at time t

N = index of a section of flow

NK = number of grid points on a flow section

NN = number of overland flow sections

n = Manning's roughness coefficient; number of raindrops per unit horizontal area

P = total storm rainfall in inches

P_e = potential runoff or effective storm rainfall in inches

Q = discharge passing through the cross-sectional area of channel flow; actual direct runoff in inches

Q_o = reference discharge of flow

Q_P = discharge of flow at point P

Q_u = discharge at upstream end

Q_* = normalized discharge of flow

q = discharge per unit width of overland flow

q_L = lateral inflow rate per unit length of channel

q_{L*} = normalized lateral inflow rate

$\bar{q}_L$ = average lateral inflow rate

q_1 = carry-over flow past the inlet between the curb and first slot of grate inlet

q_2 = carry-over flow past outside the last slot of grate inlet

R = hydraulic radius of flow

$\mathcal{R}$ = Reynolds number

R_o = hydraulic radius of reference flow

R_* = normalized hydraulic radius of flow

r = rainfall intensity in inches per hour

r_{av} = average rainfall intensity in inches per hour

r_c = radius of curvature for curved roadway

r_o = reference rainfall intensity in inches per hour

r_*^* = normalized rainfall intensity

$\bar{r}$ = average rainfall intensity in inches per hour over top width or time elapsed

S = channel slope; soil potential infiltration in inches

S_f = friction slope

S_o = reference channel slope

s = distance coordinate along road surface profile

s_J = location of the discontinuity at time t

s_J' = location of the discontinuity at time $t + \Delta t$

s_* = normalized distance along road surface profile

T = top width of flow

T_o = top width of reference flow

T_* = normalized top width of flow

$\bar{T}$ = average top width of flow

t = time

t_o = infiltration model parameter for time

t_p = time of ponding

t_s = initial time

t_* = normalized time

U = design speed for highway

$\bar{u}$ = average approaching velocity of road surface flow

u_* = normalized $\bar{u}$

V = velocity of flow

V_L = conjugate velocity of the discontinuity on region ''L''

V_o = velocity of reference flow

Vol_{in} = volume of water flowing into Vol_1 during Δt

Vol_1 = volume of water retained on the ground surface at time level 1

Vol_2 = volume of water retained on the ground surface at time level 2

V_P = velocity of flow at point P

V_R = conjugate velocity of the discontinuity on region ''R''

V_s = initial velocity of flow

V_* = normalized velocity of flow

W = velocity of the movement of rainstorm

W_* = normalized velocity of the movement of rainstorm

w = width of the grate inlet

x = distance coordinate on the horizontal plane

x_* = normalized x

y = depth of flow section perpendicular to the channel bed

z = distance coordinate in the vertical direction

α = energy correction factor for the velocity distribution of flow; infiltration model parameter

β = momentum correction factor for the velocity distribution of flow

β_L = momentum correction factor for the velocity distribution of lateral inflow

γ = skewness of storm pattern or ratio of the time before the peak of rainstorm to the total time duration

ΔA = elemental drainage area for curved roadway

ΔA_o = elemental drainage area for straight roadway

ΔS_{RS} = distance interval between two grid points in overland flow

ΔS_{GU} = distance interval between two grid points in channel flow

δ_i = equivalent size of raindrops for i=1, 2, ..., n

θ = average angle of inclination; central angle subtended by an arc

θ_g = angle between curb and gutter

θ_o = reference angle of inclination

Λ = mean terminal velocity of raindrops

Λ_* = normalized mean terminal velocity of raindrops

λ = a constant multiplier; initial abstraction index

$\bar{\lambda}$ = statistical average value of initial abstraction index

ν = kinematic viscosity of fluid

$\dot{\xi}$ = velocity of the moving discontinuity

$\dot{\xi}_*$ = normalized velocity of the moving discontinuity

ρ = mass density of fluid

τ = integration variable for time

τ_o = boundary shearing stress

Φ = angle of inclination that the mean terminal velocity of raindrops makes with the vertical line

ψ = angle of inclination that overland flow makes with the line normal to the longitudinal direction of channel flow

ε = a constant

ω = specific weight of water

INTRODUCTION

Because of the difficulty in accurately predicting the inflow at the highway drainage inlet under a given design rainstorm pattern, urban storm drainage systems today are still largely designed on the basis of the empirical rational formula using rainfall intensity modified by a coefficient of runoff. Despite the efficiency in the engineering application of the rational method to the urban highway hydrologic design, the method permits only the calculation of peak discharge for a uniform rainfall of chosen intensity. Furthermore, the determination of values of the coefficient in the rational formula is very difficult because this coefficient must represent many variables including hydrometeorological and physiographical factors of an urban highway watershed under investigation. Therefore, a more accurate method based on a physically sound concept is needed.

Many attempts have been made by previous investigators to improve the rational method. For instance, Gregory and Arnold (1932) developed a modification of the rational formula to recognize such factors as watershed shape and slope, stream pattern, and the elements of channel flow. Bernard (1938) developed similar modifications more clearly representing the many variables of runoff, with charts and nomographs to facilitate use of the more complex formulas. Application of these modifications, however, generally has been limited to areas larger than those encountered in most urban highway drainage projects.

Development of Urban Runoff Models

Among the first to consider applying hydrograph techniques to the design of storm sewers were Horner and Flynt (1936), who measured the temporal variation in rainfall and runoff on three very small (less than 5 acres) heavily urbanized areas in St. Louis, Mo., and Horner and Jens (1942), who applied modern hydrologic concepts to the determination of runoff from a single city residential block and suggested application of their techniques to larger areas. Hicks (1944) was the first to suggest the possibility of synthesizing urban runoff hydrographs. He developed a method of computing urban runoffs for the Los Angeles area based on experimental work for the determination of the principal abstractions from rainfall and actual gagings of local drainage areas in the metropolitan region. The Hicks methodology has been in use for more than 25 years in the city of Los Angeles and its satellite communities, but has not found wide use among designers in other cities. Extensive studies of a hydrograph method have been made by the city of Chicago. A detailed explanation of the hydrograph type of analysis used there is presented by Tholin and Keifer (1960), and of the synthetic storm pattern by Keifer and Chu (1957). Both a summary of the method and a comparison of measured and computed runoffs are given by Jens and McPherson (1964).

An inlet method which is essentially the same as the hydrograph method was studied at the Johns Hopkins University (1955 to 1963; Viessman and Geyer, 1962; Schaake, Geyer, and Knapp, 1964; Schaake, 1965) and New Mexico State University (Viessman and Abdel-Razaq, 1964; Viessman, 1966 and 1968). Based on rainfall measurements and inlet and sewer gagings in urban areas at Baltimore, Md. (Knapp, Schaake, and Viessman, 1963), and other municipalities (McPherson, 1958), the inlet method determines the flow to each inlet; attenuates the peak flow from each subarea (group of inlets) as it moves down the storm drain; and sums the attenuated peaks to determine the total peak at the design point. The inlet method is summarized by Jens and McPherson (1964) and also by Kaltenbach (1963).

Another approach, the unit hydrograph method (Eagleson, 1962), depends on the correlation of characteristics of measured sewer outflow hydrographs from urban areas of varying types, to permit construction of synthetic unit hydrographs for areas under design. Outflow hydrographs developed by the unit hydrograph method have particular application to the sizing of impounding basins and drainage pumping stations, for which the rational method provides no sound basis for design.

In recent years there has been increasing research activity in the field of urban hydrology. Several mathematical models yielding various degrees of accuracy in the prediction of the runoff hydrograph have been developed by many investigators. A qualitative review of several of these models is given by Linsley (1971). Worth further investigation are some of such urban models developed by the British Road Research Laboratory (Watkins, 1962; Terstriep and Stall, 1969), the Environmental Protection Agency (EPA) (Metcalf and Eddy, Inc. et al., 1969 and 1971; Chen and Shubinski, 1971), and the University of Cincinnati (Papadakis and Preul, 1972; Preul and Papadakis, 1970 and 1972). Papadakis and Preul (1973) compared the computer results obtained from the University of Cincinnati (UC) model, EPA Storm Water Management (SWM) model, Chicago hydrograph method (Tholin and Keifer, 1960), and Road Research Laboratory (RRL) model. Heeps and Mein (1974) also applied the RRL model, SWM model, and UC model to several storms on two urban watersheds in Australia, but their results did not support the Papadakis and Preul's finding that the UC model performed better than the RRL model and SWM model. Singh (1973) suggested more exact and complex methods of process simulation than the preceding three models after making his criticism and comparison of model simulation procedures used in the three models. A brief description of the differences in the three simulation procedures before storm water enters the inlet will be helpful to the present study in which a more detailed and comprehensive mathematical model will be developed to simulate the rainfall-runoff process on an urban highway watershed.

The most unusual and controversial features of the RRL model are that the areas contributing to storm runoff are taken to be only the impervious areas directly connected to the sewer system, and that these impervious areas have a runoff coefficient of 100 percent. Overland flow on these contributing areas is simulated by combining the rainfall hyetograph and an assumed linear time versus contributing area diagram (time-area routing) for each inlet. The assumed constant time of entry at an inlet is the time required for all the directly connected impervious area tributary to the inlet to contribute to runoff. No allowance is made for surface storage.

Overland flow in the SWM model is simulated by storage routing using Manning's equation and the equation of continuity, assuming that the hydraulic radius is equal to the depth of flow. The depth of flow is assumed constant along the length of the overland flow plane during any given time interval. Depression storage is treated in such a way that overland flow does not begin until the depression storage is full. However, 25 percent (arbitrary) of the impervious area is assigned zero depression storage to simulate immediate runoff. Infiltration on the pervious areas is represented by Horton's equation and may be satisfied by the rainfall during a time step, the depth of detention storage from the previous time step, or the water in depression storage.

The UC model in general considers the same catchment processes as the SWM model, but differs in simulation techniques. The UC model accepts only catchments which are wholly pervious or wholly impervious. In other words, any subcatchment has to be represented by two equivalent subcatchments—one pervious, the other impervious. Overland flow is considered by an analytical method based on an empirical relationship between outflow depth, detention storage, and detention storage at equilibrium. This empirical relation, together with Manning's equation and the equation of continuity, provide a solution for overland flow. Depression storage is simulated by an exponential relationship which assumes that the rate of filling is proportional to the unfilled volume. Infiltration on the pervious subcatchments is simulated by subtracting Horton's infiltration capacity curve from the rainfall time distribution, the infiltration curve being time-offset if the initial rainfall intensity is less than the initial potential infiltration rate.

In another approach similar to the aforementioned, more-frequently-referred, three models, Offner (1973) divided the runoff surface into a grid of square coordinates with size appropriate to the degree of surface irregularity and then on each square element assigned four parameter values describing the mass balance of outflow and inflow to the element. Overland flow is simulated by using Izzard's equation (1944, 1946) in the case of laminar flow, and if his limit for laminar flow is exceeded, using the equation for turbulent flow (Horton, 1935).

Another type of urban runoff model proposed by Anderson (1970) and Chien and Saigal (1974) is also similar to the above three models, but in a much simplified (practical) fashion. Anderson (1970) assumed a triangular shape for a basic hydrograph so that the total hydrograph for a given location was obtained by adding together several triangular hydrographs. Chien and Saigal (1974) on the other hand proposed the linearized subhydrographs method in which runoff coefficient is used to compute the peak rates of runoff; linear variation of the rising limb and the receding limb of the subhydrograph for a small basin is assumed and superimposed; and kinematic wave time to equilibrium is used as a factor for the determination of subhydrographs.

There are equivalent simplifications (or complexities) in the simulation of gutter flow among the existing urban runoff models, but most of them were developed based on uniform flow storage routing using Manning's formula. Most sewer flow was also simulated in the same way as gutter flow through storage routing using the equation of continuity and Manning's equation. It is noted that a sound procedure to route storm water through a storm sewer by using a digital computer was already developed elsewhere (Yevjevich and Barnes, 1970; Pinkayan, 1972). Since in the present study only storm water before its entry to the drainage inlet is considered, further analysis of sewer flow is beyond the scope of the present study. The most comprehensive mathematical model including all physical processes of runoff is thus developed herein for routing storm water through the drainage inlet. Formulation of a new method to accurately simulate urban highway runoff will be useful to attack storm drainage and associated problems in urban highway areas.

Objectives and Scope of the Present Study

The main objective of this study is to develop, by using a flood routing technique, a general computer model which can predict runoff from an urban highway watershed under time- and space-varying rainstorms. The three specific objectives are: (1) to formulate a rigorous one-dimensional surface flow model in the curvilinear orthogonal coordinate system, or a simiplified form thereof, which simulates the flow on the curved crown around a curved path on the straight or curved road surface; (2) to examine the validity and accuracy of the computer model using available existing data and field data collected from two typical urban highway watersheds in the Salt Lake City area; and (3) to study the effects of rainstorm and watershed parameters, such as the direction and magnitude of movement of the storm, the roughness, slope, curvature, length, and width of the roadway and shoulder, the gutter slope, infiltration characteristics of sideslope with various soils and plant covers, etc., on the inlet hydrograph.

Highways are built with crown or cross slopes to provide lateral or oblique drainage flow to the sides of the pavement, and in the case of curves, lateral or oblique flow due to superelevation of the pavement and shoulders. In urban areas, the recommended practice, if erosion is not a problem, is to allow the drain water to flow from the pavement, across the shoulder, and down the sideslopes to side ditches. However, in places of limited space, it is necessary to provide a curb along the outer edge of the pavement to conduct the flow to catch basins or other collecting devices, from which it is removed through a storm sewer system. In a broad sense, a highway watershed includes those areas within two adjacent highway drainage inlets (spaced from 400 to 1,000 ft) and the right-of-way (spaced from 200 to 400 ft) made from paved road surface (roadway), paved shoulder, sideslope or back slope (paved or grassed), median, gutter (paved or grassed), side ditch, and natural drainage area. To study the runoff process from such a small urban highway watershed requires a knowledge of flow lines and watershed divides, because within the right-of-way there are few such sub-watersheds on which storm water is routed independently of each other. For example, one of the highway sub-watersheds is made of a roadway and a curb-type gutter only. This sub-watershed is bounded by a fixed highway watershed divide which is a line connecting the vertices of the cross profiles of the roadway, two flow lines which pass two adjacent highway drainage inlets, and the curb.

Physically, runoff from a roadway under a moving or stationary rainstorm is a special case of the general watershed flow (Chen and Chow, 1968 and 1971). The runoff process on a roadway conceptually consists of two parts: (1) overland flow on the crown of the road surface; and (2) channel (or gutter) flow in the gutter. The water moving as overland flow meets with that in the gutter, most of which flows into the highway drainage inlet with part of it to be carried over. In the mathematical simulation of such flows, theoretically speaking, three-dimensional flow equations may be formulated (Chen and Chow, 1968 and 1971), but for simplicity overland flow and gutter flow each may be threated as the one-dimensional flow in space with time taken as another independent variable.

A mathematical model which consists of a set of one-dimensional flow equations, initial conditions, and boundary conditions, can be formulated for combined overland flow and gutter flow. The one-dimensional, spatially varied unsteady flow equations, commonly used in open channel, can be developed for such flow and then solved numerically on a digital computer, subject to specified initial and boundary conditions.

One of the hardest boundary conditions to cope with is at the junction or interface between the downstream end of the overland flow and any point of the gutter flow. This interface between overland flow and gutter flow may be referred to as an ''internal'' boundary which may move with space and time. Conditions at this internal boundary (Chen and Chow, 1968 and 1971) must satisfy the flow variables of both types of flow at that point.

The boundary at the crown of the roadway is a fixed watershed divide where it may be assumed to have a zero flow velocity. The condition at the drainage inlet is an overfall condition which may or may not be utilized for solution, depending on whether the flow at the inlet is subcritical or supercritical. Both boundary conditions at the highway watershed divide and the drainage inlet may be referred to as ''external'' boundary conditions, in contrast with the movable internal boundary conditions prescribed at the interface between overland flow and gutter flow.

Different types of drainage inlets, such as grate inlets and curb-opening inlets, with or without gutter depression, have been proposed to withdraw stormwater from the gutter. Because none of the existing inlets can function with 100 percent efficiency, part of the stormwater in the gutter which cannot enter an inlet will automatically become an input (i.e. carry-over) to the subsequent gutter flow at the upstream end of the gutter. The rate of carry-over flow depends on the approaching depth and velocity at the inlet as well as the type of the inlet installed. The inlet characteristic curves or relationships developed by Horner (1919), Tapley (1943), Larson (1948 and 1949), Izzard 9(1950), Li et al. (1951 and 1954), and Knapp et al. (1963) may be used as downstream boundary conditions at the inlet. However, none of these relationships developed has been proved to be satisfactory in application. Therefore, for simplicity, efficiency at the inlet will be assumed 100 percent and no carry-over flow will be imposed at the inlet.

The initial conditions on a dry surface of zero depth and velocity are of a singularity type requiring judicious assumptions of small depth and velocity in order to be able to start the computation numerically.

The flow equations (i.e., the Saint-Venant equations) will be expressed in the form of a set of quasi-linear partial differential equations. As will be reviewed in the following section, many numerical techniques have been developed to solve such a set of hyperbolic partial differential equations. Because the problem under study is only concerned with a relatively small basin area and a short-duration thunderstorm, use of an explicit finite-difference scheme with specified rectangular grid intervals based on the method of characteristics is believed to be more suitable than other methods in the numerical solution.

Although it has long been recognized that the flow equations for spatially varied unsteady flow in open channel can have discontinuous solutions (Dressler, 1949), a special technique by use of a pair of shock equations (i.e., rapidly varied flow equations) coupled with characteristic equations must be developed for tracing a bore or a train of such bores for which the method of characteristics fails to hold because characteristic in the same class cross each other. A useful application of this technique is in the computation of the wavefront which outraces the front of a moving rainstorm.

The advancing wavefront of the surface flow may outrace, or move at least with the same velocity, as the front of a rainstorm. In case the front of the flow outraces that of the rainstorm, the flow problem under study is similar to the dam-breaking problem (Stoker, 1957) and the method used in analyzing such a problem may be applied. However, a simplifying assumption must be introduced to overcome the singularity problem that is inherent at the leading edge of a wavefront moving on a dry surface. If the front of the flow advances with that of the rainstorm, the front of the flow may be assumed as a point in the continuous flow so that it can readily be computed by simply using the characteristic equations without resorting to the shock equations.

Following the review of literature on the flood routing techniques and associated numerical schemes, the mathematical model of surface runoff from an urban highway watershed under a moving or stationary rainstorm will be formulated and then solved on a digital computer. Computer solutions will be obtained for a variety of actual or design storms and drainage conditions commonly encountered on the urban highway. Significant dimensionless parameters which control the runoff process on the highway watershed will be identified and evaluated through sensitivity analysis. Comparison of computed inlet hydrographs with field data will also be performed for verification of the computer model.

Because of the difficulty in arranging what needed to be reported in one volume, some of the results will be presented without elaborating their detailed derivations and implications as far as no confusion and misunderstanding will arise. Those portions skipped from detailed analysis and presented in other volumes of the final report under separate subtitles are: Vol. 2. Laboratory studies of the resistance coefficient for sheet flows over natural turf surfaces; Vol. 3 Hydrologic data for two urban highway watersheds in the Salt Lake City area, Utah; Vol. 4. Synthetic storms for design of urban highway drainage facilities; Vol. 5. Soil-cover-moisture complex: Analysis of parametric infiltration models for sideslopes.

LITERATURE REVIEW OF RUNOFF MODELING AND ROUTING TECHNIQUES

The surface runoff from a watershed due to a rainstorm varies with the hydrometeorologic characteristics of the rainstorm and physiographic properties of the watershed. In literature many studies deal with the effects of the physiographic properties of watersheds on the runoff hydrograph, but only few studies are concerned with the influences of the movement of rainstorms on rainfall-runoff relationship (Amorocho and Orlob, 1961; Maskimov, 1964; Marcus, 1968; Yen and Chow, 1968 and 1969; Hill, 1969; Wei and Larson, 1971). A study of the combined effects of such hydrometeorologic factors of moving rainstorms and physiographic factors on the runoff process is even more meager (Iwagaki and Takasao, 1956). It is the intrinsic complexity of flow phenomenon under such combined effects that has prevented us from analyzing it in a more fundamentally sound fashion. Nevertheless, advent of an electronic computer and its ability to implement existing numerical methods have stimulated great interest in seeking the solution of such a complicated problem.

Surface Runoff Models

The flow on a runoff surface under a moving rainstorm is not difficult to describe mathematically by using the concepts of fluid mechanics. Rigorously speaking, the mathematical model of the surface flow to be developed consists of a set of three-dimensional instantaneous unsteady flow equations (i.e., the three-dimensional instantaneous equations of continuity and motion—the Navier-Stokes equations—for unsteady free-surface flow) with adequately prescribed three-dimensional instantaneous initial and boundary conditions. However, to obtain a solution by using a modern high-speed electronic computer from such a three-dimensional instantaneous model, a numerical method, if it ever exists, could result in an extremely lengthy computer program that is likely to be either uneconomical or beyond the capacity of the computer presently available, or both. A three-dimensional model may be simplified to a two-dimensional plane-flow model, application of which however is limited to a laboratory watershed flow (Chow and Ben-Zvi, 1973). In practice, the best way to circumvent this difficulty is to treat the surface flow in a watershed as a combined system of ''hydraulic'' (or one-dimensional) flows (Chen and Chow, 1968 and 1971) which are hydrodynamically distinguishable from each other. For example, the water on the crown of the roadway moves as overland flow, while the water in the gutter moves as channel flow. Both can be treated as one-dimensional flows. A combination of overland flow and channel flow with internally coupling boundary conditions between them can adequately describe the shallow water movement on the roadway with curb. When one-dimensional flow is nonuniform and unsteady, as is always the case in the runoff process, it may be called spatially varied unsteady flow.

Spatially varied unsteady flow consists of both gradually varied unsteady flow and rapidly varied unsteady flow. The equations of one-dimensional gradually varied unsteady flow can be derived from the three-dimensional flow equations by means of the time and space averaging process (Chen and Chow, 1968 and 1971; Strelkoff, 1969; and Yen, 1972 and 1973). The equations of one-dimensional rapidly varied unsteady flow, can be formulated from volume-integrated one-dimensional equations of continuity and momentum or energy (Stoker, 1957; Chen and Chow, 1968; Terzidis and Strelkoff, 1970; Yen, 1973). The relationships between dependent variables (i.e., the depth and velocity of flow) for gradually varied unsteady flow can be expressed in the form of a set of quasi-linear partial differential equations while those for rapidly varied unsteady flow, if isolated, may be formulated in the form of algebraic relationships between conjugate depths and velocities at the point of discontinuity and propagation velocity of discontinuity. Both relationships are needed in the computation of surface flow on the roadway as well as in the gutter, specifically at the points of discontinuity, such as the places where overland flow meets gutter flow, moving hydraulic jumps and rolling waves occur, and the leading edge of the wavefront moves on the dry surface.

Numerical Techniques

Many techniques have been developed to solve numerically the gradually varied unsteady flow equations with appropriately prescribed initial and boundary conditions. Among those techniques reported (e.g., Richtmyer, 1962; Yevjevich, 1964; Dronkers, 1964 and 1969; Liggett and Woolhiser, 1967; Strelkoff, 1970; Gunaratnam and Perkins, 1970), the method of characteristics (Courant and Friedricks, 1948; Stoker, 1957; Courant and Hilbert, 1962; Garabedian, 1964), because of its advantages such as suitability, accuracy, and efficiency in computation over other methods (Liggett and Woolhiser, 1967), has been used widely for computing the propagation of floods, tides, wind waves, etc., in rivers and homogeneous estuaries and on beaches. Studies conducted by Isaacson, Stoker, and Troesch (1958), Whitham (1958), Freeman and Le Mehâuté (1964), Lai (1965), Amorocho and Strelkoff (1965), Strelkoff and Amorocho (1965), Amien (1966), Fletcher and Hamilton (1967), Baltzer and Lai (1968), Liggett (1968), Chen and Chow (1968), Mozayeny and Song (1969), Ellis (1970), Wylie (1970), and Yevjevich and Barnes (1970), Pinkayan (1972), among many others are good examples of its application.

The major disadvantage of the characteristic model results from the necessity to store those computed for later interpolation and tedious computer programming to obtain the water surface and velocity profiles at a desired time level from the calculated coordinates and the corresponding depths and velocities of flow at such coordinates. This drawback, nevertheless, can be overcome by adoption of a rectangular grid network in the x, t-plane incorporated with the characteristic equations (Stoker, 1957; Amorocho and Strelkoff, 1965; Strelkoff and Amorocho, 1965) or both the characteristic curves and the characteristic equations (Lai, 1965; Streeter and Wylie, 1967; Baltzer and Lai, 1968; Chen and Chow, 1968; Wylie, 1970). The latter is an alternative technique which combines the accuracy of the method of characteristics with the convenience of a rectangular net.

Both explicit and implicit schemes can be used in the formulation of characteristic difference equations. However, there are some advantages in the computation by using an explicit scheme. For example, solving the characteristic difference equations formulated in an implicit scheme requires the simultaneous solution of a set of the nonlinear equations, but not for those equations in an explicit scheme. Even though expressed in an explicit scheme, the characteristic difference equations formulated at the point of intersection of the forward (C^+) and backward (C^-) characteristics originating from the known time level can be nonlinear in unknowns at that point. The simultaneous solutions of such a pair of nonlinear equations are difficult, but can be obtained by using an iterative procedure suggested by Liggett and Woolhiser (1967). If the forward and backward characteristic equations are linear in unknowns, such as formulated by Stoker (1957), Lai (1965), Amorocho and Strelkoff (1965), Strelkoff and Amorocho (1965), Streeter and Wylie (1967), Baltzer and Lai (1968), Chen and Chow (1968), and Wylie (1970), they can readily be solved for one grid point at a time. A computation procedure for solving such linear characteristic difference equations may be classified into the explicit scheme based on characteristic equations (Strelkoff, 1970).

Stoker's (1957) explicit scheme is only valid for flows at Froude numbers less than unity (i.e., subcritical flow), because the x-partial derivatives associated with the forward characteristic equation involve space increment to the upstream of the section in question while those associated with the backward characteristic equation involve the one to the downstream. The preceding expression of the x-partial derivatives associated with the backward characteristic equation is obviously invalid for supercritical flow, in which the backward characteristic curve lies to the upstream of the section in question instead. The explicit scheme based on characteristic equations can be made to be applied to both subcritical and supercritical flows if the orientation of the backward characteristic curve is also taken into account. The scheme used by Streeter and Wylie (1967), Chen and Chow (1968), and Wylie (1970) belongs to this category. The latter scheme is adopted in the present study.

Explicit schemes are stable only if the time interval used in the computation is sufficiently small. The criterion which sets the maximum size of this interval is referred to as the Courant criterion or condition

(Courant and Friedricks, 1948; Courant and Hilbert, 1962). For stability of explicit schemes, the Courant criterion must be satisfied; however, the explicit scheme would probably give the most accurate results if the time interval used is close to its limiting value (Strelkoff, 1970).

One of the most difficult computations of unsteady free-surface flow is the one with a moving hydraulic jump (i.e., sometimes called a shock, surge, or discontinuity), or a train thereof. Various techniques (see, e.g., Terzidis and Strelkoff, 1970) have been developed for computing gradually varied unsteady flow with a bore or a train of such bores. There are the method of characteristics (Faure and Nahas, 1961; Freeman and Le Mehâuté, 1964; Chen and Chow, 1968), von Neumann-Richtmyer method (1950), Lax method (Lax, 1954; Keller, Levine, and Whitham, 1960), Lax-Wendroff method (1960), and Lax-Wendroff-Richtmyer method (Terzidis and Strelkoff, 1970). Of all, the method of characteristics combining a pair of the algebraic shock relationships with the characteristic difference equations along characteristic curves appears the most suitable to the explicit scheme based on the characteristic equations. All the methods listed above, with the exception of Chen and Chow (1968), seemingly assume that the initial state contain a bore and in their present forms of computation procedures are not capable of treating problems in which bores develop.

MATHEMATICAL FORMULATION OF SURFACE RUNOFF

The basic laws governing the movement of water on the runoff surface are the principles of conservation of mass and momentum. Based on these laws, the flow equations (i.e., the equations of continuity and momentum) can be formulated. In the derivation of the flow equations, the flow on the runoff surface is considered as a single stream-tube bounded by two stream surfaces: the free water surface and the ground surface. For convenience, the flow on the roadway may be divided into two regions: overland (or road surface) flow and channel (or gutter) flow. The outflow from the downstream end of the overland-flow part is considered as the lateral inflow to the channel flow. The location of the internal boundary between the overland flow and channel flow depends on the depths and velocities of both flows at the point of intersection which must satisfy the internal boundary conditions.

Although the roadway is usually constructed with a parabolic transverse profile, the formulation of the flow equations for overland flow and channel flow will be generalized so that the flow equations developed can be applied to both overland and channel flows. The coupling of channel flow to overland flow is accomplished by specifying internal boundary conditions along a line which separates the two types of flow.

In the formulation of the flow equations, raindrops falling on the road surface will be treated as a continuous medium of water. The flow equations will be derived first for nonprismatic channels and later simplified to those for prismatic channels.

Flow Equations

The equation of continuity

For one-dimensional free-surface flow with lateral inflow, the equation of continuity may be derived by considering an elementary control volume of water bounded by two cross-sections of average top width T which are an infinitesimal distance, ds, apart (Figure 1), the water surface, and the boundary of the channel. The water flowing out of minus the water flowing into the control volume in ds during infinitesimal time, dt, is $(\partial Q/\partial s)$ ds dt and this must equal the change in channel storage $(\partial A/\partial t)$ ds dt plus the volume due to rainfall and infiltration $(\bar{\bar{r}} - \bar{\bar{I}})$ T ds dt $\cos\theta$ and due to lateral inflow $\bar{q}_L$ ds dt. Hence, for incompressible fluid, the principle of conservation of mass requires that

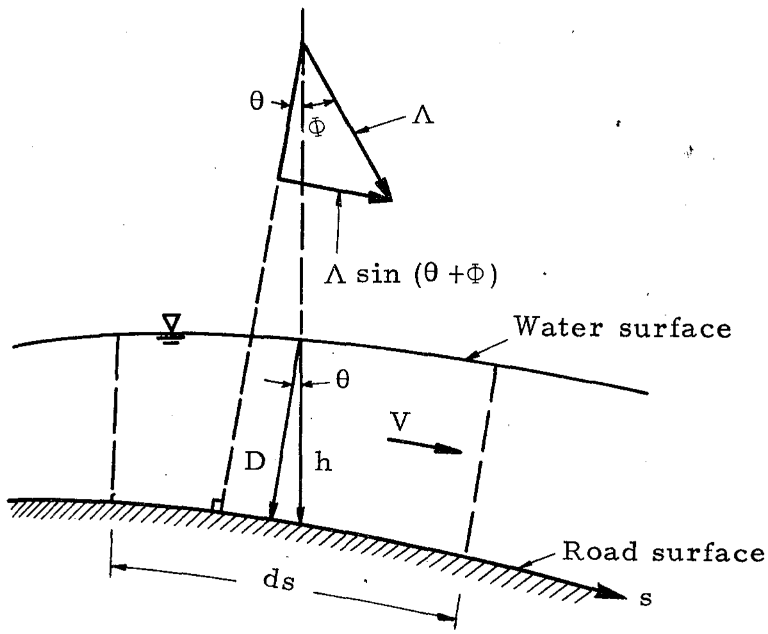


Figure 1. Definition sketch for flow profile.

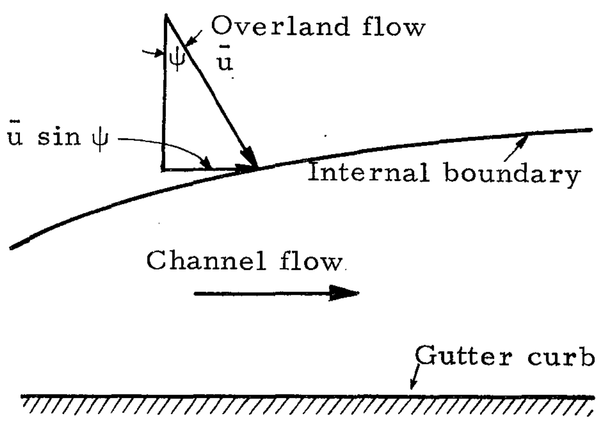


Figure 2. Plan view of internal boundary between overland flow and channel flow.

$$\frac{\partial Q}{\partial s} \, ds \, dt + \frac{\partial A}{\partial t} \, ds \, dt = (\bar{r} - \bar{i}) \, T \, ds \, dt \cos\theta + \bar{q}_L \, ds \, dt \quad \ldots \ldots \quad (1)$$

or

$$\frac{\partial Q}{\partial s} + \frac{\partial A}{\partial t} = (\bar{r} - \bar{i}) \, T \cos\theta + \bar{q}_L \quad \ldots \ldots \quad (2)$$

in which A is the cross-sectional area of the channel normal to the direction of flow; $\bar{r}$ and $\bar{i}$ are the average rainfall intensity and infiltration rate, respectively, measured in the direction of gravity over the elementary volume in dt; θ is the average angle of inclination that channel bed makes with the horizontal plane; and $\bar{q}_L$ is the rate of the lateral inflow from the downstream end of the overland flow to channel flow per unit length of channel flow. Equation 2 is the general continuity equation for one-dimensional free-surface flow with lateral inflows in a channel.

The equation of momentum

According to the principle of conservation of momentum, the total rate of momentum change in an elementary volume of water equals the net force acting on it. The forces acting on the elementary volume include the pressures on the two flow cross-sections, the weight of water, the friction and the forces due to raindrop impact. By assuming that the pressure distribution is hydrostatic, the total pressure on a flow cross-sectional area, A, is equal to $\omega A \bar{h} \cos^2\theta$, where ω is the specific weight of water, and $\bar{h}$ is the distance from water surface to the centroid of A measured in the direction of gravity. Considering all forces acting on the control volume in the direction of s axis, the total resultant pressure force, F_p, is

$$F_p = \frac{\partial(\omega A \bar{h} \cos^2\theta)}{\partial s} \, ds \quad \ldots \ldots \quad (3)$$

The force due to the weight of water, F_g, is

$$F_g = \omega A \sin\theta \, ds \quad \ldots \ldots \quad (4)$$

The friction force, F_f, is

$$F_f = \omega A \, S_f ds \quad \ldots \ldots \quad (5)$$

in which S_f is the friction slope. An additional pressure caused by the raindrop impact may be distributed uniformly over the flow cross-sectional area (Chen and Chow, 1968). This additional pressure may be referred to as overpressure. The total overpressure can be expressed by $\omega A\, h^*$, where h^* is the overpressure head and is expressed by Chen and Chow (1968) as:

$$h^* = \frac{c}{g}\, r\, \Lambda \cos\theta \cos(\theta+\Phi) \qquad (6)$$

in which g is the acceleration of gravity, r is rainfall intensity, Λ is the mean terminal velocity of raindrops, and Φ is the angle of inclination that the mean terminal velocity of raindrops makes with the vertical line (Figure 1), and c is the concentration of raindrops and is defined as

$$c = \frac{1}{\Delta B} \sum_{i=1}^{n} \frac{1}{4} \pi \delta_i^2 \qquad (7a)$$

The concentration of raindrops is the percent of the area for ''n'' number of raindrops of size, δ_i, for i=1, 2, ..., n, occupying a unit area, ΔB, in unit time, dt, assuming that no point within ΔB is hit by more than one raindrop during dt. Furthermore, if the average diameter of raindrops, δ, is assumed and the number of raindrops, n, is computed by dividing the total volume of raindrops occupying ΔB during dt (seconds), $(r/60 \times 60)\ \Delta B\, dt$, by the volume of a raindrop, $\pi\delta^3/6$, then Eq. 7a reduces to

$$c = \frac{1.5r\ dt}{60 \times 60\delta} \qquad (7b)$$

which is expressed in terms of r, δ, and dt. Incorporating the overpressure head with the total resultant pressure force, F_p, yields

$$F_p = \frac{\partial[\omega A(\bar{h} \cos^2\theta + h^*)]}{\partial s}\ ds \qquad (8)$$

The momentum, M_t, of the elementary volume of water at time, t, is

$$M_t = \rho A V\ ds \qquad (9)$$

where ρ is the mass density of water, and V is the velocity of flow. The momentum M_{t+dt} at time (t + dt) is

$$M_{t+dt} = \rho(A + dA)(V + dV)(ds + dds) \qquad (10)$$

where dA is the change in area, A, in time interval, dt; dV is the change in velocity, V, in time interval, dt; and dds is the change in length, ds, in time interval, dt. Since

$$dA = \frac{\partial A}{\partial s} ds + \frac{\partial A}{\partial t} dt = (V \frac{\partial A}{\partial s} + \frac{\partial A}{\partial t}) dt \quad . \quad . \quad . \quad . \quad . \quad . \quad (11)$$

$$dV = \frac{\partial V}{\partial s} ds + \frac{\partial V}{\partial t} dt = (V \frac{\partial V}{\partial s} + \frac{\partial V}{\partial t}) dt \quad . \quad . \quad . \quad . \quad . \quad . \quad (12)$$

$$dds = \frac{\partial V}{\partial s} ds \; dt \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (13)$$

in which ds/dt is taken as V. Substituting Eqs. 11, 12, and 13 into Eq. 10 and neglecting differentials of higher order gives

$$M_{t+dt} = \rho \left[AV + (A \frac{\partial V}{\partial t} + V \frac{\partial A}{\partial t} + V^2 \frac{\partial A}{\partial s} + 2AV \frac{\partial V}{\partial s}) \; dt \right] ds$$

$$. \quad . \quad . \quad . \quad . \quad . \quad (14a)$$

or

$$M_{t+dt} = \rho \left[AV + \left\{ \frac{\partial (AV)}{\partial t} + \frac{\partial (AV^2)}{\partial s} \right\} dt \right] ds \quad . \quad . \quad . \quad (14b)$$

During the time interval, dt, there is also a momentum influx, dM_r, from rainfall in the s-direction, which can be expressed as

$$dM_r = \rho \bar{\bar{r}} T c A \sin (\theta + \Phi) \, ds \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (15)$$

There is also a momentum influx, dM_L, due to lateral inflow, which has a velocity component in the s-direction equal to $\bar{\bar{u}} \sin \psi$, where $\bar{\bar{u}}$ is the approaching average velocity of overland flow, and ψ is the angle between the direction of overland flow and that which is perpendicular to the channel flow, as shown in Figure 2. This momentum influx can be expressed as

$$dM_L = \rho \bar{\bar{u}} \bar{\bar{q}}_L \sin\psi \; ds \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (16)$$

Thus, applying the principle of conservation of momentum to the control volume by using Eqs. 4, 5, 8, 9, 14b, 15, and 16 and assuming that the momentum efflux due to infiltration is negligible yields

$$\frac{M_{t+dt} - M_t}{dt} - dM_r - dM_L = F_g - F_p - F_f \qquad . \quad . \quad . \quad . \quad . \quad (17a)$$

or

$$\frac{\partial(AV)}{\partial t} + \frac{\partial(AV^2)}{\partial s} - \bar{r}Tc\Lambda \sin(\theta + \Phi) - \bar{\bar{u}}\bar{q}_L \sin\psi$$

$$= gA \sin\theta - gAS_f - g\frac{\partial}{\partial s}[A(\bar{h} \cos^2\theta + h^*)] \qquad . \quad . \quad . \quad . \quad (17b)$$

The left-hand side of Eq. 17b represents the rate of the change in the momentum across the surface of the elementary volume. Since the velocity distribution of the channel flow and lateral inflow are not uniform, a momentum correction factor must be introduced to each of these two terms. Thus, Eq. 17b becomes

$$\frac{\partial(AV)}{\partial t} + \frac{\partial(\beta AV^2)}{\partial s} - \bar{r}Tc\Lambda \sin(\theta + \Phi) - \beta_L \bar{\bar{u}}\bar{\bar{q}}_L \sin\psi$$

$$= gA \sin\theta - gAS_f - g\frac{\partial}{\partial s}[A(\bar{h} \cos^2\theta + h^*)] \qquad . \quad . \quad . \quad . \quad (17c)$$

in which β is the momentum correction factor for the velocity distribution of the channel flow, and has a theoretical value of 1.2 for laminar flow and $1 + 0.7812f$ for turbulent flow, where f is the friction coefficient [see Iwasa (1954) and also Appendix 1 for the derivation of the theoretical β value]; and β_L is the momentum correction factor for the velocity distribution of lateral inflow. Thus, Eq. 17c is the general form of the equation of momentum for channel flow.

From computer results obtained for several different rainstorm conditions, it was found that within the range of input data the effect of the β value on the outflow hydrograph was insignificant. Therefore, for simplicity the β value was assumed to be unity in the present study. Despite this assumption regarding the β value, the β and β_L will be retained in the following equation of motion, as expressed in Eq. 17c, throughout this investigation unless stated otherwise.

The general equations of continuity and motion, Eqs. 2 and 17c developed for channel flow can be applied to overland flow because overland flow is actually a wide open-channel flow, in which $\bar{q}_L = 0$ and flow variables such as Q and A must be expressed per unit width.

As far as the derivation of Eqs. 2 and 17c is concerned, no assumption regarding the cross-sectional shape, curvature, and alignment of the channel has been imposed. Both equations are applicable to flow in nonprismatic channels as well as on the cross profile of the roadway which in the case of concrete is a parabola with its vertex at the crown.

Evaluation of the friction slope

In one-dimensional flow, the friction slope S_f can be expressed by the Darcy-Weisbach formula,

$$S_f = \frac{fV^2}{8gR} \qquad (18)$$

in which f is the Darcy-Weisbach friction coefficient, and R is the hydraulic radius. To compute S_f by using Eq. 18 requires a knowledge of the value of f, which has yet to be determined for overland flow with shallow depth in the order of the roughness size. No theoretical formula has been developed for sheet flow except for the following special cases, which can be found elsewhere (e.g., Rouse, 1965; Chow, 1959):

For turbulent flow on the rough surface,

$$\frac{1}{\sqrt{f}} = 2 \log_{10} \frac{2R}{k} + 1.74 \qquad (19)$$

in which k is the roughness size of texture of the runoff surface.

For turbulent flow on the smooth surface,

$$\frac{1}{\sqrt{f}} = 2 \log_{10} \mathbf{R} \sqrt{f} + 0.404 \qquad (20)$$

in which $\mathbf{R} = VR/\nu$ is the Reynolds number.

For laminar flow,

$$f = \frac{C}{\mathbf{R}} \qquad (21)$$

in which C is a constant that depends on the cross-sectional shape of the channel (Chow, 1959) and in the case of sheet flow on the rainfall intensity and channel slope (Wenzel, 1970; Yoon, 1970; Yoon and Wenzel, 1971; Woo and Brater, 1961 and 1962). The value of C for sheet flows over natural turf surfaces was experimentally determined and reported in the laboratory phase of this study (Chen, 1975a).

For flow in the transition region, an empirical formula for the computation of f is available, but is not reliable enough to be used in this study because of the technical difficulty in adaptation to complete description of f by Eqs. 19, 20, and 21. Equations 19, 20, and 21, as shown in Figure 3, are computed with the Reynolds number, $\mathbf{R}$, as a controlling parameter for the selection of the equations and hence the determination of the f value.

Initial Conditions

If the ground surface is initially (t = 0) dry, then

$$V = 0 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (22)$$

$$h = 0 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (23)$$

in which h is the depth of flow. As h = 0, the cross-sectional area of flow, A, top width, T, hydraulic depth, D, and hydraulic radius, R, all become zero. The initial conditions specified by Eqs. 22 and 23 are singularity conditions, which would result in an immediate problem to obtain the solutions to the flow equations. Some judicious assumptions have to be made to overcome this singularity problem. Details of the assumptions will be discussed later.

Boundary Conditions

As mentioned previously, the boundary condition at the inlet changes as the flow changes from subcritical to supercritical and vice versa. The Froude number can be used to describe such changes in the state of flow. It will be shown later in this study that the Froude number, $\mathbf{F}$, under the effect of raindrop impact must be defined somewhat differently from a conventional way (Chow, 1959); that is, with the overpressure head, h^*, (Chen and Chow, 1968 and 1971)

$$\mathbf{F} = \frac{V}{\sqrt{g(D \cos\theta + h^*)/\beta}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (24)$$

This definition also includes the correction factors for channel slope, θ and momentum correction factor, β. If the Froude number defined in Eq. 24 is less than, equal to, or greater than unity, the flow is referred to as subcritical, critical, or supercritical.

The external and internal boundary conditions will be described separately as follows.

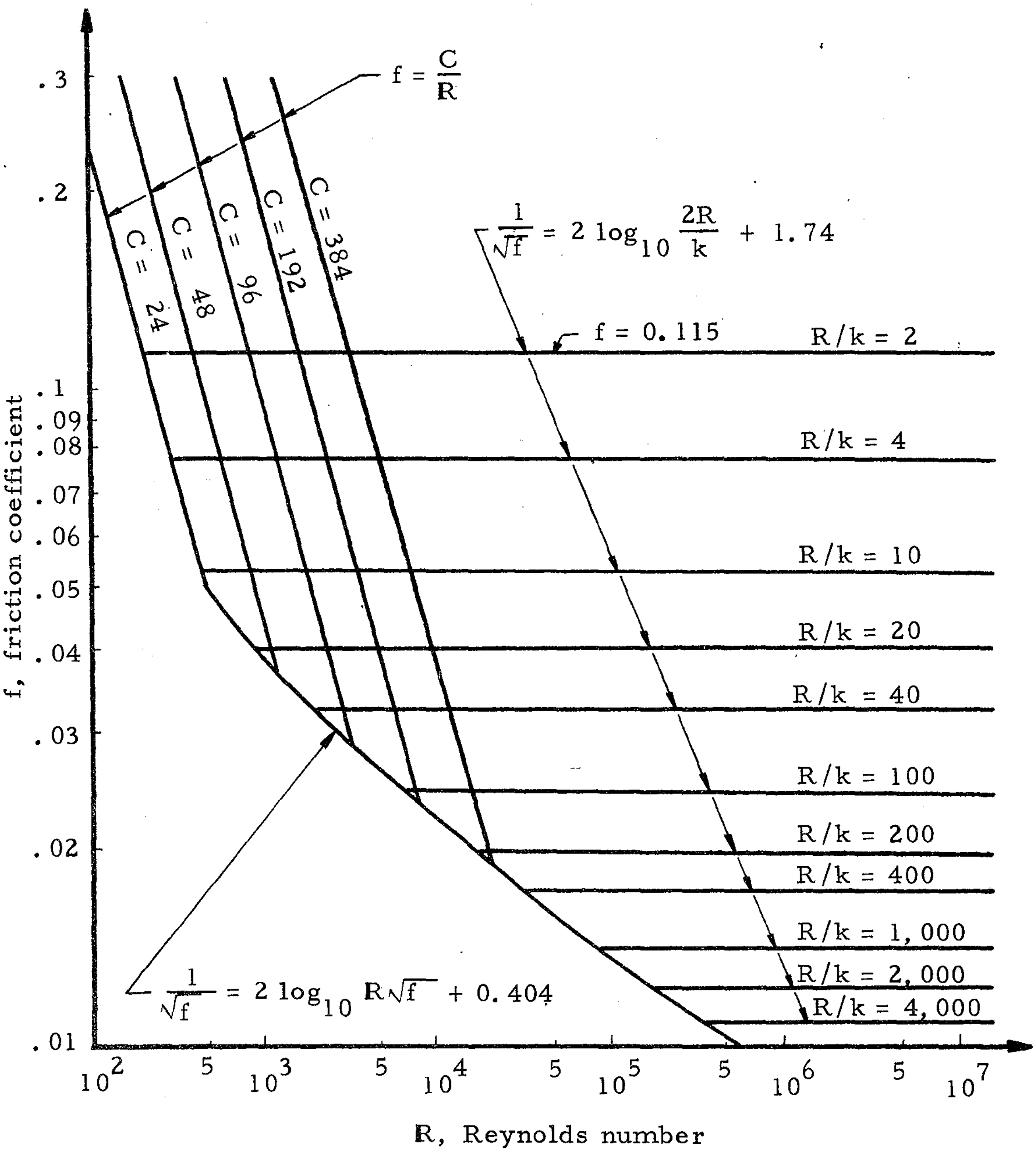


Figure 3. Selection of friction coefficient, f.

External boundary conditions

Upstream boundary condition. The upstream boundary condition is

$$Q_u = AV \qquad (25)$$

in which Q_u is the discharge at the upstream end. For overland flow, Q_u can be assumed equal to zero, whereas for gutter flow, it is equal to the carryover flow rate from the upstream adjacent gutter. If the inlet is assumed to be operated at 100 percent, Q_u is again set equal to zero.

Downstream boundary condition. The boundary condition at the inlet of a highway watershed is an overfall condition which depends on the flow characteristics. The flow before reaching the outlet can be either subcritical or supercritical. If it is subcritical, the overfall condition prescribed at the outlet is

$$\mathbf{F} = \frac{V}{\sqrt{g(D\cos\theta + h^*)/\beta}} = 1 \qquad (26)$$

which states that the outlet is the critical section where the Froude number is unity. No condition exists for supercritical flow.

Internal boundary conditions

The internal boundary conditions can be derived by using the continuity and momentum equations formulated around the neighborhood of a discontinuity in flow variables (Stoker, 1957). Let $\dot{\xi}$ be the propagation velocity of the discontinuity along the direction of flow. Then ignoring the length of the discontinuity the law of conservation of mass yields

$$A_L(V_L - \dot{\xi}) = A_R(V_R - \dot{\xi}) \qquad (27a)$$

or

$$\dot{\xi} = \frac{A_L V_L - A_R V_R}{A_L - A_R} \qquad (27b)$$

in which A and V are the cross-sectional area and velocity of flow, respectively, with subscripts ''L'' and ''R'' referring to the left-hand (upstream) side and right-hand (downstream) side of the discontinuity, respectively. By taking into account the effect of the raindrop impact (Chen and Chow, 1968) and applying the law of conservation of momentum to the same neighborhood of the discontinuity and then incorporated with Eq. 27, the following expression for V_L is obtained:

$$V_L = V_R + |A_L - A_R| \left[\frac{g}{A_L A_R} \left(\frac{A_L \bar{h}_L - A_R \bar{h}_R}{A_L - A_R} \cos^2\theta + h^* \right) \right]^{1/2} \qquad (28)$$

in which $\bar{h}_L$ and $\bar{h}_R$ are the depths of the centroids of the cross-sectional areas of flow, A_L and A_R, respectively. Note that in Eq. 28, the difference between A_L and A_R is expressed in absolute value so that the equation is applicable to both cases of $A_L < A_R$ and $A_L > A_R$. Equations 27 and 28 constitute the internal boundary conditions that must be satisfied at the moving hydraulic jump, the bore, the wavefront, and the intersection between overland flow and channel flow. There are five flow variables: $\dot{\xi}$, V_L, V_R, A_L, and A_R in Eqs. 27 and 28. If three of them are known or solvable from other conditions or equations, the rest of the five variables can be obtained from Eqs. 27 and 28.

It is noted that A_L and A_R are the conjugate cross-sectional areas at a bore and the one on the front side of the bore is always smaller than that on the back side of the bore (Stoker, 1957). Two general cases of the dynamic behaviors of a bore result as a consequence of such definition regarding the front and back sides of the bore. Several inequalities among the five flow variables can be established for both cases (Chen and Chu, 1973), which are useful in the computation of the generation and propagation of the bore. Thus, from Eqs. 27 and 28 or alternative forms thereof, the following inequalities at the bore can be developed:

For $V_L > V_R > \dot{\xi}$ and $A_L < A_R$,

$$|V_L - \dot{\xi}| > \sqrt{g(D_L \cos\theta + h^*)/\beta} \qquad (29)$$

$$|V_R - \dot{\xi}| < \sqrt{g(D_R \cos\theta + h^*)/\beta} \qquad (30)$$

Equations 29 and 30 express mathematically the physical statement that the velocity of flow relative to the bore is supercritical on the front side (A_L) of the bore and subcritical on the back side (A_R) of the bore (Stoker, 1957). Furthermore, from Eqs. 29 and 30, it can be readily shown (Chen and Chu, 1973) that

$$V_L + \sqrt{g(D_L \cos\theta + h^*)/\beta} > V_L - \sqrt{g(D_L \cos\theta + h^*)/\beta}$$

$$> \dot{\xi} > V_R - \sqrt{g(D_R \cos\theta + h^*)/\beta} \quad \ldots \ldots \quad (31)$$

This inequality reveals that there are two characteristics, C_L^+ and C_L^-, on the front side and only one characteristic, C_R^-, on the back side of the bore meeting at the point of discontinuity.

For $\dot{\xi} > V_L > V_R$ and $A_L > A_R$,

$$|V_L - \dot{\xi}| < \sqrt{g(D_L \cos\theta + h^*)/\beta} \quad \ldots \ldots \quad (32)$$

$$|V_R - \dot{\xi}| > \sqrt{g(D_R \cos\theta + h^*)/\beta} \quad \ldots \ldots \quad (33)$$

whence

$$V_L + \sqrt{g(D_L \cos\theta + h^*)/\beta} > \dot{\xi} > V_R + \sqrt{g(D_R \cos\theta + h^*)/\beta}$$

$$> V_R - \sqrt{g(D_R \cos\theta + h^*)/\beta} \quad \ldots \ldots \quad (34)$$

In this case, obviously the front side of the bore is in a flow region associated with A_R and the back side associated with A_L. The inequality, Eq. 34, again holds the same property that the front side has two characteristics, C_R^+ and C_R^-, while the back side has only one characteristic, C_L^+, meeting at the point of discontinuity.

The inequalities, Eqs. 29 through 34, can be used for the selection of three characteristic difference equations in the numerical computation of a bore. Details of computational procedures by using such inequalities, the corresponding characteristic difference equations, and the shock equations, Eqs. 27 and 28, especially for solving a moving wavefront due to a rainstorm on a dry bed, will be given later.

The mathematical model of runoff from a dry surface under a moving rainstorm thus consists of the flow equations, Eqs. 2 and 17c, the initial conditions, Eqs. 22 and 23, and the boundary conditions, Eqs. 25 through 28. Equations 2 and 17c form a set of quasi-linear partial differential equations, which cannot be solved analytically with the present knowledge in mathematics, except for a few special cases. It is imperative that the analytical model so formulated be transformed into a numerical form so that it can be solved by using a digital computer. As mentioned previously, an explicit scheme based on characteristic equations was adopted in this study to formulate the numerical model. For convenience in analysis and computation, the mathematical model will be first normalized so that the significant dimensionless parameters that control the runoff process from the runoff surface are also defined.

NUMERICAL MODEL USING THE METHOD OF CHARACTERISTICS

The flow equations, Eqs. 2 and 17c expressed in terms of A and Q (or V) are valid for nonprismatic channels as well as for flow with moving channel boundaries. However, if these flow equations are transformed into those expressed in terms of the flow depth, h, and Q (or V), a term representing departure of cross-sectional area from a prismatic channel (Liggett, 1968; Strelkoff, 1969; Wylie, 1970) in the flow equations complicates the numerical solution considerably. To solve the flow equations for moving channel boundaries is evidently more difficult than that for fixed boundary of nonprismatic channels because the spatial and temporal variations of cross-sectional area for flow with moving boundaries are unknown a priori. The flow on the roadway is very shallow in comparison with that in the gutter, thus a term representing the change in cross-sectional area of gutter flow due to the movement of the internal boundary is believed to be of small order of magnitude and thus ignored.

Let $A = DT$, where D is the hydraulic depth, and assume that $dA = T\ dy$, where y is the depth of flow section perpendicular to the channel bed, $y = h \cos \theta$, $d(A\bar{h}) = A\ dh$, $h^* =$ constant along the s-axis, and $S = \sin \theta$. Then Eqs. 2 and 17c can be transformed into the ones expressed in terms of h and Q (or V), as stated. For convenience, the flow equations so transformed are further normalized by using the following dimensionless quantities:

$$
\begin{aligned}
&s_* = s/L_o, && h_* = h \cos\theta_o/D_o, && V_* = V/V_o \\
&t_* = tV_o/L_o, && D_* = D/D_o, && T_* = T/T_o \\
&r_* = \bar{r}/r_o, && i_* = \bar{i}/r_o, && q_{L*} = \bar{q}_L \cos\theta_o/V_o D_o \\
&h_*^* = h^*/D_o \cos\theta_o, && R_* = R/R_o, && \Lambda_* = \Lambda/V_o \\
&u_* = \bar{u}/V_o, && &&
\end{aligned}
\qquad (35)
$$

in which variables with asterisk subscripts are dimensionless quantities and those with ''o'' subscripts are reference quantities. Specifically, L_o is defined as the reference length which may be either overland-flow length or channel-flow length, or a combination thereof. After several manipulations, Eq. 2 becomes

$$\frac{\partial h_*}{\partial t_*} + V_* \frac{\partial h_*}{\partial s_*} + \frac{\cos\theta_o}{\cos\theta} D_* \frac{\partial V_*}{\partial s_*} = \frac{L_o}{D_o \cos\theta_o} \left[(r_* - i_*) \left(\frac{r_o}{V_o}\right) \cos^2\theta_o \right.$$

$$\left. + \frac{\cos\theta_o}{\cos\theta} \left(\frac{D_o}{T_o}\right) \frac{q_{L*}}{T_*} \right] \quad . \; . \; . \; . \; . \; . \; . \; . \quad (36)$$

If Eq. 36 is multiplied by βV_* and then subtracted from the normalized form of Eq. 17c, the normalized momentum equation in terms of h_* and V_* becomes

$$(1 - \beta) \frac{\cos\theta}{\cos\theta_o} \frac{V_*}{D_*} \frac{\partial h_*}{\partial t_*} + \frac{\beta}{\mathbf{F}_o^2} \frac{\cos\theta}{\cos\theta_o} \left(\frac{\cos\theta}{\cos\theta_o} + \frac{h_*^*}{D_*}\right) \frac{\partial h_*}{\partial s_*} \frac{\partial V_*}{\partial t_*}$$

$$+ \beta V_* \frac{\partial V_*}{\partial s_*} = \frac{L_o}{D_o \cos\theta_o} \left[\frac{\beta}{\mathbf{F}_o^2} (S - S_f) + \frac{r_*}{D_*} \left(\frac{r_o}{V_o}\right) \left(c\Lambda_* \frac{\sin(\theta + \Phi)}{\cos\theta_o} \right.\right.$$

$$\left. - \beta V_* \frac{\cos\theta}{\cos\theta_o} \right) \cos^2\theta_o + \frac{\beta V_* i_*}{D_*} \left(\frac{r_o}{V_o}\right) \cos\theta \cos\theta_o$$

$$\left. + (\beta_L u_* \sin\psi - \beta V_*) \frac{q_{L*}}{D_* T_*} \left(\frac{D_o}{T_o}\right) \right] \quad . \; . \; . \; . \; . \; . \quad (37)$$

in which $\mathbf{F}_o = V_o/\sqrt{gD_o \cos\theta_o/\beta}$, may be referred to as the normal flow Froude number.

For brevity, the subscript asterisk used to denote the dimensionless nature of the variables will be dropped hereafter in dimensionless expressions unless otherwise specified.

The normalized equations of continuity and momentum, Eqs. 36 and 37, form a set of hyperbolic partial differential equations, which are in suitable form to be solved by the method of characteristics. Let Eqs. 36 and 37 be identified by M_1 and M_2, respectively; or

$$M_1 = \frac{\partial h}{\partial t} + V\frac{\partial h}{\partial s} + \frac{\cos\theta_o}{\cos\theta} D \frac{\partial V}{\partial s} - \frac{L_o}{D_o \cos\theta_o} \left[(r - i) \left(\frac{r_o}{V_o}\right) \cos^2\theta \right.$$

$$\left. + \frac{\cos\theta_o}{\cos\theta} \left(\frac{D_o}{T_o}\right) \frac{q_L}{T} \right] \quad . \; . \; . \; . \; . \; . \; . \; . \quad (38)$$

$$M_2 = (1 - \beta) \frac{\cos\theta}{\cos\theta_o} \frac{V}{D} \frac{\partial h}{\partial t} + \frac{\beta}{\mathbf{F}_o^2} \frac{\cos\theta}{\cos\theta_o} \left(\frac{\cos\theta}{\cos\theta_o} + \frac{h^*}{D} \right) \frac{\partial h}{\partial s} + \frac{\partial V}{\partial t}$$

$$+ \beta V \frac{\partial V}{\partial s} - \frac{L_o}{D_o \cos\theta_o} \left[\frac{\beta}{\mathbf{F}_o^2} (S - S_f) + \frac{r}{D} \left(\frac{r_o}{V_o} \right) \left(c\Lambda \frac{\sin(\theta + \Phi)}{\cos\theta_o} \right.\right.$$

$$\left. - \beta V \frac{\cos\theta}{\cos\theta_o} \right) \cos^2\theta_o + \frac{\beta V i}{D} \left(\frac{r_o}{V_o} \right) \frac{\cos\theta}{\cos\theta_o} \cos^2\theta_o$$

$$\left. + (\beta_L u \sin\psi - \beta V) \frac{q_L}{DT} \left(\frac{D_o}{T_o} \right) \right] \quad . \quad . \quad . \quad . \quad . \quad . \qquad (39)$$

Then Eqs. 38 and 39 can be combined linearly by using an unknown multiplier, λ, to form

$$M = \lambda M_1 + M_2 = 0 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (40)$$

whence the following two ordinary differential equations in terms of λ are formulated:

$$\left[\lambda + (1 - \beta) \frac{\cos\theta}{\cos\theta_o} \frac{V}{D} \right] \frac{dh}{dt} + \frac{dV}{dt} - \frac{L_o}{D_o \cos\theta_o} \left[\frac{\beta}{\mathbf{F}_o^2} (S - S_f) \right.$$

$$+ \frac{r}{D} \left(\frac{r_o}{V_o} \right) \left(\lambda D + c\Lambda \frac{\sin(\theta + \Phi)}{\cos\theta_o} - \beta V \frac{\cos\theta}{\cos\theta_o} \right) \cos^2\theta_o$$

$$+ \frac{i}{D} \left(\frac{r_o}{V_o} \right) \left(- \lambda D + \beta V \frac{\cos\theta}{\cos\theta_o} \right) \cos^2\theta_o + \frac{q_L}{TD} \left(\frac{D_o}{T_o} \right) \left(\lambda \frac{\cos\theta_o}{\cos\theta} D \right.$$

$$\left.\left. + \beta_L u \sin\psi - \beta V \right) \right] = 0 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (41)$$

$$\frac{ds}{dt} = \frac{\lambda V + \frac{\beta}{\mathbf{F}_o^2} \frac{\cos\theta}{\cos\theta_o} \left(\frac{\cos\theta}{\cos\theta_o} + \frac{h^*}{D} \right)}{\lambda + (1 - \beta) \frac{\cos\theta}{\cos\theta_o} \frac{V}{D}} = \lambda D \frac{\cos\theta_o}{\cos\theta} + \beta V \quad . \quad . \quad . \qquad (42)$$

From Eq. 42, the following two particular values of λ are obtained.

$$\lambda = \pm \frac{1}{D} \frac{\cos\theta}{\cos\theta_o} \sqrt{\beta(\beta - 1) V^2 + \frac{\beta}{\mathbf{F}_o^2} \left(D \frac{\cos\theta}{\cos\theta_o} + h^* \right)} \quad . \quad . \qquad (43)$$

By substituting these two values of λ back into Eqs. 41 and 42, a set of ordinary differential equations is formulated as follows. From Eq. 42 with the help of Eq. 43, two sets of curves, C^+ and C^- curves, which are often called characteristic curves, are obtained:

$$C^+: \quad \frac{ds}{dt} = \beta V + \sqrt{\beta(\beta - 1)\, V^2 + \frac{\beta}{F_o^2}\left(D \frac{\cos\theta}{\cos\theta_o} + h^*\right)} \quad . \quad . \quad . \qquad (44)$$

$$C^-: \quad \frac{ds}{dt} = \beta V - \sqrt{\beta(\beta - 1)\, V^2 + \frac{\beta}{F_o^2}\left(D \frac{\cos\theta}{\cos\theta_o} + h^*\right)} \quad . \quad . \quad . \qquad (45)$$

The characteristic differential equations which apply along these characteristic curves are obtained from Eq. 41 upon substitution of the λ expressions from Eq. 43.

$$\begin{aligned}
C^+: \quad & \frac{1}{D}\frac{\cos\theta}{\cos\theta_o}\left[(1 - \beta)\, V + \sqrt{\beta(\beta - 1)\, V^2 + \frac{\beta}{F_o^2}\left(D \frac{\cos\theta}{\cos\theta_o} + h^*\right)}\right]\frac{dh}{dt} \\
& + \frac{dV}{dt} = \frac{L_o}{D_o \cos\theta_o}\left[\frac{\beta}{F_o^2}(S - S_f) + \frac{r}{D}\left(\frac{r_o}{V_o}\right)\left(c\Lambda \frac{\sin(\theta + \Phi)}{\cos\theta}\right.\right. \\
& \left. - \beta V + \sqrt{\beta(\beta - 1)\, V^2 + \frac{\beta}{F_o^2}\left(D \frac{\cos\theta}{\cos\theta_o} + h^*\right)}\right)\cos\theta \cos\theta_o \\
& + \frac{i}{D}\left(\frac{r_o}{V_o}\right)\left(\beta V - \sqrt{\beta(\beta - 1)\, V^2 + \frac{\beta}{F_o^2}\left(D \frac{\cos\theta}{\cos\theta_o} + h^*\right)}\right)\cos\theta \cos\theta_o \\
& \left. + \frac{q_L}{TD}\left(\frac{D_o}{T_o}\right)\left(\beta_L u \sin\psi - \beta V + \sqrt{\beta(\beta - 1)\, V^2 + \frac{\beta}{F_o^2}\left(D \frac{\cos\theta}{\cos\theta_o} + h^*\right)}\right)\right] \\
& \quad . \quad . \quad . \quad . \quad . \quad . \qquad (46)
\end{aligned}$$

$$\begin{aligned}
C^-: \quad & \frac{1}{D}\frac{\cos\theta}{\cos\theta_o}\left[(1 - \beta)\, V - \sqrt{\beta(\beta - 1)\, V^2 + \frac{\beta}{F_o^2}\left(D \frac{\cos\theta}{\cos\theta_o} + h^*\right)}\right]\frac{dh}{dt} \\
& + \frac{dV}{dt} = \frac{L_o}{D_o \cos\theta_o}\left[\frac{\beta}{F_o^2}(S - S_f) + \frac{r}{D}\left(\frac{r_o}{V_o}\right)\left(c\Lambda \frac{\sin(\theta + \Phi)}{\cos\theta}\right.\right. \\
& \left. - \beta V - \sqrt{\beta(\beta - 1)\, V^2 + \frac{\beta}{F_o^2}\left(D \frac{\cos\theta}{\cos\theta_o} + h^*\right)}\right)\cos\theta \cos\theta_o
\end{aligned}$$

$$+ \frac{i}{D}\left(\frac{r_o}{V_o}\right)\left(\beta V + \sqrt{\beta(\beta - 1)\ V^2 + \frac{\beta}{F_o^2}\left(D \frac{\cos\theta}{\cos\theta_o} + h^*\right)} \right) \cos\theta \cos\theta_o$$

$$+ \frac{q_L}{TD}\left(\frac{D_o}{T_o}\right)\left(\beta_L u \sin\psi - \beta V - \sqrt{\beta(\beta - 1)\ V^2 + \frac{\beta}{F_o^2}\left(D \frac{\cos\theta}{\cos\theta_o} + h^*\right)} \right)\Bigg] \quad . \quad . \quad . \quad . \quad (47)$$

These ordinary differential equations so derived will be expressed in a difference form from which the depth and velocity of flow, h and V, can be solved orderly, one at a time, on the computer, at the intersection of the C^+ and C^- characteristic curves.

An Explicit Scheme with Specified Intervals

The derivatives in the equations of the characteristic curves, Eqs. 44 and 45, and the characteristic differential equations, Eqs. 46 and 47, will be replaced by first order differences for use in an explicit scheme with specified grid intervals, as shown in Figure 4. In the present study, the grid distance interval, Δs, is taken as a constant. In order to insure stability of the solution obtained from the explicit finite-difference equations, the relative value of the time interval, Δt, and grid distance interval, Δs, must satisfy the Courant criterion (Courant et al., 1952):

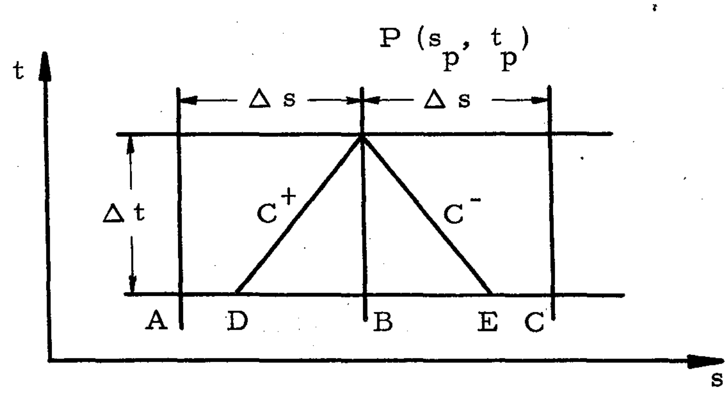
$$\Delta t < \frac{\Delta s}{\beta V + \sqrt{\beta(\beta - 1)\ V^2 + \frac{\beta}{F_o^2}\left(D \frac{\cos\theta}{\cos\theta_o} + h^*\right)}} \quad . \quad . \quad . \quad . \quad (48)$$

The specified grid interval is used to assign definite values of s_P and t_p at point P in the s, t-plane (Figure 4) throughout the computation. Thus, only two unknowns, the velocity and depth of flow at point P, V_P and h_P, remain to be determined. If the velocity and depth of flow are known at points A, B, and C (Figure 4), the velocity and depth at points D and E (or E') can be evaluated by linear interpolation incorporating with the equations for the characteristic curves, C^+ and C^-.

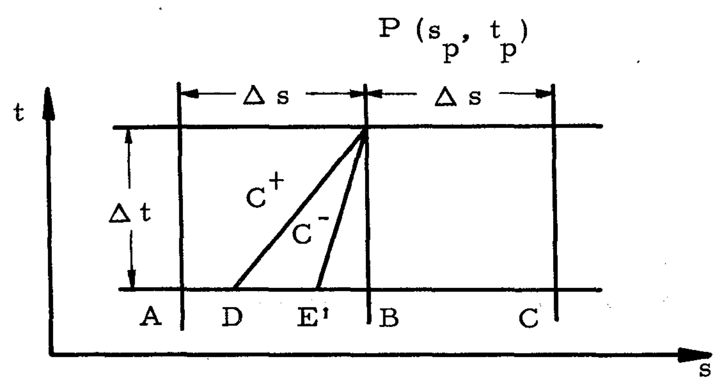
The characteristic curves and the characteristic differential equations, Eqs. 44 through 47, can thus be transformed into the following explicit finite-difference forms with specified grid intervals. All the variables with subscripts, ''A,'' ''B,'' ''C,'' ''D,'' ''E,'' (or E'), and ''P'' used in the following equations denote the corresponding quantities at point A, B, C, D, E (or E'), and P in Figure 4, respectively.

For the C^+ -characteristic curve, Eqs. 44 and 46 give

$$s_P - s_D = \left[\beta V_D + \sqrt{\beta(\beta - 1)\ V_D^2 + \frac{\beta}{F_o^2}\left(D_D \frac{\cos\theta_D}{\cos\theta_o} + h_D^*\right)} \right] \Delta t \quad . \quad . \quad . \quad . \quad (49)$$



a. For subcritical flow



b. For supercritical flow

Figure 4. Explicit scheme with specified grid intervals.

$$\frac{1}{D_D}\frac{\cos\theta_D}{\cos\theta_o}\left[(1-\beta)\,V_D+\sqrt{\beta(\beta-1)\,V_D^2+\frac{\beta}{F_o^2}\left(D_D\frac{\cos\theta_D}{\cos\theta_o}+h_D^*\right)}\right](h_P-h_D)$$

$$+(V_P-V_D)=\frac{L_o}{D_o\cos\theta_o}\left[\frac{\beta}{F_o^2}(S_D-S_f)+\frac{r_D}{D_D}\left(\frac{r_o}{V_o}\right)\left(c\Lambda_D\frac{\sin(\theta_D+\Phi_D)}{\cos\theta_D}\right.\right.$$

$$\left.-\beta V_D+\sqrt{\beta(\beta-1)\,V_D^2+\frac{\beta}{F_o^2}\left(D_D\frac{\cos\theta_D}{\cos\theta_o}+h_D^*\right)}\right)\cos\theta_D\cos\theta_o$$

$$+\frac{i_D}{D_D}\left(\frac{r_o}{V_o}\right)\left(\beta V_D-\sqrt{\beta(\beta-1)\,V_D^2+\frac{\beta}{F_o^2}\left(D_D\frac{\cos\theta_D}{\cos\theta_o}+h_D^*\right)}\right)\cos\theta_D\cos\theta_o$$

$$\left.+\frac{q_{LD}}{T_D D_D}\left(\frac{D_o}{T_o}\right)\left(\beta_L u\sin\psi-\beta V+\sqrt{\beta(\beta-1)V_D^2+\frac{\beta}{F_o^2}\left(D_D\frac{\cos\theta_D}{\cos\theta_o}+h_D^*\right)}\right)\right]\Delta t \quad \ldots\ldots \quad (50)$$

respectively.

For C^- - characteristic curve, Eqs. 45 and 47 give

$$s_P-s_E=\left[\beta V_E-\sqrt{\beta(\beta-1)\,V_E^2+\frac{\beta}{F_o^2}\left(D_E\frac{\cos\theta_E}{\cos\theta_o}+h_E^*\right)}\right]\Delta t \quad \ldots\ldots \quad (51)$$

$$\frac{1}{D_E}\frac{\cos\theta_E}{\cos\theta_o}\left[(1-\beta)\,V_E-\sqrt{\beta(\beta-1)\,V_E^2+\frac{\beta}{F_o^2}\left(D_E\frac{\cos\theta_E}{\cos\theta_o}+h_E^*\right)}\right](h_P-h_E)$$

$$+(V_P-V_E)=\frac{L_o}{D_o\cos\theta_o}\left[\frac{\beta}{F_o^2}(S_E-S_f)+\frac{r_E}{D_E}\left(\frac{r_o}{V_o}\right)\left(c\Lambda_E\frac{\sin(\theta_E+\Phi_E)}{\cos\theta_E}\right.\right.$$

$$\left.-\beta V_E-\sqrt{\beta(\beta-1)\,V_E^2+\frac{\beta}{F_o^2}\left(D_E\frac{\cos\theta_E}{\cos\theta_o}+h_E^*\right)}\right)\cos\theta_E\cos\theta_o$$

$$+\frac{i_E}{D_E}\left(\frac{r_o}{V_o}\right)\left(\beta V_E+\sqrt{\beta(\beta-1)\,V_E^2+\frac{\beta}{F_o^2}\left(D_E\frac{\cos\theta_E}{\cos\theta_o}+h_E^*\right)}\right)\cos\theta_E\cos\theta_O$$

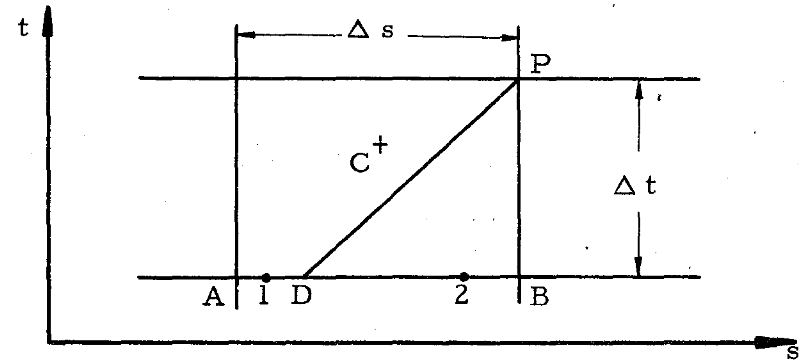
$$+ \frac{q_{LE}}{T_E D_E}\left(\frac{D_o}{T_o}\right)\left(\beta_L u \sin\psi - \beta V_E - \sqrt{\beta(\beta-1)V_E^2 + \frac{\beta}{\mathbf{F}_o^2}\left(D_E \frac{\cos\theta_E}{\cos\theta_o} + h_E^*\right)}\right)\Bigg] \Delta t \quad . \quad . \quad . \quad . \quad . \quad . \qquad (52)$$

Equations 51 and 52 are developed only for subcritical flow, in which point E lies between points B and C (Figure 4a). In the case of supercritical flow, the C^- -characteristic curve has a positive slope in the s, t-plane so that point E lies between points A and B, as shown in Figure 4b. However, Eqs. 51 and 52 are still applicable to the supercritical flow case if subscript ''E'' for all variables in Eqs. 51 and 52 is changed to subscript ''E''' .

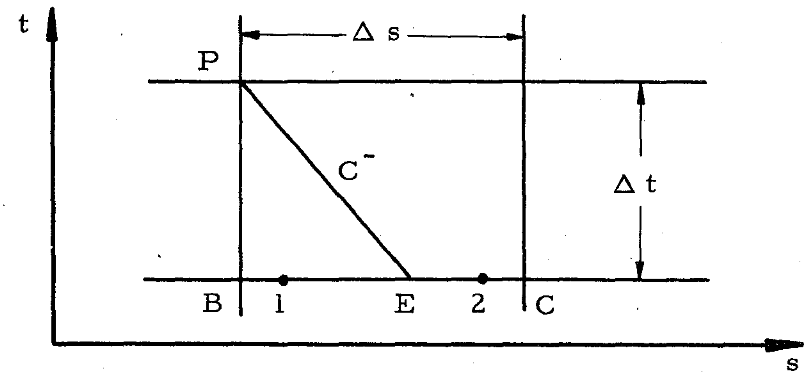
In order to solve Eqs. 50 and 52 simultaneously for V_P and h_P, all other quantities at points D and E (or E') in the equations must be evaluated first. Within the same flow region, these quantities such as at points D and E (or E'), can be expressed in terms of known or calculated quantities at given grid points such as at points A, B, and C, by interpolation. In other words, for any given non-closed channel section, where the geometric elements of channel section, such as A, D, R, and T, can be defined entirely by the section geometry and the depth of flow, the velocity of flow and any geometric element of channel section anywhere between two grid points, if in the same flow region, can be evaluated by interpolation. For convenience, the hydraulic depth of flow, D, is used as a representative geometric element of the channel section under study.

When grid points A, B, and C utilized in the interpolation of the values of flow variables at points D and E (or E') are not in the same flow region, such as in the case of bores which develop between any two grid points, great care must be given to the formulation of linear interpolation or extrapolation formulas which, if derived for flow on the front side of the bore, should not be expressed in terms of the known values for flow on the back side of the bore and vice versa. It is essential that the interpolation or extrapolation formulas for flow variables at points D and E (or E') be generalized so that they can also be applied to a situation in which a bore exists in between grid points A, B, and C. The generalization of interpolation or extrapolation can be done in the following manner.

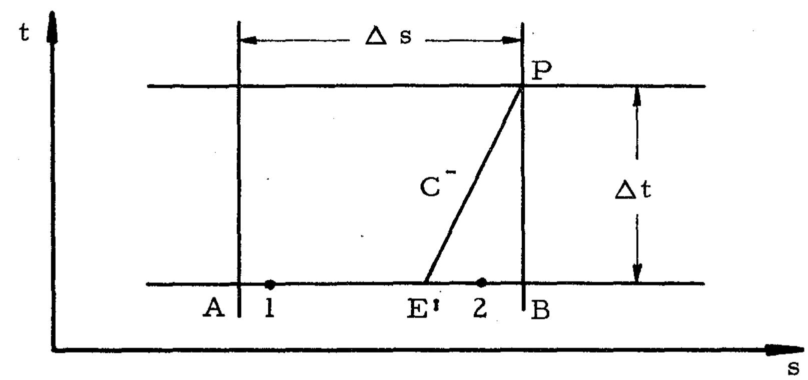
Let points 1 and 2 be given and sit in the upstream (left-hand) side and downstream (right-hand) side, respectively, of point D (Figure 5a), point E (Figure 5b), and point E' (Figure 5c). Points 1 and 2 may or may not be grid points A and B (Figures 5a and 5c), or B and C (Figure 5b), depending upon whether there is a bore or a train of such bores in between. If all the points 1, D, 2, and P are in the same flow region in the case of the C^+ characteristic curve, then



a. For C^+-characteristic curve



b. For C^--characteristic curve (subcritical)



c. For C^--characteristic curve (supercritical)

Figure 5. Location of characteristic curves.

$$\frac{s_2-s_D}{s_2-s_1} = \frac{s_2-s_P}{s_2-s_1} + \frac{\Delta t}{s_2-s_1}\left[\beta V_D + \sqrt{\beta(\beta-1)V_D^2 + \frac{\beta}{\mathbf{F}_o^2}\left(D_D\frac{\cos\theta_D}{\cos\theta_o} + h_D^*\right)}\right] \quad . \quad . \quad . \quad . \quad (53)$$

in which s_1 and s_2 are the coordinates of points 1 and 2, respectively.

With the C^- -characteristic curve, two separate cases must be examined. In the case of subcritical flow,

$$\beta V_E - \sqrt{\beta(\beta-1)V_E^2 + \frac{\beta}{\mathbf{F}_o^2}\left(D_E\frac{\cos\theta_E}{\cos\theta_o} + h_E^*\right)} < 0 \quad . \quad . \quad . \quad . \quad (54a)$$

or simply

$$V_E < \frac{1}{\mathbf{F}_o}\sqrt{D_E\frac{\cos\theta_E}{\cos\theta_o} + h_E^*} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (54b)$$

point E falls between points B and C, as shown in Figure 5b. If points 1 and 2 are again introduced, then

$$\frac{s_2-s_E}{s_2-s_1} = \frac{s_2-s_P}{s_2-s_1} + \frac{\Delta t}{s_2-s_1}\left[\beta V_E - \sqrt{\beta(\beta-1)V_D^2 + \frac{\beta}{\mathbf{F}_o^2}\left(D_E\frac{\cos\theta_E}{\cos\theta_o} + h_E^*\right)}\right] \quad . \quad . \quad . \quad (55)$$

In the case of supercritical flow

$$\beta V_{E'} - \sqrt{\beta(\beta-1)V_{E'}^2 + \frac{\beta}{\mathbf{F}_o^2}\left(D_{E'}\frac{\cos\theta_{E'}}{\cos\theta_o} + h_{E'}^*\right)} > 0 \quad . \quad . \quad . \quad . \quad (56a)$$

or simply

$$V_{E'} > \frac{1}{\mathbf{F}_o}\sqrt{D_{E'}\frac{\cos\theta_{E'}}{\cos\theta_o} + h_{E'}^*} \quad . \quad . \quad . \quad . \quad . \quad . \quad (56b)$$

point E' falls between points A and B, as shown in Figure 5c. If points 1 and 2 are again introduced, then

$$\frac{s_2-s_{E'}}{s_2-s_1} = \frac{s_2-s_P}{s_2-s_1} + \frac{\Delta t}{s_2-s_1}\left[\beta V_{E'} - \sqrt{\beta(\beta-1)V_{E'}^2 + \frac{\beta}{F_o^2}\left(D_{E'}\frac{\cos\theta_{E'}}{\cos\theta_o} + h_{E'}^*\right)}\right] \qquad (57)$$

For convenience, Eqs. 53, 55, and 57 may be expressed in a general form such as

$$\frac{s_2-s_i}{s_2-s_1} = \frac{s_2-s_P}{s_2-s_1} + \frac{\Delta t}{s_2-s_1}\left[\beta V_i + \pi_i \sqrt{\beta(\beta-1)V_i^2 + \frac{\beta}{F_o^2}\left(D_i\frac{\cos\theta_i}{\cos\theta_o} + h_i^*\right)}\right] \qquad (58)$$

in which the index ''i'' for variables s_i, V_i, D_i, θ_i, and h_i^* signifies the corresponding variables, at points D, E, and E'. It can readily be seen from Eqs. 53, 55, and 57 that for i = D, E, and E', $\pi_D = 1$, $\pi_E = -1$, and $\pi_{E'} = -1$, respectively. Use of Eq. 58 thus simplifies greatly the computer programming.

There are three unknowns, s_i, V_i, and D_i, in Eq. 58. To solve Eq. 58 for three unknowns two more equations are needed, i.e.,

$$\frac{s_2-s_i}{s_2-s_1} = \frac{V_2-V_i}{V_2-V_1} = \frac{D_2-D_i}{D_2-D_1} \qquad (59)$$

The Newton-Raphson Second Method (Moursund and Duris, 1967) can be applied to Eqs. 58 and 59 for simultaneous solution of three unknowns s_i, V_i, and D_i, which may be expressed in terms of supposedly known values at points 1 and 2.

After the interpolated quantities at points D and E (or E'), such as s_D and s_E (or $s_{E'}$), V_D and V_E (or $V_{E'}$), and D_D and D_E (or $D_{E'}$) are evaluated, the values of other geometric elements of the channel section at points D and E (or E') can be calculated from the geometry of the section and the values of D_D and D_E (or $D_{E'}$). Other variables such as rainfall intensities, r_D and r_E (or $r_{E'}$), the infiltration rates, i_D and i_E (or $i_{E'}$), the lateral inflow rates from the downstream ends of the overland flow parts, q_{LD} and q_{LE} (or $q_{LE'}$), the terminal velocities of raindrops Λ_D and Λ_E (or $\Lambda_{E'}$), and overpressure heads due to the raindrop impact, h_D^* and h_E^* (or $h_{E'}^*$), can be evaluated from the known functions, at points s_D and s_E (or $s_{E'}$), respectively. Substituting all known quantities at points D and E (or E') into Eqs. 50 and 52 and then solving Eqs. 50 and 52 simultaneously yields the values of V_P and h_P. Because Eqs. 50 and 52 are linear in V_P and h_P, the solutions are straightforward.

The Procedures of Computation

Mathematical expression of cross profile for roadway

The quadratic equation,

$$z = C_1x^2 + C_2x + C_3 \qquad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (60)$$

is the basic equation in formulating the cross profile of the roadway, as shown in Figure 6. Here z and x are the vertical and horizontal coordinates, respectively. From the coordinates of any three points on the road surface the coefficients of the equation, C_1, C_2, and C_3 can be determined. Furthermore, Eq. 60 can be used to express s-coordinate along the roadway profile with $s = 0$ corresponding to $x = 0$ and $z = 0$ because the following relationship exists between x and s coordinates.

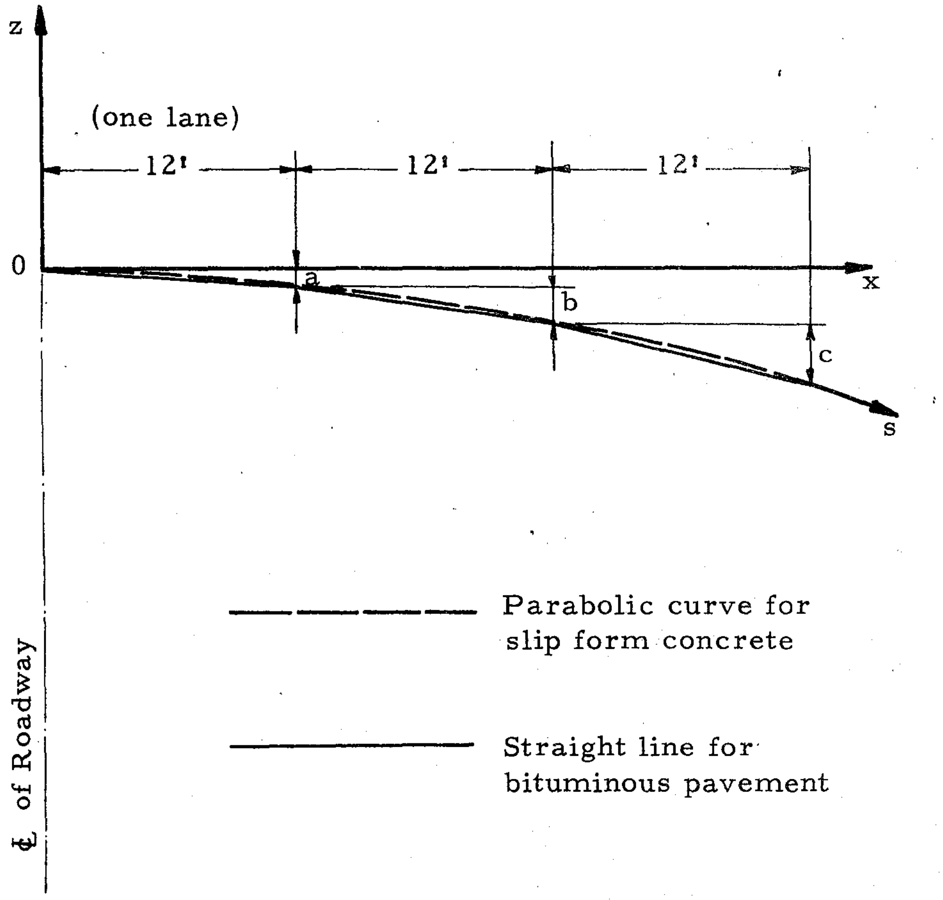
$$\begin{aligned}
s &= \int \sqrt{(dz/dx)^2 + 1} \quad dx = \int \sqrt{4C_1^2x^2 + 4C_1C_2x + C_2^2 + 1} \quad dx \\
&= \frac{2C_1x + C_2}{4C_1} \sqrt{4C_1^2x^2 + 4C_1C_2x + C_2^2 + 1} \\
&+ \frac{1}{4\sqrt{C_1^2}} \log_e \left(8C_1^2x + 4C_1C_2 + 4\sqrt{C_1^2} \sqrt{4C_1^2x^2 + 4C_1C_2x + C_2^2 + 1}\right) \\
&- \frac{C_2}{4C_1} \sqrt{C_2^2 + 1} - \frac{1}{4\sqrt{C_1^2}} \log_e \left(4C_1C_2 + 4\sqrt{C_1^2}\sqrt{C_2^2 + 1}\right)
\end{aligned} \qquad . \quad . \quad . \quad . \quad . \qquad (61)$$

Given the coordinate of s, the coordinate of x can be calculated from Eq. 61 and vice versa. The Newton-Raphson method may be used for numerical solution of Eq. 61 for x with s known. Note that the transformation of coordinate systems from s to x is needed because the characteristic difference equations, Eqs. 50 and 52, are solved on the s, t-plane, but not on the x, t-plane.

For solving Eqs. 50 and 52, the bed slope, S, that changes along the cross profile of the roadway must be evaluated at points D and E (or E') (Figures 4 and 5). The bed slope at any point on the roadway is

$$S = \sin\theta = \sin\left(\tan^{-1}\frac{dz}{dx}\right) \qquad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (62a)$$

or



	a	b	c
Minimum (in. per ft.)	1 1/2" (1/8")	2 1/4" (3/16")	3" (1/4")
Maximum (in. per ft.)	3" (1/4")	4 1/2" (3/8")	6" (1/2")

Figure 6. Typical cross (or crown) slope of roadway.

$$S = \sin\left[\tan^{-1}(2C_1x + C_2)\right] \quad \ldots\ldots\ldots \quad (62b)$$

Arrangement of overland flow and gutter flow sections

For delineating the entire flow region on the roadway between two adjacent drainage inlets, the flow lines that enter the inlets should be known. Unfortunately there is no such information associated with the hydraulic (one-dimensional) approach. Since a sheet flow has a small depth, a line starting at the inlet perpendicular to the contour lines is believed to be the closest to the actual flow line one can guess. Therefore, the entire flow region becomes a plane flow net consisting of contour lines and flow lines, as depicted in area HIJK of Figure 7.

Along a flow line of overland flow, say curve AB in Figure 7, the maximum bed gradient at any point, P, is tangent to curve AB, as shown by arrow PT in Figure 7, and is the vector summation of the bed gradient in the gutter direction, PC, and the bed gradient of the roadway crown, PR. Similarly the resultant velocity along AB can be considered as the vector summation of two velocity components: one along the crown of the roadway and the other in the direction of gutter flow. Both velocity components at the upstream end of overland flow must be zero (i.e., boundary conditions). In the true simulation of overland flow, the resultant velocity along the flow line should be considered. However, if flow lines, such as shown in area HIJK of Figure 7, are curvilinear, the computation should proceed along the curvilinear flow lines that are unfortunately very difficult, if not impossible, to be traced. Instead of tracing the flow line and having the resultant velocity computed along the flow line, one can simply compute the velocity component along the crown of the roadway, which is in the direction perpendicular to the gutter flow. This simplification in the computation is justified because the velocity component in parallel to gutter flow is equal for a line connecting the same crown slope and is equivalent to making the assumption that the true flow region HIJK is transformed into the conceptual rectangular flow region H'I'JK. Thus, only the velocity component along the cross profile of the roadway is routed.

The lateral inflow rate, q_L, per unit length of the gutter is actually equal to the overland-flow discharge per unit width along flow line AB at point B on the internal boundary multiplied by the cosine of the angle ψ that the direction of overland flow at point B makes with the line perpendicular to the gutter flow (Figure 2). This lateral inflow rate, q_L, is of the same magnitude as that calculated from overland flow along line A'B at the same point B on the internal boundary. Therefore, routing the overland flow in the conceptual area H'I'JK with

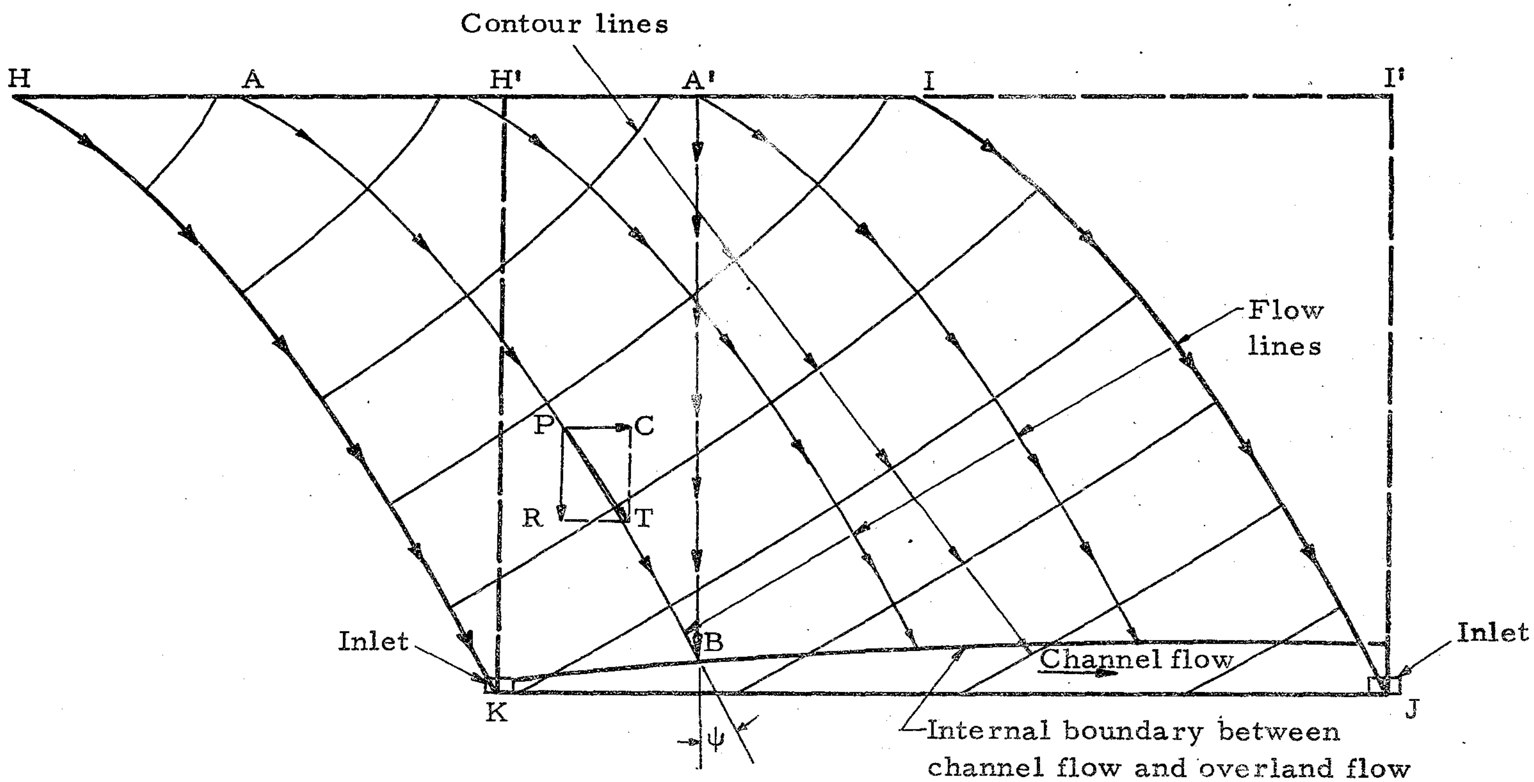


Figure 7. Contour lines and flow lines on the road surface.

the velocity component perpendicular to the channel flow is tantamount to routing it in the actual area HIJK with the resultant velocity along the flow line. The validity and practical applications of the present technique routing storm water over the conceptual rectangular area H'I'JK can only be examined by comparing the computed results with field data.

Given the conceptual rectangular watershed area, the routing arrangement of overland flow and channel flow can proceed as follows. As shown in Figure 8, let the value of N indicate the location of the given section associated with both overland flow and gutter flow, that of K the location of the given grid point, and that of T the time level. For example, N = 1 is the overland flow section 1 at the upstream end of gutter flow, N = NN is the overland flow section NN at the downstream end of gutter flow, and N = NN + 1 is the gutter flow itself. The grid points associated with K = 1 correspond to those at the upstream ends of both overland flow and gutter flow. The values of KN and NN represent the total numbers of grid points in the overland-flow and gutter-flow parts, respectively. Therefore, any given variable with a given grid point (N, K, T) will be specifically referred to that variable at the N-th section, K-th grid point, and T-th time level. Note that corresponding to each grid point of gutter flow, there is a section of overland flow. Consequently there are a total of ''NN'' number of overland flow sections. The number of the grid points, KN, in the overland-flow part changes with the location of the moving internal boundary between overland flow and channel flow with the last grid point, KN, being designated as the first one to the right of the internal boundary.

The distance interval between two grid points in the overland-flow part is denoted by Δs_{RS}, as shown in Figure 8, and that in the channel-flow part by Δs_{GU}. For convenience, the distance interval between grid points KN-1 and KN in the overland-flow part does not need to be limited to Δs_{RS}.

Elementary drainage area for curved roadway

To apply the same one-dimensional numerical model formulated in the previous section for runoff on the straight roadway to the case on the curved roadway requires only a slight modification on the elementary drainage area at each grid point. Note that for straight roadway, the elementary drainage area, ΔA_o (= Δs_{RS} x Δs_{GU}), as shown in Figure 8 is constant everywhere on the roadway, provided that the distance intervals, Δs_{RS} and Δs_{GU}, taken in both overland and gutter flow directions are invariant. However, this is not always the case on a curved roadway which is considered as a composition of several sections of different curvatures with straight longitudinal slopes. There are two alternative ways by which runoff on the curved roadway can be modeled. One is to keep ΔA_o constant by adjusting the Δs_{RS} and Δs_{GU} lengths and the other, vice versa. It seems more difficult to handle a problem with varying Δs_{RS} and Δs_{GU} in the curvilinear coordinate system (s_{RS}, s_{GU}) associated with the curved roadway than that with varying ΔA_o for specified Δs_{RS} and

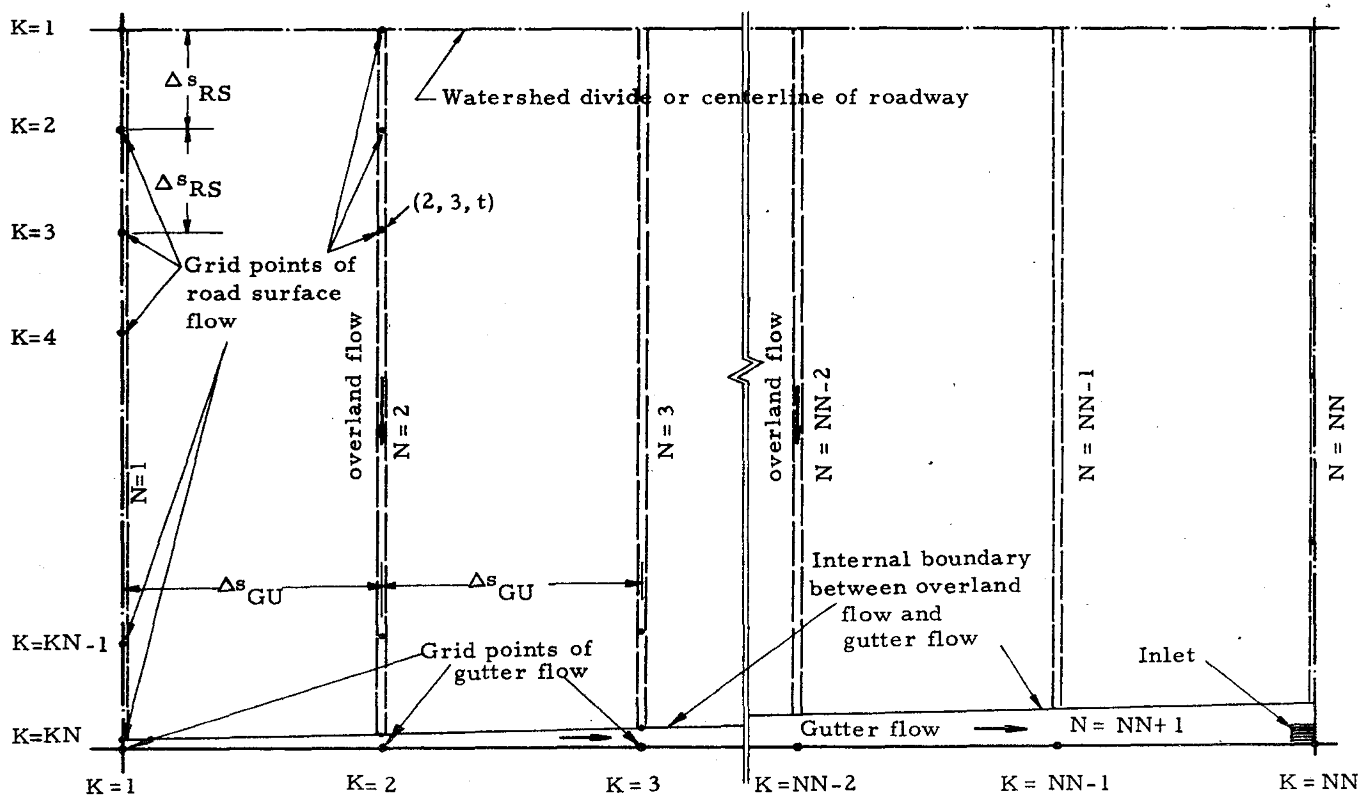


Figure 8. The routing arrangement of overland flow and gutter flow.

Δs_{GU}. Therefore, the latter method is used to find a correction factor for the variation in ΔA_o with specified Δs_{RS} and Δs_{GU} on the curved roadway. The value of the correction factor so formulated should depend on the coordinates of a grid point in question and thus apply only to those quantities defined with reference to ΔA_o such as the rainfall intensity, r, and the infiltration rate, i.

Consider an elementary drainage area, ΔA, (shaded) as shown in Figure 9, on the curved roadway. If the inner and outer radii of curvature for ΔA are assigned r_1 and r_2, respectively, then

$$\Delta A = \frac{\theta}{2} (r_2^{\,2} - r_1^{\,2}) \quad \ldots \ldots \ldots \quad (63)$$

in which θ is the central angle in radians subtended by Δs_{GU}, or

$$\theta = \frac{\Delta s_{GU}}{r_c} \quad \ldots \ldots \ldots \quad (64)$$

in which r_c is the radius of curvature for the gutter flow length, L_{ch}. Geometrically on the average,

$$r_2 = r_c + L_{rs} - s + \frac{\Delta s_{RS}}{2} \quad \ldots \ldots \ldots \quad (65)$$

$$r_1 = r_c + L_{rs} - s - \frac{\Delta s_{RS}}{2} \quad \ldots \ldots \ldots \quad (66)$$

in which L_{rs} is the overland flow length and s is the overland-flow coordinate of the center of ΔA. Substituting Eqs. 64, 65, and 66 into Eq. 63 yields

$$\Delta A = \Delta A_o \left(1 + \frac{L_{rs} - s}{r_c}\right) \quad \ldots \ldots \ldots \quad (67)$$

or

$$\left(1 + \frac{L_{rs} - s}{r_c}\right) = \frac{\Delta A}{\Delta A_o} \quad \ldots \ldots \ldots \quad (68)$$

The ratio of the elementary drainage areas, ΔA on the curved roadway to ΔA_o on the straight roadway is indeed a correction factor, Eq. 68, which will be used to multiply all the terms containing r and i in Eqs. 50 and 52. The correction factor becomes unity as an overland-flow grid point approaches to the gutter ($s = L_{rs}$). Furthermore, no

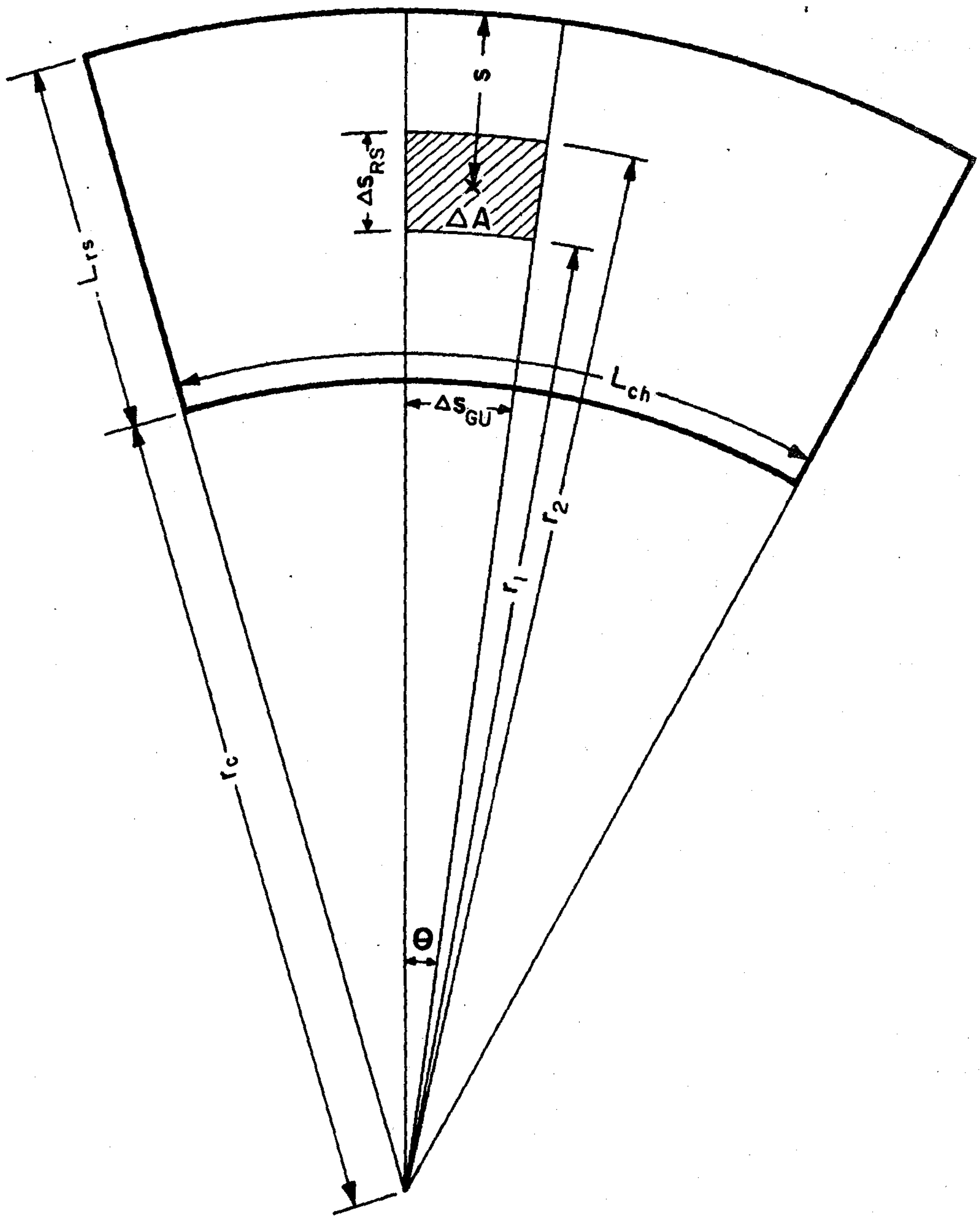


Figure 9. An elementary drainage area of the curved roadway.

contradiction seems to be induced by multiplying the correction factor to the r and i terms even in the case of the straight roadway, for the correction factor automatically becomes unity as r_c approaches to infinity. In application, however, the r_c value in Eq. 68 needs to be determined in advance.

The minimum permissible radius of curvature, r_c, in ft is determined by the highway design speed, U, in mph, and the maximum superelevation, e, in ft per ft of roadway width of the curved roadway as follows (Highway Research Board, 1957; Noble 1960):

$$r_c = \frac{0.067U^2}{e + f} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (69)$$

in which f is the side friction (cornering ratio) between tires and road surface. American Association of State Highway Officials (AASHO, 1973) has specified that (1) maximum superelevation rates of 0.04 to 0.06 are commonly used on arterial streets, (2) on freeways maximum superelevation rates of 0.06 to 0.08 usually apply, and (3) maximum superelevation rates of 0.10 to 0.12 are applicable for those highways if snow and ice are not factors. Highway curve design data for assumed maximum superelevations of 0.04, 0.06, 0.08, 0.10, and 0.12 can be found in AASHO (1973, 1965). A friction of $f = 0.10$ is a conservative value to be used for main-line highway design (Moyer, 1934).

Reference (or normalizing) quantities

The angle of inclination of the gutter bottom is taken as the reference angle of inclination, θ_o. Therefore the reference slope, S_o, is the gutter slope, defined as $\sin\theta_o$. The reference length, L_o, can be either the length of gutter flow or that of overland flow, or a combination thereof. The discharge at the downstream end of gutter flow at the equilibrium stage is considered as the reference discharge, Q_o, corresponding to the reference rainfall intensity, r_o. That is

$$Q_o = r_o B = A_o V_o \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (70)$$

in which B is the total projected area of the runoff surface on the horizontal plane, A_o is the reference cross-sectional area of flow, and V_o is the reference velocity of flow. The value of A_o cannot be determined unless V_o is known and vice versa. Thus, both quantities can only be calculated by a trial and error as follows. Assuming that water with the reference discharge Q_o flows uniformly in the gutter with the reference slope S_o, one obtains from Eq. 18

$$S_o = \frac{f_o V_o^2}{8gR_o} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (71)$$

in which f_o is the reference friction coefficient and R_o is the reference hydraulic radius. Combination of Eqs. 70 and 71 yields

$$Q_o = \sqrt{\frac{8g}{f_o}}\ A_o\ \sqrt{R_o S_o} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (72)$$

Equation 72 can be solved for the reference hydraulic depth, D_o, because A_o and R_o are all functions of D_o and the value of f_o can be calculated by using Eq. 19, 20, or 21. For simplicity, the reference gutter flow with Q_o is conceptually treated as 1-ft rectangular channel flow in the present analysis. Therefore, the reference top width, T_o, simply becomes unity and $A_o = R_o = D_o$. Solution of Eq. 72 needs an iteration method such as used by Chen and Chow (1968). After D_o is determined, the corresponding value of A_o, and hence V_o, can be obtained from the geometric relationship of the 1-ft rectangular channel and Eq. 70, respectively.

The reference Froude number is defined as

$$\mathbf{F}_o = \frac{V_o}{\sqrt{gD_o \cos\theta_o/\beta}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (73)$$

Assuming initial conditions

Immediate difficulty arises when the initial conditions, Eqs. 22 and 23, in the form of difference scheme are used to start the computation. If the velocity and depth of flow are all zero everywhere at the initial stage, the method of characteristics using an explicit scheme with specified grid intervals fails immediately at the subsequent time level. Therefore, it appears necessary for each problem to assume an appropriate initial condition.

In the case of stationary uniform rainfall (i.e., equivalent to have an infinite storm velocity), assume that the initial depth of flow on the roadway, h_{rs}, is small, say one fifth of the flow depth at the second grid point on the roadway at the equilibrium stage or the roughness size, k, of the ground surface, whichever is smaller. The corresponding time for this condition is

$$t_s = \frac{h_{rs}}{r} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (74)$$

When the top width of gutter flow becomes zero, an immediate failure of computation by use of Eqs. 50 and 52 will result unless an initial depth higher than h_{rs} is assumed in the gutter. Let us assume the depth of gutter flow, h_{gs}, to be

$$h_{gs} = 2h_{rs} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (75)$$

Then the non-zero top width of gutter flow can be obtained accordingly at the initial state.

The initial velocity of flow, V_s, at any point on a roadway assumed to be that of the uniform flow with the corresponding bed slope, S, roughness size, k, and flow depth, h_{rs} or h_{gs}, at the point under consideration. Because the bed slope of the roadway steepens as it approaches the point where overland flow meets with gutter flow (i.e., the internal boundary), the initial velocity of flow so computed increases considerably with the cross profile of the roadway.

For moving rainstorms, the initial conditions must be set up differently from that of stationary rainstorms, as described above. The storm front may move in any direction with a storm velocity, W, which may differ considerably, depending upon physiographical and hydrometeorological factors. It is possible that the storm moves so slowly that the wavefront produced on the dry bed outraces the storm front. Although the assumed initial conditions, if generalized, can be applied to a storm moving in any direction, only those related to storms moving in the same direction as those of overland flow and gutter flow, or in the opposite direction, are treated herein. When the roadway is initially dry and a storm just enters the upstream end (i.e., highway watershed divide), the amount of water coming from rainfall and then staying on the ground around the upstream end is too little to be utilized as a starting condition of the subsequent computation. Furthermore, there is no way to know beforehand how this little amount of water behaves around the upstream end of the ground surface. In fact, it is part of the solution being sought. In order for the present method to be valid in this case, it appears that the assumption of a non-zero depth of water extending over at least the two uppermost grid points is necessary for the numerical computation to start with. An alternative way to circumvent this starting problem is to subdivide the distance interval between the two uppermost grid points into finer distance intervals and then the same assumption of a non-zero depth of water applied to the uppermost, finer distance interval. Results obtained from the latter approach are believed to be more accurate than those obtained from the former approach; however, in view of a considerable increase in the computer time with the latter approach, the uppermost distance interval is not subdivided herein.

The initial location of the stormfront, say at the second grid point (i.e., K = 2 in Figure 8) from the upstream end, will be assumed and the corresponding time for the stormfront to reach that point will be computed. Similarly the initial location of the wavefront, say halfway between the second and the third grid points, will also be assumed and the corresponding depth and velocity of flow will be computed on the assumption that they are uniform throughout the wavefront and the volume of water retained on the ground surface is equal to that of rainwater falling on the ground surface during that period of the initial time. Hopefully, the depth and velocity of flow so assumed at the upstream end (i.e., $K = 1$ in Figure 8), at the second grid point, and at the wavefront will adjust themselves in the computations at subsequent time levels. As shown by Chu (1973), if the location of the wavefront assumed is too far downstream, the wavefront will move slightly upstream to make automatic adjustments of its location in the subsequent computations. These are the initial conditions assumed for a storm moving in the direction of overland flow.

The number of initial conditions to be assumed for a storm moving in the direction of gutter flow is more than that in the direction of overland flow. As soon as a storm enters the roadway in the direction of gutter flow, immediately a combined overland and gutter flow occurs at the upstream end of the gutter. Both locations of the stormfront and the wavefront of gutter flow can be assumed as those for a storm moving in the direction of overland flow, but the depth and velocity of flow in the overland-flow part at different sections of gutter flow for the initial time period must be computed accordingly. It appears that the initial depth of flow which is assumed uniform throughout the wavefront in the gutter needs to be assumed larger than that at the internal boundary, preferably three times greater, in order to proceed smoothly in subsequent computations.

When a storm is moving in the opposite direction to the flow, either overland flow or gutter flow, (i.e., from the downstream end to the upstream end), no advancing wavefront exists and the initial conditions can be assumed as those for a stationary rainstorm extending over a certain distance interval from the downstream end to the assumed stormfront.

Evaluation of the friction coefficient

Equation 19, 20, or 21, as depicted in Figure 3, is used to evaluate the friction coefficient, f. However, if the depth of flow, h, or hydraulic radius, R, is very small with almost the same order of magnitude as the roughness size, k, an unrealistically large value of the friction coefficient, f, may result from Eq. 19, 20, or 21. To improve this poor evaluation of f, Chen and Chow (1968) proposed the friction slope, S_f, at the initial stage to be evaluated from the energy equation formulated at each grid point. As shown in Figure 10, the head loss, h_f due to friction between points D and E (or E') is assumed equal to $S_f \Delta s_{DE}$ (or $S_f \Delta s_{DE'}$), in which Δs_{DE} and $\Delta s_{DE'}$ are the channel distances between points D and E and between points D and E', respectively. Thus

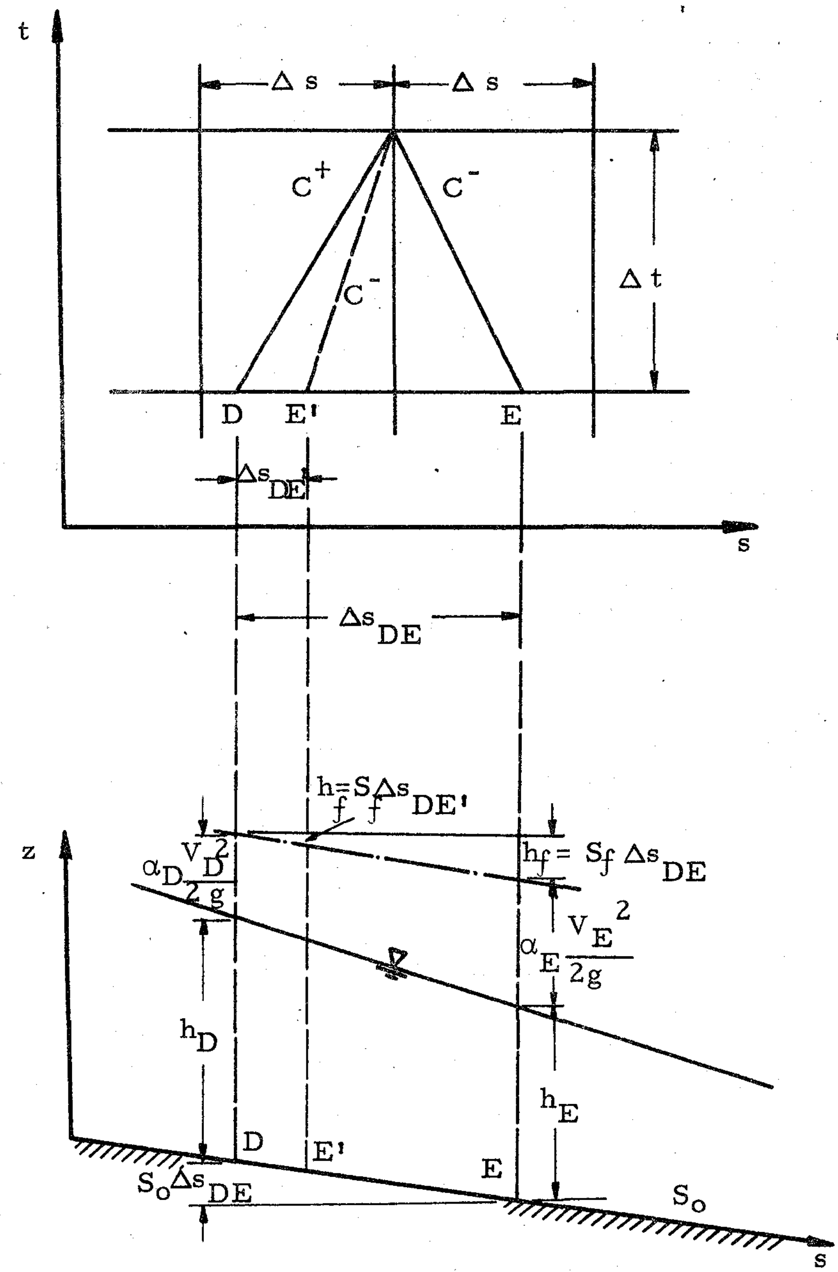


Figure 10. The value of friction slope, S_f, evaluated by the energy equation.

$$S_f = S_{DE} + \frac{h_D - h_E}{\Delta s_{DE}} + \frac{\alpha_D \frac{V_D^2}{2g} - \alpha_E \frac{V_E^2}{2g}}{\Delta s_{DE}} \quad . \; . \; . \; . \; . \qquad (76a)$$

or

$$S_f = S_{DE'} + \frac{h_D - h_{E'}}{\Delta s_{DE'}} + \frac{\alpha_D \frac{V_D^2}{2g} - \alpha_{E'} \frac{V_{E'}^2}{2g}}{\Delta s_{DE'}} \quad . \; . \; . \; . \qquad (76b)$$

in which α_D and α_E (or $\alpha_{E'}$) are the energy correction factors at points D and E (or E'), respectively. The theoretical evaluation of the energy correction factor for laminar and turbulent flow is appended to this report (Appendix 1).

A few preliminary computer experiments revealed that use of Eq. 76a or 76b alone resulted in the erroneous longitudinal velocity distribution which changes only slightly, if not at all, with time. In view of this problem, it appears that Eq. 76 can only be used whenever Eq. 19, 20, or 21 fails to compute the realistic f value. In effect Eq. 76 plays only a role of transition in the evaluation of the friction slope, S_f, or friction coefficient, f. Chen and Chow (1968) compared the value of S_f computed from Eq. 18 with that from Eq. 76 and selected the smaller one. However, if Eq. 76 simply plays a role of transition in the evaluation of S_f from one value to another computed by using Eq. 19, 20, or 21, both equations should give about the same computed value of S_f or f at the equilibrium state where the depth of flow is much higher, possibly many times higher, than the roughness size. For most cases of the problems investigated, use of Eq. 76 happened both at the initial stage of the computation and at the final stage of receding flow after rain stops. Because the initial conditions formulated at the beginning of the computation are nothing but assumptions, as already described before, the f value estimated by use of Eq. 19, 20, or 21 at the beginning stage of the computation was so unrealistic that the depth and velocity computed at each grid point by means of Eqs. 50 and 52 easily became too low or too high. If this undesirable situation had developed, the computation at next time level could have immediately broken down unless some kind of bypassing alternatives were built into the computer program. Use of Eq. 76 might be regarded as one of such alternatives. There were some other instances, in which Chen and Chow's (1968) scheme might also fail when the S value determined from Eq. 76 is always smaller than that obtained from Eq. 18, even at the equilibrium state. This in a sense implies another undesirable situation in which Eq. 76 has been used alone all the time in the evaluation of the S_f. A few exploratory computer experiments indicated that in some cases, especially for extensively long overland flow consisting of combined regimes of flow resistance such as partially laminar upstream and partially turbulent downstream, the flow would probably never reach the equilibrium state if only Eq. 76 was used in the computation. A compromise between the use of Eq. 18 and that of Eq. 76 must thus be in order. The role of transition played by Eq. 76 suggests that taking the average value of S_f or f computed by both equations at each time level may be a good approximation for practical purposes (Chu, 1973).

Although there are few more technical difficulties in the computation than just described above in connection with the present numerical scheme, similar alternatives were used to overcome such difficulties, wherever they occurred. In some problems, for example, with low rainfall intensity and steep slope, the depth of flow throughout the channel remains very small with an order of magnitude of the roughness size, k, or less even at the equilibrium state. In this case, additional judicious assumptions have to be made because the evaluation of S_f or f by using the method, as described above, still produces unrealistic values. Physically, when the depth of flow becomes smaller than the roughness size, the water movement around protruded roughness particles on the ground surface must be slow, in a way analogous to porous media flow regardless of whether or not raindrops are impinging on the water surface. Therefore, one may assume that there exists a minimum depth below which the flow is so slow (i.e., laminar) that the laminar flow equation (i.e., a combination of Eqs. 18 and 21) applies. The minimum depth may change with channel slope and rainfall intensity, but for simplicity it is assumed constant herein. An analysis of Woo and Brater's (1961) data reveals that the minimum depth approaches asymptotically twice the roughness size with the increase in the bed slope within their slope range tested. The value of f corresponding to the minimum depth is computed from Eq. 19 for $R/k = 2$ to be about 0.115, as indicated in Figure 3, and the value of C in Eq. 21 may be evaluated as follows.

Let the value of C depend on the bed slope, S, the rainfall intensity, r, and the roughness size, k. Then for uniform laminar flow with depth less than the minimum depth, say εk, where ε is assumed constant [i.e., $\varepsilon = 2$ in Chu's (1973) study], the Darcy-Weisbach equation, Eq. 18, is expressed as

$$S = \frac{fV^2}{8gR} \qquad \ldots\ldots\ldots\ldots \qquad (77)$$

which upon combination with Eq. 21 reduces to

$$S = \frac{C\nu V}{8gR^2} \qquad \ldots\ldots\ldots\ldots \qquad (78)$$

However, when the depth of flow increases and the hydraulic radius exceeds εk, the flow under study can become either laminar or turbulent. Consequently, one may assume that at $R = \varepsilon k$, both Eqs. 19 and 21 satisfy Eq. 77 as follows:

$$S = \frac{C \nu V}{8g(\varepsilon k)^2} \quad \text{. . . . .} \quad (79)$$

$$S = \frac{1}{8g[2\log(2\varepsilon) + 1.74]^2} \; \frac{V^2}{\varepsilon k} \quad \text{. . . . .} \quad (80)$$

Eliminating V from Eqs. 79 and 80 yields

$$C = \frac{[8gS(\varepsilon k)^3]^{1/2}}{\nu[2\log(2\varepsilon) + 1.74]} \quad \text{. . . . .} \quad (81)$$

This is the formula for C, the value of which is assumed to be greater than the theoretical 24 and varies with S and k, as shown in Figure 11 for $\varepsilon = 2$. Equation 81 for $\varepsilon = 2$ and $k = 0.00333$ ft is also plotted in Figure 11 and compared with Woo and Brater's (1961) result. It is not surprising to see that they deviate significantly from each other, for the value of ε in Woo and Brater's data varies from 4 for small S to 2 for large S. No way of improving the expression of Eq. 81 was discovered unless one knows the variation of ε with S and k <u>a priori</u>. Despite the difficulty in the analytical expression of the C value, Eq. 81 was used in Chu's (1973) study as a first-order approximation. Apparently there is a question regarding the general applicability of Eq. 81 which merits a few comments in the following.

To make use of Eq. 81 for assumed $\varepsilon = 2$, one has to know the roughness height, k, for a surface under investigation. However, the k value for a given surface is the hardest to determine. Usually most kinds of material determined from experiments have a wide range of the k value. For example, the k value for concrete varies from 0.0015 to 0.0100 ft (Chow, 1959). Because the k value for a glued-sand surface used in Woo and Brater's (1961) experiments lies within the range of concrete, the C values determined from their experimental data may be used as a basis for the computation of sheet flows over concrete or bituminous surfaces without further determining the k value. This approach seems to be more acceptable than use of Eq. 81 in the engineering practice, for a highway engineer does not need to measure or determine the roughness height for concrete or other kinds of material.

In general, the following relationship exits between the C value and bed slope, S, for a given surface (Chen, 1975a):

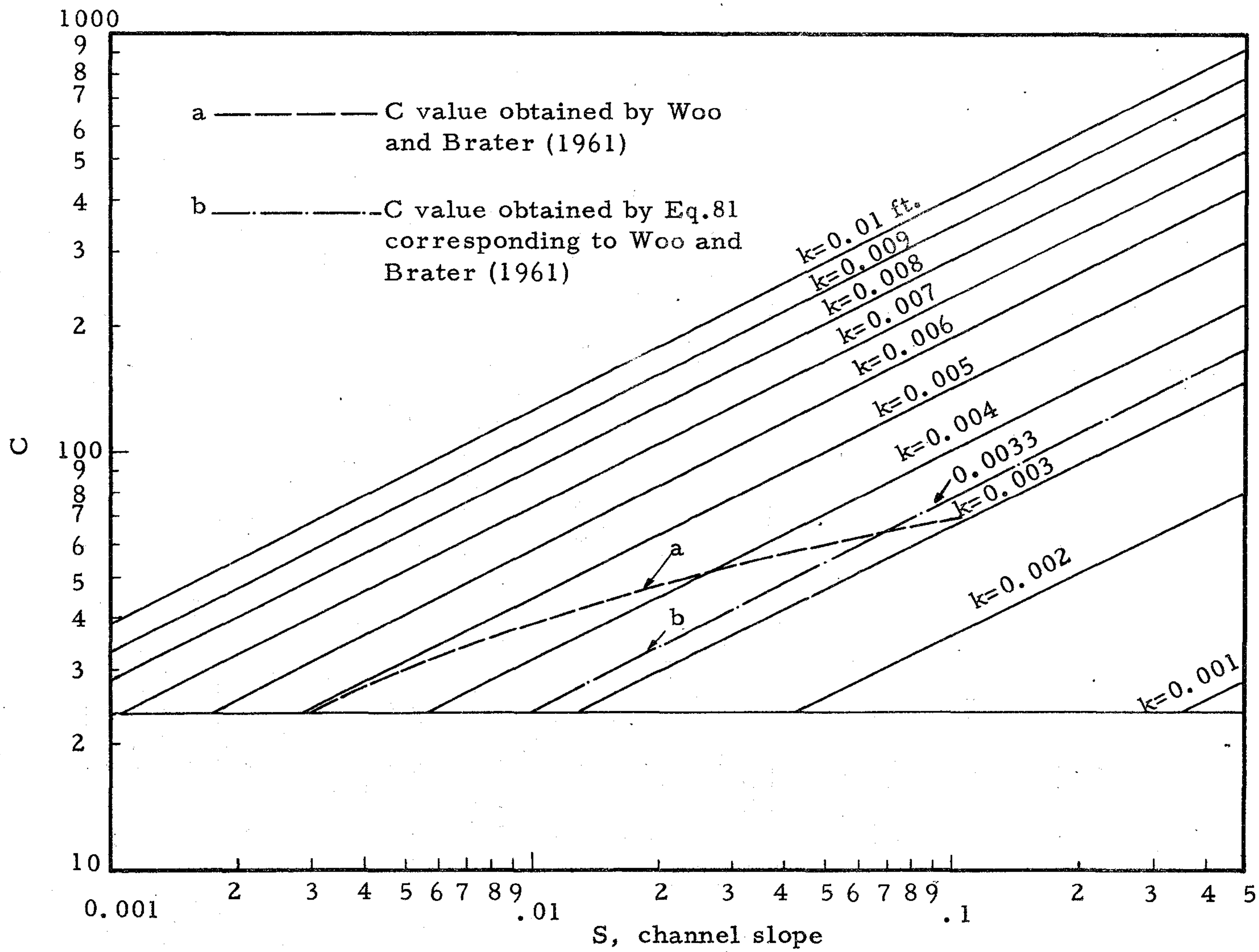


Figure 11. Relationship between C value, S, and k.

$$C = aS^b \qquad (82)$$

in which a and b are parameters, the values of which seem to vary with k and r, the rainfall intensity, if it is under rain. A further analysis of Woo and Brater's (1961) experimental data resulted in approximately a = 235 and b = 0.296 for a glued-sand surface which will be assumed to have the same roughness height as a concrete or bituminous surface in the present study. For use in the computation of overland flow on the side-slope, Chen (1975a) has experimentally determined a = 510,000 and b = 0.662 for natural turf surfaces. Thus, Eq. 82 assigned with the preceding values of a and b for concrete and turf surfaces is used throughout this runoff modeling study.

Given the expression of C, the velocity V in the shallow laminar flow range can now be expressed by substituting Eq. 82 into Eq. 78 as

$$V = \frac{8g}{a\nu} R^2 S^{(1-b)} \qquad (83)$$

which shows an interesting result because the values of the exponent, (1 - b), of S in Eq. 83, 0.704 for concrete and 0.338 for turf, are less than theoretical unity. In the present study, the laminar flow using Eq. 83 is assumed for $R < \varepsilon k$, in which the value of ε may be determined by best fitting the computed hydrographs to the measured ones obtained from field data.

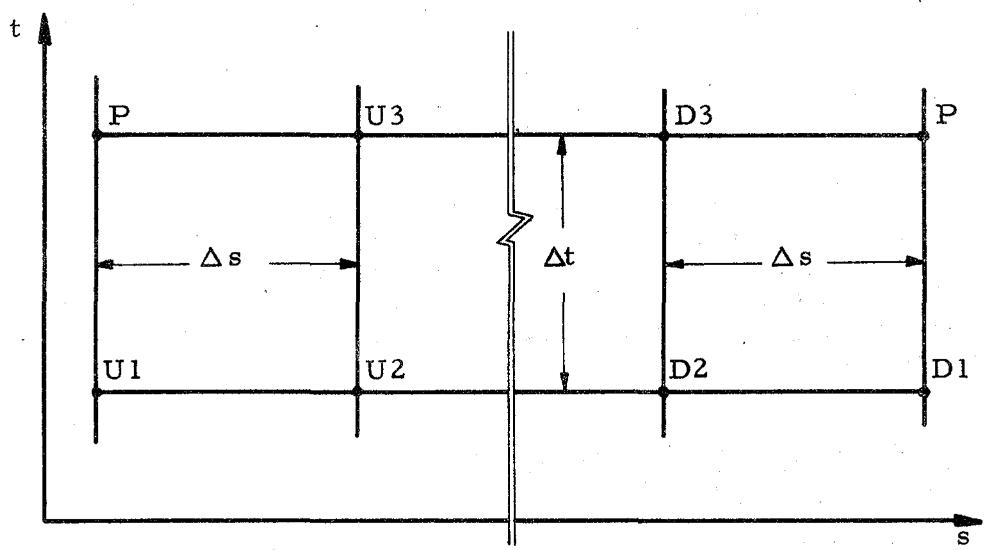
Numerical formulation of external and internal boundary conditions

Upstream boundary conditions. Equation 2 in dimensionless form using normalized variables such as defined in Eq. 35 is

$$\frac{\partial Q}{\partial s} + \frac{\partial A}{\partial t} = \frac{L_o T_o r_o}{A_o V_o} (\bar{r} - \bar{i})\, \bar{T}\ \overline{\cos\theta} + \frac{L_o}{T_o \cos\theta_o}\, \bar{q}_L \qquad (84)$$

in which asterisk subscript used to represent normalization was already dropped from all the variables for brevity and $\overline{\cos\theta}$ is the average value of $\cos\theta$ between two grid points under consideration. Consider two uppermost grid points as shown in Figure 12a. The partial derivatives in Eq. 84 can be expressed by the following finite-differences

$$\frac{\partial Q}{\partial s} = \frac{1}{2}\left(\frac{A_{U3}V_{U3} - Q_u}{\Delta s} + \frac{A_{U2}V_{U2} - A_{U1}V_{U1}}{\Delta s}\right) \qquad (85)$$



a. Upstream end b. Downstream end

Figure 12. Grid points at upstream end and downstream end.

$$\frac{\partial A}{\partial t} = \frac{1}{2}\left(\frac{A_P - A_{U1}}{\Delta t} + \frac{A_{U3} - A_{U2}}{\Delta t}\right) \quad \text{. . . . .} \quad (86)$$

in which all subscripts refer to the grid points defined in Figure 12a. The upstream boundary condition is

$$V_P = \frac{Q_P}{A_P} = \frac{Q_u}{A_P} \quad \text{. . . . .} \quad (87)$$

in which Q_u is the carry-over discharge, if any, from the upstream end. Specifically, for overland flow, $Q_u = 0$. Replacing the partial derivatives in Eq. 84 by the corresponding finite-differences, Eqs. 85 and 86, yields

$$A_P = A_{U1} + A_{U2} - A_{U3} - \frac{\Delta t}{\Delta s}(A_{U2}V_{U2} + A_{U3}V_{U3} - Q_u - A_{U1}V_{U1})$$

$$+ 2\Delta t\left[\frac{L_oT_or_o}{A_oV_o}\ (\bar{r} - \bar{i})\ \bar{T}\ \overline{\cos\theta} + \frac{L_o}{T_o\cos\theta_o}\ \bar{q}_L\right]$$

$$\text{. . . . . . .} \quad (88)$$

in which

$$\bar{r} = (r_{U1} + r_{U2} + r_{U3} + r_P)/4 \quad \text{. . . . . . .} \quad (89)$$

$$\bar{i} = (i_{U1} + i_{U2} + i_{U3} + i_P)/4 \quad \text{. . . . . . .} \quad (90)$$

$$\bar{T} = (T_{U1} + T_{U2} + T_{U3})/3 \quad \text{. . . . .} \quad (91)$$

$$\overline{\cos\theta} = (\cos\theta_{U1} + \cos\theta_{U2} + \cos\theta_{U3} + \cos\theta_P)/4 \quad \text{. . . . .} \quad (92)$$

$$\bar{q}_L = (q_{LU1} + q_{LU2} + q_{LU3} + q_{LP})/4 \quad \text{. . . . . .} \quad (93)$$

Specifically, for overland flow, where $Q_u = 0$, $V_P = 0$, $\bar{q}_L = 0$, and $\bar{T} = T_{U1} = T_{U2} = T_{U3} = T$, Eq. 88 reduces to

$$A_P = A_{U1} + A_{U2} - A_{U3} - \frac{\Delta t}{\Delta s} (A_{U2}V_{U2} + A_{U3}V_{U3})$$

$$+ 2\Delta t \left[\frac{L_o T_o r_o}{A_o V_o} (\bar{r} - \bar{i}) \bar{T} \overline{\cos\theta} \right] \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (94)$$

then the depth of flow, h_P, can be computed from

$$h_P = A_P \left(\frac{A_o \cos\theta_o}{D_o \cos\theta} \right) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (95)$$

In the gutter, the flow depth, h_P, must be computed simultaneously with the corresponding overland-flow profile. The procedure of this computation will be discussed in detail in the section on "Internal boundary conditions."

<u>Downstream boundary conditions</u>. The downstream boundary conditions at inlet depend on the flow conditions, viz., whether the flow is supercritical or subcritical.

In the case of supercritical flow, both points D and E' of C^+ - and C^- -characteristic curves fall inside the flow region, as shown in Figure 4b (i.e., to the left of the downstream end of gutter flow). Therefore, no boundary condition is needed to be specified and the velocity and depth of flow at the downstream end point P (Figure 12b), V_P and h_P, can be obtained by treating point P as an interior grid point.

For subcritical flow, because point E of C^- -characteristic curve, falls outside the flow region, as shown in Figure 4a, finite-difference equations along C^- -characteristic curve, Eqs. 51 and 52, cannot be used. Water flowing into the inlet may be regarded as that of free overfall flow and the boundary condition there is assumed as a critical flow condition, Eq. 26, or in terms of dimensionless V_P and h_P as

$$F_o \cdot \frac{V_P}{\sqrt{D_P \frac{\cos\theta_P}{\cos\theta_o} + h_P^*}} = 1 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (96)$$

This is the boundary condition at the inlet for subcritical flow. Equation 96 has two unknowns, V_P and h_P (or D_P) which can only be solved for by using another equation, either the C^+ -characteristic difference equation, Eq. 50, or the finite-difference equation of continuity. Because of the intrinsic difficulty in evaluating the friction slope included in Eq. 50, as mentioned previously, it was decided to use the finite-difference equation of continuity which is formulated, in reference to Figure 12b, as follows:

$$A_P = A_{D1} + A_{D2} - A_{D3} - \frac{\Delta t}{\Delta s}(A_{D1}V_{D1} - A_{D2}V_{D2} - A_{D3}V_{D3} + A_P V_P)$$

$$+ 2\Delta t \left[\frac{L_o T_o r_o}{A_o V_o} (\bar{r} - \bar{i}) \, \bar{T} \, \overline{\cos\theta} + \frac{L_o}{T_o \cos\theta_o} \bar{q}_L \right] \qquad (97)$$

in which all subscripts refer to the grid points defined in Figure 12b; and $\bar{r}$, $\bar{i}$, $\bar{T}$, $\overline{\cos\theta}$, and $\bar{q}_L$ are computed by equations similar to Eqs. 89, 90, 91, 92, and 93, respectively, except that subscripts ''U1,'' ''U2,'' and ''U3'' for all variables in Eqs. 89 through 94 must be changed to subscripts ''D1,'' ''D2,'' and ''D3,'' respectively. Solving Eqs. 96 and 97 simultaneously for V_P and D_P requires the internal boundary condition between overland flow and channel flow at the inlet because the cross-sectional area of flow, A_P, varies with the location of the internal boundary and can be computed by the Newton-Raphson Second Method.

The calculation of the carry-over flow. There are two types of storm inlet on the highway: one is called grate inlet and the other, curb-opening (or side-opening). Each type can be with or without gutter depression.

For the grate inlet, the carry-over flow may occur in three ways:

1. Flow past the inlet between the curb and the first slot, q_1.
2. Flow outside the last slot, q_2.
3. Carry-over across the grate itself.

Although from the model studies in the laboratory, Li, Geyer, and Benton (1951) derived the minimum length of grate inlet required to trap the central portion of the flow, the minimum length of grate inlet required to trap the outside portion of flow with or without gutter depression, and carry-over flow rates, q_1 and q_2, it has been found that the derived equations are not valid outside of their experimental conditions. The complicated flow conditions at the inlet area has so far prevented the development of a sound analytical method to compute inlet efficiencies. For simplicity, the inlet will be assumed herein to be operated at 100 percent efficiency without further determining the carry-over flow rates.

The calculation of the carry-over flow for the curb-opening type inlet is not available at present (Li, Sortegerg, and Geyer, 1951).

Internal boundary conditions. Equations 27 and 28 can be written in a dimensionless form by using the normalized variables defined in Eq. 35 and

$$\dot{\xi}_* = \dot{\xi}/V_o, \quad \bar{h}_* = \bar{h}\cos\theta_o/D_o \qquad (98)$$

After dropping asterisk subscript, normalized Eqs. 27 and 28 become

$$A_L(V_L - \dot{\xi}) = A_R(V_R - \dot{\xi}) \qquad (99)$$

$$V_L = V_R + |A_L - A_R| \left[\frac{\beta}{F_o^2} \frac{1}{A_L A_R} \left(\frac{A_L\bar{h}_L - A_R\bar{h}_R}{A_L - A_R} \frac{\cos^2\theta}{\cos^2\theta_o} + h^* \right) \right]^{1/2} \qquad (100)$$

Equations 99 and 100 are the internal boundary conditions which will be incorporated with three other equations for solutions of five unknowns, A_L, V_L, A_R, V_R, and $\dot{\xi}$.

For convenience, the computation for obtaining the discontinuity solution by using Eqs. 99 and 100 can proceed in two steps (Chen and Chu, 1973): One is at the inception of a discontinuity and the other is during its propagation. The computation procedures for the two steps are somewhat different and the former is more difficult than the latter.

1. Generation of a discontinuity. Consider that previously (i.e., at a time level t) there is no discontinuity and a discontinuity suddenly occurs at time level $(t + \Delta t)$ between two grid points A and B, as shown in Figure 13.

Whether or not a discontinuity occurs between two grid points, A and B, at any time level requires a test of Eq. 100 at each grid point with the help of extrapolation formulas extended from the adjacent grid points of both sides. In addition to Eqs. 99 and 100, four linear extrapolation formulas such as formulated by Chen and Chow (1968) are needed in the case of occurrence of a discontinuity for solution of six unknowns: A_L, V_L, A_R, V_R, $\dot{\xi}$, and s_J, where s_J is the location of the discontinuity. In order to satisfy Eq. 100, V_L must be greater than V_R. This condition for Eq. 100 in turn leads to the inequality that

$$V_A > V_B \qquad (101)$$

which should be satisfied if there is a discontinuity between two grid points, A and B.

With Eq. 100 and four extrapolation formulas, an iteration procedure such as the Newton-Raphson Second Method can be developed to locate the discontinuity, s_J, between points A and B. After s_J, A_L (or h_L), V_L, A_R (or h_R), and V_R are determined, the propagation velocity, $\dot{\xi}$, can

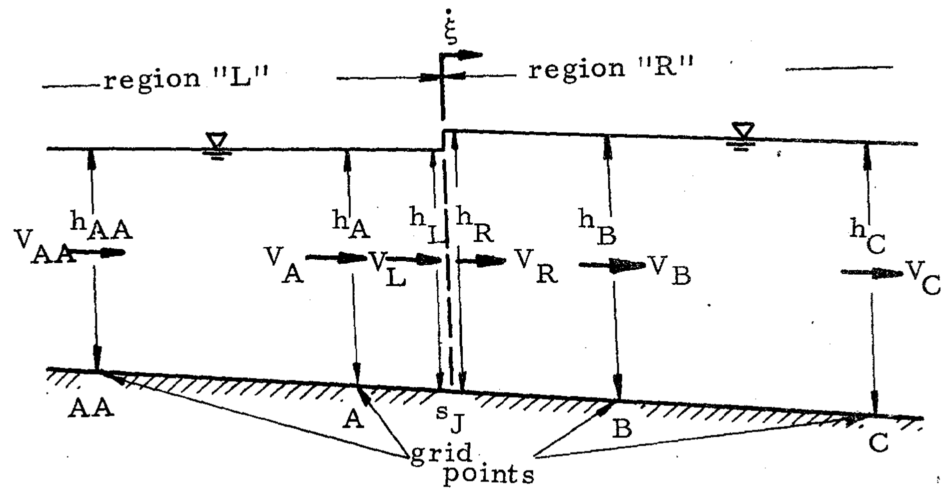
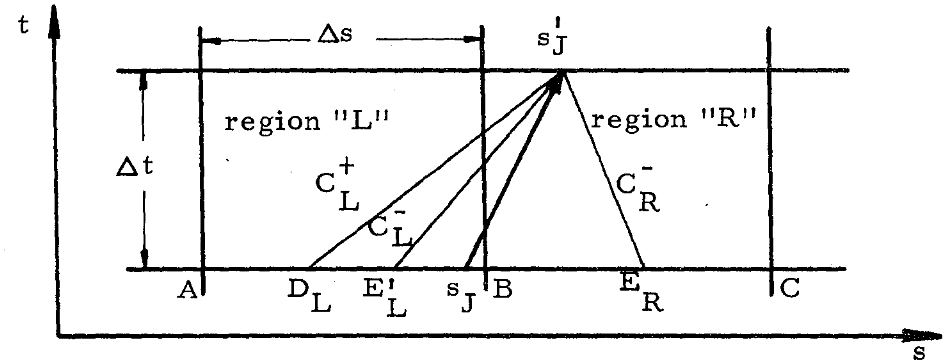
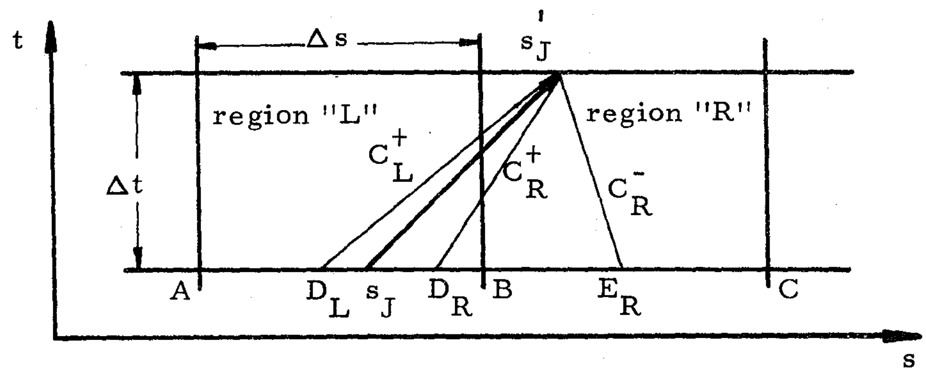


Figure 13. Generation of the discontinuous water surface.



a. For $A_L < A_R$ and $V_L > V_R$



b. For $A_L > A_R$ and $V_L > V_R$

Figure 14. Propagation of a discontinuity.

be computed by means of Eq. 99. Other variables such as $\bar{h}_L$ and $\bar{h}_R$ are evaluated from channel geometric relationships. As a final check, the solutions so obtained should satisfy another set of inequalities, Eqs. 29 and 30 in a dimensionless form (for $V_L > V_R > \dot{\xi}$ and $A_L < A_R$) or Eqs. 32 and 33 in a dimensionless form (for $\dot{\xi} > V_L > V_R$ and $A_L > A_R$); otherwise, there would be no discontinuity between grid points A and B.

2. Propagation of a discontinuity. To find the new location of the discontinuity, s_J', as shown in Figure 14, the conjugate depths, h_L and h_R, and velocities, V_L and V_R, of the discontinuity, and the propagation velocity of the discontinuity, $\dot{\xi}$, at time level $(t + \Delta t)$ from the previous ones at time level t seems relatively easy. The new location, s_J', is related to the previous one, s_J by

$$s_J' = s_J + \dot{\xi}\Delta t \qquad (102)$$

in which Δt is the time increment adopted in the computation at interior points and cannot be taken to be greater than the Courant criterion. Once the new location of the discontinuity is determined, the new values of $\dot{\xi}$, V_L, V_R, h_L and h_R are computed by using the two discontinuity equations, Eqs. 99 and 100, and three appropriate characteristic difference equations formulated along the corresponding characteristic curves for each of the two adjacent gradually varied flow regions from the point of discontinuity. Because there are only five unknowns to be determined, two characteristic difference equations from one flow region and only one characteristic difference equation from the other flow region are sufficient for unique solution. The flow region that has only one characteristic difference equation can be determined from inequalities, Eqs. 31 and 34, for two different cases.

In the case of $A_L < A_R$ and $V_L > V_R > \dot{\xi}$, Eqs. 29, 30, and 31 in a dimensionless form are:

$$V_L - \dot{\xi} > \frac{1}{\mathbf{F}_o} \sqrt{D_L \frac{\cos\theta}{\cos\theta_o} + h_L^*} \qquad (103)$$

$$V_R - \dot{\xi} < \frac{1}{\mathbf{F}_o} \sqrt{D_R \frac{\cos\theta}{\cos\theta_o} + h_R^*} \qquad (104)$$

and

$$V_L + \frac{1}{\mathbf{F}_o} \sqrt{D_L \frac{\cos\theta}{\cos\theta_o} + h_L^*} > V_L - \frac{1}{\mathbf{F}_o} \sqrt{D_L \frac{\cos\theta}{\cos\theta_o} + h_L^*} > \dot{\xi}$$

$$> V_R - \frac{1}{\mathbf{F}_o} \sqrt{D_R \frac{\cos\theta}{\cos\theta_o} + h_R^*} \qquad (105)$$

respectively. From the expressions for C^+ - and C^- -characteristic curves (for $\beta = 1$) in the flow regions ''L'' and ''R,'' and the inequality, Eq. 105, it can readily be seen that there are two characteristic curves, C_L^+ and C_L^-, in flow region ''L,'' but only one characteristic curve, C_R^-, in flow region ''R,'' as shown in Figure 14a. Therefore, the characteristic difference equation along C_R^+ in flow region ''R'' is not needed for the computation of the discontinuity in this case (Figure 14a).

In the case of $A_L > A_R$ and $\dot{\xi} > V_L > V_R$, Eqs. 32, 33, and 34 in a dimensionless form are:

$$\dot{\xi} - V_L < \frac{1}{\mathbf{F}_o} \sqrt{D_L \frac{\cos\theta}{\cos\theta_o} + h_L^*} \qquad (106)$$

$$\dot{\xi} - V_R > \frac{1}{\mathbf{F}_o} \sqrt{D_R \frac{\cos\theta}{\cos\theta_o} + h_R^*} \qquad (107)$$

and

$$V_L + \frac{1}{\mathbf{F}_o} \sqrt{D_L \frac{\cos\theta}{\cos\theta_o} + h_L^*} > \dot{\xi} > V_R + \frac{1}{\mathbf{F}_o} \sqrt{D_R \frac{\cos\theta}{\cos\theta_o} + h_R^*}$$

$$> V_R - \frac{1}{\mathbf{F}_o} \sqrt{D_R \frac{\cos\theta}{\cos\theta_o} + h_R^*} \qquad (108)$$

respectively. Again, from the expressions for C^+ - and C^- -characteristic curves and the inequality, Eq. 108, it can be shown that the characteristic difference equation along C_L^- in flow region ''L'' is not required in this case (Figure 14b).

The preceding criteria for the selection of three characteristic difference equations for use in the computation of a discontinuity are believed to be unique because they do not depend on the direction of the velocities, V_L and V_R, as well as the states of flow in regions ''L'' and ''R.'' In other words, a discontinuity may occur and propagate (or disappear), regardless of subcritical or supercritical flow in regions ''L'' and ''R,'' or a combination thereof, as long as the required conditions for different cases, as stated above, are satisfied.

A good example of the method for computing the discontinuity, as described above, is an advancing wave on the dry surface due to a moving rainstorm. When a moving rainstorm enters the upstream end with relatively small velocity, the water falling on the ground forms an advancing wave moving down the slope on the dry surface. In order for the preceding method to be valid, the singularity in the discontinuity equation, Eq.

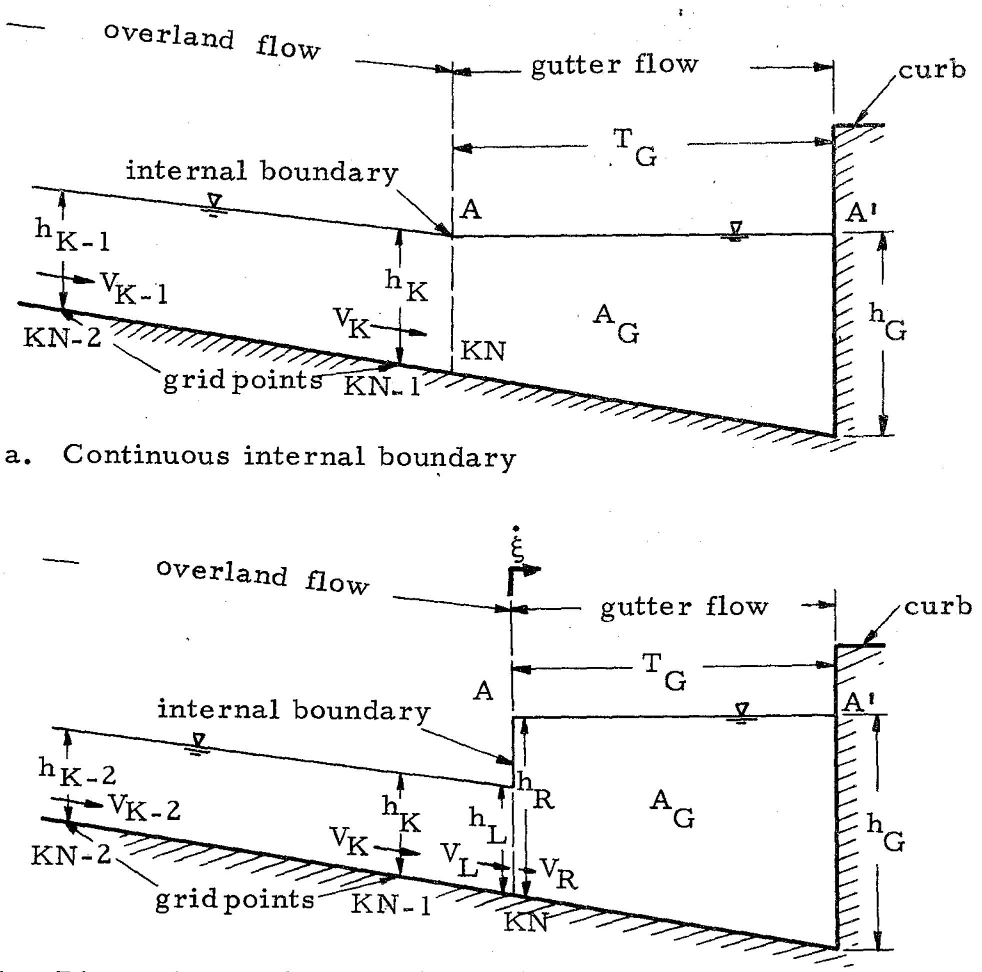
100, where A_R is equal to zero because of the dry surface, has led to the assumption that the right-hand side of the discontinuity (i.e., on the dry surface) has a very small depth with the order of magnitude of the roughness size, k, or less. Regardless of how small A_R is assumed, Eq. 102 used to locate the advancing wavefront should remain valid if the previous location, s_J, is correct. Unfortunately, because the initial conditions of flow and hence the initial location of the wavefront were assumed, as mentioned previously, use of Eq. 102 right after the assumed initial conditions becomes questionable. In order to avoid an inaccuracy in the computation of the wavefront resulting from the use of Eq. 102, the following lumped equation of continuity is used to locate the wavefront:

$$Vol_2 = Vol_1 + Vol_{in} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (109)$$

in which Vol_1 and Vol_2 are the volumes of water retained on the ground surface at time levels 1 and 2, respectively, and Vol_{in} is the total volume of water flowing into Vol_1 during Δt (i.e., from time level 1 to time level 2). Expressions of the volumes can be normalized by using A_o times L_o. In Eq. 109, Vol_1 and Vol_{in} are supposedly known or can be computed directly from input data at time level 1, while Vol_2 can be obtained from the results just computed at time level 2. An iteration procedure such as the Newton-Raphson Second Method can be set up to find s_J' as follows: (1) assume s_J', (2) solve Eqs. 50 and 100 simultaneously for A_L (or h_L) and V_L, (3) compute $\dot{\xi}$ by use of Eq. 99, (4) check if Eq. 109 is satisfied, and (5) if Eq. 109 is not satisfied, repeat steps (1) through (4).

Another good example of the application of the discontinuity equations, Eqs. 99 and 100, is the calculation of the internal boundary between overland flow and channel flow, where the water surface in the gutter flow is assumed to be horizontal, such as shown by line AA' in Figure 15, but may become continuous (Figure 15a) or discontinuous (Figure 15b) with the water surface of overland flow depending upon the flow conditions at the internal boundary. The generation and propagation of the discontinuous internal boundary can proceed in the same way as described above. In this case, the depth on the right-hand side of the discontinuity, h_R, is the depth of gutter flow, h_G, which can be calculated from the geometric relationship of the gutter cross-section in relation with the overland flow profile and the location of the internal boundary. The velocity and depth on the left-hand side of the discontinuity, V_L and h_L, can be extrapolated from the two adjacent upstream grid points, KN-1 and KN-2, (see Figure 15b) in the overland flow part.

If there is no discontinuity at the internal boundary, i.e., inequalities 107 and 108 are not satisfied, the location of the internal boundary is the intersection of the water surface between overland flow and gutter flow (see Figure 15a).



a. Continuous internal boundary

b. Discontinuous internal boundary

Figure 15. Internal boundary between overland flow and gutter flow.

If the gutter flow is of fixed channel type, as shown in Figure 16, as along as the depth of flow, h_G, in the gutter is less than the allowable maximum channel depth, h_{ch}, the internal boundary between the overland flow and channel flow is fixed. Therefore, the boundary condition at the downstream end (i.e., grid point KN) of overland flow is an overfall condition, Eq. 96, and the method described in the section of downstream boundary condition can be applied to the computation of the depth and velocity of overland flow at grid point, KN.

Geometric elements of gutter flow section

The computer model so developed consists of a number of equations expressed in terms of basic geometric elements of the flow section such as the flow cross-sectional area, A, the flow depth, h, the hydraulic radius, R, the hydraulic depth, D, the depth of the centroid of the flow cross-sectional area, $\bar{h}$, and the top width, T. Given or specified one of the geometric elements for a channel with fixed flow boundary such as fixed channel-type gutter flow (Figure 16), the rest of the geometric elements can readily be determined from the relationships characterizing the geometry of the flow section. This is not the case, however, for a channel with moving boundary, such as curb-type gutter flow as shown in Figure 15, in which in addition to one of the geometric elements as indicated above, the top width, T, that moves independently with time must be specified by extrapolation from the geometry of gutter for known gutter and overland flow depths. Because the correct expressions of the geometric elements are essential to the computation of gutter flow, especially for curb type gutter, they are formulated and appended to this report (Appendix 2).

Location of critical section

The location of the critical section (i.e., the section at which the flow changes from subcritical to supercritical) has no direct bearing on the determination of h_P and V_P at each grid point in the various flow regimes. Nevertheless, it was computed wherever such a change in the flow regime took place because it can be used to check the assumptions made in the evaluation of the flow resistance for sheet flow over a rough or smooth surface. Let there be a critical section in a channel between two grid points A and B and x_S denote the position of the critical section. Then the following relationship must exist at x_S [Chen and Chow (1968)]:

$$V_S = \frac{1}{\mathbf{F}_o} \sqrt{D_S \frac{\cos\theta}{\cos\theta_o} + h_S} \qquad \ldots\ldots\ldots \qquad (110)$$

in which the velocity and hydraulic depth of flow at the critical section, V_S and D_S, can be linearly interpolated from the known values of V and D at points A and B; or

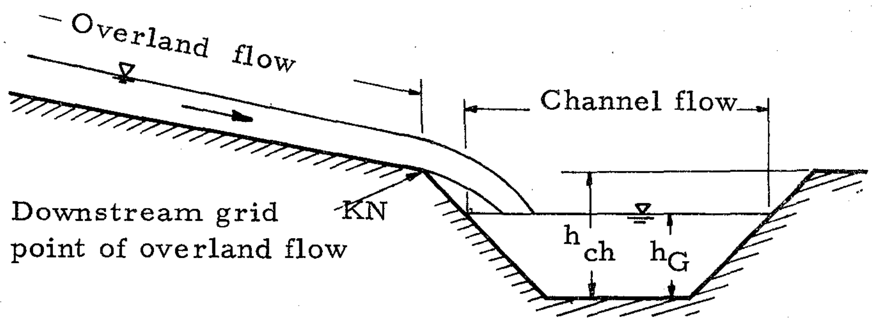


Figure 16. Fixed channel type gutter flow.

$$V_S = V_A + \frac{x_S - x_A}{\Delta x}(V_B - V_A) \qquad (111)$$

$$D_S = D_A + \frac{x_S - x_A}{\Delta x}(D_B - D_A) \qquad (112)$$

Substituting Eqs. 111 and 112 into Eq. 110 yields a quadratic equation in x_S or Δx_S, in which $\Delta x_S = x_S - x_A$, as follows:

$$A_1(\Delta x_S)^2 + B_1(\Delta x_S) + C_1 = 0 \qquad (113)$$

in which

$$A_1 = \left(\frac{V_B - V_A}{\Delta x}\right)^2 \qquad (114)$$

$$B_1 = \frac{2V_A(x_B - x_A)}{\Delta x} - \frac{1}{F^2}\left(\frac{D_B - D_A}{\Delta x}\right)\frac{\cos\theta}{\cos\theta_o} \qquad (115)$$

$$C_1 = V_A^2 - \frac{1}{F_o^2}\left(D_A\frac{\cos\theta}{\cos\theta_o} + h_S^*\right) \qquad (116)$$

The solution of the quadratic equation, Eq. 113, is well known; namely

$$\Delta x_S = \frac{-B_1 + \sqrt{B_1^2 - 4A_1C_1}}{2A_1} \qquad (117)$$

Because Δx_S must be positive and C_1 is always negative, only a positive sign in front of the square root sign in Eq. 117 is used.

The foregoing procedures of computation are programmed in FORTRAN language and executed on the UNIVAC 1108 computer. Detail of the whole program is appended to this report.

PARAMETRIC INFILTRATION MODEL FOR SIDESLOPE

The highway sideslope is either paved or grassed. If it is paved, the ground surface is impervious ($i = 0$) and the analysis made previously for the computation of runoff from the roadway can directly apply. However, if the sideslope is grassed, the ground surface is pervious $[i=f(t)]$ and the infiltration rate, $i(t)$, that varies with time will have to be evaluated at any desired time level along with the numerical computation of the surface runoff. Rigorously speaking, the infiltration rate can be computed by solving the boundary-value problem of rain infiltration (Chen, 1975c) in which the flow equation used may be the Richards equation. However, it is simpler and more useful in the engineering practice to compute the infiltration rate by means of a small number of parameters combined in certain forms of algebraic equation than by use of the Richards equation. Although many algebraic infiltration equations have been published in the literature, the major obstacle that has prevented more effective use of them lies in the difficulty in the evaluation of their parameter values. In order to have them widely accepted as predictive models in the subsurface runoff computation, reappraisal on the methods determining their parameter values as well as theoretical concepts behind their developments is necessary. This task was accomplished in another phase of the research project (Chen, 1975c).

All the algebraic infiltration equations were developed for computing under a special condition the maximum possible rate of infiltration (hereafter referred to as infiltration capacity). If the rainfall intensity is greater than the final constant infiltration rate (or the hydraulic conductivity at saturation), the rain infiltration process in general can be divided into two stages: One is before ponding and another after ponding. Therefore, a parametric infiltration model, if valid, must consist of both stages. Before ponding the infiltration rate is equal to the rainfall intensity and after ponding it is greater than or equal to the infiltration capacity, depending upon whether or not there is a non-zero water depth on the soil surface. Mathematically the parametric infiltration model can be expressed as

$$i = r(t) \qquad \text{for } 0 \le t \le t_p \qquad \ldots\ldots\ldots \qquad (118)$$

$$i = f(t) \qquad \text{for } t \ge t_p \qquad \ldots\ldots\ldots \qquad (119)$$

in which t_p is the time of ponding. Note that the rainfall intensity, $r(t)$, may or may not vary with time, and that the infiltration capacity function, $f(t)$, can be in any form of the algebraic infiltration equations except for the Green-Ampt equation that is expressed implicitly as a function of f and t. Evidently, in addition to the parameters in $f(t)$ needed to be evaluated, the time of ponding, t_p, must be determined before the parametric infiltration model, Eqs. 118 and 119, can apply.

Each of the available algebraic infiltration equations to be used in Eq. 119 such as the Green-Ampt equation, the Kostiakov equation, the Philip equation, the Horton equation, and the Holtan equation was already analyzed by the writer in another report (Chen, 1975c). However, for simplicity, only the generalized Kostiakov equation that is believed to be the most suitable form in fitting different infiltration capacity curves for various soil-cover-moisture complexes is presented herein.

The Kostiakov equation with three parameters A, t_o, and α may be expressed as

$$f(t) = f_\infty + A(t - t_o)^{-\alpha} \quad \ldots\ldots\ldots \quad (120)$$

in which f_∞ is the final infiltration rate equal to the hydraulic conductivity of soil at saturation, K_s. Factors that affect the infiltration capacity are numerous. Combined effects of a specific soil, a specific cover, and a specific antecedent moisture condition on the infiltration capacity must be reflected on the parameter values of A, t_o, and α. According to the recent study conducted by the writer (Chen, 1975c), the original three-parameter infiltration model, Eq. 120, can be shown to be in a typical form of the two-parameter model because the parameter t_o can be expressed in terms of the other parameters, A and α, aside from r, the rainfall intensity. The respective expressions of t_p and t_o in terms of A, α, and r, are recapitulated from Chen (1975c) for use in the present study as follows:

$$t_p = \frac{1}{1-\alpha}\left(\frac{A}{\bar{r} - K_s}\right)^{1/\alpha} \quad \ldots\ldots\ldots \quad (121)$$

$$t_o = \frac{\alpha}{1-\alpha}\left(\frac{A}{\bar{r} - K_s}\right)^{1/\alpha} \quad \text{or } t_o = \alpha t_p \quad \ldots\ldots \quad (122)$$

in which $\bar{r}$ is the mean rainfall intensity that also varies with time and is defined as

$$\bar{r}(t) = \frac{1}{t}\int_o^t r(t)\, d\tau \quad \ldots\ldots\ldots \quad (123)$$

Because of the definition of $\bar{r}(t)$, Eq. 123, the determination of the t_p value by using Eq. 121 can only be accomplished by trial and error as follows: (1) Assume t and then compute $\bar{r}$ from Eq. 123; (2) substitute the $\bar{r}$ value into Eq. 121 for the computation of the t_p value; and (3) if the value of t_p just computed is larger than the time, t, at which $\bar{r}(t)$ was determined, the computation of $\bar{r}$ and t_p will continue until $t = t_p$.

The values of A and α for each combination of various soil-cover-moisture complexes corresponding to distinctly different field conditions of rainwater intake on the highway sideslope may be first estimated according to the four major hydrologic soil groups and then modified in accordance with plant covers and antecedent soil moisture conditions. This and other aspects of soil-cover-moisture complex analysis of the parametric infiltration model were discussed in detail in the other phase of the research project (Chen, 1975c).

DESIGN STORM PATTERNS

Knowledge of the time distribution of rainfall in heavy storms constitutes a basis for design of an urban storm drainage system. Several methods have been developed to formulate a synthetic (design) storm pattern for the urban watershed runoff study. An extensive review of literature on the various formulations of design storms conducted by the writer (Chen, 1975b) has led to the development of the following general approach in which design storm patterns using the rainfall intensity-duration-frequency relationships were developed for all localities in the United States.

The rainfall intensity-duration-frequency relationship that can be used to derive the design hyetograph equation may be expressed as

$$r_{av} = \frac{a}{(t_d \pm b)^c} \qquad (124)$$

in which r_{av} is the average rainfall intensity in inches per hour; t_d is the time duration of rainfall in minutes; and a, b, and c are parameters depending upon the location and frequency of the storm under study. It was found from the U.S. Weather Bureau Technical Paper Nos. 25 and 40 that a positive sign in Eq. 124 mainly applied to a large section of the country—perhaps to the portion east of the Rocky Mountains—while a negative sign generally applies to the west of the Rocky Mountains (Chen, 1975b). However, in the case of the negative b, Eq. 124 is not valid for $t_d \leq b$.

Consider that the area under a curve representing the time distribution of the rainfall intensity, r, from the beginning of rainfall to any time, t, is equal to that having r_{av} for the same time period, namely

$$\int_0^t r \, d\tau = r_{av} t \qquad (125)$$

in which τ is the integration variable for time and r is the rainfall intensity in inches per hour at any time in the synthetic storm. Substituting the expression of r_{av} (from Eq. 124 after changing its t_d to t) into Eq. 125 and then differentiating the result with respect to t yields the design hyetograph equation.

Hyetograph Equations

The design hyetographs so formulated are somewhat different between the case of the positive b and that of the negative b. Furthermore, the design storms in each case can be classified into a completely advance type storm pattern, a completely delayed type storm pattern, and an intermediate type storm pattern. The three types of storm pattern are defined according to the skewness of the pattern, γ, (i.e., the ratio of the time before the peak to the total time duration).

Case (1): For positive b

For a completely advanced type storm pattern ($\gamma = 0$)

$$r = \frac{a[(1 - c)t + b]}{(t + b)^{1+c}} \quad . \ . \ . \ . \ . \ . \ . \ . \ . \ . \quad (126)$$

For a completely delayed type storm pattern ($\gamma = 1$)

$$r = \frac{a[(1 - c)(t_d - t) + b]}{[(t_d - t) + b]^{1+c}} \quad \text{for } 0 \le t \le t_d \quad . \ . \ . \ . \quad (127)$$

For an intermediate type storm pattern ($0 < \gamma < 1$)

$$r = \frac{a[(1 - c)(t_d - t/\gamma) + b]}{[(t_d - t/\gamma) + b]^{1+c}} \quad \text{for } 0 \le t \le \gamma t_d \quad . \ . \ . \quad (128)$$

$$r = \frac{a[(1 - c)(t - \gamma t_d)/(1 - \gamma) + b]}{[(t - \gamma t_d)/(1 - \gamma) + b]^{1+c}} \quad \text{for } \gamma t_d \le t \le t_d \quad . \quad (129)$$

Case (2): For negative b (c < 1)

For a completely advanced type storm pattern ($\gamma = 0$)

$$r = \frac{a}{b^c}\left(\frac{1 - c}{1 + c}\right)^c \quad \text{for } t \le \frac{2b}{1 - c} \quad . \ . \ . \ . \ . \ . \quad (130)$$

$$r = \frac{a[(1 - c)t - b]}{(t - b)^{1+c}} \quad \text{for } t \ge \frac{2b}{1 - c} \quad . \ . \ . \ . \ . \quad (131)$$

For a completely delayed type storm pattern ($\gamma = 1$)

$$r = \frac{a[(1 - c)(t_d - t) - b]}{[(t_d - t) - b]^{1+c}} \quad \text{for } 0 \le t \le t_d - \frac{2b}{1 - c} \qquad (132)$$

$$r = \frac{a}{b^c}\left(\frac{1 - c}{1 + c}\right)^c \quad \text{for } t_d - \frac{2b}{1 - c} \le t \le t_d \qquad (133)$$

For an intermediate type storm pattern ($0 < \gamma < 1$)

$$r = \frac{a[(1 - c)(t_d - t/\gamma) - b]}{[(t_d - t/\gamma) - b]^{1+c}} \quad \text{for } 0 \le t \le \gamma t_d - \frac{2b\gamma}{1 - c} \qquad (134)$$

$$r = \frac{a}{b^c}\left(\frac{1 - c}{1 + c}\right)^c \quad \text{for } \gamma t_d - \frac{2b\gamma}{1 - c} \le t \le \gamma t_d + \frac{2b(1 - \gamma)}{1 - c} \qquad (135)$$

$$r = \frac{a[(1 - c)(t - \gamma t_d)/(1 - \gamma) - b]}{[(t - \gamma t_d)/(1 - \gamma) - b]^{1+c}} \quad \text{for } \gamma t_d + \frac{2b(1 - \gamma)}{1 - c} \le t \le t_d \qquad (136)$$

The methods of determining the parameter values of a, b, c, and γ were described in detail in the other phase of this research project (Chen, 1975b).

Mean Rainfall Intensity

The mean rainfall intensity, $\bar{r}$, needed in the calculation of the time of ponding, t_p, by means of Eq. 121 can be expressed specifically for the design storm equations, Eqs. 126 through 136. Each of the expressions of r in Eq. 126 through 136 can be integrated with respect to time and then divided by the elapsed time of rainfall, t, as shown in Eq. 123. The following results for different cases and types of storms are obtained.

Case (1): For positive b

1. $\gamma = 0$

$$\bar{r} = \frac{a}{(t + b)^c} \quad \ldots \quad (137)$$

2. $\gamma = 1$

$$\bar{r} = \frac{1}{t}\left[\frac{at_d}{(t_d + b)^c} - \frac{a(t_d - t)}{(t_d - t + b)^c}\right] \quad \ldots \quad (138)$$

3. $0 < \gamma < 1$

$$\bar{r} = \frac{1}{t}\left[\frac{a\gamma t_d}{(t_d + b)^c} - \frac{a\gamma(t_d - t/\gamma)}{[(t_d - t/\gamma) + b]^c}\right] \qquad 0 \le t \le \gamma t_d \quad \ldots \quad (139)$$

$$\bar{r} = \frac{1}{t}\left[\frac{a\gamma t_d}{(t_d + b)^c} + \frac{a(t - \gamma t_d)}{[(t - \gamma t_d)/(1 - \gamma) + b]^c}\right] \qquad \gamma t_d \le t \le t_d \quad \ldots \quad (140)$$

Case (2): For negative b ($c < 1$)

1. $\gamma = 0$

$$\bar{r} = \frac{a}{b^c}\left(\frac{1 - c}{1 + c}\right)^c \qquad t \le \frac{2b}{1 - c} \quad \ldots \quad (141)$$

$$\bar{r} = \frac{a}{(t - b)^c} \qquad t \ge \frac{2b}{1 - c} \quad \ldots \quad (142)$$

2. $\gamma = 1$

$$\bar{r} = \frac{1}{t}\left[\frac{at_d}{(t_d - b)^c} - \frac{a(t_d - t)}{[(t_d - t) - b]^c}\right] \qquad 0 \le t \le t_d - \frac{2b}{1 - c} \quad \ldots \quad (143)$$

$$\bar{r} = \frac{1}{t}\left[\frac{at_d}{(t_d - b)^c} - \frac{a}{b^c}\left(\frac{1-c}{1+c}\right)^c (t_d - t)\right] \quad t_d - \frac{2b}{1-c} \le t \le t_d \qquad . \; . \; . \; . \; . \quad (144)$$

3. $0 < \gamma < 1$

$$\bar{r} = \frac{1}{t}\left[\frac{a\gamma t_d}{(t_d - b)^c} - \frac{a\gamma(t_d - t/\gamma)}{[(t_d - t/\gamma) - b]^c}\right] \quad 0 \le t \le \gamma t_d - \frac{2b\gamma}{1-c}$$

$$. \; . \; . \; . \quad (145)$$

$$\bar{r} = \frac{1}{t}\left[\frac{a\gamma t_d}{(t_d - b)^c} + \frac{a}{b^c}\left(\frac{1-c}{1+c}\right)^c (t - \gamma t_d)\right]$$

$$\gamma t_d - \frac{2b\gamma}{1-c} \le t \le \gamma t_d + \frac{2b(1-\gamma)}{1-c} \qquad . \; . \; . \; . \; . \quad (146)$$

$$\bar{r} = \frac{1}{t}\left[\frac{a\gamma t_d}{(t_d - b)^c} + \frac{a(t - \gamma t_d)}{[(t - \gamma t_d)/(1-\gamma) - b]^c}\right]$$

$$\gamma t_d + \frac{2b(1-\gamma)}{1-c} \le t \le t_d \qquad . \; . \; . \; . \; . \; . \; . \quad (147)$$

ACCURACY OF THE MATHEMATICAL MODEL

An urban highway watershed consists of several sub-basins, as described previously. Runoff from each of these sub-basins jointly or independently contributes to the total flow of storm water at the drainage inlet. For example, storm water on roadway and shoulder first moves as overland flow, then at the far downstream end of the overland flow enters as gutter flow which may or may not collect an additional amount of water coming from the sideslopes, depending upon a highway drainage condition, and finally all the storm water so collected enters the inlet, if the inlet is operated with 100 percent efficiency. Whether the computer model so formulated can accurately simulate all the parts of the rainfall-runoff processes in a highway watershed must be examined. In other words, the physically-determined values of the friction parameters such as C, ε, k, a, and b embedded in the friction slope expressions (e.g., Eqs. 81 and 82) have yet to be validated before their general use in practice. For convenience, the validation of the computer model was carried out in two stages: First, it was made on the overland flow only and next, on the combined overland and gutter flow.

The accuracy of the computer model developed for overland flow was checked by using basic hydrograph field data obtained from the Los Angeles District Corps of Engineers (1949-51) airfield drainage investigation at Santa Monica, California, and that for combined overland and channel flow, by using field data collected from two urban highway watersheds in the Salt Lake City area, Utah (Fletcher and Chen, 1975).

Examination of Overland Flow Computer Sub-model

Six different sets of input data were chosen from the Corps of Engineers (1949-51) airfield drainage hydrographs for examining the overland flow computations on a paved surface. Table 1 lists for 6 runs the values of the rainfall intensity and duration, channel length, and bed slope for a paved surface tested.

Included in the Corps of Engineers (1949-51) airfield drainage investigations are the measured hydrographs for simulated turf surfaces which were made either of expanded metal or of combined chickenwire and expanded metal. No attempt was made, however, to examine the hydrographs for simulated turf surfaces because the values of the parameters, a and b in Eq. 82 and k in Eq. 19, for such surfaces are unknown. Note that the determination of the friction parameters for unknown surfaces requires an evaluation (identification) process using either a physical model (Chen, 1975a) or a mathematical model (including the governing equations with appropriate initial and boundary conditions) as well as a set of concurrent input (rainfall) and output (hydrograph) measurements.

Table 1. List of input data for Los Angeles District Corps of Engineers (LADCE) airfield experimental runs on a paved surface.

Present Study Run No.	LADCE Test Code No.	LADCE Test Date M/D/Y	''Rainfall'' Application rate r(in./hr)	''Rainfall'' Application Duration t_d(min.)	Channel Length L(ft)	Bed Slope S(%)
1	A6	10/27/49	8.128	8	84	0.5
2	A7	12/ 3/49	0.860	16	84	0.5
3	A45	10/25/49	8.306	14	336	0.5
4	B6	9/22/50	7.350	9	84	1.0
5	B6	9/22/50	7.230	1.15,1.50,1.75	84	1.0
6	C10	3/24/51	7.460	6	168	2.0

The latter approach using a mathematical model is an inverse problem which has been solved by trial and error (Burman, 1969; Schreiber and Bender, 1972) and more systematically and efficiently by an influence coefficient algorithm developed by Becker and Yeh (1972a, 1972b, and 1973) and Yeh (1973). Although the influence coefficient algorithm has been shown to be very powerful in the evaluation of the friction parameters embedded in a hyperbolic partial differential equation describing the hydrodynamics of unsteady open channel flow, it is at present limited to the subcritical flow range that detracts us from its general application. From the practical point of view, however, it would be much simpler to determine the friction parameters experimentally for flow at the equilibrium state than the application of an optimization technique to an unsteady, nonlinear flow system by minimizing the maximum of the absolute values of the errors (differences) between the observations and the solutions of the system equations. For particular use in the present study, the friction parameters for natural turf surfaces have been experimentally determined (Chen, 1975a), as already summarized in the previous section. Since it is not the objective of this study to develop a new method to identify the friction parameters, the parameter identification problems in unsteady open channel flows are not discussed further herein.

The roughness size of a paved surface used in the Corps of Engineers (1949-51) airfield drainage investigation happened to be approximately equal to that of the glued-sand surface used in Woo and Brater's (1961) experiments. It is thus necessary to examine the validity of Eq. 82 with a = 235 and b = 0.296 using the field data. Note that in a similar study involving the comparisons of measured and computed hydrographs, Chu (1973) has used Eq. 81 instead of Eq. 82.

Rainfall duration for each field run selected, except for run No. 5, was long enough so that the outflowing discharge had actually attained the equilibrium state before rain stopped. All the runs were performed on a 3-ft wide impervious paved surface which has roughness equivalent to Manning's n = 0.012.

The roughness size, k, for turbulent flow in the mathematical model (Eq. 19) must be specified before executing it on the computer. The Strickler formula can be used to convert the value of Manning's n to that of the hydraulically ''equivalent'' roughness size, k. However, considering the wide range of the relative roughness, R/k, that overland flow covers, one may prefer the following formula to the Strickler formula.

$$\frac{n}{k^{1/6}} = 0.0309 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (148)$$

This equation was derived by Chen and Chow (1968) using the relationship between Eq. 19 and the Manning formula. Therefore, for given n = 0.012, k equals 0.0034 ft.

The distance interval, Δs, for the channel is obtained by dividing the channel length equally into 7 sections (arbitrary, i.e., the size sufficient in the computer operation within practical accuracy, but not too excessive) with each section having a length $\Delta s = L/7$, where L is the total length of the channel. Thus, Δs = 12 ft for all runs except for runs 3 and 6. The values of Δs for runs 3 and 6 were equal to 48 ft and 24 ft, respectively. Because the computation is conducted on a dimensionless basis, the dimension of the distance or distance interval is no longer important. The accuracy of the computation may change with the number of grid points selected, but it should not vary drastically unless the number of grid points considered is too small.

The time interval, Δt, can be determined by solving the Courant limit in Eq. 48. However, when the ground surface is initially dry, the flow starts with very small hydraulic depth, D, and velocity, V, which in turn give a large Δt for a fixed Δs from Eq. 48. Unfortunately, use of a large Δt at the initial state may produce computational instability which is often beyond control at subsequent time levels. To avoid such computation instability a much smaller Δt is required which, however, in terms of the increased computer time, cannot be considered as a practical improvement. Chu (1973) showed that the following empirical formula was suitable for use in the selection of Δt with this type of initial boundary-value problem.

$$\Delta t = \Delta t_{eq} \cdot \text{Time} \cdot \text{Factor} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (149)$$

in which Δt_{eq} is the time interval at the equilibrium stage and is set to a value a little bit less than the Courant limit; ''Time'' is the normalized time from the beginning of rainfall; and ''Factor'' is a coefficient equal to 0.1 divided by the normalized initial time when the normalized initial time is greater than 0.1. If the normalized initial time is less than 0.1, ''Factor'' must be set to a value of 1. Note that use of Eq. 149 enables the numerical computation to be started with the time interval, $0.1\Delta t_{eq}$ or less. It was programmed in such a way that by the time the flow approaches the equilibrium state, the time interval is automatically controlled by the Courant criterion, Eq. 48, or Δt_{eq}.

The computed and measured hydrographs for run 1 through run 6 are depicted in Figures 17 through 22, respectively. It can readily be seen from these figures that the agreement between the computed and measured hydrographs in general seems to be good for most large flows under high intensities, but rather poor for small flows under low intensities or no rainfall. The poor results were anticipated for lack of a better expression of flow resistance than use of an empirical formula, Eq. 82, for shallow flows with flow rate per unit width, q, as low as 0.002 cfs/ft or less. It appears that there must exist some intrinsic natures of the low flow regime which the present theory failed to describe, but would account for large errors in the computed hydrographs. This and other peculiar features of the computed hydrographs, different from the measured ones, require justification prior to the general use of the overland flow submodel. The following comments with regard to the accuracy of the computed hydrographs merit attention.

1. At the beginning of rainfall, the computed hydrograph seems to rise ahead of the measured hydrograph for most runs examined. This consistent lag in time in the rising stage can be attributed to the initial detention of the rainfall by the surface material and depression storage, if any, before the surface runoff starts. It is well known that the initial detention refers to the storage effect due to overland flow in transit at the beginning of rainfall and varies with the degree of dryness of the surface material. Horton (1935) stated that this initial detention ''commonly ranges from 1/8 to 3/4 inches for flat areas and 1/2 to 1.5 inches for cultivated fields and for natural grass lands or forests.''

The specific magnitude of depression storage has never been measured in the field because of obvious difficulties in obtaining meaningful data. For practical purposes, however, an average value may be assumed. On moderate or gentle slopes, for example, Horton (1935) estimated that pervious surface depression ''can commonly hold the equivalent of 1/4 to 1/2 inch depth of water and even more on natural meadow and forest land.'' On the other hand, based on analysis of periods of high rates of rainfall and runoff, Hicks (1944) has estimated depression storage losses of 0.20, 0.15, and 0.10 inch for sand, loam, and clay, respectively. For a series of analyses, Tholin and Keifer (1960) assumed an overall total depression storage of 1/4 inch on pervious areas with a range of depths of specific depression up to 1/2 inch and 1/16 inch, on paved areas with a range of depths up to 1/8 inch; for another series these depths were doubled.

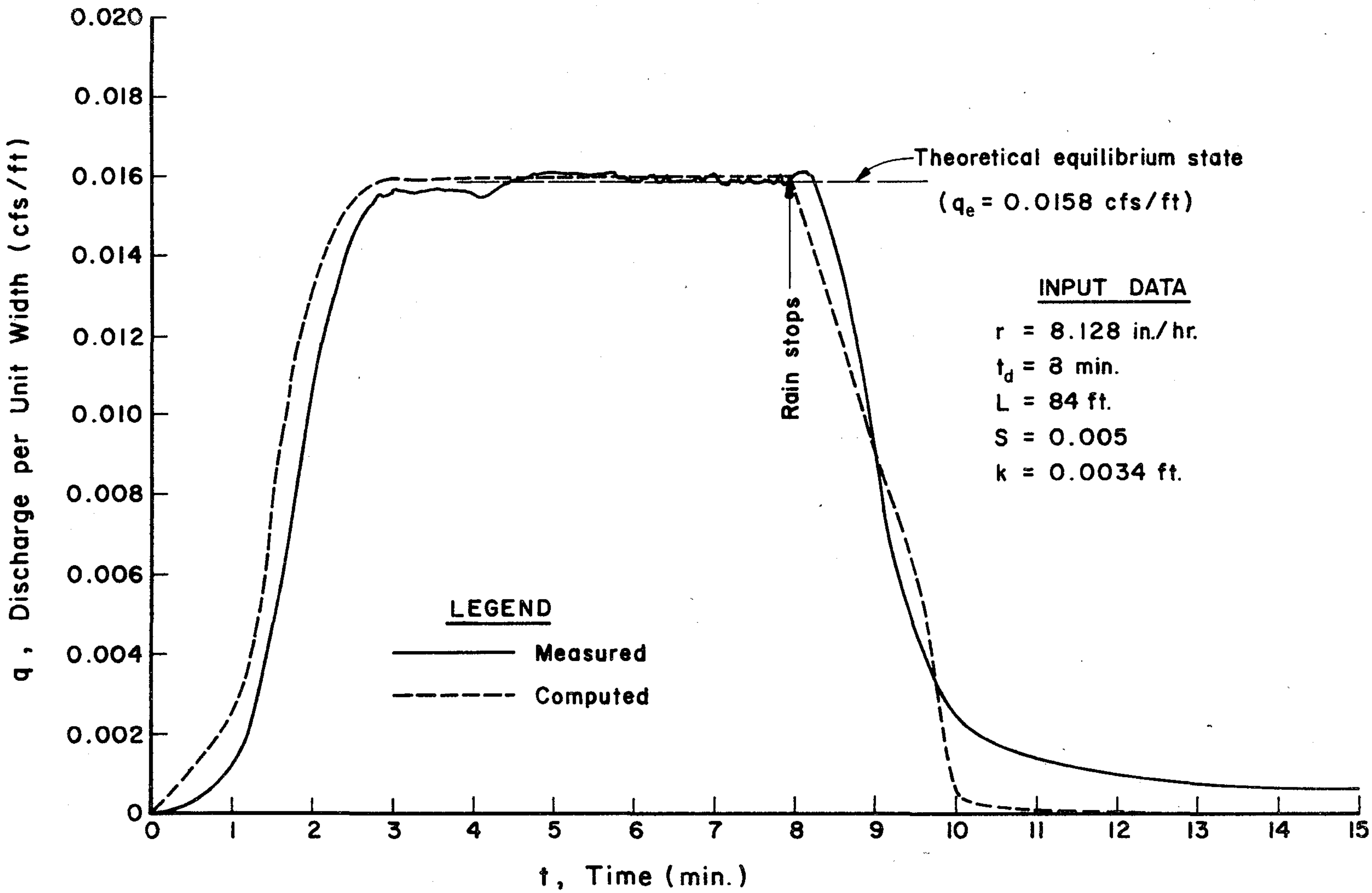


Figure 17. Comparison of measured and computed hydrographs for run 1 of Los Angeles District Corps of Engineers Airfield Experiment.

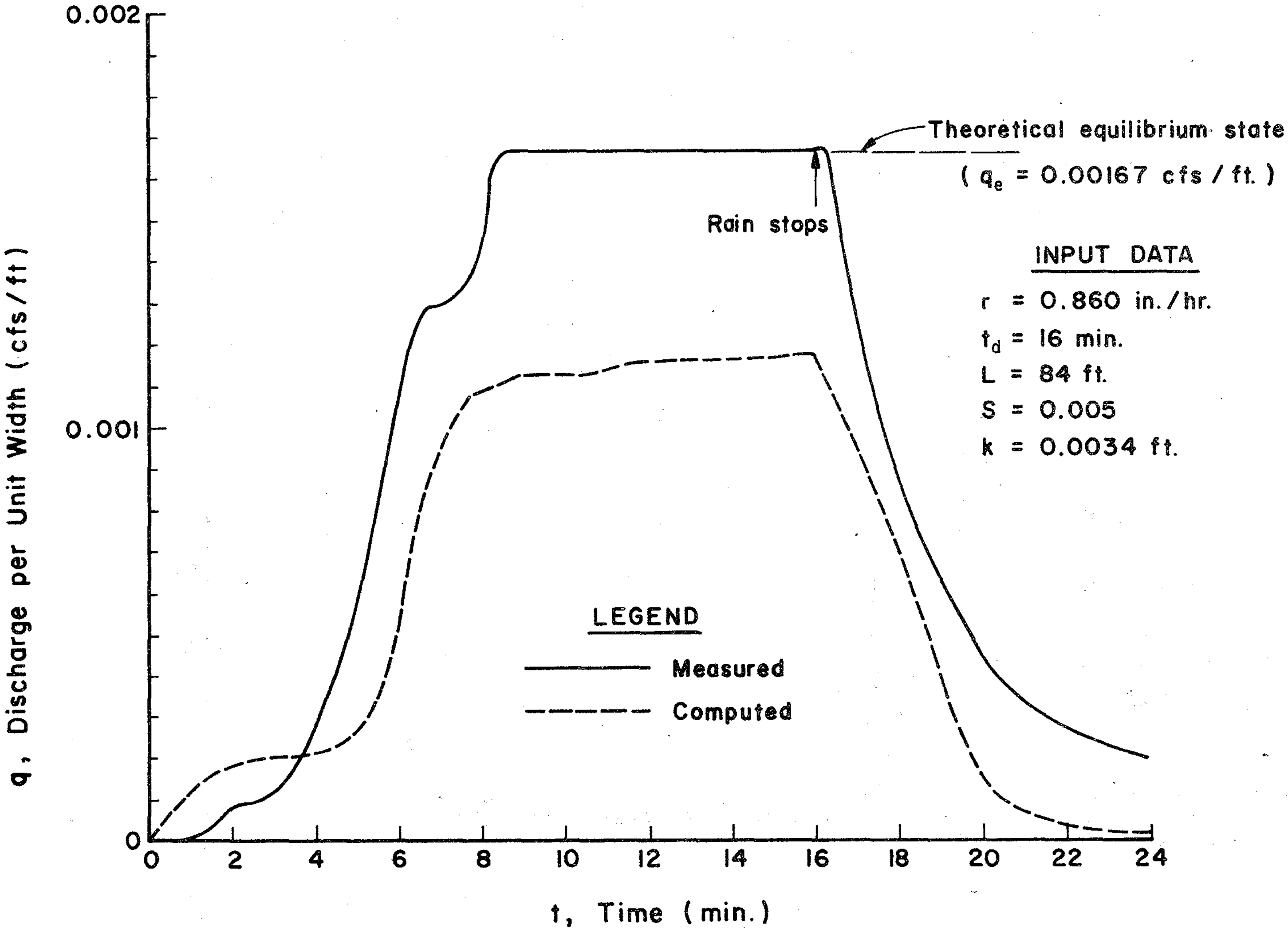


Figure 18. Comparison of measured and computed hydrographs for run 2 of Los Angeles District Corps of Engineers Airfield Experiment.

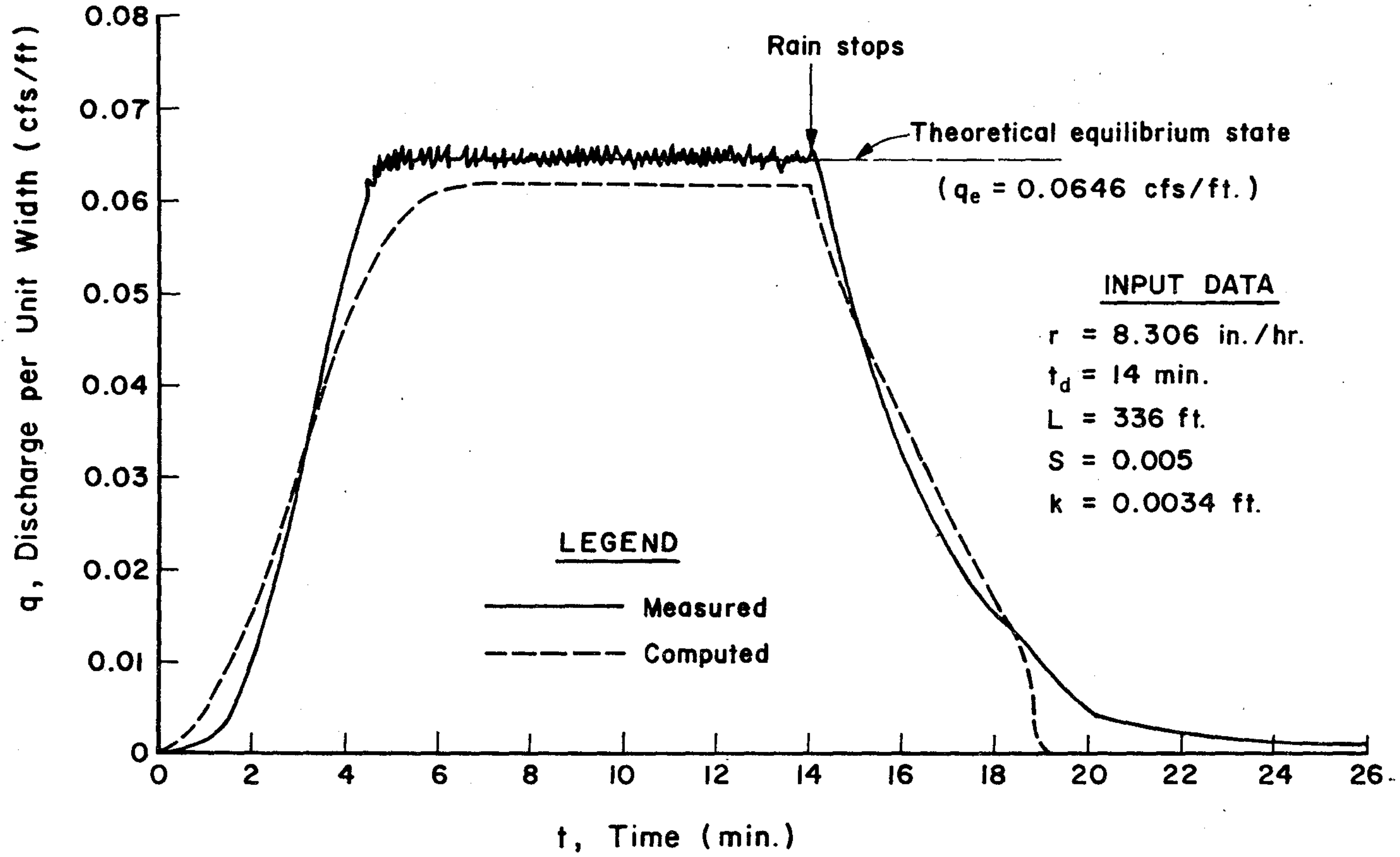


Figure 19. Comparison of measured and computed hydrographs for run 3 of Los Angeles District Corps of Engineers Airfield Experiment.

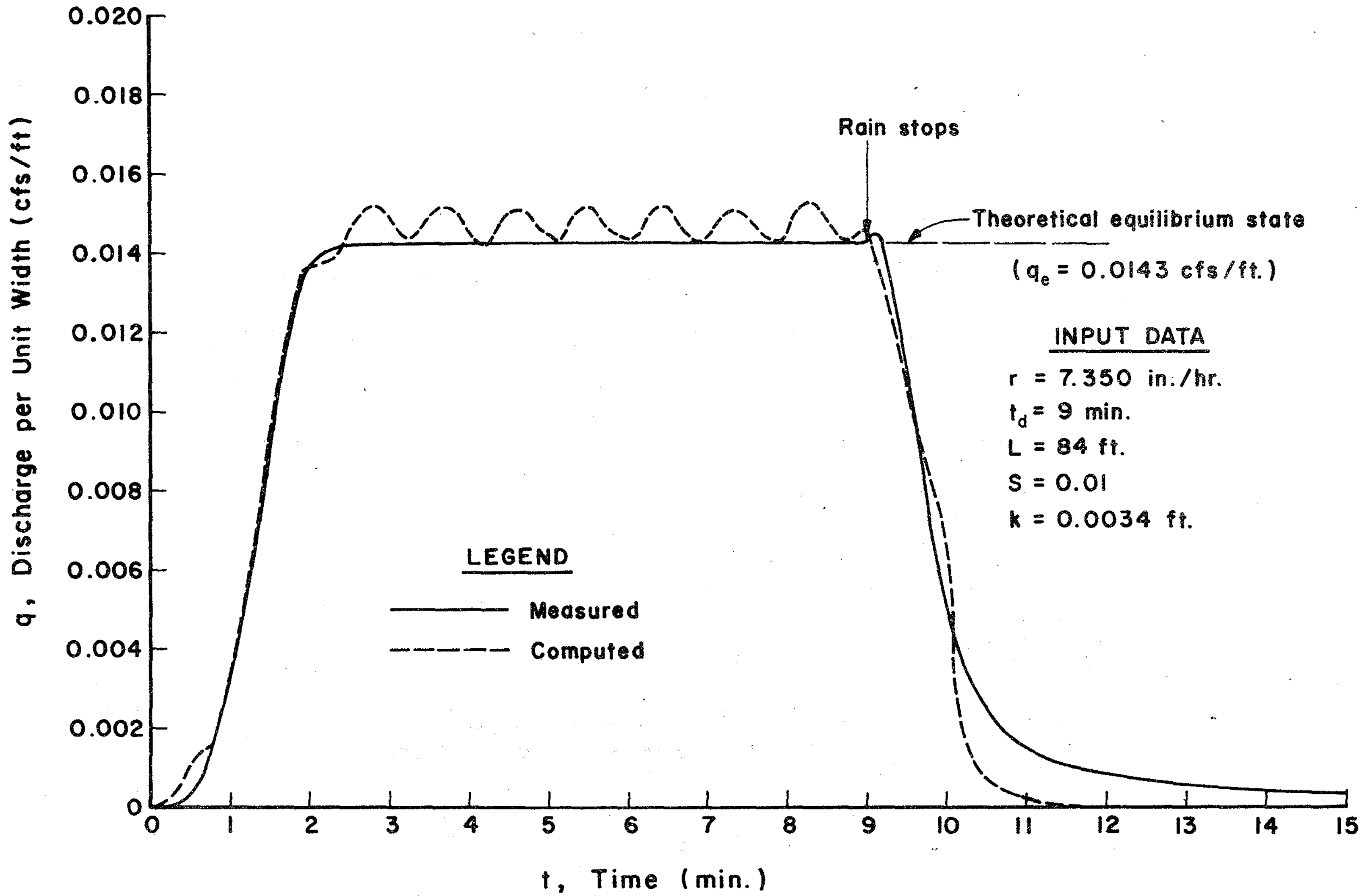


Figure 20. Comparison of measured and computed hydrographs for run 4 of Los Angeles District Corps of Engineers Airfield Experiment.

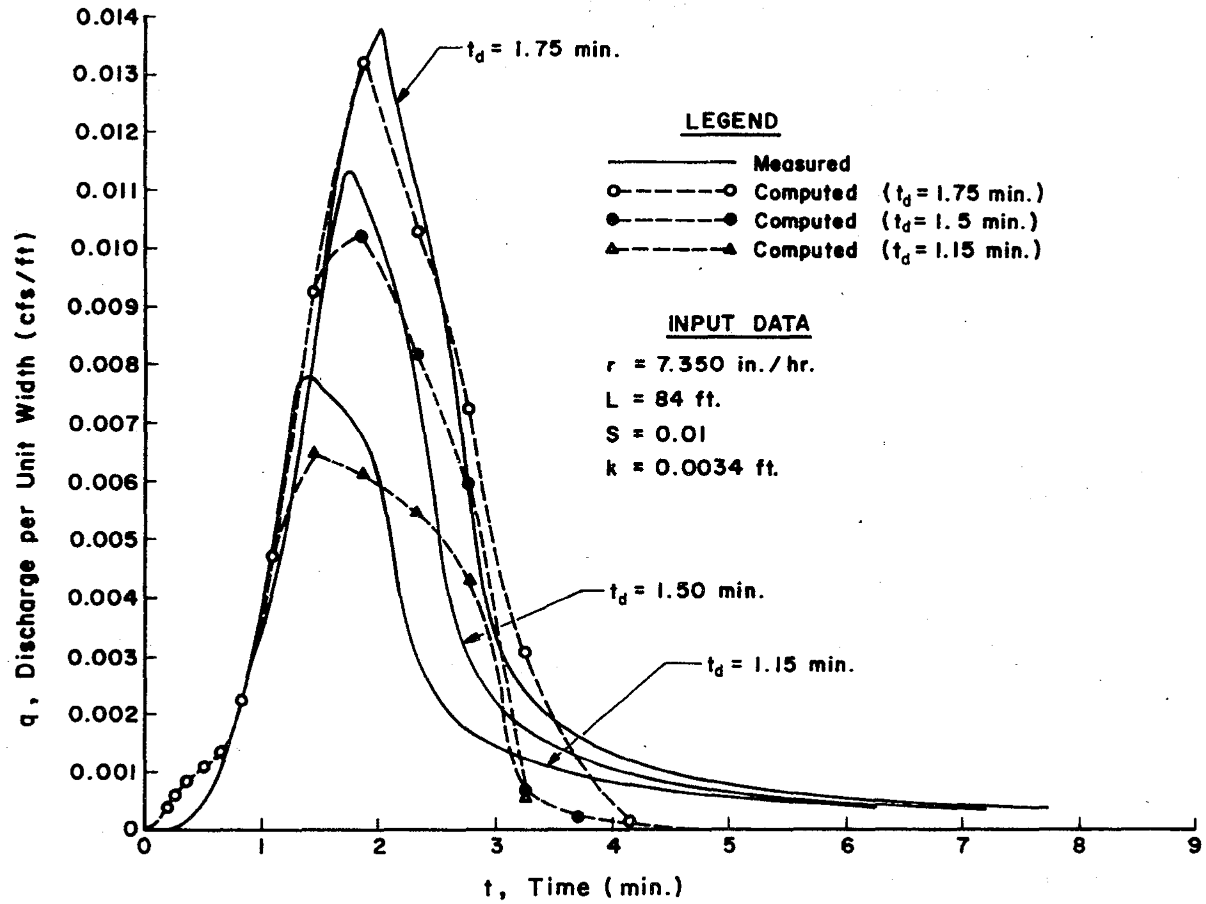


Figure 21. Comparison of measured and computed hydrographs for run 5 of Los Angeles District Corps of Engineers Airfield Experiment.

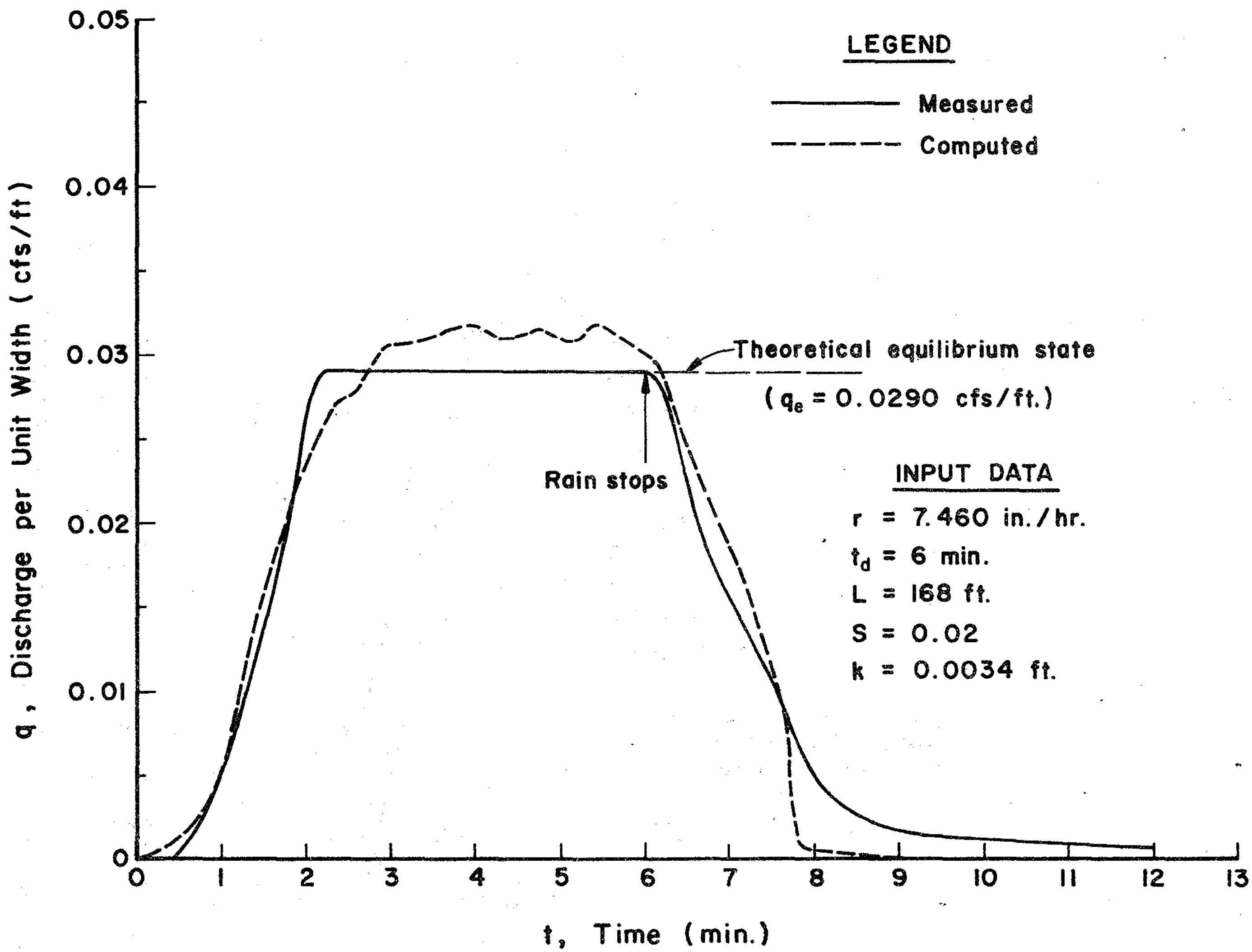


Figure 22. Comparison of measured and computed hydrographs for run 6 of Los Angeles District Corps of Engineers Airfield Experiment.

The small depth assumed at the initial state in the present numerical scheme, as described in the preceding section, is tantamount to assuming the initial detention, though it appears much smaller than what should be in terms of Horton's (1935) suggested values. The hardest to determine is, of course, the magnitude of depression storage which is unknown *a priori* and may vary from case to case although one can easily estimate it using a least squares procedure by best fitting the computed hydrograph to the measured one or by trial and error. For simplicity, however, the adequate magnitude of depression storage is not imposed in the model at this stage, partly because of the necessity in evaluating the difference between the measured and computed hydrographs resulting from this unknown, but important, variable and partly because of its relatively insignificant effect on the hydrograph, magnitudewise and timewise, under a uniformly prolonged storm except by a time lag (or shift in time coordinate) corresponding to the length of time required to fill it up. In general, the more nonuniform in space and time a given storm, the more sensitive is the peak and shape of the computed hydrograph to the difference in the amount of depression storage assumed. This and other possible improvements of the computer model will be considered in the later computation, especially when field data on storm and runoff from the two urban highway watersheds in the Salt Lake City area are analyzed.

2. In all of the measured hydrographs, it is observed that the discharge suddenly increases by a small amount immediately after rain stops. This is probably due to the spontaneous disappearance in the resistance force produced by the raindrops on the water surface. This phenomenon is prominent for runs 1 and 3 under heavy rain on small slopes such as shown in Figures 17 and 19 respectively. Apparently, the additional resistance to the flow resulting from the raindrop impact was not accurately accounted for by the overpressure head alone, as expressed by Eq. 6. It is believed that raindrops not only increase the pressure of the flow, but also affect its velocity distribution which has not been considered in this study.

3. Whether or not the computed runoff rate per unit width, q, is stable and convergent at the equilibrium state depends in some degree upon the states or regimes of flow predominating over the bed. Basing on the computer outputs obtained from the six runs, it is discovered that the effect of gravity relative to inertia, as represented by the Froude number, upon the computational stability and convergency of flow is much greater than that of viscosity relative to inertia, as represented by the Reynolds number. For example, the computed hydrograph for run 1 (Figure 17) under a uniform application rate is quite stable and converges to the theoretical value at the equilibrium state where the flow so computed is in the regime being all the way subcritical, partially laminar upstream, and partially turbulent downstream. Although the flow for run 3 is also subcritical all the way from the upstream end to the downstream end, the computer model apparently underestimated the runoff rate at the equilibrium state (Figure 19). A comparison of the computed flow regimes for run 1 and run 3 reveals that there is a significant difference percentagewise in the Froude

number along the channel, but not very much in the Reynolds number. The flow in run 1 is subcritical, but not so nearly critical (**F** = 1) as found in run 3. It appears that the adverse effect of gravity on the computational stability and convergency worsens with the increase in the Froude number. This is exemplified by the computed hydrographs for runs 4 and 6, as shown in Figures 20 and 22, respectively.

The oscillation of the computed runoff rate, q, at the quasi-equilibrium state for run 4 (Figure 20) seems to be a typical flow phenomenon resulting from the time-varying state of flow. In this case, the flow produced under a given input and a certain combination of channel conditions is computed sometimes as subcritical all the way and sometimes as partially supercritical downstream, resulting in the oscillation of the computed q corresponding to the periodic change in the state of flow. In other words, when the flow is found all the way subcritical, the computed q is just about the theoretical value at the equilibrium state, whereas it rises more than the theoretical value when the flow is partially supercritical downstream. The overestimation of q as a result of a high Froude number in flow can be more clearly demonstrated in Figure 22 for run 6 in which the flow over a large portion of the channel length is found supercritical.

4. The computed peak discharge, as measured in terms of its magnitude and time of occurrence, in response to each of the various non-equilibrium durations of the ''rainfall'' time (e.g., t_d = 1.15, 1.50, and 1.75 minutes in Figure 21) confirms quite well to the measured value. It appears that the longer the duration of the application time, the higher is the accuracy of the computed peak discharge, both magnitudewise and timewise.

5. The accuracy of the computed runoff rate, q, worsens noticeably with the lower flow, as indicated previously. A typical example of this poor computation using the present technique is depicted in Figure 18 for run 2 under an application rate less than 1 in./hr. The computer model underestimated quite badly the theoretical value for run 2 at the equilibrium state. The underestimation of the q for very low flows under small application rates is also evidenced in the lower part of the computed hydrograph in the receding stage of all runs. Despite this technical problem in the computation of such low flows, no attempt could be made to improve the present approach for lack of a better method presently available in the computation. Of course, in future studies, any new method which is found to improve the numerical computation of low flows can be incorporated into the computer model without impairing the validity of the present approach.

6. Errors involved in the computer results would more likely increase with the incorrect evaluation of the Darcy-Weisbach friction coefficient, f, than with the reduction in the number of grid points adopted in the computation. Because the present numerical scheme has been developed on a dimensionless basis, accuracy in the computation does not seem to be greatly affected by the distance interval, Δs, unless the number of

grid points selected becomes excessively too small to carry the normal operation of the expected computation. With the present approach, as described previously, dividing the channel length into a number of sections less than 4 is not recommended. For illustrating the sensitivity of accuracy of the computation to the distance interval (or the number of grid points), the hydrographs for run 1 were again computed by using Δs = 6 and 21 ft and are plotted in Figure 23 for comparison with the one using Δs = 12 ft (Figure 17). It can be readily seen from Figure 23 that the computation by using 5 grid points (i.e., equivalent to 4 sections plus 1 for the end point) yields as good accuracy as the ones produced by using the larger numbers of grid points. Since one of the major concerns regarding the use of the explicit numerical scheme is the comparatively large amount of the computer time required in the solution over a prolonged time span of rainfall, the reduction in the number of grid points down to as minimum as 5 for a channel of any length without impairing the accuracy of computation may be considered as a practical improvement. Henceforth, the minimum number of grid points, namely 5, will be taken in the computation if the situation permits.

Examination of Combined Flow Computations

Rainfall-runoff data on major storms during the 1972-73 rainy season (April to November) from two typical urban highway cross-sections in the Salt Lake City area were collected for examining the validity of the combined flow computer model. Because details of hydrologic data collected both at Layton site and at Parleys site No. 1 and No. 2 were already given in another report (Fletcher and Chen, 1975) under the field phase of the present research project, they are not recapitulated herein except for those which were used as input data in the computer model.

Input data

Layton site. The highway watershed at Layton site is a 3-lane roadway with shoulders of different widths paved on both sides and connected along a steep sideslope on one side, as shown in Figure 24(a). The drainage area under investigation is not exactly rectangular in shape, but on the average may be considered as a rectangle, 574 ft long and 106 ft wide (on the horizontal plane), including the top width of a fixed channel-type gutter (Figure 16) lying in between the roadway and the sideslope. The transverse profile of the roadway plus the paved shoulders measured in the field is not a parabolic curve (Figure 6), but rather a straight line with cross slope varying from 1.96 percent at the upstream end of the channel to 1.24 percent at the inlet side. For simplicity, the average cross slope of the roadway and the paved shoulders may be taken as 1.6 percent. The slope of the sideslope also varies from 64.4 percent to 60.5 percent at the upstream and downstream ends of the channel, respectively. Again, for simplicity, the average value, 62.5 percent, was used in the computation. The gutter slope was measured at 0.296 percent.

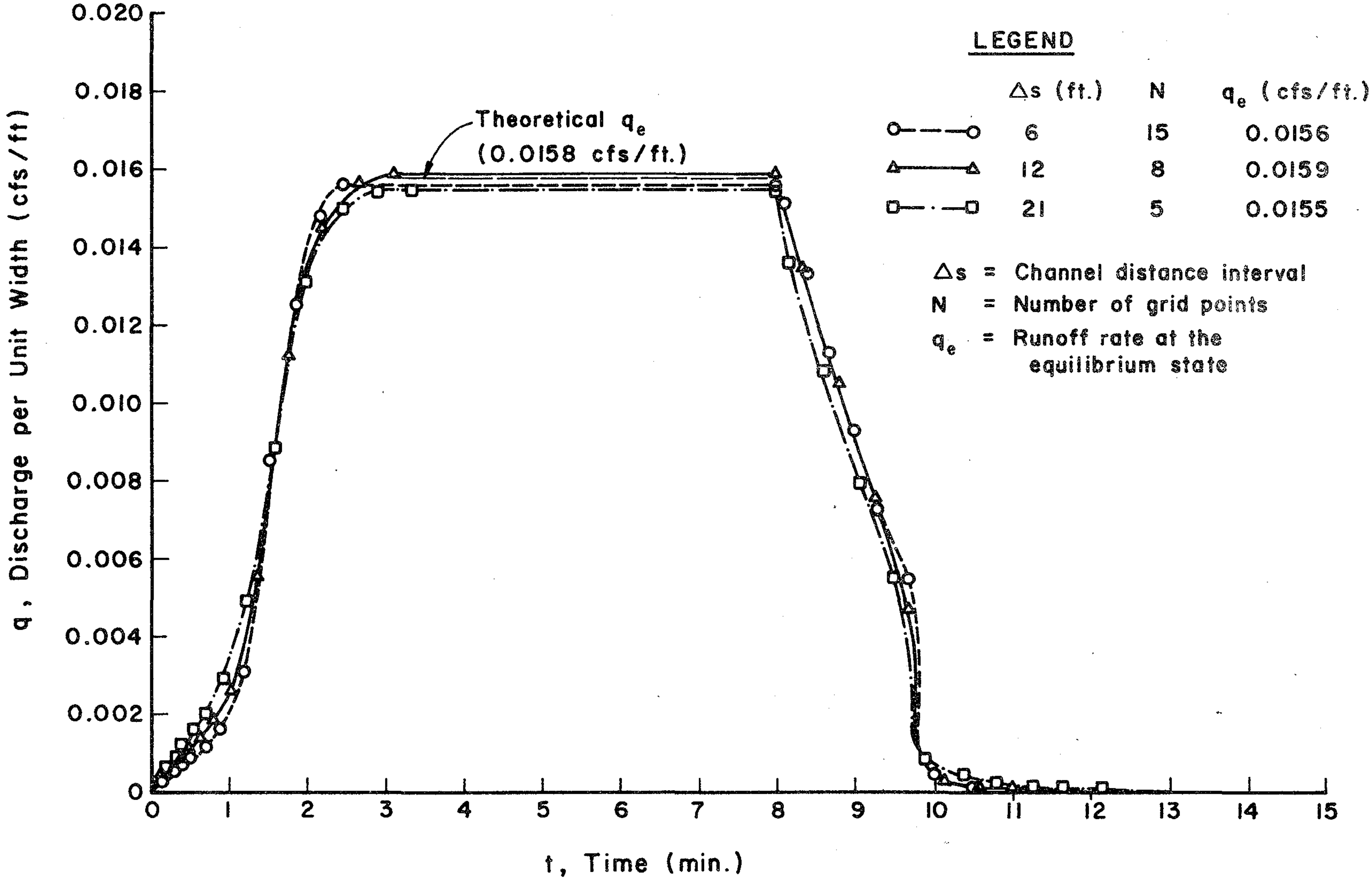


Figure 23. Comparison of computed hydrographs for various distance intervals or number of grid points used in the computation of run 1.

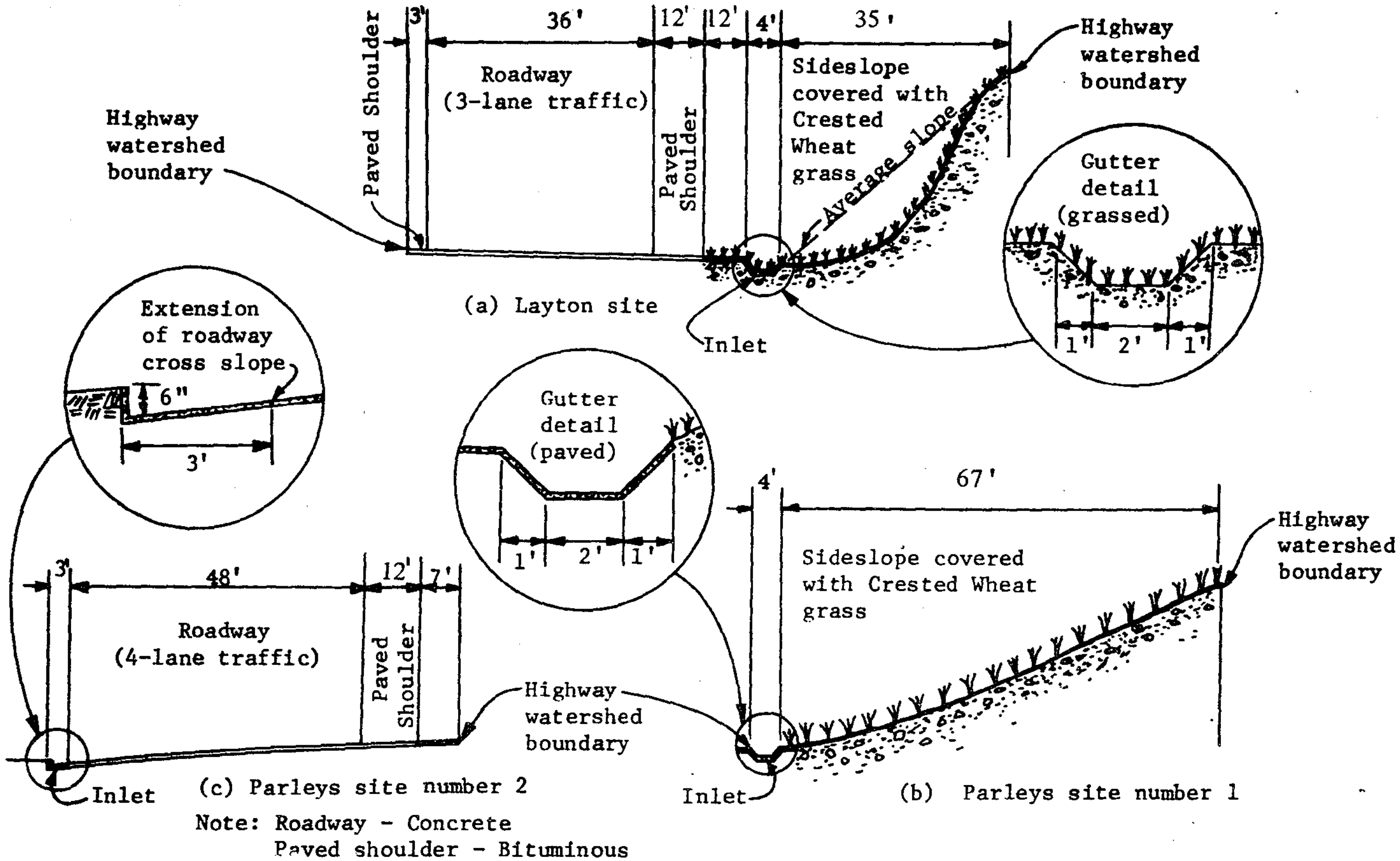


Figure 24. Typical urban highway cross-sections in the Salt Lake City area.

The roughness size of the road surface including the roadway and paved shoulders was assumed that of glued sand (Woo and Brater, 1961) or Los Angeles District Corps of Engineers' (1949-51) paved surface which possesses approximately $k = 0.0034$ ft. The sideslope and the drainage channel are covered with Crested Wheat grass which does not look so dense as the ones tested in the laboratory environment (Chen, 1975a). Despite this discrepancy in appearance between the grasses tested and simulated, the C value in Eq. 21 for laminar flow was computed by means of Eq. 82 with the experimentally-determined values of a and b for good solid natural turf having been assumed throughout the present computation for lack of a better expression.

The infiltration rate was computed by using the Kostiakov equation (Eq. 120) in which $f_\infty = 0.05$ in./hr, $\alpha = 0.5$, and the value of A was determined, for practical purposes, in terms of the potential infiltration, S, in inches as (Chen, 1975c)

$$A = [0.2\ S(1 - \alpha)]^{\alpha}\ (\bar{r} - f_\infty)^{1-\alpha} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (150)$$

in which $S = 0.05$ in. corresponding to the runoff curve number (CN) equal to 99.5 was evaluated from the estimated infiltration capacity curve (Fletcher and Chen, 1975).

Two storms were selected from the major storms analyzed and tabulated by Chen (1975b). An inspection of field data for major storms (Fletcher and Chen, 1975) reveals that there are not too many storms which are large and long enough to be meaningful for validation tests. The two storms selected at Layton site are those which occurred on September 5, 1972 and May 25-26, 1973. The former storm at rain gage L-2 can be best fitted by using Eqs. 128 and 129 with $a = 28.19$, $b = 11.21$, $c = 0.980$, $t_d = 345$ min., and $\gamma = 0.177$ while the latter storm at rain gage L-5, if expressed in the parametric equation (Eqs. 128 and 129), has the parameter values $a = 54.62$, $b = 40.55$, $c = 1.156$, $t_d = 60$ min., and $\gamma = 0.323$. For simplicity, the time-varying rainfall intensity for each storm was thus determined from the idealized hyetograph, Eqs. 128 and 129, rather than from the actual hyetograph, as characterized by a number of step pulses in unequal magnitude and time length or a series of such pulses.

Parleys site. The highway watershed at Parleys site is composed of two independent ones. As shown in Figure 24(b) and (c), one which drains storm water from a steep sideslope to a fixed channel-type gutter is referred to as Parleys site No. 1 and the other which drains storm water from a paved shoulder and a 4-lane roadway to a curb-type gutter (Figure 15), Parleys site No. 2. The drainage areas at both sites which are adjacent to each other are again not exactly rectangular in shape, but for convenience were considered as rectangles having the areas equal to 352 ft x 71 ft (including the top width of gutter) and 339 ft x 70 ft at sites No. 1 and No. 2, respectively.

Because the alignment of the roadway under investigation is curved, construction of ''super elevation'' apparently changes the transverse profile of the road surface throughout the whole length of the roadway. Since the present computer model did not take more than one transverse profile of the road surface into account, as mentioned previously, the average cross slope of the roadway including the paved shoulder was estimated from 4.28 percent at the upstream end of the gutter to 2.99 percent at the inlet side. The average of both values is 3.64 percent, which was used in the computation. The slope of the sideslope also varies from 42.5 percent at the upstream end of the gutter to 32.6 percent at the inlet side. The average slope of the sideslope is thus 37.5 percent which was again given as an input data for solution. The gutter slopes at the two sites were assumed to be both 2.52 percent.

Regarding the roughness sizes of the paved and grass surfaces, the magnitudes cited at Layton site were also assumed to be equally applicable here. Therefore, the value of the Darcy-Weisbach friction coefficient was estimated by using the same equations as used at Layton site.

The infiltration capacity was also simulated by means of the Kostiakov equation (Eq. 120) that has f_∞ = 0.05 in./hr, α = 0.5, and S = 0.10 in. (Eq. 150) corresponding to CN = 99 of a soil-moisture-cover complex.

Three major storms were selected from the field data (Fletcher and Chen, 1975; Chen, 1975b) at Parleys site as rainfall input. Those selected are storms which occurred on October 4, 1972, July 19, 1973, and August 16, 1973. None of them appears to be large and long enough for the present method to solve the routed storm flow within tolerable accuracy. The actual hyetographs of all the storms were best fitted by using Eqs. 128 and 129 with the values of the storm parameters a, b, c, and γ having been determined from a least squares procedure (Chen, 1975b). It was found that for October 4, 1972 storm at rain gage P-6, a = 16.43, b = 2.15, c = 0.938, t_d = 286 min., and γ = 0.052; for July 19, 1973 storm at rain gage P-3, a = 62.39, b = 19.10, c = 1.027, t_d = 145 min., and γ = 0.216; and for August 16, 1973 storm at rain gage P-5, a = 27.57, b = 3.01, c = 1.019, t_d = 73 min., and γ = 0.096. The time-varying rainfall intensity for each storm was thus directly determined from Eqs. 128 and 129 with each of the preceding set of storm parameter values.

Computed hydrographs

Because the pattern in which a storm actually occurs and the field conditions under which storm water moves from the watershed divide to the drainage inlet are somehow different from what can be described by using a set of the mathematical equations, it is expected that there are some disagreements between the computed and measured hydrographs. It is generally understood that the more complicated the system under study (including both a rainfall event, or a series of such events, and an elementary watershed, or a combination of such elementary watersheds), the larger would be the disagreement between the computed and measured values.

Although both highway cross-sections under investigation are small watersheds with drainage area less than 0.1 square mile, the complicacy of the storm patterns and field conditions such as strong local disturbance and car splash caused by passing vehicles (Fletcher and Chen, 1975) may greatly reduce the reliability of field data so collected and thus eventually destroy the ''mean-value'' approach on which the mathematical model is based. Consequently, if there are any disagreements between the measured and computed hydrographs, they may be attributed to one or a combination of the following:

(1) Accuracy and representativeness of the measured input and output data are questionable. As indicated above, traffic disturbance might significantly alter the measured values at various rain gages and discharge-measuring flumes. For example, an inspection of the field data (Fletcher and Chen, 1975) reveals that none of the six recording rain gages installed on each site has measured exactly the same intensity as the rest of the gages even under the same storm. It is not clear whether this is caused by the nature of a thunder storm which is moving or the adverse aerodynamic effects of highway vehicles. The variety of the rainfall intensity, magnitudewise and timewise, makes it extremely difficult to select the one that represents the storm under study. Criterion of selection for those which were used as input is rather arbitrary. In general they were selected as closely as possible to the ones which might hopefully produce the corresponding measured hydrographs. Since the patterns of the measured hyetographs at the six rain gages are nearly identical [i.e., about equal γ values (Chen, 1975b)] for each major storm analyzed, simply the largest one among the six was chosen in order to maintain the better accuracy of computation. However, the more representative hyetograph can be obtained by first plotting isopluvial maps at different time intervals and then averaging the accumulated amount of rain over the area and time interval considered. Of course, the latter method of improvement on input data is only possible if a network of more than six point measurements is available.

An amount of water lost or ''diverted'' in splash and spray caused by moving traffic during a storm, especially at Parleys site No. 2, was substantial (Fletcher and Chen, 1975). This would in effect change significantly the shape of the measured hydrograph, magnitudewise and timewise, from the one which would have been otherwise. Because the present computer model does not take this effect into account, a large discrepancy between the measured and computed hydrographs from the roadway (Parleys site No. 2) alone is expected. Unfortunately there is no way to separate this effect from others and determine the significance (or insignificance) of its effect.

This inaccuracy in the measured hydrograph at Parleys site No. 2 was further aggravated by inherent instrumentation problems (Fletcher and Chen, 1975) which cannot be corrected without resorting to a new instrumentation system. Bad output is evidently reflected in the measured hydrograph, for example, of the August 16, 1973 storm, which, due to some unknown causes, could not be simulated by using the present model. Therefore, the comparison of the measured and computed hydrographs for storms from the roadway cannot be made herein.

(2) The smaller the rainfall intensity of a storm under study, the worse is the accuracy of the computer results. As shown in Figure 18, the present model underestimates very badly the computed discharge of the low flow. It is noted that most of the major storms under investigation, except for one, merely amount to the highest of 3 inches per hour or less for a period of 2 to 3 minutes. Such small storms cannot produce the surface flow which is large and deep enough to be computed reliably with the method of characteristics due mainly to the difficulty in the expression of the Darcy-Weisbach friction coefficient, f.

Another possible source of large computational errors might result from the computation of the moving internal boundary where overland flow meets with gutter flow, aside from the shock-wave computation that might occasionally give trouble, too. Since small errors induced in the numerical computation may travel upstream and downstream depending upon the state of flow and grow unboundedly with hydrodynamic instability, the computation of the shock waves, except at the wavefront of a moving storm, was not performed in the present study by using a few control statements although it is included in the computer program. Details of such control statements are given in the appendix.

For simplicity, the actual hyetograph was best fitted by using a least squares procedure to Eqs. 128 and 129 (Chen, 1975b) with storm parameters a, b, c, t_d, and γ. This is a good approximation which may be valid for practical purposes in view of varieties in measurements at different gages, but may not be accurate enough for some storms which have more than one peak. Because most of the thunder storms which we are interested in studying are likely single-peaked, this type of the simplification of the storm pattern is justified and maintained throughout this study.

Another simplification in the mathematical modeling is related with the evaluation of infiltration capacity at both sites. The values of the infiltration parameters such as f_∞, α, and S in Eqs. 120 and 150 were determined on the basis of the October 4, 1972 storm (Fletcher and Chen, 1975). It is possible that the parameter values for other storms are quite different from those determined from the October 4, 1972 storm because of the differences in antecedent moisture condition (Chen, 1975c). This judgment in accounting for the differences is seemingly confirmed by comparing the measured and computed hydrographs for the selected storms, each of which is briefly discussed below.

The October 4, 1972 storm at Parleys site No. 1. A comparison of the measured rainfall intensity and runoff rate, as shown in Figure 25, reveals that a large amount of precipitation was apparently lost in the initial abstraction, I_a. The initial abstraction that consists of interception and subsurface and surface storage (including initial detention and depression storage) before runoff begins cannot be theoretically determined with the present knowledge in hydrology. The present computer model

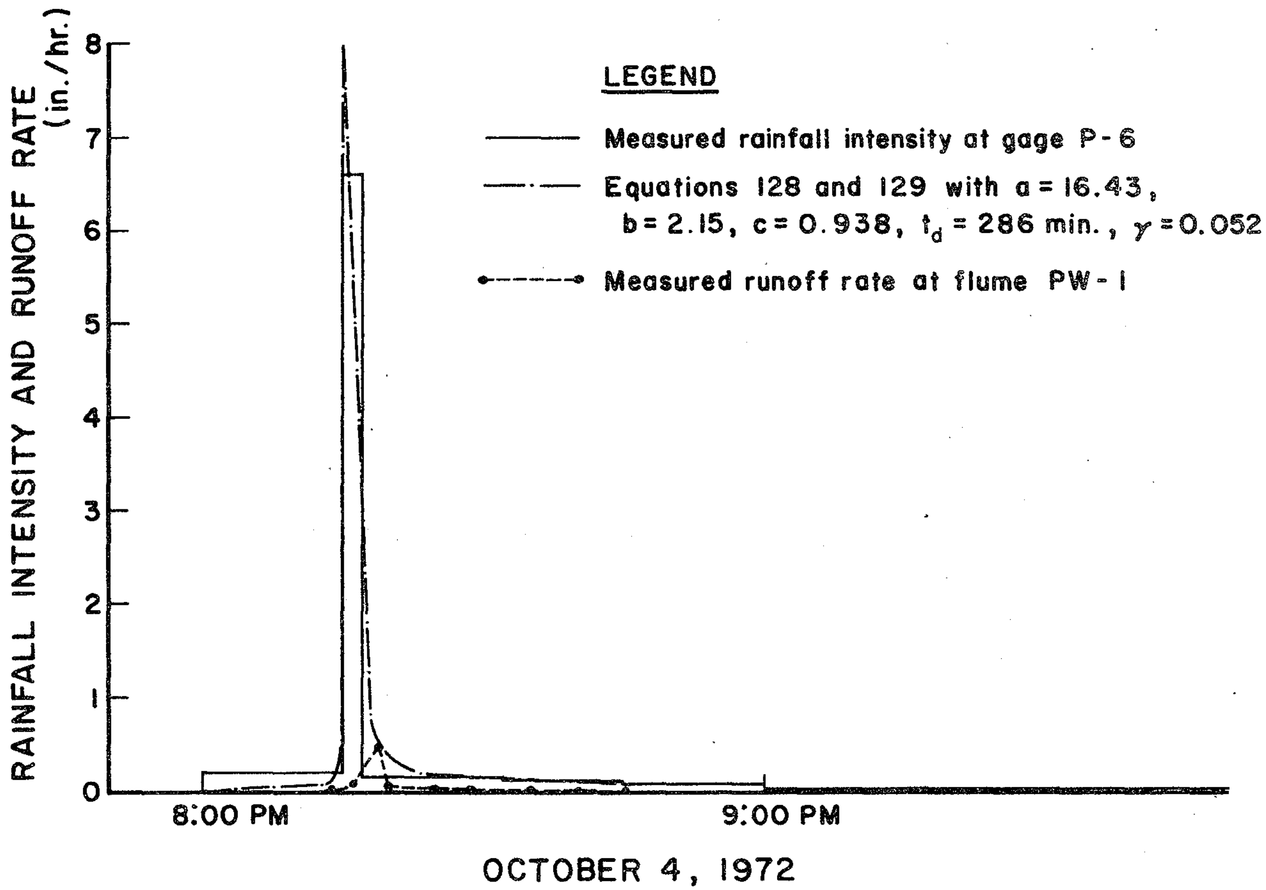


Figure 25. Measured October 4, 1972 storm and runoff from highway sideslope at Parleys site No. 1.

does not contain the computation of I_a, but assumes its value as an input data. Various values of I_a were thus input under the ''simulated'' storm (broken line in Figure 25) and the corresponding hydrographs computed for the purpose of comparison, as shown in Figure 26. The agreement between the measured and computed hydrographs, despite apparent differences in the assumed I_a value, is strikingly good for the following major reasons. (1) The storm pattern is single-peaked and Eqs. 128 and 129 are quite accurate for the representation of the actual hyetograph. (2) The input infiltration capacity was determined based on this storm.

In connection with the development of the parametric infiltration models (Chen, 1975c) using the Soil Conservation Service (SCS) approach, the writer has formulated a theoretical relationship between the initial abstraction, I_a, and the soil potential infiltration, S, (Appendix 3) as

$$I_a = 0.25\ S \qquad \text{(151)}$$

which has the ratio of I_a to S equal to 0.25 instead of 0.20 assumed by SCS. Equation 151 was then used to correct any possible errors that might be induced by the inaccuracy in the assumed expression of infiltration capacity. Because the parametric models of the infiltration capacity at both sites were developed based on the October 4, 1972 storm, no further improvement on the computed hydrograph thanks to Eq. 151 (Figure 26) was appreciated, however. It is hoped that use of Eq. 151 will improve the computed hydrographs for the other storms.

For an assumed I_a value, it is necessary to determine the time when runoff starts. Thus, rainfall mass curve, which can be constructed by integrating Eqs. 128 and 129 over time (i.e., equivalent to multiplying the right-hand side of Eqs. 139 and 140 by time, t), may be used to compute the time required for rain to accumulate the assumed I_a value. The Newton-Raphson method may be used for this computation; however, the method failed sometimes because of the peculiar nature of Eqs. 128 and 129, or integrated forms thereof, Eqs. 139 and 140 at the peak. Instead, the Interval Halving or Bisection Method (Fenves, 1967) was used.

The July 19, 1973 storm at Parleys site No. 1. The role that the initial abstraction, I_a, plays in the computation of the inlet hydrograph is very important. The sensitivity of the computed hydrograph to the assumed magnitude of I_a is reflected not only on the time when runoff starts, but also on the shape of the hydrograph which responds subsequently to the storm input as depicted in Figure 27. The various values of I_a were tested and the corresponding hydrographs computed, as shown in Figure 28, for comparison. It can readily be seen from the comparison of the computed hydrographs that the one with I_a = 3/8 in. and S = 1.50 in. (from Eq. 151) best fit the measured hydrograph, timewise and magnitudewise, except for a small span of time around the peak of the hydrograph where the runoff discharge is overestimated. In view of the fact that a small increase in the assumed value of I_a, say by 1/8 in., to a total of 1/2 in. (See Figure 28) has resulted in a substantial reduction in the peak as well

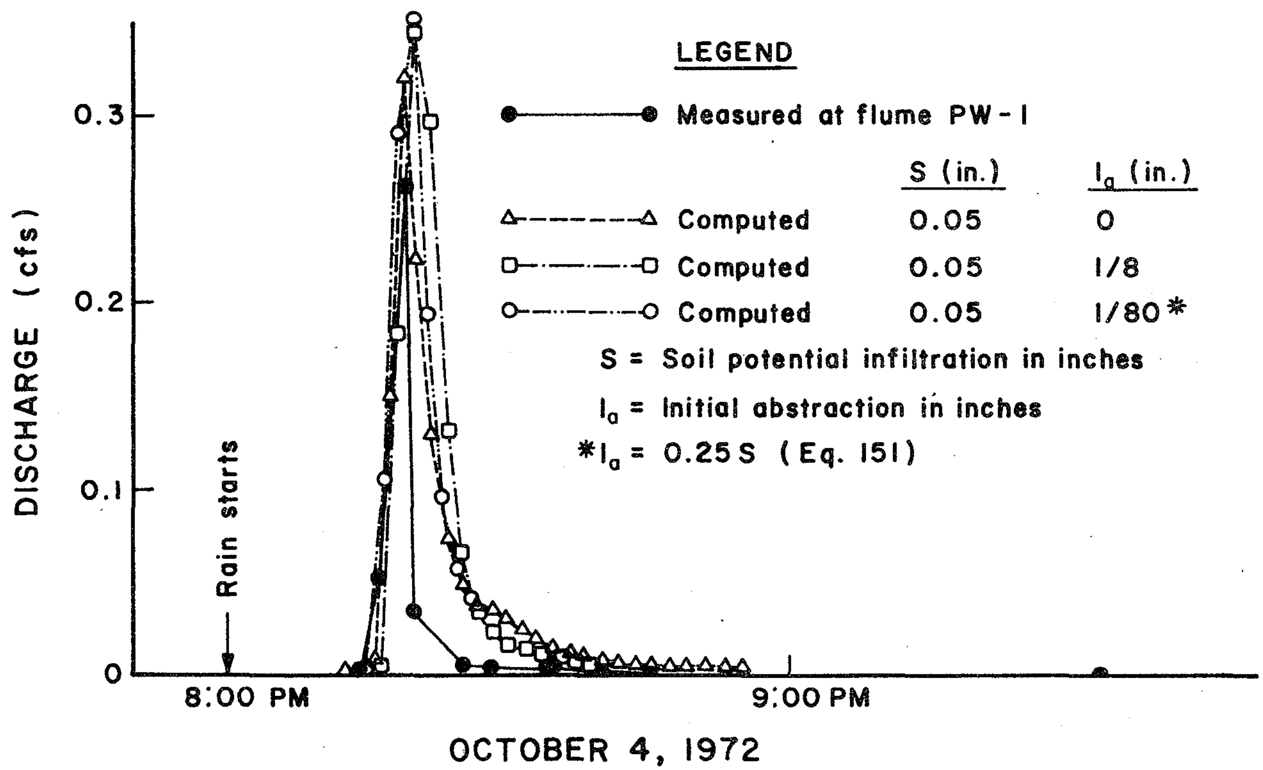


Figure 26. Comparison of computed and measured hydrographs for October 4, 1972 storm at Parleys site No. 1 (sideslope).

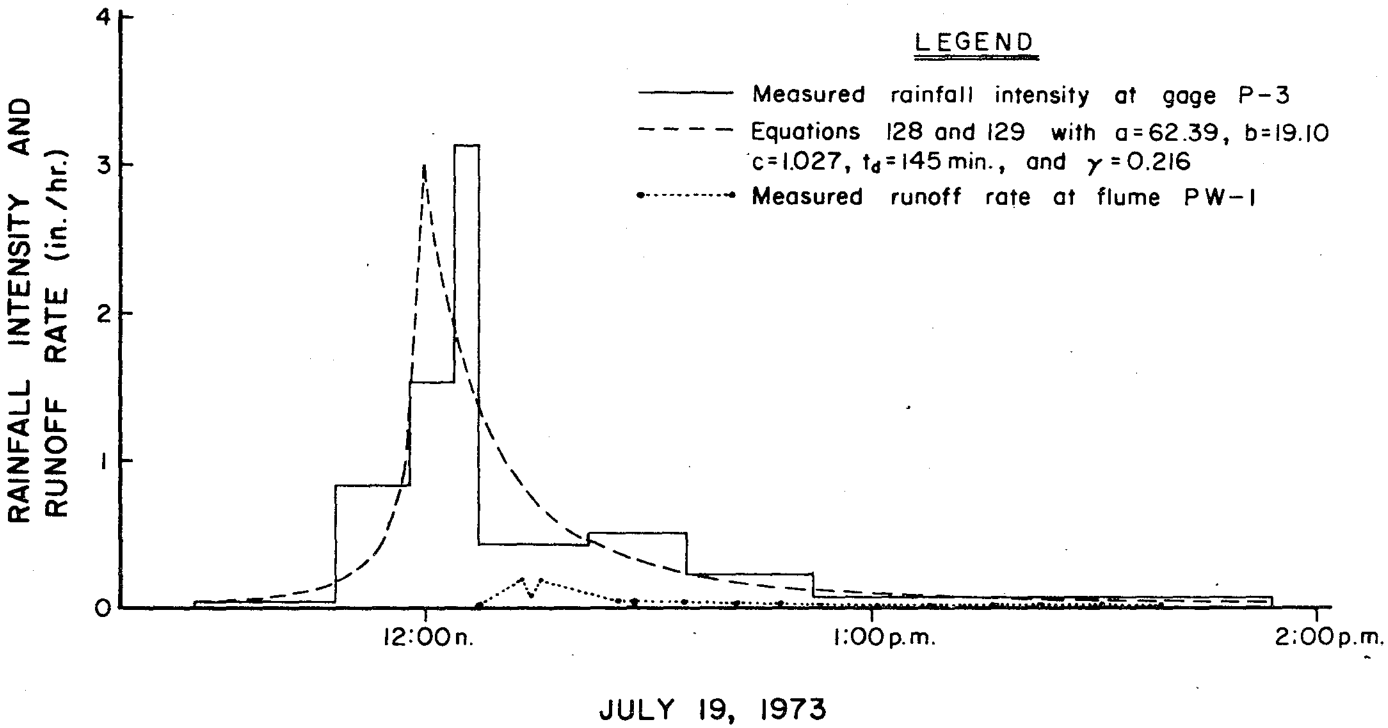


Figure 27. Measured July 19, 1973 storm and runoff from highway sideslope at Parleys site No. 1.

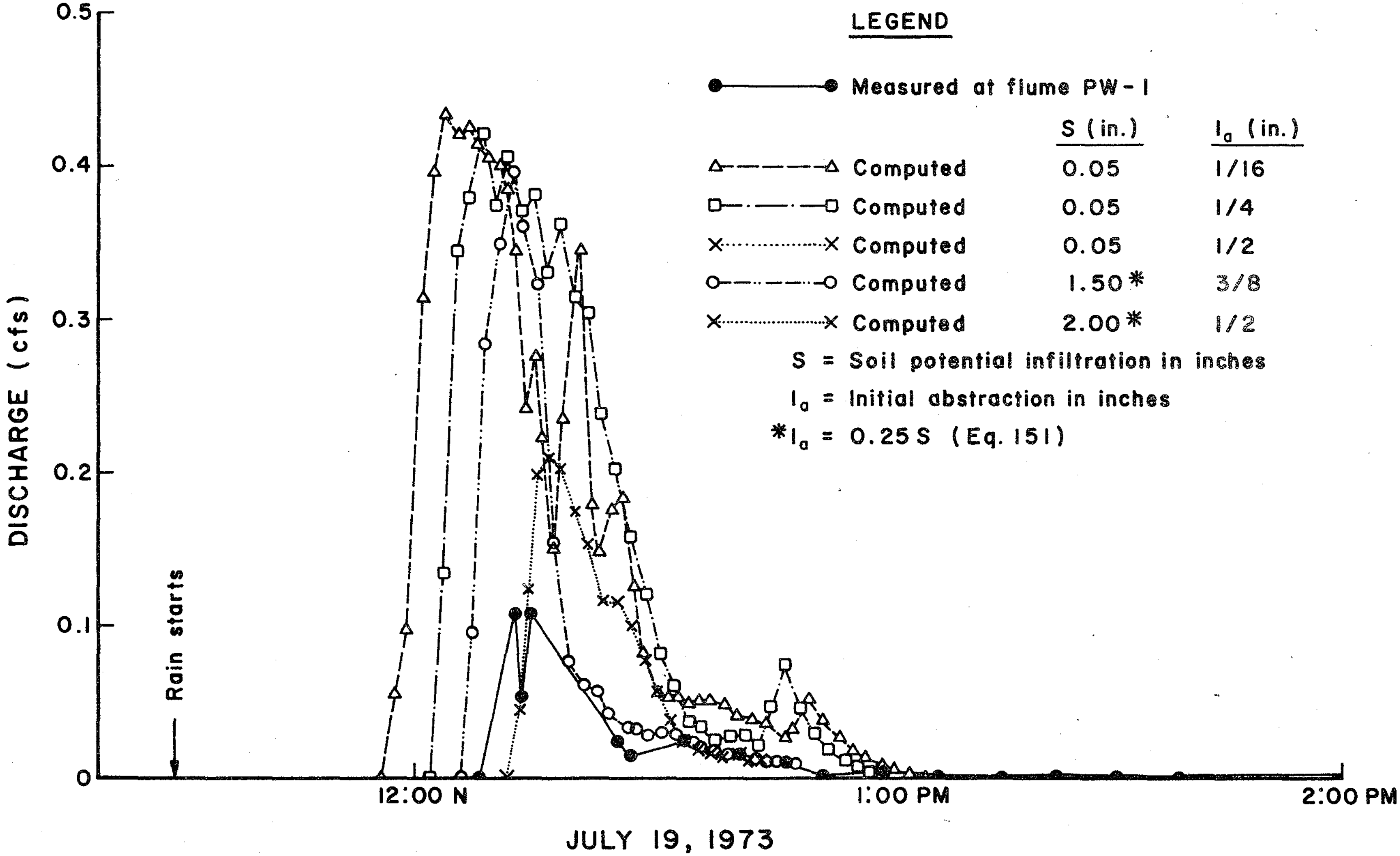


Figure 28. Comparison of computed and measured hydrographs for July 19, 1973 storm at Parleys site No. 1 (sideslope).

as a time shift or delay in response without changing the shape of the hydrograph, a further improvement on the computed hydrograph due to I_a seems still possible.

The results from these computer experiments indicate that the quantity I_a appears to be the most important, single factor to be considered in the successful modeling of the surface runoff from the practical point of view. Unfortunately it happens to be the most difficult, unknown quantity to determine from the theoretical point of view. Since the proposed parametric infiltration model (Eqs. 120 and 150) can be expressed in terms of the soil potential infiltration, S (Chen, 1975c), the value of I_a can be determined either from Eq. 151 by using the known S value or from

$$I_a = 0.25 \left(\frac{1000}{CN} - 10\right) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (152)$$

in terms of the known runoff curve number, CN, for a soil-cover-moisture complex in question. For convenience in engineering application, the initial abstraction values in inches for highway soil-cover-moisture complexes are computed from Eq. 152 for CN values given by the writer in the other report (Table 8 of Chen, 1975c) and tabulated in Table 2. Should the rating table based on the catena concept (Chiang, 1971) be used as the refined SCS classification for hydrologic soil groups, I_a values for groups + B, + C, and + D can be interpolated accordingly from Table 2. Since the I_a value so determined at Parleys site No. 1 varies from almost zero (for the October 4, 1972 storm) to a little bit more than 0.375 in. (for the July 19, 1973 storm) in the hydrologic soil group D (Chen, 1975c), the corresponding antecedent moisture conditions (AMC) for both storms are evidently different, viz., from Table 2 varying from AMC III for the former storm to AMC I for the latter storm on the highway sideslope with the same soil and plant cover at Parleys site. The variation of the I_a value demonstrates in part the applicability and usefulness of Table 2 for engineering practice.

Table 2. Estimated initial abstraction (I_a) in inches for highway soil-cover-moisture complexes.

Antecedent Moisture Condition (AMC)	Hydrologic Soil Group			
	A	B	C	D
AMC I	1.288	0.925	0.625	0.441
AMC II	0.549	0.374	0.247	0.160
AMC III	0.217	0.132	0.077	0.051

The September 5, 1972 storm at Layton site. The hydrograph at Layton site can be thought of as a combination of one from the sideslope at Parleys site No. 1 and the other from the roadway at Parleys site No. 2. Unfortunately for those storms examined, none of the measured hydrographs at Parleys site No. 2 appears to be reliable enough to be used in the validation of the computer model. However, the validation of the computer model including both parts (i.e., one from the sideslope and the other from the roadway) may be inferred to imply that if either part of the two is valid, the other part must also be true. Therefore, the hydrographs in response to the September 5, 1972 storm, as shown in Figure 29, were computed for various values of I_a and plotted in Figure 30 for comparison.

An inspection of Figure 30 reveals that the computed hydrograph for I_a = 5/16 in. (0.3125 in.) appears to best fit the measured hydrograph timewise. The peak of the computed hydrograph is much larger than that of the measured hydrograph, but it is reasoned more likely in the light of the relative magnitude of the measured rainfall intensity and runoff rate as depicted in Figure 29. In other words, the measured runoff rate for this storm appears to be too small at Layton site in comparison with those obtained from Parleys site No. 1 (see Figures 25 and 27), despite the fact that approximately half of the inlet discharge at Layton site is contributed by runoff coming from the roadway. However, the opposite tendency in the measured hydrograph is found on the other storm investigated. This seemingly indicates a data-collection problem at flume LW-1.

The May 26, 1973 storm at Layton site. For the storm, as shown in Figure 31, the measured runoff rate at flume LW-1 looks larger than that for the September 5, 1972 storm. Two I_a values were assumed and the corresponding hydrographs computed, as shown in Figure 32, for comparison. None of them fits well the measured hydrograph. Disagreements between the measured and computed hydrographs may be attributed to one or a combination of the sources of errors which were already given earlier.

The computer model so developed is of course not perfect as many difficulties are yet to be solved, but it has been demonstrated that it is accurate enough for practical purposes. In the following section, the model will thus be used to study runoff from typical urban highway cross-sections under idealized stationary and moving storms, and thereby to explore the feasiblity of developing standardized dimensionless inlet hydrographs for design storms having any desired recurrence intervals.

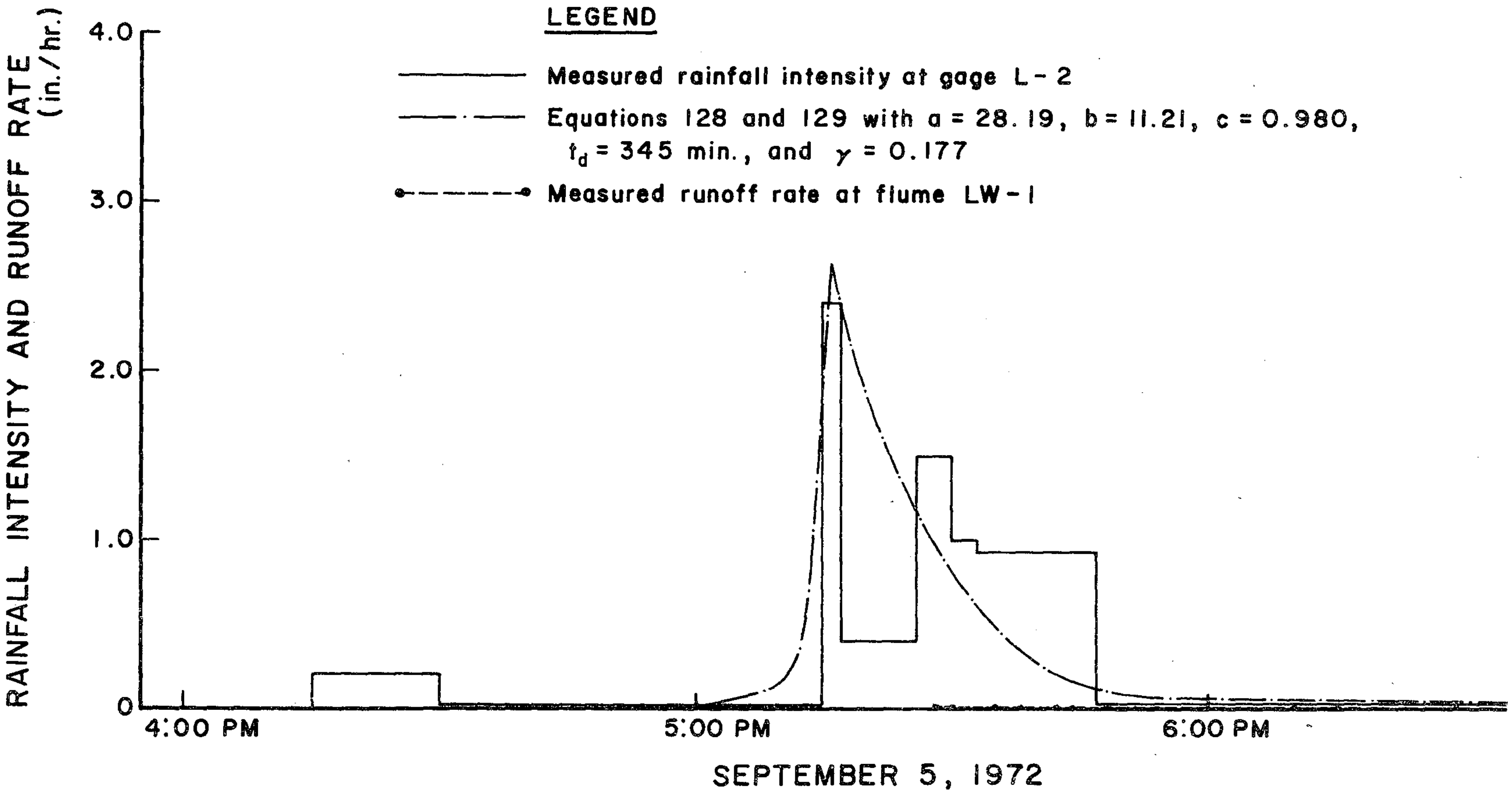


Figure 29. Measured September 5, 1972 storm and runoff from combined roadway and sideslope at Layton site.

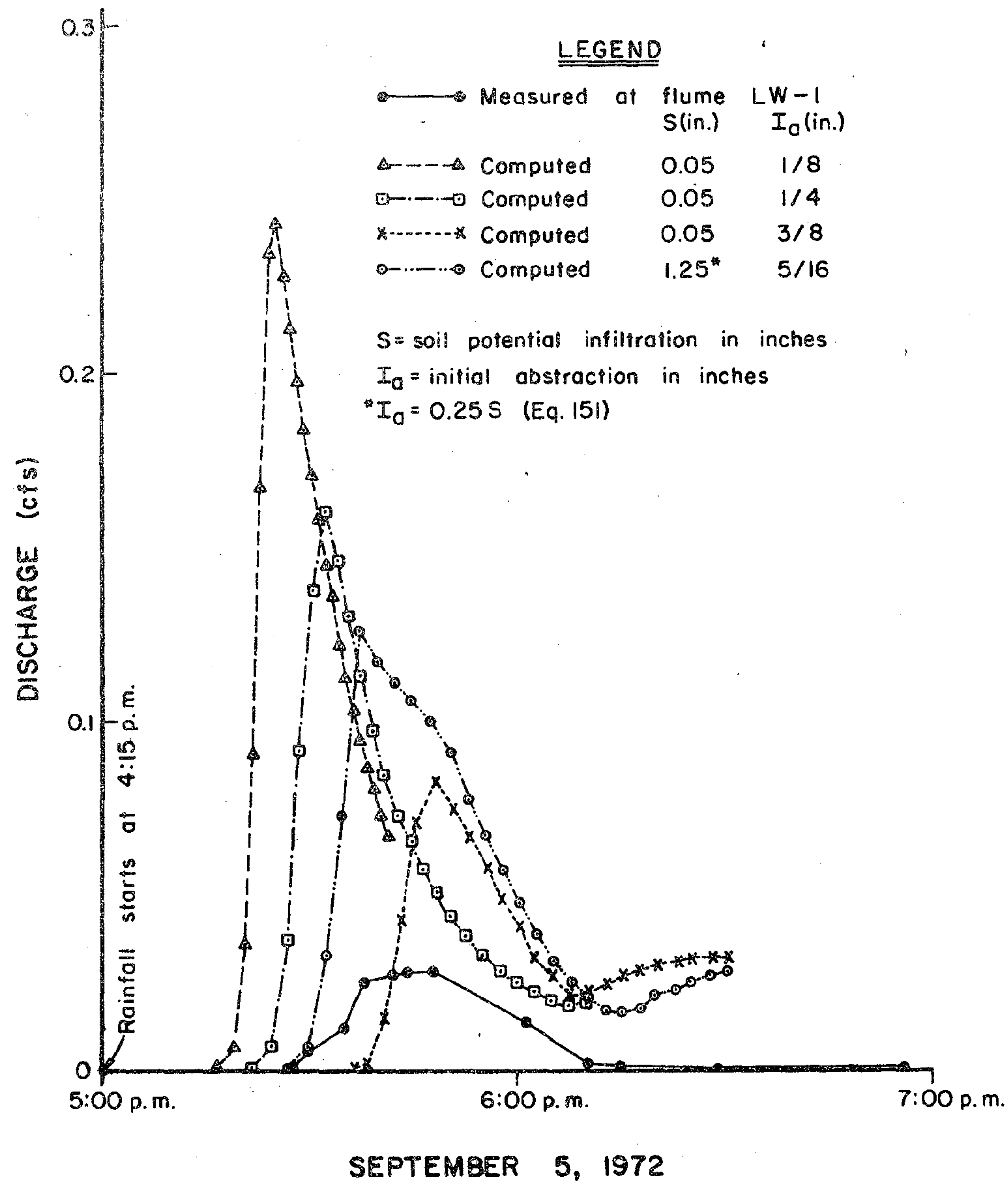


Figure 30. Comparison of computed and measured hydrographs for September 5, 1972 storm at Layton site (combined roadway and sideslope).

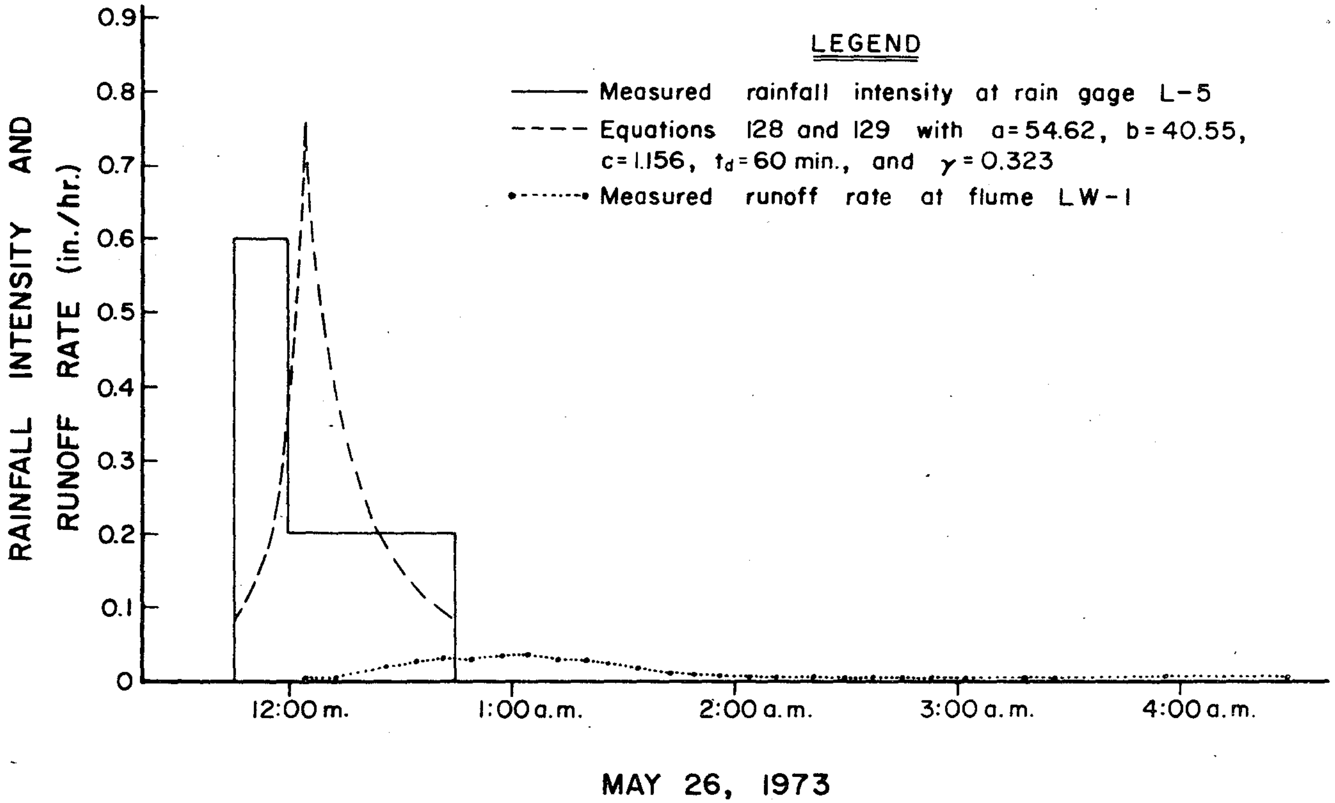


Figure 31. Measured May 26, 1973 storm and runoff from combined roadway and sideslope at Layton site.

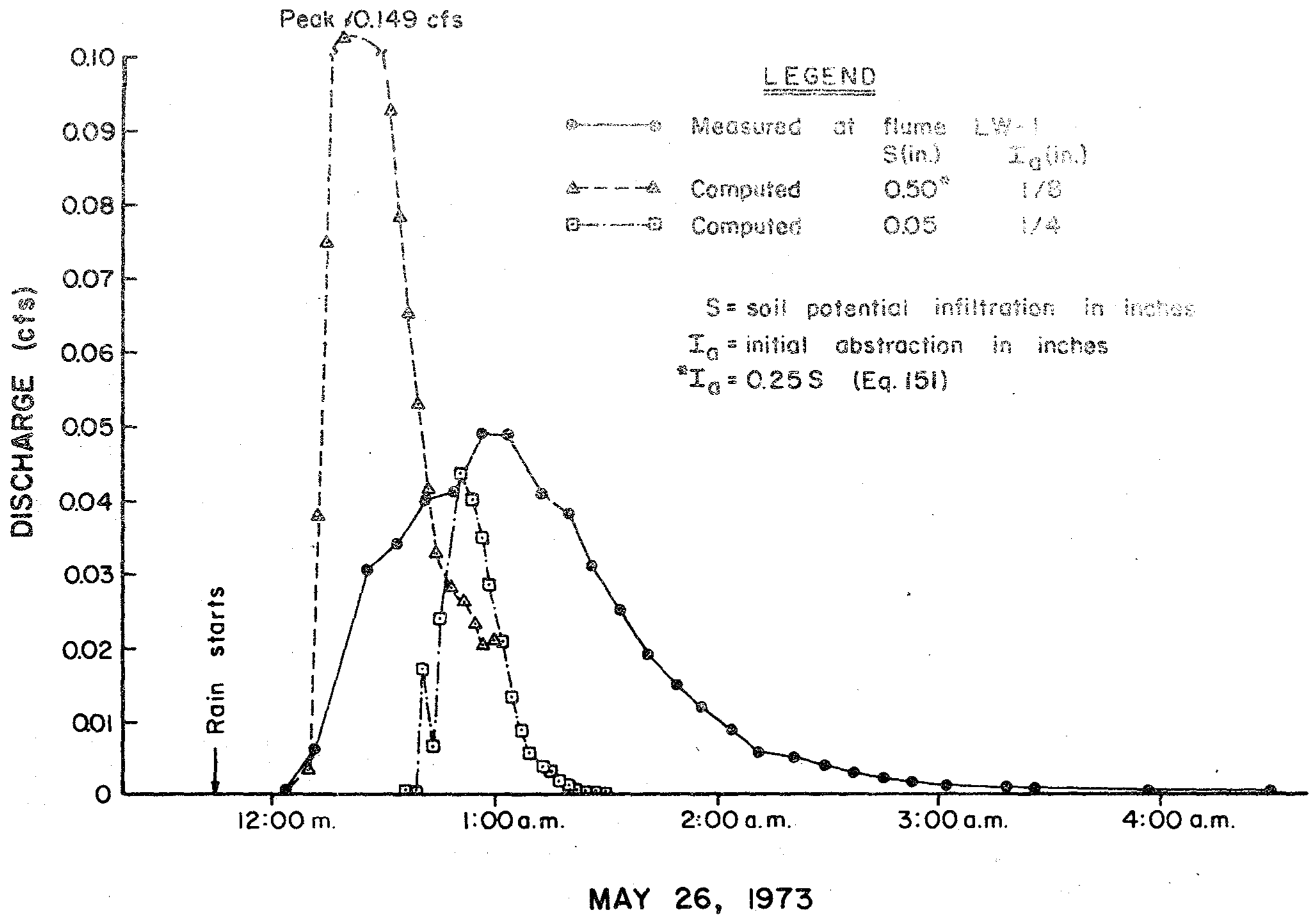


Figure 32. Comparison of computed and measured hydrographs for May 26, 1973 storm at Layton site (combined roadway and sideslope).

COMPUTATION OF RUNOFF FROM TYPICAL

URBAN HIGHWAY CROSS-SECTIONS

Accuracy of the computer model has only been tested for the limited cases in which field data are available. From the results obtained from such limited tests, it has been shown that the model can simulate, within practical tolerance limits, the actual hydrograph, should appropriate or average hydrometeorologic and physiographic data for the subject watershed be given. There seems no way to know, however, whether the model can also accurately compute the inlet hydrograph for other cases in which field data are not available, without resorting to some kind of computer experiments. Time did not permit computer experiments to be performed on all possible cases. Those which were tested in this study are some idealized, hypothetical cases which are nevertheless believed to be essential to the subsequent development of non-computerized, dimensionless inlet hydrographs for highway engineers. Suffice it to say that while continuing efforts will be made on the collection of valid field data as well as the modifications and improvements of the present computer model, the appraisal of the results obtained from the exploratory computer experiments must also be in order. It is hoped that sensitivity analysis made by varying some significant parameters through the computer model will lead to the ultimate generation of design parameters for computing desired inlet hydrographs.

Four typical highway cross-sections provided by the Federal Highway Administration, as shown in Figure 33, approximately represent those found in the major urban and suburban interstate highway system. Among them, type 1a (Figure 33a) is similar to the one at Layton site (Figure 24a) which was already examined. Also examined extensively is the one at Parleys site No. 1 (Figure 24b) which is only a ''sideslope'' part of type 1a or type 2b (Figure 33c). Parleys site No. 2 (Figure 24c) consisting of a curb-type gutter could not be examined due partly to invalid field data and partly to difficulty in making the computer model operational under such small storms, as mentioned previously. It appears that the latter site corresponds to a ''roadway'' part of type 1b (Figure 33b) without paved shoulder or type 2 (Figure 33c). Since this part of the highway cross-section is the most common in urban highway traffic that requires more due attention as far as the inlet design is concerned, runoff from the roadway with or without paved shoulder under hypothetical heavy storms must be thoroughly investigated. Note that the present approach of computing runoff from the roadway with paved shoulder is technically treated the same as that from the roadway without paved shoulder. Therefore, for simplicity, only runoff from the roadway without paved shoulder is studied herein.

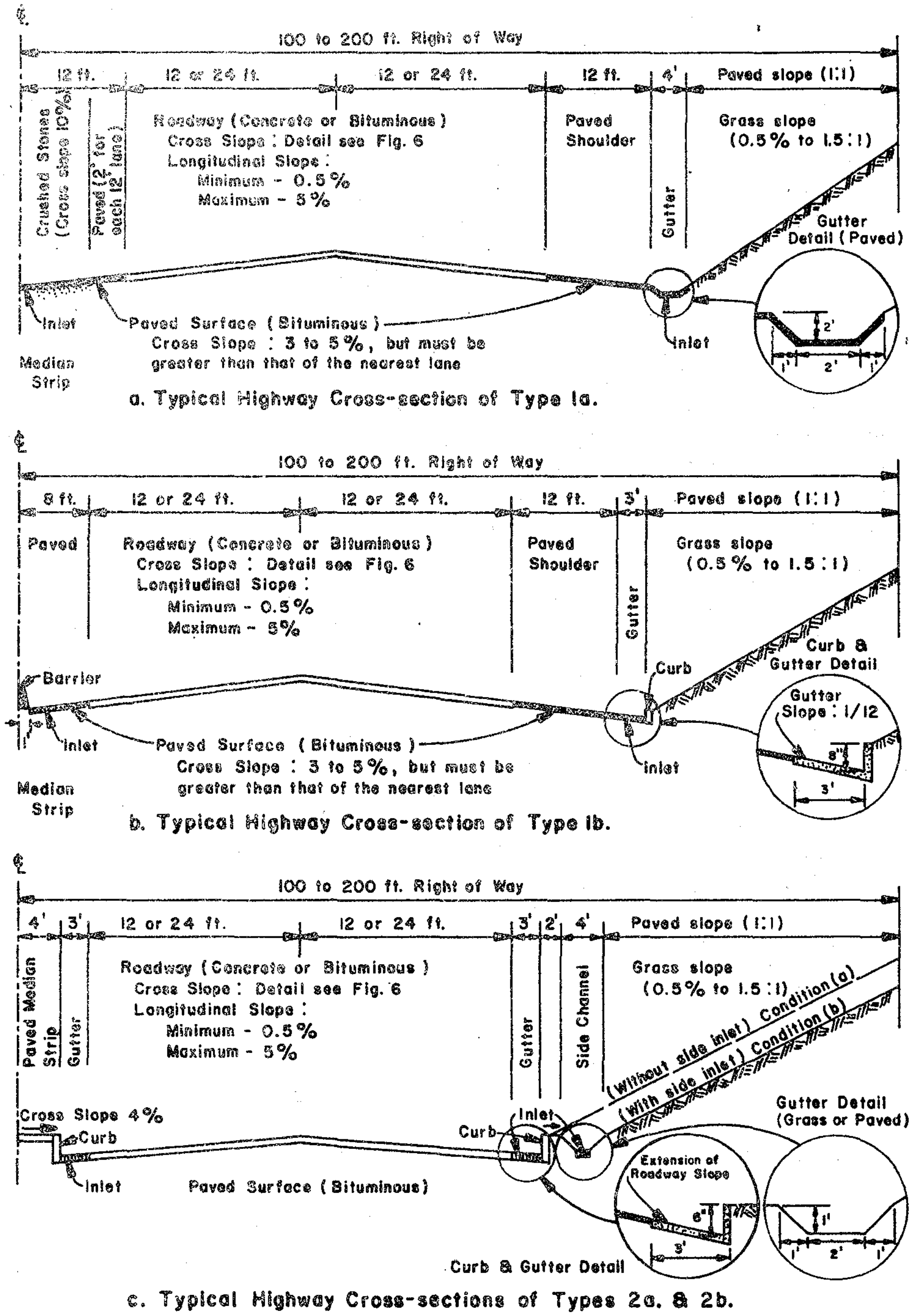


Figure 33. Schematic diagrams of typical urban highway cross-sections.

Runoff from Roadway with Curb-Type Gutter

The computer model was used to study the effects of the different parameters on the inlet hydrograph. The parameters studied are: gutter slope, gutter length, cross slope of the roadway, roadway width, rainfall intensity, and direction of the moving rainstorm. Ten different computer runs (Table 3), were conducted and the effects of the aforementioned parameters on the inlet hydrograph were determined. The common hydrometeorologic and physiographic data input in the computer model are: $\nu = 1.21 \times 10^{-5}$ ft^2/sec, $\Phi = 0$, $\Lambda = 28.5$ fps, $\delta = 0.1575$ in., $k = 0.0034$ ft for paved surface, $T_o = 1$ ft, and $i = 0$ in./hr.

The gutter flow is divided into 4 sections with distance interval Δs taken as large as 100 ft for all runs except run 4 which has $\Delta s = 250$ ft. The horizontal width of each lane, 12 ft, (Figure 6) is divided into three sections with the horizontal distance interval, Δx, for overland flow equal to 4 ft so that all the runs except for run 5 have eight grid points on the roadway.

The selection of the time interval, Δt, is programmed in the same way as mentioned previously. In other words, Δt is chosen between the values obtained from Eqs. 48 and 149, whichever is smaller.

In Table 3, the values of input parameters for run 1 are arbitrarily selected as ''standard'' ones and subsequently changed to other possible values, one at a time, for each of the other runs. For example, the gutter slope in run 1 is changed from 5 percent to 0.5 percent (i.e., underlined in Table 3) for run 2 while the remaining parameters in run 2 are all kept the same values as those used in run 1, and so forth. Because there are too many factors which may affect the inlet hydrograph including those which are currently under consideration, the sensitivity of its response (i.e., hydrograph) to the variation of any input parameter value can only be studied in such a tedious way. All the computer runs were executed on UNIVAC 1108 and analyzed. There is a tremendous amount of computer output at different time levels for each run, including velocity and discharge distributions, flow profiles, Reynolds and Froude number distributions, friction coefficient and slope distributions, and so forth (see, e.g., sample output in Appendix 4). These output data are helpful to the study of the mechanism of water movement on the roadway under a stationary or moving rainstorm. One may be interested in plotting the building-up or receding flow profiles on the roadway at various sections and in the gutter at different time levels. Some of these were already conducted by Chu (1973) using the same computer model, but in a rather limited version of capability, developed in the early stage of this research. Since our main thrust of this research is to develop the inlet hydrograph, analysis of many flow characteristics other than hydrograph, are not further pursued herein.

Table 3. List of the values of different parameters used in computer experiments.

Run	Gutter slope (%)	Cross slope of roadway (max. or min.)*	Gutter length (ft)	Roadway width (no. of lanes)	Rainfall intensity (in/hr)	Storm front velocity** (mi/hr)	Moving storm direction (in parallel with)
1	5	max.	400	2	20	∞	–
2	0.5	max.	400	2	20	∞	–
3	5	min.	400	2	20	∞	–
4	5	max.	1,000	2	20	∞	–
5a	5	max.	400	1	20	∞	–
5b	5	max.	400	3	20	∞	–
5c	5	max.	400	4	20	∞	–
6	5	max.	400	2	5	∞	–
7	5	max.	400	2	20	+ 0.136	overland flow
8	5	max.	400	2	20	– 0.136	overland flow
9	5	max.	400	2	20	+ 0.682	gutter flow
10	5	max.	400	2	20	– 0.682	gutter flow

*The values of the coordinates used in the maximum and minimum cross slopes of the roadway are shown in Figure 6.

**Infinity sign "∞" means a stationary rainfall, positive sign means in the direction of flow, and negative sign means in the opposite direction of flow.

The dimensionless inlet hydrograph, Q_* (= Q/A_oV_o) versus t_*(= tV_o/L_o) for all runs except for run 9 (which failed for unknown causes) are plotted in Figure 34 for comparison. For convenience, rainfall for run 1 through run 6 was made to stop arbitrarily at $t_* = 5$, which thus gives all runs various time durations of rainfall, t_d, in minutes because of the differences in the normalizing quantities A_o, V_o, and L_o used in each run (see Table 4). Obviously, even by t_d, some runs have not reached the theoretical equilibrium state yet, aside from the possible numerical errors involved in the computation.

Accuracy of the computed hydrograph

To examine the accuracy of the computation without resorting to field data, the theoretical point in the hydrograph has always been checked. This is the theoretical equilibrium state at which runoff rate in a dimensionless form, Q_*, must be equal to unity under a stationary, prolonged uniform rain. Any deviation from this theoretical value for the rain lasting more than the time of concentration may be attributed either to the flow characteristics of runoff in question or to computational errors, or both. An inspection of run 1 through run 6 in Figure 34 reveals that only run 3 which has the minimum cross slope of the roadway (Table 3) has reached the theoretical equilibrium point. A further examination of the computer output for all runs reveals that run 3 is the only run with the major portion of the runoff on the roadway fallen in the subcritical flow range. This finding confirms our earlier statement in connection with the accuracy of the overland-flow submodel that the adverse effect of gravity on the computational stability and convergency worsens with the increase in the Froude number.

The time durations of rainfall for run 5a and run 1 which have only one-lane and two-lane traffic, respectively, should be long enough for runoff to reach the theoretical equilibrium, should there be no computational errors. Apparently there are numerical errors, about 3 to 4 percent, in the computation of run 1 and run 5a. Other runs such as run 2 which has a smaller gutter slope, run 4 which has a longer gutter reach to the inlet, and run 5b and run 5c which have more traffic lanes, all in comparison with run 1, do not quite seemingly reach the theoretical equilibrium discharge by the time rain stops (i.e., $t_* = 5$ or dimensional time thereof for each run as listed in Table 4). From the errors involved in the computation of run 1 and run 5a, it is estimated that the computational errors in those runs should not exceed more than 3 to 4 percent.

The difficulty in computing runoff resulting from a light storm with the rainfall intensity as small as 5 in./hr or less manifests itself in an unstable hydrograph such as computed for run 6, as shown in Figure 34. One of the most difficult parts in the runoff computation using the present model is the computation of the internal boundary where overland flow meets with gutter flow. Since the internal boundary moves from time to time, a slight error in the computation of the location of the internal

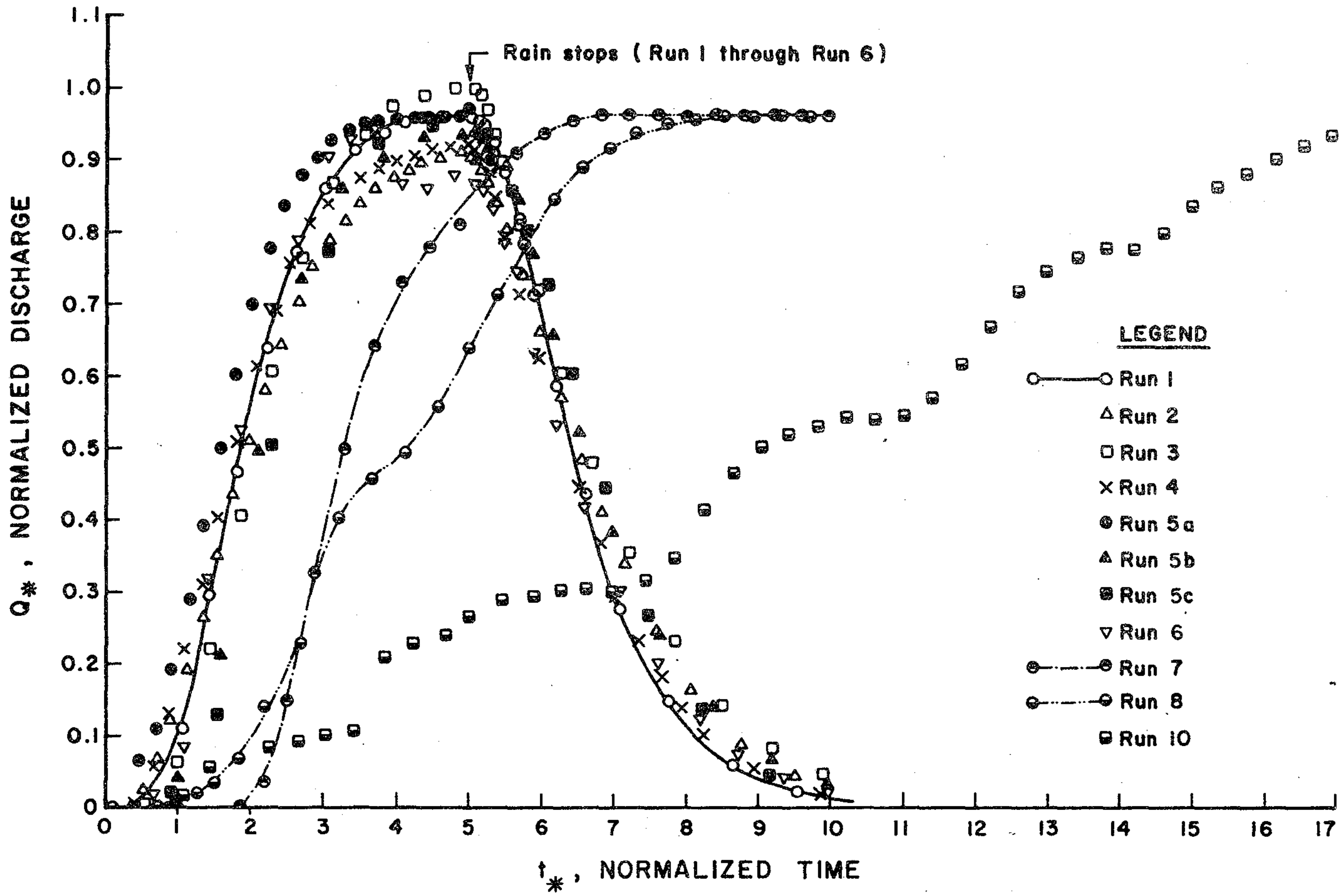


Figure 34. Computed dimensionless inlet hydrographs for runoff from roadway with curb-type gutter under stationary and moving rainstorms.

Table 4. Normalizing quantities A_o, V_o, and L_o and time duration of rainfall, t_d, used in the computation and construction of dimensionless hydrographs for all runs shown in Figure 34.

	Run											
	1	2	3	4	5a	5b	5c	6	7	8	9	10
A_o (ft^2)	0.362	0.734	0.362	0.634	0.253	0.453	0.534	0.155	0.362	0.362	-	0.362
V_o (ft/sec)	13.81	6.82	13.81	19.68	10.98	15.92	17.66	8.02	13.81	13.81	-	13.81
L_o (ft)	400	400	400	1000	400	400	400	400	400	400	-	400
t_d (min.)	2.42	4.89	2.42	4.24	3.04	2.09	1.89	4.16	-	-	-	-

boundary would also propagate upstream and downstream in the gutter, resulting in the subsequent computations with unrealistically too high or too low gutter flow depth and velocity. The small intensity is probably one among many reasons, runoff at Parleys site No. 2 could not be computed, as mentioned previously. No attempt was made in this study to refine or improve the computation of the internal boundary under a light rain, but it must be made in the future if the capability and applicability of the present model will be broadened.

The computed hydrograph for run 7 represents the response of the roadway to a uniform storm with a storm front moving at velocity W = 0.136 miles per hour in the direction of overland flow. Theoretically speaking, when the equilibrium state for run 7 is reached, it must have the same theoretical equilibrium discharge as run 1 because both runs have the identical physiographical and hydrometeorological inputs at the equilibrium state. Therefore, run 7 has approximately the same accuracy of computation as run 1, as shown in Figure 34. The computed hydrograph for run 8, which has a storm front moving in the opposite direction of overland flow, starts earlier, but has a less steep slope than that for run 7. Finally, at the equilibrium state, run 8 also has approximately the same accuracy of computation as run 1 and run 7, as shown in Figure 34.

For run 9, the writer has failed to get the desired solution, as mentioned previously, so that it cannot be shown in Figure 34 for comparison. While a continuing effort is still made to solve it at the time of writing this report, it is worth pointing out here that the failure may be caused either by a large distance interval (i.e., 100 ft) adopted in the computation or by a similar problem encountered in the computation of the internal boundary at the wave front, or both. A large distance interval causing trouble in the computation is also reflected in the computed hydrograph for run 10. Each of the hydrograph humps shown in Figure 34 for run 10 represents an addition of a grid point in the computation in response to the current position of the storm front. There is a total of five humps corresponding to the five grid points taken in the computation. The humps can be eliminated or smoothed out either by adopting more grid points or by refining the numerical scheme at the wave front. The latter method of improvement seems to be more practical than the former in terms of the less computer time required in the computation. At the equilibrium state, run 10 also reaches the same runoff discharge as run 1.

Development of dimensionless inlet hydrograph

For run 1 through run 6, despite the significant difference in the values of the parameters tested, their normalized inlet hydrographs look very similar to each other except for apparent time lag among some of them. If the normalizing (or reference) quantities can be chosen in such a way that they can represent more the overall flow characteristics, then these normalized inlet hydrographs can be collapsed much closer than what is shown in Figure 34. For instance, the reference length can be chosen to be equal to the summation of the gutter flow length and overland flow length. Although Chu (1973) has replotted the normalized hydrographs for run 1 through run 6 using the latter reference length, small spreads among the runs do not seem to warrant much improvement of the newly-plotted hydrographs over those shown in Figure 34. In the future, if more data on the computed hydrographs generated from a variety of ranges of the values of the input parameters such as those related to design storms (Chen, 1975b), soil infiltration capacity (Chen, 1975c), and initial abstraction (Eq. 151) are available, the construction of dimensionless design hydrographs, similar to Figure 34, for the four typical urban highway cross-sections (Figure 33) seems possible.

Regarding the inlet hydrograph due to a moving rainstorm, the construction of such a dimensionless hydrograph would be more complicated than that presented herein. It is conceivable that if the storm front in overland flow direction outraces the wave front, the inlet hydrograph for run 7 must differ with that for run 1 by merely a time lag which accounts for the time needed for the storm front to move from the upstream end of overland flow to the downstream end of overland flow. On the other hand, if the wave front outraces the storm front, the situation will be somewhat different from what was just described above, of course, depending upon the speed of the storm front. As shown in Figure 34, the effect of both direction and magnitude of the moving storm on the inlet hydrograph is quite significant. As a matter of fact, the inlet hydrograph for run 1 actually represents the one for the storm front velocity, W, approaching infinity (Table 3) and the abscissa of the hydrograph, where $Q_* = 0$, represents the inlet hydrograph for $W = 0$. Hence, the area enclosed by the abscissa and the inlet hydrograph for run 1 is the domain of the inlet hydrograph in which the moving rainstorm has a storm front velocity varying from zero to infinity. Therefore, in addition to the normalized quantities, unless some kind of a moving and deforming time coordinate system is adopted to adjust for such a wide variety of Q_* versus t_* areas, the development of a unified dimensionless hydrograph for a moving storm seems unlikely.

SUMMARY AND CONCLUSIONS

The mathematical model which consists of a set of flow equations, initial conditions, and boundary conditions, is developed for a combined overland and gutter flow. Based on the laws of the conservation of mass and momentum, the one-dimensional spatially-varied unsteady flow equations are formulated to simulate such flow and then solved numerically on a digital computer subject to prescribed initial and boundary conditions. Several assumptions and approximations were made in the formulation of the mathematical model. The major ones made are as follows:

1. In the derivation of the momentum equation, Eq. 17c, two momentum correction factors, β and β_L, are introduced to account for the velocity distributions of the main flow and the lateral inflow, respectively. The actual values of β and β_L cannot be determined. In wide open channels, the momentum correction factor β has a theoretical value of 1.2 for laminar flow and $1 + 0.78125f$ for turbulent flow, where f is the Darcy-Weisbach friction coefficient. For simplicity, the values of the momentum correction factors used in the present study are assumed to be unity. The computer solutions for several different rainstorms indicate that within the range of different parameter values used, no significant differences occur for β's ranging from 1.0 to 1.2 (for laminar flow) or to $1 + 0.78125f$ (for turbulent flow).

2. The value of the Darcy-Weisbach friction coefficient, f, is difficult to determine, but can be approximated by using Eqs. 19, 20, and 21. For turbulent flow on the rough surface, Eq. 19 can be used to evaluate the f value. However, if the depth of flow is almost of the same order of magnitude as the roughness size or less, Eq. 19 in terms of the logarithm of the relative roughness (R/k) may not be valid. Whether or not Eq. 19 is valid under such small flow depth must be checked by experiment.

For laminar flow, Eq. 21 is used to evaluate the f value. To avoid difficulty in the computation, the flow is treated as laminar when the hydraulic radius, R, is less than a certain value, denoted by εk. The value of ε is unknown, but presently assumed as unity. The value of C in Eq. 21 is evaluated in terms of channel slope, S, as expressed by Eq. 82. The coefficient and exponent in Eq. 82 were experimentally determined for natural turf surfaces.

The results obtained from the computer experiments indicate that the flow often falls in the transition region (i.e., partially laminar and partially turbulent), a region in which none of Eqs. 19, 20, and 21 should apply. This failure in the accurate evaluation of the friction coefficient may sometimes result in computational instability, as mentioned previously. Although Eqs. 19, 20, and 21 were used throughout the present analysis, a more accurate formula should be formulated to evaluate the friction coefficient in the transition region.

The flow equations so formulated are expressed in the form of a set of quasi-linear partial differential equations. This set of the equations was solved numerically by using an explicit finite-difference scheme with specified rectangular grid intervals based on the method of characteristics. A special technique by use of a pair of shock equations and characteristic equations was developed for tracing a bore or a train of such bores.

For solving the conjugate depths and velocities at the discontinuity, the internal boundary condition, Eq. 100, must be solved simultaneously with both C^+ - and C^- - characteristic equations on the front side of the discontinuity and only one, either C^+ - or C^- - characteristic equation, on the back side of the discontinuity. With the help of Eq. 109, this numerical technique was applied in tracing the wavefront moving on a dry surface due to a moving rainstorm.

The mathematical model developed in this study was programmed in FORTRAN language and executed on the UNIVAC 1108 computer. The computer model, including a main program, 38 subroutine subprograms, and 2 function subprograms, has been verified to be accurate enough for simulating overland flow as well as a combined overland and gutter flow under a stationary or moving rainstorm. Although there are several limitations in the computer model, the model is generalized so that it can be applied to any runoff routing problem on the highway cross-section including roadway, shoulder, sideslope, gutter, etc. The limitations such as the uniform cross slope of the roadway and the direction of a moving rainstorm restricted in parallel to or perpendicular to the direction of the gutter flow, can be removed, if desired, in a future study.

The proposed model computes not only the flow profiles, velocity distributions, discharge distributions, top width distributions, Froude number distributions, Reynolds number distributions, and friction slope (or coefficient) distributions, but also the locations of moving critical sections and bores, if any.

In the initial stage of the hydrograph when the velocity and hydraulic depth are small, the value of the time interval, Δt, is chosen from Eq. 48 or 149, whichever is smaller. Equation 149 was formulated by experience and is believed to be suitable for this type of the initial-value problem within the range of data input. Nevertheless, the time interval selected for circumventing the computational instability, especially in the initial stage of the hydrograph, needs further investigation.

The accuracy of the mathematical model was tested by comparing the computed hydrographs with field data under various physiographical and hydrometeorological conditions. For lack of available field data on runoff from the roadway with curb-type gutter, the model was also tested under some hypothetical storm and drainage conditions. It was found that the initial abstraction played an important role in the simulation of actual inlet hydrographs. The accuracy of the model is believed to be good enough for most practical purposes.

For improving the accuracy of the present mathematical model, the assumptions and approximations made in the evaluation of the friction coefficient, in the formulations of the initial conditions and internal boundary conditions, and in the arrangement of the numerical computational procedures must be refined or removed. Of course, some assumptions and approximations used require an experimental verification.

The computer solutions indicate that under the condition of uniform stationary rainfall, the effects of the parameters, such as the gutter slope, gutter length, cross slope of the roadway, roadway width, and rainfall intensity on the normalized inlet hydrograph are not significant, as shown in Figure 34. Therefore, if the reference quantities used to normalize the discharge and time are adequate, a unified dimensionless inlet hydrograph under a uniform stationary rainfall condition looks very promising. By the same token, if more data on the computed hydrographs generated from a variety of ranges of the values of the input parameters such as those related to design storms, soil infiltration capacity, initial abstraction are available in the future, the development of dimensionless design hydrographs, similar to Figure 34, for typical urban highway cross-sections seems possible.

The effects of the velocity of a moving rainstorm on the normalized inlet hydrograph are significant. The development of a unified dimensionless hydrograph for a moving storm does not look promising. However, because the range of influence of the velocity of the moving storm on the normalized hydrograph is clear, one may be able to obtain the desired hydrograph by interpolation or extrapolation.

RECOMMENDATIONS

The principal future work recommended for the further investigations of computer modeling and analysis of runoff from typical urban highway cross-sections is as follows:

1. The computation of low flows under light storms is very difficult using the present method of solution. It sometimes failed due partly to inaccuracy in the evaluation of the friction coefficient and partly to computational instability induced by the internal boundary computation. For lack of a better method available in the computation of such low flows, it has been simply assumed that the flows are laminar and the uniform flow equation (Eq. 83) applied. However, it has been found during the model validation tests that such an assumption may cause large errors in the computation. An effort must be made on the improvement of the computation for such low flows.

2. The unstable results shown in the computation of runoff under a storm moving in the opposite direction of gutter flow can be overcome by refining the current numerical scheme in use at the storm front. This refinement may also help solve the difficulty experienced in the computation of runoff under a storm moving in the same direction as gutter flow.

3. It has been shown from the model validation tests that the initial abstraction is probably the most important, single factor which may greatly affect the computation of the entire inlet hydrograph. Unfortunately it happens to be the most difficult, unknown quantity to deal with in the mathematical modeling. For the future modeling of the surface runoff, more attention should be paid on the evaluation of the initial abstraction.

4. Efforts must be made on the development of a unified dimensionless inlet hydrograph or a family of such hydrographs for typical urban highway cross-sections. This can be readily done by analyzing the computed hydrographs generated from the present or modified computer model by inputing a variety of ranges of the values of the parameters such as those related to design storms, soil infiltration capacity, initial abstraction, etc.

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APPENDICES

Appendix 1

Evaluation of the Momentum and Energy Coefficients

Laminar flow

The modified velocity distribution over the flow section for wide open-channel flow is given by,

$$u = \frac{24gS}{C\nu}\left(zd - \frac{1}{2}z^2\right) \quad \ldots \ldots \ldots \ldots \quad (153)$$

in which u is the velocity of flow in s-direction, S is the channel slope, ν is the kinematic viscosity, and d is the depth of flow. The mean velocity of flow, $\overline{u}$, can be calculated from Eq. 153 as

$$\overline{u} = \frac{1}{d}\int_0^d u\,dz = \frac{1}{d}\int_0^d \frac{24gS}{C\nu}\left(zd - \frac{1}{2}z^2\right) dz \quad \ldots \ldots \quad (154a)$$

or

$$\overline{u} = \frac{8gS}{C\nu}d^2 \quad \ldots \ldots \ldots \ldots \quad (154b)$$

Therefore, the momentum coefficient, β, can be given by

$$\beta = \frac{1}{d}\int_0^d \left(\frac{u}{\overline{u}}\right)^2 dz = \frac{1}{\left(\frac{8gS}{C\nu}\right)^2 d^5}\int_0^d \left[\frac{24gS}{C\nu}\left(zd - \frac{1}{2}z^2\right)\right]^2 dz$$

$$\ldots \ldots \ldots \ldots \quad (155a)$$

or

$$\beta = 1.2 \quad \ldots \ldots \ldots \ldots \quad (155b)$$

Similarly, the energy coefficient, α, can be given by

$$\alpha = \frac{1}{d}\int_0^d \left(\frac{u}{\overline{u}}\right)^3 dz = \frac{1}{\left(\frac{8gS}{C\nu}\right)^3 d^7}\int_0^d \left[\frac{24gS}{C\nu}\left(zd - \frac{1}{2}z^2\right)\right]^3 dz$$

$$\ldots \ldots \ldots \ldots \quad (156a)$$

or

$$\alpha = 1.543 \quad \ldots \ldots \ldots \ldots \quad (156b)$$

Turbulent flow

The velocity distribution for turbulent flow on smooth surfaces is given by the Kármán-Prandtl logarithmic equation,

$$\frac{u}{\sqrt{\tau_o/\rho}} = 2.5 \ln \frac{\sqrt{\tau_o/\rho}\, z}{\nu} + 5.5 \quad \text{(157)}$$

in which ρ is the mass density of fluid and τ_o is the boundary shearing stress, which may be given by

$$\tau_o = \frac{f}{4} \frac{\rho \bar{u}^2}{2} \quad \text{(158)}$$

in which f is the Darcy-Weisbach friction coefficient. The mean velocity of flow is

$$\bar{u} = \frac{1}{d}\int_0^d u\, dz = \frac{1}{d}\int_0^d \sqrt{\tau_o/\rho}\left(2.5 \ln \frac{\sqrt{\tau_o/\rho}\, z}{\nu} + 5.5\right) dz \quad \text{(159a)}$$

or

$$\bar{u} = \sqrt{\tau_o/\rho}\left(2.5 \ln \frac{\sqrt{\tau_o/\rho}\, d}{\nu} + 3\right) \quad \text{(159b)}$$

The velocity distribution for turbulent flow on rough surfaces is also given by the Kármán-Prandtl logarithmic equation,

$$\frac{u}{\sqrt{\tau_o/\rho}} = 2.5 \ln \frac{z}{k} + 8.5 \quad \text{(160)}$$

in which k is the roughness size. The mean velocity is

$$\bar{u} = \frac{1}{d}\int_0^d u\, dz = \frac{1}{d}\int_0^d \sqrt{\tau_o/\rho}\left(2.5 \ln \frac{z}{k} + 8.5\right) dz \quad \text{(161a)}$$

or

$$\bar{u} = \sqrt{\tau_o/\rho}\left(2.5 \ln \frac{d}{k} + 6\right) \quad \text{(161b)}$$

Subtracting Eq. 161b from Eq. 160, or Eq. 159b from Eq. 157, yields

$$\frac{u - \bar{u}}{\sqrt{\tau_o/\rho}} = 2.5 \ln \frac{z}{d} + 2.5 \quad \text{(162)}$$

Eq. 158 can be rewritten as

$$\sqrt{\frac{\tau_o}{\rho}} = \sqrt{\frac{f}{8}}\ \bar{u} \quad \ldots\ldots\ldots \quad (163)$$

Substituting Eq. 163 into Eq. 162 gives

$$\frac{u}{\bar{u}} = 1 + 2.5\sqrt{\frac{f}{8}} + 2.5\sqrt{\frac{f}{8}}\ \ln\frac{z}{d} \quad \ldots\ldots\ldots \quad (164)$$

Therefore, the momentum coefficient, β, for turbulent flow on both smooth and rough surfaces can be expressed by

$$\beta = \frac{1}{d}\int_0^d\left(\frac{u}{\bar{u}}\right)^2 dz = \frac{1}{d}\int_0^d\left(1 + 2.5\sqrt{\frac{f}{8}} + 2.5\sqrt{\frac{f}{8}}\ \ln\frac{z}{d}\right)^2 dz \quad \ldots\ldots\ldots \quad (165a)$$

or

$$\beta = 1 + 0.78125\,f \quad \ldots\ldots\ldots \quad (165b)$$

Similarly the energy coefficient, α, for turbulent flow on both smooth and rough surfaces can be expressed by

$$\alpha = \frac{1}{d}\int_0^d\left(\frac{u}{\bar{u}}\right)^3 dz = \frac{1}{d}\int_0^d\left(1 + 2.5\sqrt{\frac{f}{8}} + 2.5\sqrt{\frac{f}{8}}\ \ln\frac{z}{d}\right)^3 dz \quad \ldots\ldots\ldots \quad (166a)$$

or

$$\alpha = 1 + 2.344\,f - 1.381\,f^{3/2} \quad \ldots\ldots\ldots \quad (166b)$$

Appendix 2

Expressions of Geometric Elements for Curb-Type Gutter Flow Section

An inspection of a typical urban highway cross-section reveals that only 3-ft horizontal width is provided for each curb-type gutter flow section which is built adjacent to the roadway or paved shoulder with various horizontal widths. During a heavy thunderstorm, however, the downstream reach of the 3-ft wide gutter does not appear wide enough to accommodate the suddenly rising level of overflowing storm water and a portion of the paved shoulder and/or roadway tends to be subjected to the encroachment of flooding gutter flow. Thus, for completeness in the description of gutter flow, every point on the roadway crown and across paved shoulder will be regarded as a potential boundary point of the gutter flow and the corresponding geometric elements expressed according to the position of the internal boundary. Three different cases of the internal boundary position are treated herein.

The gutter flow boundary is assumed to be composed of three parts, as schematically shown in Figure 35. The left part is the crown of the roadway (Figure 6) with the horizontal width, L_{rs}, the middle portion is the surface of the paved shoulder with the horizontal width, L_{ps}, and the right side is the boundary surface of gutter with the horizontal width, L_{gu}. The hydraulic depth, D, will be used as a reference quantity in the definitions of the other geometric elements so that it must be expressed in terms of the given or specified geometric element in addition to the top width, T. For example, if the cross-sectional area, A, is given, D will be expressed in terms of A and T.

Case (1): $T \le L_{gu}$

1. Given A, the cross-sectional area, find D.

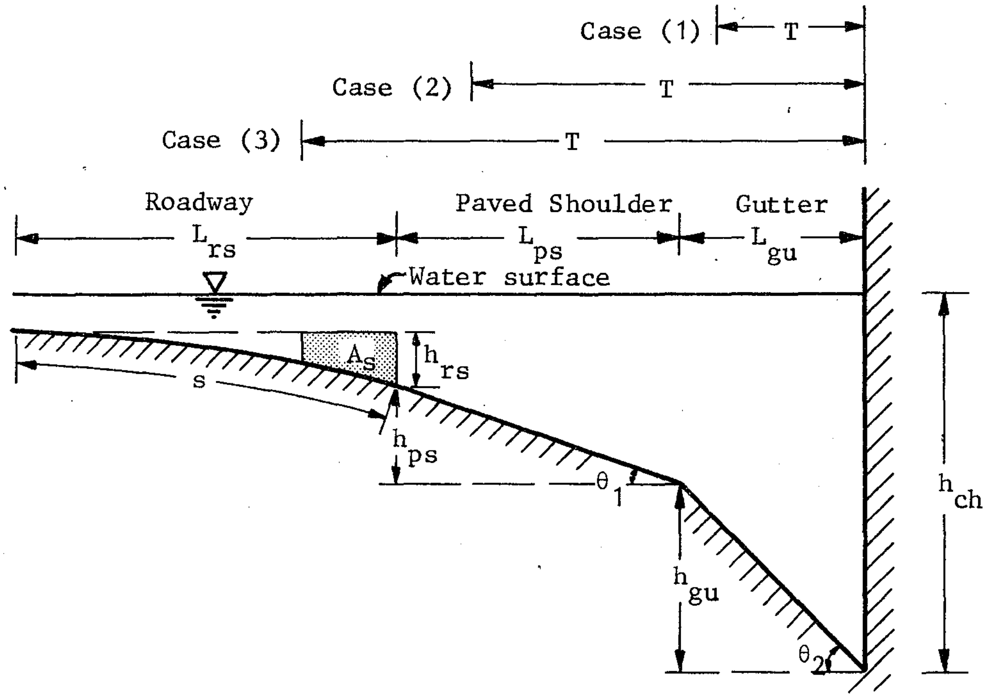
$$D = \frac{A}{T} \qquad (167)$$

2. Given h_{ch}, the gutter flow depth, find D.

$$D = h_{ch} - \frac{1}{2} T \tan \theta_2 \qquad (168)$$

3. Given R, the hydraulic radius, find D.

$$D = \frac{R}{1 - R/T}\left(\frac{1}{2} \tan \theta_2 + \sec \theta_2\right) \qquad (169)$$



h_{ch} = gutter flow depth

T = top width of gutter flow

L_{rs} = horizontal width of roadway

L_{ps} = horizontal width of paved shoulder

L_{gu} = horizontal width of gutter

$h_{ps} = L_{ps} \tan \theta_1$

$h_{gu} = L_{gu} \tan \theta_2$

Case (1) : $T \leq L_{gu}$

Case (2) : $L_{gu} \leq T \leq L_{ps} + L_{gu}$

Case (3) : $T \geq L_{ps} + L_{gu}$

Figure 35. Schematic diagram of gutter flow with various locations of internal boundary.

4. Given h_{ch}, find $\bar{h}$, the depth of the centroid of A, in terms of h_{ch} and T.

$$\bar{h} = \frac{\left(h_{ch} - T \tan \theta_2\right)^2 + T \tan \theta_2 \left(h_{ch} - \frac{2}{3} T \tan \theta_2\right)}{(2h_{ch} - T \tan \theta_2)} \quad . \; . \; . \quad (170)$$

<u>Case (2): $L_{gu} \leq T \leq L_{ps} + L_{gu}$</u>

1. Given A, find D.

$$D = \frac{A}{T} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad (167)$$

2. Given h_{ch}, find D.

$$D = \frac{L_{gu}}{2T} (2h_{ch} - L_{gu} \tan \theta_2) + \frac{(T - L_{gu})}{2T} [2h_{ch} - 2L_{gu} \tan \theta_2 - (T - L_{gu}) \tan \theta_1] \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad (171)$$

3. Given R, find D.

$$D = \frac{R}{T - R} \left[\frac{\left(T - \frac{1}{2} L_{gu}\right)}{T} L_{gu} \tan \theta_2 + \left(\frac{T - L_{gu}}{2T}\right)(T - L_{gu}) \tan \theta_1 + L_{gu} \sec \theta_2 + (T - L_{gu}) \sec \theta_1\right] \quad . \; . \; . \; . \; . \; . \; . \; . \; . \quad (172)$$

4. Given h_{ch}, find $\bar{h}$.

$$\begin{aligned} \bar{h} = \; & \{L_{gu} (h_{ch} - L_{gu} \tan \theta_2)^2 + L_{gu}^{\;2} \tan \theta_2 (h_{ch} - \tfrac{2}{3} L_{gu} \tan \theta_2) \\ & + (T - L_{gu}) [h_{ch} - L_{gu} \tan \theta_2 - (T - L_{gu}) \tan \theta_1]^2 \\ & + (T - L_{gu})^2 \tan \theta_1 [h_{ch} - L_{gu} \tan \theta_2 - \tfrac{2}{3} (T - L_{gu}) \tan \theta_1]\} \\ & \div \{L_{gu} (2h_{ch} - L_{gu} \tan \theta_2) + (T - L_{gu}) [2h_{ch} - 2L_{gu} \tan \theta_2 \\ & - (T - L_{gu}) \tan \theta_1]\} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad (173) \end{aligned}$$

<u>Case (3): $T \geq L_{ps} + L_{gu}$</u>

1. Given A, find D.

$$D = \frac{A}{T} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (167)$$

2. Given h_{ch}, find D.

$$D = \frac{L_{gu}}{2T}(2h_{ch} - L_{gu} \tan\theta_2) + \frac{L_{ps}}{2T}(2h_{ch} - 2L_{gu} \tan\theta_2 - L_{ps} \tan\theta_1) + \frac{A_s}{T} + \frac{(T - L_{ps} - L_{gu})}{T}(h_{ch} - L_{gu} \tan\theta_2 - L_{ps} \tan\theta_1 - h_{rs}) \quad \ldots\ldots\ldots \quad (174)$$

in which A_s is the hatched area, as shown in Figure 35, defined by using Eq. 60 as

$$A_s = \int_{L_{rs} + L_{ps} + L_{gu} - T}^{L_{rs}} (-z)\,dx$$

$$= - \left[\frac{1}{3} C_1 x^3 + \frac{1}{2} C_2 x^2 + C_3 x \right]_{L_{rs} + L_{ps} + L_{gu} - T}^{L_{rs}} \quad \ldots \quad (175)$$

The quantity, h_{rs}, is the summation of the drops in height, a, b, and c in Figure 6 for each lane of traffic according to the parabolic equation, Eq. 60, and defined as

$$h_{rs} = - \left[C_1 x^2 + C_2 x + C_3 \right]_{L_{rs}}^{0} \quad \ldots\ldots\ldots\ldots \quad (176)$$

3. Given R, find D.

$$D = \frac{R}{T - R} \left[\frac{(T - \frac{1}{2} L_{gu})}{T} L_{gu} \tan\theta_2 + \frac{(T - \frac{1}{2} L_{ps} - L_{gu})}{T} L_{ps} \tan\theta_1 + \frac{(T - L_{ps} - L_{gu})}{T} h_{rs} + \frac{A_s}{T} + L_{gu} \sec\theta_2 + L_{ps} \sec\theta_1 + s \right]$$

$$\ldots\ldots\ldots\ldots\ldots \quad (177)$$

in which s is the actual width of roadway, as shown in Figure 35 and defined in Eq. 61.

4. Given h_{ch}, find $\bar{h}$.

$$\bar{h} = \Big[\frac{1}{2} L_{gu}(h_{ch} - L_{gu} \tan \theta_2)^2 + \frac{1}{2} L_{gu}^{\ 2} \tan \theta_2 (h_{ch} - \frac{2}{3} L_{gu} \tan \theta_2)$$

$$+ \frac{1}{2} L_{ps}(h_{ch} - L_{ps} \tan \theta_1 - L_{gu} \tan \theta_2)^2 + \frac{1}{2} L_{ps}^{\ 2} \tan \theta_1 (h_{ch}$$

$$- \frac{2}{3} L_{ps} \tan \theta_1 - L_{gu} \tan \theta_2) + \frac{1}{2} (T - L_{ps} - L_{gu})(h_{ch} - L_{ps} \tan \theta_1$$

$$- L_{gu} \tan \theta_2 - h_{rs})^2 + A_s (h_{ch} - L_{ps} \tan \theta_1 - L_{gu} \tan \theta_2$$

$$- h_{rs} + \bar{h}_s) \Big] \div \Big[\frac{L_{gu}}{2} (2h_{ch} - L_{gu} \tan \theta_2) + \frac{L_{ps}}{2} (2h_{ch}$$

$$- 2L_{gu} \tan \theta_2 - L_{ps} \tan \theta_1) + A_s + (T - L_{ps} - L_{gu})(h_{ch}$$

$$- L_{gu} \tan \theta_2 - L_{ps} \tan \theta_1 - h_{rs}) \Big] \quad . \ . \ . \ . \ . \ . \ . \ (178)$$

in which $\bar{h}_s$ is the depth of the centroid of A_s from the top edge of A_s and defined by

$$\bar{h}_s = \left[\frac{1}{5} C_1^2 x^5 + \frac{1}{2} C_1 C_2 x^4 + \frac{1}{3} (C_2^{\ 2} + 2C_1 C_3) x^3 + C_2 C_3 x^2 + C_3^2 x \right]_{L_{rs} + L_{ps} + L_{gu} - T}^{L_{rs}} \div A_s \quad . \ . \ . \ . \ . \ . \ . \ . \ (179)$$

Appendix 3

Theoretical Evaluation of Initial Abstraction by Using the SCS Rainfall-Runoff Relation

It seems reasonable to assume that the SCS rainfall-runoff relation may have the following general form:

$$Q = cP \quad \ldots \quad (180)$$

in which Q = actual direct runoff in inches, P = total storm rainfall in inches, and c = ''runoff'' coefficient. The way in which Eq. 180 is constructed is similar to that of the rational formula in which instead the rainfall intensity is related to the peak runoff rate through the runoff coefficient.

One of the primary assumptions in the SCS method is

$$\frac{F}{S} = \frac{Q}{P_e} \quad \ldots \quad (181)$$

in which F = actual infiltration excluding the initial abstraction, I_a, in inches, S = potential infiltration in inches, and P_e = potential runoff or effective storm rainfall in inches, i.e.,

$$P_e = P - I_a \quad \ldots \quad (182)$$

and

$$P = I_a + F + Q \quad \ldots \quad (183)$$

Substituting Eq. 182 and the expression of F from Eq. 184 into Eq. 181 yields

$$Q = \frac{(P - I_a)^2}{P - I_a + S} \quad \text{for } P \geq I_a \quad \ldots \quad (184)$$

Note that the limitation, $P \geq I_a$, is imposed because Q in the form of Eq. 184 is not valid outside the limitation.

If an assumption on I_a is made, Eq. 184 can reduce to the well-known rainfall-runoff equation that is related to CN by the definition

$$CN = \frac{1000}{S + 10} \quad \ldots \quad (185)$$

The initial abstraction, I_a, consists of interception and surface and subsurface storage, all of which occur before runoff begins. To remove the necessity for estimating these variables, the relation between I_a and S (which includes I_a) was roughly assumed by the SCS through rainfall-runoff data for experimental small watersheds less than 10 acres in size as

$$I_a = 0.2\ S \qquad (186)$$

Although Eq. 186 has a large standard error of estimate, it was assumed valid in the SCS method for lack of any better relationship. In a more generalized treatment, it may be assumed herein that

$$I_a = \lambda S \qquad (187)$$

in which λ = ratio of I_a to S with its value ranging between 0 and 1. For brevity, λ may be referred to as the initial abstraction index. Substituting Eq. 187 into Eq. 184 yields

$$Q = \frac{(P - \lambda S)^2}{P + (1 - \lambda)S} \quad \text{for } P \geq \lambda S \qquad (188)$$

The solution of Eq. 188 for S in terms of P and Q is

$$S = \frac{1}{2\lambda^2}\left[2\lambda P + (1 - \lambda)Q - \sqrt{4\lambda PQ + (1 - \lambda^2)Q^2}\right] \qquad (189)$$

Note that the expression of S for $\lambda = 0.2$ was already developed by Hawkins (1973). Substitution of the Q expression from Eq. 180 into Eq. 189 gives

$$S = \frac{1}{\lambda}\, f(\lambda,\ c)P \qquad (190)$$

in which

$$f(\lambda,c) = \frac{1}{2\lambda}\left[2\lambda + (1 - \lambda)c - \sqrt{4\lambda c + (1 - \lambda)^2 c^2}\right] \qquad (191)$$

Hence the expression of I_a in terms of a fraction of P is obtained by incorporating Eq. 190 with Eq. 187 as

$$I_a = f(\lambda,\ c)P \qquad (192)$$

Upon substitution of the expressions of Q and I_a from Eqs. 180 and 192, Eq. 183 yields the expression of F in terms of P as

$$F = g(\lambda,\ c)P \qquad (193)$$

in which

$$g(\lambda, c) = \frac{1}{2\lambda} [-(1 + \lambda)c + \sqrt{4\lambda c + (1 - \lambda)^2c^2}] \quad . \quad . \quad . \quad . \qquad (194)$$

Again, for brevity, $f(\lambda, c)$ and $g(\lambda, c)$ may be called the ''initial abstraction'' coefficient and ''infiltration'' coefficient, respectively. For given λ and c values, the values of $f(\lambda, c)$ and $g(\lambda, c)$ (henceforth abbreviated as f and g, respectively) can be determined from Eqs. 192 and 194, respectively.

From Eq. 191,

$$\lambda = \frac{cf}{(1 - f)(1 - c - f)} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (195)$$

Note that not any values of λ, c, and f ranging from 0 to 1 satisfy Eq. 195. Certainly there are restrictions on the λ, c, and f values outside of which Eq. 195 is not valid.

From the way in which Eq. 187 is constructed, the theoretical maximum value of λ is unity. Therefore, from Eq. 191 or 195, one can readily derive a relationship between c and f under this limiting value for $\lambda(=1)$:

$$f = 1 - \sqrt{c} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (196)$$

or

$$c = (1 - f)^2 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (197)$$

Equation 196 or 197 is plotted, as shown in Figure 36. For illustration, the c versus f relationships for other λ values are also shown in Figure 36. It is obvious from Figure 36 that any point (c, f) within the area enclosed by the three lines (i.e., Eq. 196, abscissa, and ordinate) is a possible combination of the c and f values which individual storms passing a watershed will produce. In view of an infinite number of combinations of the c and f values within the enclosed area, the λ value computed from Eq. 195 cannot be grossly assumed constant, even for the first approximation. It is more logical to assume that for a given watershed, there may be a statistical law under which certain combinations of the c and f values occur more often than the other and vice versa. In other words, a statistical dimension (or the probability of occurrence) for each combination of the c and f values should be evaluated so as to determine the statistical mean (or average) value of λ, which is essential to the SCS method.

The distribution of the number of occurrence in the enclosed c, f space can be represented by a density function, $\phi(c, f)$, in this space,

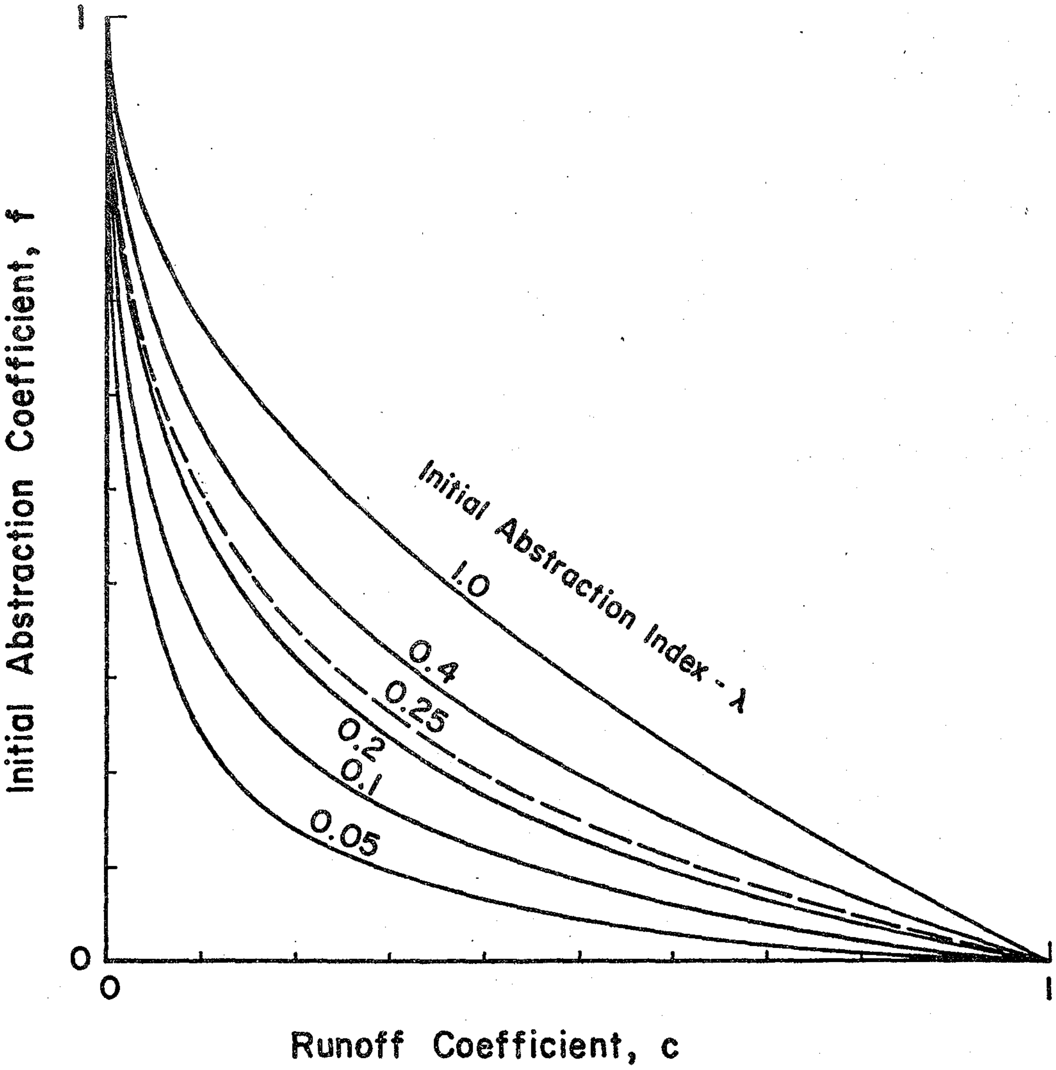


Figure 36. Interrelationship between initial abstraction index, λ, runoff coefficient, c, and initial abstraction coefficient, *f*.

having the property that $\phi(c, f)$ dc df represents the number of occurrence in the infinitesimal element dc df. To find the density function $\phi(c, f)$ usually requires a statistical analysis of a large amount of field data on P, Q, and I_a which is unfortunately not available on non-recorded basins. For convenience, however, if it is assumed uniformly distributed with constant density (i.e., equal probability of occurrence), the average λ value, $\bar{\lambda}$, can now be estimated by using Eqs. 195 and 196 as follows:

$$\bar{\lambda} = \frac{\int_0^1 \int_0^{1 - \sqrt{c}} \frac{cf}{(1 - f)(1 - c - f)} \, dc \, df}{\int_0^1 \int_0^{1 - \sqrt{c}} dc \, df} = \frac{1}{4} \quad . \quad . \qquad (198)$$

It is interesting to see that the statistical average value of λ so obtained ($\bar{\lambda}$ = 0.25) does not differ greatly from the assumed 0.2 in the SCS method. Both curves for λ = 0.2 and 0.25 are plotted in Figure 36 for comparison. Without knowledge on the exact expression of the density function in the real situation, one can only conclude that for the average value of λ being less than 0.25 (e.g., the assumed 0.20 in the SCS method) the probability of occurrence in the lower part of the enclosed c, f domain from the line representing λ = 0.25 must be higher than that in the upper part of the same domain.

Appendix 4

The Computer Program

1. Program Narrative

The methods and procedures of computing storm runoff from an urban highway watershed, as described in the text, were programmed in FORTRAN language and executed on the UNIVAC 1108 computer. The computer program was originally written by Min-shoung Chu in June 1973 as part of his dissertation. Since then, subsequent modifications have been made by George C. Shih in December 1973 and later mainly by the writer in an attempt to correct inaccuracies, ambiguities, and excessive limitations found in the original program. Chu's program can only compute runoff from a straight roadway with a curb-type gutter under a uniform stationary or moving rainstorm. Shih expanded it to include the computation of runoff from a curved roadway. The final phase of the program, as appended here, has the capability of computing runoff from any of the typical urban highway cross-sections (Figure 33), straight or curved, under a time- or space-varying storm, expressed by one of the hyetograph equations, Eq. 126 through Eq. 136.

The computer program consists of a main program, 38 subroutine subprograms, and 2 function subprograms. Many commonly-used variables are grouped in the COMMON statements. Some statements are self-explanatory, while others which need clarification are further explained by means of comment cards. The major options in the present program are as follows:

(1) The computation of the shock waves, except at the wavefront of a moving storm, was not executed in the present study by using some control statements although it is included in the program. Variables used in such control are IFC in the MAIN program, IFA in the subroutine INBDY, and IFC in the subroutine SLOPE. Presently the program is set to IFC = 1 and IFA = 1, but to release the control, set IFC = 2 and IFA = 2. A subroutine subprogram ignored in the computation of shock waves is NEWJ.

(2) Rainfall can be controlled either by specifying the value of STR (dimensionless time for rain to stop) or by deleting statement numbers 55 and 56 in the subroutine PARA.

2. Subroutines and Functions

2.1 Definition of the variables used in the COMMON statements

COMMON / B1 /

Variable		Definition	Unit
B(1)	β	momentum correction factor	-
B(2)	ε	a constant multiplier for the minimum depth, εk, in Eq. (81)	-
B(3)	β_L	momentum correction factor for lateral inflow	-
B(4)	θ_o	reference angle of inclination	rad
B(5)	k_{ch}	roughness size of gutter (grass or paved)	ft
B(6)	Φ	angle between terminal rainfall velocity and vertical direction	rad
B(7)	δ	average diameter of raindrops	in.
B(8)	θ	angle of inclination of bed slope	rad
B(9)	L_g	horizontal bed width of channel-type gutter (2 ft)	ft
B(10)	T_o	reference top width	ft
B(11)	L_o	reference length	ft
B(12)	V_o	reference velocity	ft/sec
B(13)	f_o	reference friction coefficient	-
B(14)	$\mathbf{R}_o$	reference Reynolds number	-
B(15)	h_o	reference depth of flow	ft
B(16)	D_o	reference hydraulic depth	ft
B(17)	R_o	reference hydraulic radius	ft
B(18)	A_o	reference cross-sectional area	ft^2
B(19)	r_o	reference rainfall intensity	in./hr
B(20)	$\mathbf{F}_o$	reference Froude number	-
B(21)	L_{ch}	length of channel flow	ft
B(22)	L_{rs}	horizontal width of traffic lanes	ft
B(23)	k	roughness size of roadway, reference surface, or a surface under study	ft
B(24)	ν	kinematic vicosity of water	ft^2/sec
B(25)	Λ	terminal velocity of raindrop	ft/sec
B(26)	r	rainfall intensity	in./hr
B(27)	i	infiltration rate	in./hr
B(28)	Q_u	carry-over discharge at the upstream end of gutter	cfs

Variable		Definition	Unit
B(29)	q_L	lateral inflow rate	cfs/ft
B(30)	W	velocity of a moving storm	ft/sec
B(31)	h_R/h_{min}	ratio of the conjugate depth of the discontinuity on region ''R'' to the minimum depth	-
B(32)		a computer storage for rainfall intensity of a moving storm	in./hr
B(33)	L_s	horizontal width of sideslope	ft
B(34)	S_s	slope of sideslope	-
B(35)	k_s	roughness size of sideslope	ft
B(36)	a	parameter in $C = aS^b$ for paved surfaces	-
B(37)	b	exponent in $C = aS^b$ for paved surfaces	-
B(38)	a	parameter in $C = aS^b$ for turf surfaces	-
B(39)	b	exponent in $C = aS^b$ for turf surfaces	-
B(40)	I_a	rainfall amount (depth) accounted for initial detention and depression storage	in.

Variable		Definition
C(1)	β	momentum correction factor
C(2)	$\sin\psi$	
C(3)	β_L	momentum correction factor for lateral inflow
C(4)	$\sin\theta_o$	
C(5)	$\cos\theta_o$	
C(6)	$\sin(\theta+\Phi)$	
C(7)	c	concentration of raindrops
C(8)	$\sin\theta$	
C(9)	$\cos\theta$	
C(10)	L_{g*}	normalized horizontal bed width of channel-type gutter (L_g/L_o)
C(11)		$L_o/(D_o\cos^8\theta_o)$
C(12)	k_{ch*}	normalized roughness size of gutter (grass or paved)
C(19)		$r_o/(V_o \times 12 \times 60 \times 60)$
C(20)		$1/F_o^2$
C(21)	L_{ch}	normalized channel length (L_{ch}/L_o)
C(22)	L_{rs*}	noralized horizontal width of traffic lanes (L_{rs}/L_o)
C(23)	k_*	normalized roughness size of roadway, reference surface, or a surface under study (k/R_o)
C(24)	u_*	normalized approaching velocity of lateral inflow (u/V_o)
C(25)	Λ_*	normalized average terminal velocity of raindrops (Λ/V_o)
C(26)	r_*	normalized rainfall intensity (r/r_o)
C(27)	i_*	normalized infiltration rate (i/r_o)
C(28)	Q_{u*}	normalized carry-over discharge at the upstream end of gutter (Q_u/A_oV_o)
C(29)	q_{L*}	normalized lateral inflow $(q_L \cos\theta_o/D_oV_o)$
C(30)	W_*	normalized velocity of a moving rainstorm (W/V_o)
C(33)	L_{s*}	normalized horizontal width of sideslope (L_s/L_o)
C(34)	θ_s	angle of inclination of sideslope
C(35)	k_{s*}	normalized roughness size of sideslope (k/R_o)

Variable	Definition
C(36) a	parameter in $C = aS^b$ for a surface under computation
C(37) b	exponent in $C = aS^b$ for a surface under computation
C(40) $I_a \cos\theta_o/D_o$	

Variable	Definition
Z's	special indication: Z(1) = dimensionless time for rain to stop Z(2) = 1, indicating that there is a carry-over flow at the upstream end Z(2) = 0, indicating that there is no carry-over flow at the upstream end Z(3) = 1, indicating the need of outputing the computed interior boundary data Z(3) = 0, indicating no need of outputing the computed interior boundary data
TIME	dimensionless time, t_*
OPH	overpressure head due to raindrop
NN	number of overland flow sections
N	index for any section of flow
NCH	index for channel flow section
RSL	actual width of curved road surface
CURVE	curvature of curved roadway

COMMON / B2 /

Variable	Definition
H(N,K,T)	normalized flow depth at grid point K of section N at time T
V(N,K,T)	normalized flow velocity at grid point K of section N at time T
HL(N,J,T)	normalized conjugate depth on region ''L'' of the Jth discontinuity on section N at time T
HR(N,J,T)	normalized conjugate depth on region ''R'' of the Jth discontinuity on section N at time T
VR(N,J,T)	normalized conjugate velocity on region ''R'' of the Jth discontinuity on section N at time T
VL(N,J,T)	normalized conjugate velocity on region ''L'' of the Jth discontinuity on section N at time T
VJ(N,J,T)	normalized propagation velocity of the Jth discontinuity on section N at time T
XJ(N,J,T)	normalized location of the Jth discontinuity on section N at time T
JI(N,K,T)	index of discontinuity = 1, indicating that there is a discontinuity (or discontinuities) between grid points K and K-1, on section N at time T

Variable	Definition
	= 0, indicating that there is no discontinuity between grid points K and K-1 on section N at time T
KN	number of grid points on an overland flow section under computation
NJJ	number of discontinuities on a section under computation

COMMON / B3 /

Variable	Definition
NK(N)	number of grid points on section N
NJ(N)	number of dicontinuities on section N
DX	normalized grid point interval
DT	normalized time interval
DIST	normalized horizontal length of a section under computation
HMIN	normalized minimum depth of flow
VMIN	normalized minimum velocity of flow
ITYPE	index for the type of problem = 1, uniform stationary rainfall = 2, moving rainstorm in parallel with gutter flow direction = 3, moving rainstorm in parallel with overland flow direction = 4, moving rainstorm in parallel with overland flow direction after the wavefront reaches the road curb = 5, moving rainstorm in the opposite direction of gutter flow = 6, moving rainstorm in the opposite direction of overland flow = 7, moving rainstorm in parallel with gutter flow direction after the wavefront reaches the inlet
IO	index for outputing results = 0, indicating skipping output = 1, indicating the need of output
OC(N,J)	outputing the name of the subroutine by which the Jth discontinuity on section N is computed
S	normalized distance measured along the curved roadway
DS	normalized grid point interval along the curved roadway

COMMON / B4 /

Variable	Definition
II(N,T)	index for the type of the internal boundary between overland flow of section N and gutter flow at time T = 0, indicating continuous water surface = 1, indicating discontinuous water surface
XI(N,T)	normalized horizontal length at the downstream end of overland flow section N at time T

Variable	Definition
HI(N,T)	normalized flow depth at the downstream end of overland flow section N at time T
VI(N,T)	normalized flow velocity at the downstream end of overland flow section N at time T
QI(N,T)	normalized discharge at the downstream end of overland flow section N at time T
WI(N,T)	normalized propagation velocity of the discontinuity when there is a discontinuity at the internal boundary between overland flow section N and gutter flow at time T
CT(K,T)	normalized top width of gutter flow at grid point K and time T
CH(N,T)	normalized conjugate depth of the discontinuity on the gutter-flow part when there is a discontinuity at the internal boundary between overland flow section N and gutter flow at time T
CV(N,T)	normalized conjugate velocity of the discontinuity on the gutter-flow part when there is a discontinuity at the internal boundary between overland flow section N and gutter flow at time T

COMMON / B5 /

Variable	Definition
NG(N,K)	index for outputing how the friction slope at grid point K on section N is evaluated = 0, evaluated by Darcy-Weisbach equation = 1, evaluated by energy equation = 2, at downstream boundary control
SG(N,K)	friction slope at grid point K on section N
FG(N,K)	friction coefficient at grid point K on section N
NF	index for outputing how the friction coefficient is evaluated
SF	friction slope
FF	friction coefficient

COMMON / B6 /

Variable	Definition
AA1, BB1, CC1	coefficients of an equation for the transverse profile of the road surface
SNK	bed slop at the end of overland flow on roadway
IDG	index for the type of gutter flow = 1, indicating curb-type gutter flow = 2, indicating channel-type gutter flow
SP1	cross slope of paved shoulder (3 to 5 percent)
XPG1	horizontal width of paved shoulder (12 ft, 4 ft, or 2 ft for each traffic lane)

Variable	Definition
SP2	cross slope of gutter or median (1/12 or 10 percent)
XPG2	horizontal width of gutter or median (3 ft or 12 ft minus 2 ft times number of traffic lanes)

COMMON / B7 /

Variable	Definition
NL(N,J)	index for outputing how the friction coefficient on region ‘‘L’’ of the Jth discontinuity on section N is evaluated
NR(N,J)	index for outputing how the friction coefficient on region ‘‘R’’ of the Jth discontinuity on section N is evaluated
SL(N,J)	friction slope on region ‘‘L’’ of the Jth discontinuity on section N
SR(N,J)	friction slope on region ‘‘R’’ of the Jth discontinuity on section N
FL(N,J)	friction coefficient on region ‘‘L’’ of the Jth discontinuity on section N
FR(N,J)	friction coefficient on region ‘‘R’’ of the Jth discontinuity on section N
NFJ	index for outputing how the friction coefficient is evaluated at the Jth discontinuity
SFJ	friction slope at the Jth discontinuity
FFJ	friction coefficient at the Jth discontinuity

COMMON / B8 /

Variable	Definition
ACCU	specified accuracy
ACCUX	specified accuracy in horizontal direction
ACCUY	specified accuracy in vertical direction
HDRY	dimensionless small depth of water assumed on dry surface below which there is no flow
CC	C value in the equation $f = C/R$

COMMON / B9 /

Variable	Definition
TL(J,T)	top width on region ‘‘L’’ of the Jth discontinuity in gutter flow at time T
TR(J,T)	top width on region ‘‘R’’ of the Jth discontinuity in gutter flow at time T

COMMON / B10 /

Variable	Definition
DXCH	dimensionless grid interval of gutter flow
DXRS	dimensionless grid interval of overland flow
DDXCH	dimensional grid interval of gutter flow
DDXRS	dimensional grid interval of overland flow

COMMON / B11 /

Variable	Definition
HRR	depth of water assumed on region ''R'' of the advancing wavefront
VRR	velocity of flow assumed on the region ''R'' of the advancing wavefront

COMMON / B12 /

Variable	Definition
NDEPTH	index for locating the advancing wavefront = 0, indicating the flow depth on the back side greater than zero = 1, indicating the flow depth on the back side less than zero

COMMON / B13 /

Variable	Definition
STR	time for rainfall to stop

COMMON / B14 /

Variable	Definition
IWET(N)	index for determining whether or not a storm front reaches section N = 0, indicating that the storm front has not reached section N = 1, indicating that the storm front has already passed section N

COMMON / B15 /

Variable	Definition
VO or VO1	normalized total volume of water retained on the ground surface at the initial time

Variable	Definition
VT or VT1	normalized total volume of water retained on the ground surface at time T
VIN or VIN1	normalized total volume of water inflowing into the initial volume ''VO'' during time interval ''DT''
VOUT or VOUT1	normalized total volume of water outflowing from the initial volume ''VO'' during time interval ''DT''

COMMON / B16 /

Variable	Definition
AAA	storm parameter, in./hr
BBB	storm parameter, minutes
CCC	storm parameter, dimensionless
TD	time duration of rainstorm, minutes
RTO	ratio of the time before the peak to the total time duration of rainstorm
RMN	average rainfall intensity, in./hr, for partial duration of rainfall up to time, t
RAV	average rainfall intensity, in./hr, for total duration of rainfall

COMMON / B17 /

Variable	Definition
FINF	final infiltration rate of soil, in./hr
BETTA	soil infiltration parameter, dimensionless
ALPHA	soil infiltration parameter, dimensionless
TO	soil infiltration parameter, minutes
TP	time of ponding, minutes
VSF	cumulative infiltration volume per unit surface area, inches
SPI	potential infiltration, inches

2.2 Description of subroutine subprograms

Name	Description
ADW	solve the advancing wavefront problem due to a moving rainstorm
CEQS	solve two characteristic equations to obtain the velocity and depth of flow at grid points
CONJ	evaluate the conjugate depths and velocities of the discontinuity
CRISEC	locate critical sections, if any
CROSS	calculate the velocity and depth of flow at a grid point when a discontinuity crosses the grid point
CROWN	formulate the equation of the transverse profile of a road surface

Name	Description
CS	interpolate hydraulic depth and velocity of flow and the locations of C^+ - and C^- -characteristic curves between two grid points
DBDY	arrange downstream boundary condition
DPT	compute the velocity and depth of flow at the downstream grid point
ERR	compute the computational error
EVDT	evaluate next time interval in the subsequent computation
FRIC	evaluate the Darcy-Weisbach friction coefficient
GEOM	compute the geometric elements of channel sections
GOON	substitute the values of all variables computed at time level 2 into the corresponding variables at time level 1
INBDY	compute the velocity and depth of flow at the internal boundary between road surface and curb-type gutter
INFLT	compute the infiltration rate and time of ponding
INLET	compute the runoff rate at the inlet and the carry-over flow rate, if any
INPT	arrange the computation of flow velocity and depth at interior grid points
INTAL	arrange the various assumptions of initial conditions
JL	compute the velocity and depth of flow on region ''L'' of the discontinuity
JL1	use C^+ -characteristic equation and one of the equations of discontinuity to compute the velocity and depth of flow on region ''L'' of the discontinuity
JR	compute the velocity and depth of flow on region ''R'' of the discontinuity
JR1	use C^- -characteristic equation and one of the equations of discontinuity to compute the velocity and depth of flow on region ''R'' of the discontinuity
JUMP	compute the location and propagation velocity of the discontinuity
NEWJ	search new discontinuity, if any
OPHEAD	compute the overpressure head due to raindrop impact
OUPT	output the results of computation
PACKJ	eliminate any discontinuity which disappears
PARA	compute dimensionless variable C listed in COMMON / B1 /
PREP	compute the values of those parameters which change with section N
RAIN	compute the rainfall intensity
REF	compute the reference parameters
SLOPE	compute the runoff discharge from the sideslope
STORM	compute the values of those parameters which change with the longitudinal coordinate
TYPE 4	arrange the gutter flow conditions for the computation of type 3 moving rainstorm when the advancing wavefront reaches the road curb
UBDY	arrange upstream boundary conditions

Name	Description
UPT	compute the velocity and depth of flow at the upstream grid point
WRITJ	output the computed results at discontinuities

2.3. Description of function subprograms

Name	Description
EQDIS	expression of conditions at discontinuity
FRTST	expression of Froude number

3. Input Data Description

Card No.	Variable	Format	Card Columns	Description
1	ITYPE	I5	1 to 5	defined in COMMON /B3/
	NOUT	I5	6 to 10	output at each n-th iteration
	NN	I5	11 to 15	defined in COMMON /B1/
	TEND	F5.0	16 to 20	dimensionless time of this program ending
	DDXCH	F5.0	21 to 25	defined in COMMON /B10/
	DDXRS	F5.0	26 to 30	defined in COMMON /B10/
	CURVE	F5.0	31 to 35	defined in COMMON /B1/
2	B(1)	F10.0	1 to 10	defined in COMMON /B1/
	B(2)	F10.0	11 to 20	defined in COMMON /B1/
	B(3)	F10.0	21 to 30	defined in COMMON /B1/
	B(4)	F10.0	31 to 40	defined in COMMON /B1/
	B(5)	F10.0	41 to 50	defined in COMMON /B1/
	B(6)	F10.0	51 to 60	defined in COMMON /B1/
	B(7)	F10.0	61 to 70	defined in COMMON /B1/
	B(8)	F10.0	71 to 80	defined in COMMON /B1/
3	B(9)	F10.0	1 to 10	defined in COMMON /B1/
	B(10)	F10.0	11 to 20	defined in COMMON /B1/
	B(11)	F10.0	21 to 30	defined in COMMON /B1/
	B(12)	F10.0	31 to 40	defined in COMMON /B1/
	B(13)	F10.0	41 to 50	defined in COMMON /B1/
	B(14)	F10.0	51 to 60	defined in COMMON /B1/
	B(15)	F10.0	61 to 70	defined in COMMON /B1/
	B(16)	F10.0	71 to 80	defined in COMMON /B1/

Card No.	Variable	Format	Card Columns	Description
4	B(17)	F10.0	1 to 10	defined in COMMON /B1/
	B(18)	F10.0	11 to 20	defined in COMMON /B1/
	B(19)	F10.0	21 to 30	defined in COMMON /B1/
	B(20)	F10.0	31 to 40	defined in COMMON /B1/
	B(21)	F10.0	41 to 50	defined in COMMON /B1/
	B(22)	F10.0	51 to 60	defined in COMMON /B1/
	B(23)	F10.0	61 to 70	defined in COMMON /B1/
	B(24)	F10.0	71 to 80	defined in COMMON /B1/
5	B(25)	F10.0	1 to 10	defined in COMMON /B1/
	B(26)	F10.0	11 to 20	defined in COMMON /B1/
	B(27)	F10.0	21 to 30	defined in COMMON /B1/
	B(28)	F10.0	31 to 40	defined in COMMON /B1/
	B(29)	F10.0	41 to 50	defined in COMMON /B1/
	B(30)	F10.0	51 to 60	defined in COMMON /B1/
	B(31)	F10.0	61 to 70	defined in COMMON /B1/
	B(32)	F10.0	71 to 80	defined in COMMON /B1/
6	B(33)	F10.0	1 to 10	defined in COMMON /B1/
	B(34)	F10.0	11 to 20	defined in COMMON /B1/
	B(35)	F10.0	21 to 30	defined in COMMON /B1/
	B(36)	F10.0	31 to 40	defined in COMMON /B1/
	B(37)	F10.0	41 to 50	defined in COMMON /B1/
	B(38)	F10.0	51 to 60	defined in COMMON /B1/
	B(39)	F10.0	61 to 70	defined in COMMON /B1/
	B(40)	F10.0	71 to 80	defined in COMMON /B1/
7	NL	I5	1 to 5	number of traffic lanes
	IDG	I5	6 to 10	defined in COMMON /B6/
	Y(1)	F10.0	11 to 20	vertical drop of crown at the highest elevation of roadway, usually taken as zero
	Y(2)	F10.0	21 to 30	vertical drop of crown in ft for one-lane width
	Y(3)	F10.0	31 to 40	vertical drop of crown in ft for two-lane widths
	SUPEL	F10.0	41 to 50	super elevation, ft per ft of roadway width
	TRFCT	F10.0	51 to 60	side friction (cornering ratio) between tires and road surface
	SPEED	F10.0	61 to 70	design speed for roadway, miles per hour

Card No.	Variable	Format	Card Columns	Description
8	SP1	F10.0	1 to 10	defined in COMMON /B6/
	XPG1	F10.0	11 to 20	defined in COMMON /B6/
	SP2	F10.0	21 to 30	defined in COMMON /B6/
	XPG2	F10.0	31 to 40	defined in COMMON /B6/
9	AAA	F10.0	1 to 10	defined in COMMON /B16/
	BBB	F10.0	11 to 20	defined in COMMON /B16/
	CCC	F10.0	21 to 30	defined in COMMON /B16/
	TD	F10.0	31 to 40	defined in COMMON /B16/
	RTO	F10.0	41 to 50	defined in COMMON /B16/
10	FINF	F10.0	1 to 10	defined in COMMON /B17/
	BETTA	F10.0	11 to 20	defined in COMMON /B17/
	ALPHA	F10.0	21 to 30	defined in COMMON /B17/
	TO	F10.0	31 to 40	defined in COMMON /B17/
11	NRSOUT	80I1	1 to 80	any of the 80 columns punched with any digit except zero represents the corresponding flow sections needed to be output

4. Program Flowchart

The hand-drawn flowchart of the computer program is shown in Figure 37.

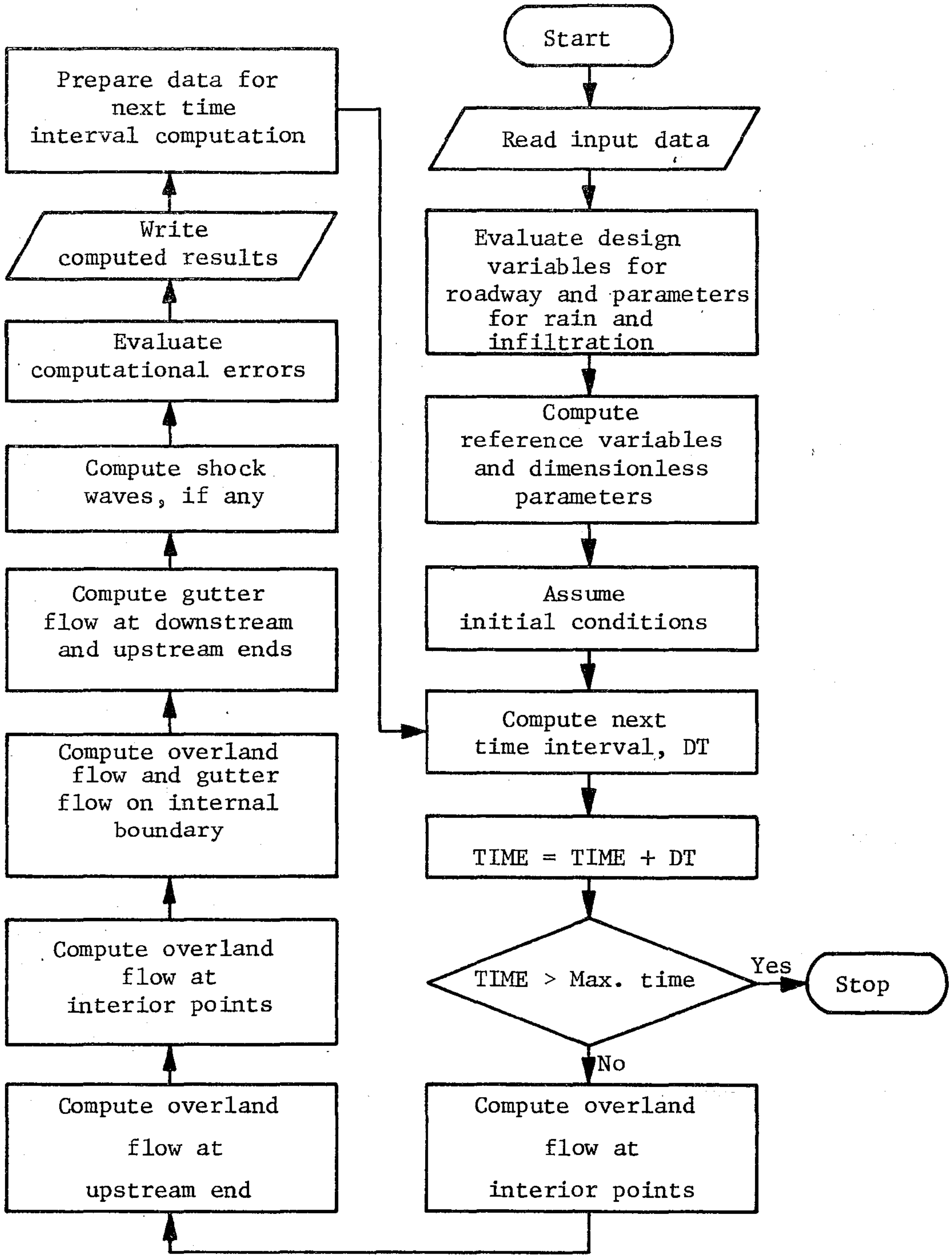


Figure 37. Flow chart of the computer program.

5. Description of Variables Used as Counters and Accumulators

Program Name	Variable Name	Initial Value	Reset (yes or no)	Description
MAIN	IOUT	1	no	Search for which of the overland flow sections needed to be output.
MAIN	NOCT	0	no	Count the number of iterations in the computation of time required for filling depression.
MAIN	NCT	0	no	Count the number of time levels in the computation.
ADW	NCTT	0	yes	Count the number of iterations in the computation of wavefront location. Reset at new time level.
CRISEC	NCT	0	yes	Count the number of iterations in the computation of critical section. Reset whenever there is a new critical section in the flow.
CROSS	NCT	0	yes	Count the number of iterations in the computation of V and h at a point on the path of the discontinuity in the x, t-plane when the discontinuity crosses the grid point. Reset whenever such computation is needed.
CS	NCT	0	yes	Count the number of iterations in the computation of D, V, and the location of C^{+}- or C^{-}-characteristic curve. Reset for every computation at a grid point.

Program Name	Variable Name	Initial Value	Reset (yes or no)	Description
DPT	NCT	0	yes	Count the number of iterations in the computation of V and h for subcritical flow at the downstream end of flow. Reset whenever such computation is needed.
FRIC	NCT	0	yes	Count the number of iterations in the computation of the Darcy-Weisbach coefficient, f, using Eq. 20. Reset whenever such computation is needed.
INBDY	NCT	0	yes	Count the number of iterations in the computation of new discontinuous water surface on the internal boundary. Reset for every computation at the internal boundary.
INFLT	NCT	0	no	Count the number of iterations in the computation of t_p and t_o from rainstorm and soil infiltration parameters.
INPT	NCT	0	yes	Count the number of iterations in the computation of V in the overland flow part for an ITYPE 2 or 5 storm. Reset whenever such computation is needed.
INTAL	NCT	0	no	Count the number of iterations in the computation of time required to reach the initial detention assumed.

Program Name	Variable Name	Initial Value	Reset (yes or no)	Description
INTAL	NCT	0	no	Count the number of iterations in the computation of initial V on the ground surface corresponding to the assumed initial detention.
JL1	NCT	0	yes	Count the number of iterations in the computation of V_L and h_L on region "L" of the discontinuity. Reset whenever such computation is needed.
JR1	NCT	0	yes	Count the number of iterations in the computation of V_R and h_R on region "R" of the discontinuity. Reset whenever such computation is needed.
NEWJ	NCT	0	yes	Count the number of iterations in search for a new discontinuity between two grid points. Reset for every such computation before computing V and h at a grid point.
REF	NCT	0	no	Count the number of iterations in the computation of reference (normalizing) quantities such as the flow depth, h_o, using Eq. 72.
REF	NCT	0	no	Count the number of iterations in the computation of the Darcy-Weisbach friction coefficient, f, for reference flow.
TYPE4	NCT	0	no	Count the number of iterations in the computation of V for gutter when the advancing wavefront reaches the road curb under TYPE 3 storm.

6. Program Listing

6.1. The Job Control Language (JCL)

In preparing and executing computer programs on the UNIVAC 1108, the following EXEC-8 system control cards are needed. Note the symbol @ which is used in column 1 of all control cards is a 7-8 punch. To punch this symbol, hold the MULT PCH and NUM keys, and punch a 7 and 8.

(1) The Run card is the first card of each job deck. This card contains the project number, estimated time, and estimated pages.

(2) The HDG card is used to place a heading at the top of each page of both the program listing and any output.

(3) A FOR card must precede each FORTRAN deck included in the job. It is used to inform the system that a FORTRAN deck follows.

(4) The XQT card must follow all the FORTRAN decks. It is used to indicate that execution is desired. If one wants to compile only, simply delete this card. The data cards should immediately follow the XQT card.

(5) The FIN card indicates the end of the job deck.

(6) The remote control card is simply a card with a 7-8 punch in columns 1 and 2. This card followed immediately by two blank cards is needed on a remote terminal UNIVAC 9200.

An example of a complete FORTRAN job deck is as follows:

```
@RUN
@HDG
@FOR, IS MAIN,MAIN
@FOR, IS ADW,ADW
      .
      .
      .
@FOR, IS WRITJ,WRITJ
@XQT
      .
      .
      .
data cards, if any
      .
      .
      .
```

@FIN
@@remote control card
blank card
blank card

There are a wide variety of options in preparing and executing the control cards. For example, the @ASG statement is used to name magnetic tape or Fastrand drum files, to assign temporary or catalogued files to the requesting run, to specify files to be catalogued, and to specify storage methods and requirements for these files. Other executive control statements, too many to be cited herein, can be found in the UNIVAC 1108 user's guide.

6.2. Source listing

The main program is listed first and then followed by the subprograms in the alphabetic order. For convenience in reference, the statement numbers in each of the main program and subprograms are given.

```
C       *******************************************************************
C       *      DYNAMIC BEHAVIOR OF RUNOFF FROM HIGHWAY WATERSHEDS         *
C       *          UNDER TIME- AND SPACE-VARYING RAINSTORMS               *
C       *******************************************************************
C
C       MAIN PROGRAM
        COMMON /B1/ B(40),C(40),Z(10),TIME,OPH,NN,N,NCH,RSL,CURVE
        COMMON /B2/ H(27,27,2),V(27,27,2),HL(27,10,2),HR(27,10,2),
       $VR(27,10,2),VL(27,10,2),VJ(27,10,2),XJ(27,10,2),JI(27,27,2),KN,NJJ
        COMMON /B3/ NK(27),NJ(27),DX,DT,DIST,HMIN,VMIN,ITYPE,IO,OC(27,10),
       $S,DS
        COMMON/B6/AA1,BB1,CC1,SNK,IDG,SP1,XPG1,SP2,XPG2
        COMMON/B8/ACCU,ACCUX,ACCUY,HDRY,CC
        COMMON /B10/ DXCH,DXRS,DDXCH,DDXRS
        COMMON /B14/ IWET(27)
        COMMON/B16/AAA,BBB,CCC,TD,RTO,RMN,RAV
        COMMON/B17/FINF,BETTA,ALFHA,TO,TP,VSF,SPI
        DIMENSION NRSOUT(27),NST(27)
        DIMENSION STAR(18)
        DATA NCT/0/,STAR/18*' * * *'/
        READ(5,100) ITYPE,NOUT,NN,TEND,DDXCH,DDXRS,CURVE
    100 FORMAT(3I5,10F5.0)
C       NOUT    OUTPUT AT EACH N-TH ITERATION
C       NN      NUMBER OF SECTIONS OF ROADSURFACE FLOW
C       TEND    DIMENSIONLESS TIME OF THIS PROGRAM ENDING
        NCH=NN+1
C       N=NCH FOR CHANNEL FLOW
        NS=NCH+1
C       NS FOR FLOW ON SIDESLOPE
C       CURVE=CURVATURE OF ROADWAY , 1/RADIUS (FT).  SET ZERO FOR STRAIGHT
C       ROADWAY
        READ(5,101) (B(I),I=1,40)
    101 FORMAT(8F10.0)
C       EVALUATE THE EQUATION OF ROAD SURFACE CROWN
        IF(NN.GT.1) CALL CROWN
C
        CALL RAIN(1,0.)
C       COMPUTATION OF THE REFERENCE QUANTITIES
        CALL REF
        CALL INFLT(1,0.)
C       COMPUTATION OF THE PARAMETERS USED IN THE PROGRAM
        CALL PARA
C
        WRITE(6,201)ITYPE,NOUT,NN,TEND,DDXCH,DDXRS
    201 FORMAT(/'  ITYPE =',I2,'  NOUT =',I3,'  NN =',I3,'  TEND =',F6.2 ,
       $' DDXCH = ',F6.2,' FT DDXRS = ',F6.2,' FT')
C
C       SET UP INITIAL CONDITIONS
        CALL INTAL
        IF(NN.EQ.1) GO TO 6
C
C       READ IN SECTION NOS. OF ROAD SURFACES NEEDED TO BE OUTPUT
        READ(5,102)(NRSOUT(I),I=1,NN)
    102 FORMAT(80I1)
        IOUT=1
        DO 5 I=1,NN
```

```
      IF(NRSOUT(I).EQ.0) GO TO 5
      NST(IOUT)=I
      IOUT=IOUT+1
    5 CONTINUE
C
C     COMPUTE TIME REQUIRED FOR FILLING DEPRESSION, B(40), INCHES
C     TRFDS=DIMENSIONLESS TIME FOR OVERCOMING DETENTION AND DEPRESSION
      IF(B(40).LE.0.) GOTO 53
      NOCT=0
      TRFDS=TD*60.*B(12)/B(11)
      CALL RAIN(3,TRFDS)
      PTL=RMN*TRFDS*B(11)/B(12)/3600.
      IF(B(40).LT.PTL) GOTO 50
      WRITE(6,300)
  300 FORMAT(/' THERE IS NO RUNOFF')
      STOP
   50 T1=0.
      T2=TRFDS
   51 TRFDS=T1+(T2-T1)/2.
      NOCT=NOCT+1
      IF(NOCT.GT.30) SS=SQRT(-1.)
      IF((T2-T1).LT.ACCU) GOTO 52
      CALL RAIN(3,TRFDS)
      PTL=RMN*TRFDS*B(11)/B(12)/3600.
      IF(ABS(B(40)-PTL).LT.ACCU) GOTO 52
      IF(B(40).LT.PTL) GOTO 55
      T1=TRFDS
      GOTO 51
   55 T2=TRFDS
      GOTO 51
   52 IF(TIME.LT.TRFDS) TIME=TRFDS
   53 TDIM=TIME*B(11)/B(12)
      WRITE(6,202) TIME,TDIM
  202 FORMAT(/' DIMENSIONLESS TIME FOR DEPRESSION STORAGE -- INTERCEPTIO
     $N = ',E10.4,' (DIMENSIONAL TIME = ',F10.3,' SEC.)')
C     EVALUATION OF TIME INTERVAL, DT
    6 CALL EVDT
C
C     START TO NEXT TIME INTERVAL COMPUTATION
      TIME=TIME+DT
      IF(TIME.GT.TEND) STOP
C
C      IO    INDICATES OUTPUT CONTROL
C            0  NO OUTPUT
C            1  OUTPUT
      IO=0
      NCT=NCT+1
      IF(NCT/NOUT*NOUT.EQ.NCT) IO=1
   11 IF(IO.EQ.0) GO TO 12
      TDIM=TIME*B(11)/B(12)
      WRITE(6,200) STAR,STAR,STAR(1),TIME,TDIM,(STAR(I),I=1,7),STAR
  200 FORMAT(2(/18A6)/A6,'   TIME =',F9.3,5X,'(DIMENSIONAL TIME =',F9.3,
     $' SEC.)    *',7A6/18A6)
   12 IOO=IO
      IO=0
      IF(ITYPE.EQ.2) GO TO 35
C     COMPUTE FLOW ON SIDESLOPE
```

```
      N=NS
      IF(TIME.LT.TP*60.*B(12)/B(11)) GOTO 15
      CALL SLOPE
   15 DO 20 N=1,NCH
C
      CALL PREP
C
      IF(KN.LT.2) GOTO 20
      IF(ITYPE.EQ.3) GO TO 41
      CALL INPT
C
C     COMPUTATION OF UPSTREAM BOUNDARY
      IF(N.LT.NCH) CALL UBDY
      IF(ITYPE.EQ.4) GO TO 42
      IF(NN.EQ.1) CALL DBDY
      IF(NN.EQ.1) GO TO 21
   20 CONTINUE
C     IFC=INDEX FOR COMPUTATION OF NEWLY OCCURRING SHOCK WAVES
C     ASSUME THE OCCURRENCE OF SHOCK WAVES (IFC=2), OTHERWISE (IFC=1)
      IFC=1
C     TO COMPUTE THE UPSTREAM AND DOWNSTREAM END OF CHANNEL FLOW AND
C     INTERNAL BOUNDARY
   21 DO 30 N=1,NCH
      CALL PREP
C
      IF(KN.LT.2) GOTO 30
      IF(N.LT.NN.AND.N.GT.1) CALL INBDY(1,DIST,HH,TT,2)
      IF(N.EQ.NN.AND.IDG.EQ.2) CALL INBDY(2,DIST,HH,TT,2)
C
C     COMPUTE UPSTREAM AND DOWNSTREAM BOUNDARY OF CHANNEL FLOW
   25 IF(ITYPE.NE.5.AND.N.EQ.NCH) CALL UBDY
      IF(N.EQ.NCH) CALL INLET
C
      IF(NJ(N).GT.0) CALL PACKJ
C     THE FOLLOWING STATEMENT IS OPTIONAL
      IF(IFC.EQ.2) CALL NEWJ
   30 CONTINUE
   32 IO=IOO
C
C     OUTPUT RESULTS
      IF(IO.EQ.0) GO TO 31
      DO 40 I=1,IOUT
      N=NST(I)
      IF(I.EQ.IOUT) N=NCH
      IF(ITYPE.EQ.2.AND.IWET(N).EQ.0) GO TO 40
      IF(ITYPE.EQ.5.AND.IWET(N).EQ.0) GO TO 40
      Z(3)=0.
      IF(I.EQ.IOUT-1) Z(3)=1.
      CALL PREP
      CALL OUPT
      IF(NN.EQ.1) GO TO 31
   40 CONTINUE
      N=NS
      CALL PREP
      CALL OUPT
C
C     CALCULATE THE COMPUTATIONAL ERROR
```

```
   31 CALL ERR(2)
C
C     GO ON ITERATION
      CALL GOON
      GO TO 6
   35 N=NCH
      CALL PREP
      CALL ADW
      IF(NJ(NCH).GT.0) CALL PACKJ
      GO TO 32
   41 CALL ADW
      IF(NJ(N).GT.0) CALL PACKJ
      IF(ITYPE.EQ.4) GO TO 42
   43 Z(3)=0.
      IO=IOO
      IF(IO.EQ.0) GO TO 31
      CALL PREP
      CALL OUPT
      GO TO 31
   42 CALL TYPE4
      GO TO 32
      END
```

```
      SUBROUTINE ADW
C     SOLVE THE ADVANCING WAVEFRONT PROBLEM DUE TO A MOVING RAINSTORM
      COMMON /B1/ B(40),C(40),Z(10),TIME,GPH,NN,N,NCH,RSL,CURVE
      COMMON /B2/ H(27,27,2),V(27,27,2),HL(27,10,2),HR(27,10,2),
     $VR(27,10,2),VL(27,10,2),VJ(27,10,2),XJ(27,10,2),JI(27,27,2),KN,NJJ
      COMMON /B3/ NK(27),NJ(27),DX,DT,DIST,HMIN,VMIN,ITYPE,IO,OC(27,10),
     $S,DS
      COMMON /B4/ II(27,2),XI(27,2),HI(27,2),VI(27,2),QI(27,2),WI(27,2),
     $CT(27,2),CH(27,2),CV(27,2)
      COMMON /B5/ NG(27,27),SG(27,27),FG(27,27),NF,SF,FF
      COMMON/B6/AA1,BB1,CC1,SNK,IDG,SP1,XPG1,SP2,XPG2
      COMMON /B7/ NL(27,10),NR(27,10),SL(27,10),SR(27,10),FL(27,10),
     $FR(27,10),NFJ,SFJ,FFJ
      COMMON /B8/ ACCU,ACCUX,ACCUY,HDRY,CC
      COMMON /B9/ TL(10,2),TR(10,2)
      COMMON /B10/ DXCH,DXRS,DDXCH,DDXRS
      COMMON /B11/ HRR,VRR
      COMMON /B12/ NDEPTH
      COMMON /B14/ IWET(27)
      COMMON /B15/ VO,VT,VIN,VOUT
      DIMENSION HH(2)
      DIMENSION FTT(2),XJ2TT(2)
      DATA NCO/0/,NAME/' ADW'/
      TIM=TIME-DT
      CNK=COS(ASIN(SP2))
      DXPG1=XPG1/B(11)
      DXPG2=XPG2/B(11)
      XJ1=XJ(N,NJJ,1)
      KJ=XJ1/DX+1.99999
      K1=KJ-1
      IF(ITYPE.EQ.2.OR.ITYPE.EQ.7) GOTO 50
    4 DO 5 K=2,K1
      XK=FLOAT(K-1)*DX
      CALL STORM(XK,TIM)
      CALL OPHEAD
      KA=K-1
      KC=K+1
      XA=XK-DX
      XB=XK
      XC=XK+DX
      IF(K.EQ.K1) XC=XJ1
      HA=H(N,KA,1)
      HB=H(N,K,1)
      HC=H(N,KC,1)
      IF(K.EQ.K1) HC=HL(N,NJJ,1)
      VA=V(N,KA,1)
      VB=V(N,K,1)
      VC=V(N,KC,1)
      IF(K.EQ.K1) VC=VL(N,NJJ,1)
      CALL GEOM(2,AA,HA,RA,TA,DA,1,1,XA)
      CALL GEOM(2,AB,HB,RB,TB,DB,1,1,XB)
      CALL GEOM(2,AC,HC,RC,TC,DC,1,1,XC)
      FRB=FRTST(VB,DB,GPH,C(1),C(5),C(9),C(20),1)
      CALL CS(1.,XA,XB,XD,XB,DA,DB,DD,VA,VB,VD)
      IF(FRB.GT.0.) GO TO 1
      IF(XC-XB.LT.ACCU) GO TO 6
```

```
      CALL CS(-1.,XB,XC,XE,XB,DB,DC,DE,VB,VC,VE)
      IF(NDEPTH.EQ.1) GO TO 6
      IF(XE.GT.XC.AND.K.EQ.K1) GO TO 6
      GO TO 2
    1 CALL CS(-1.,XA,XB,XE,XB,DA,DB,DE,VA,VB,VE)
    2 CALL CEQS(VD,DD,VE,DE,V(N,K,2),H(N,K,2),XD,XE,DT,DT,XB)
      NG(N,K)=NF
      SG(N,K)=SF
      FG(N,K)=FF
    5 CONTINUE
      GO TO 7
    6 K1=K1-1
      XK=FLOAT(K1-1)*DX
      IF(K1.LT.2) SS=SQRT(-1.)
    7 IF(ITYPE.EQ.2) GO TO 52
      CALL UBDY
      IF(NCO.EQ.1) GO TO 3
      NCO=1
      GO TO 8
    3 VO=VT
    8 XR=(TIME-DT/2.)*C(30)
      VIN=B(32)/B(19)*XR*DT*TB*C(19)*B(10)*B(11)/B(18)+C(28)*B(12)/B(11)
      VT1=0.
      DO 10 K=2,K1
      XK=FLOAT(K-1)*DX
      XK1=XK-DX
      XKA=(XK+XK1)/2.
      CALL STORM(XKA,TIME)
      CALL GEOM(2,AA,H(N,K-1,2),RA,TA,DA,1,2,XK1)
      CALL GEOM(2,AB,H(N,K,2),RB,TB,DB,1,2,XK)
      VT1=VT1+(AA+AB)*DX/2./C(9)
   10 CONTINUE
   24 VT2=VO+VIN-VT1
      ITT=1
      NCTT=0
      XJ2=XJ1+VJ(N,NJJ,1)*DT
      XJ2TT(ITT)=XJ2
    9 CALL JL1(XJ2TT(ITT),NJJ,VLL,HLL,VRR,HRR,$28)
   17 NCTT=NCTT+1
      XKJ=(XJ2TT(ITT)+XK)/2.
      CALL STORM(XKJ,TIME)
      CALL GEOM(2,ALL,HLL,RLL,TLL,DLL,1,2,XJ2TT(ITT))
      CALL GEOM(2,ARR,HRR,RRR,TRR,DRR,1,2,XJ2TT(ITT))
      DXJ=XJ2TT(ITT)-FLOAT(K1-1)*DX
      CT22=(AB+ALL)*DXJ/2./C(9)
      IF(VT2.LT.ACCU) GO TO 26
      FTT(ITT)=VT2-CT22
      IF(ABS(FTT(ITT)).LT.ACCU) GO TO 18
      IF(ITT.EQ.1) GO TO 27
      IF(NCTT.GT.20) SS=SQRT(-1.)
      XJ2=(FTT(1)*XJ2TT(2)-FTT(2)*XJ2TT(1))/(FTT(1)-FTT(2))
      XJ2TT(1)=XJ2TT(2)
      XJ2TT(2)=XJ2
      FTT(1)=FTT(2)
      GO TO 9
   27 ITT=2
      XJ2=XJ2+0.1*DX
```

```
      XJ2TT(2)=XJ2
      GO TO 9
   18 CONTINUE
   26 VT=VT1+(AB+ALL)/2.*DXJ/C(9)
   22 IF(ITYPE.EQ.3.AND.XJ2.GT.DIST) GO TO 80
      IF(ITYPE.EQ.2.AND.XJ2.GT.C(21)) GO TO 57
      IF(TIME*C(30).GT.XJ2) GO TO 20
   25 IF(DXJ.LT.DX) GO TO 21
      K=K1+1
      H(N,K,2)=H(N,K1,2)-(H(N,K1,2)-HLL)*DX/DXJ
      V(N,K,2)=V(N,K1,2)-(V(N,K1,2)-VLL)*DX/DXJ
      NNNN=N
      N=K
      IF(ITYPE.EQ.2) CALL INBDY(1,XX,HH,TT,2)
      N=NNNN
      CALL PREP
   21 CALL FRIC(VLL,HLL,FLL,RLL,REL,RECL,IRL,2,XJ2)
      SL(N,NJJ)=C(4)*FLL*ABS(VLL)*VLL/(B(13)*RLL)
      FL(N,NJJ)=FLL
      VOUT=0.
      OC(N,NJJ)=NAME
   19 HL(N,NJJ,2)=HLL
      VL(N,NJJ,2)=VLL
      IF(ABS(ALL-ARR).LE.ACCU) VJ(N,NJJ,2)=0.
      IF(ABS(ALL-ARR).LE.ACCU) GOTO 23
      VJ(N,NJJ,2)=(ALL*VLL-ARR*VRR)/(ALL-ARR)
   23 VR(N,NJJ,2)=VRR
      HR(N,NJJ,2)=HRR
      XJ(N,NJJ,2)=XJ2
      IF(ITYPE.EQ.2) TL(NJJ,2)=TLL
      IF(ITYPE.EQ.2) TR(NJJ,2)=TRR
      IF(ITYPE.EQ.2) KJ2=XJ2/DXCH+0.99999
      IF(ITYPE.EQ.2) IWET(KJ2)=1
      RETURN
   20 IF(TIME*C(30).GT.DIST) GO TO 80
      HL(N,NJJ,2)=HRR
      VL(N,NJJ,2)=VRR
      VJ(N,NJJ,2)=0.
      HR(N,NJJ,2)=HRR
      VR(N,NJJ,2)=VRR
      XJ(N,NJJ,2)=TIME*C(30)
      IF(ITYPE.EQ.2) KJ2=TIME*C(30)/DXCH+0.99999
      IF(ITYPE.EQ.2) IWET(KJ2)=1
      RETURN
   28 VJ1=VJ(N,NJJ,1)
      NJJ=NJJ-1
      HR(N,NJJ,2)=HRR
      VR(N,NJJ,2)=VRR
      XJ(N,NJJ,2)=XJ2
      VJ(N,NJJ,2)=VJ1
      RETURN
   80 ITYPE=4
      HL(N,NJJ,2)=HLL
      VL(N,NJJ,2)=VLL
      HL2=(HL(N,NJJ,1)+HL(N,NJJ,2))/2.
      VL2=(VL(N,NJJ,1)+VL(N,NJJ,2))/2.
      CALL GEOM(2,AL2,HL2,RL2,TL2,DL2,1,2,DIST)
```

```
      B(29)=VL2*AL2*B(12)*B(18)
      NJJ=NJJ-1
      NJ(N)=NJJ
      HCH=C(26)*B(19)*DT*B(11)/B(12)+SQRT((C(26)*B(19)*DT*B(11)/B(12))**
     $2+2.*B(29)*DT*B(11)/B(12)*TAN(ASIN(SP2)))
      H(NCH,N,2)=HCH*C(5)/B(16)
      B(29)=0.
      RETURN
   50 DO 51 N=1,NN
      CALL PREP
      CALL INPT
      CALL UBDY
   51 CONTINUE
      N=NCH
      CALL PREP
      IF(ITYPE.EQ.7) GOTO 59
      GO TO 4
   52 DO 58 N=2,K1
      CALL PREP
      CALL INBDY(1,XX,HH,TT,2)
   58 CONTINUE
      N=NCH
      CALL PREP
      CALL UBDY
      IF( NCO.EQ.1) GO TO 53
      NCO=1
      VO=0.
      DO 63 N=2,3
      IF(IWET(N).EQ.0.AND.IWET(N-1).EQ.0) GO TO 63
      KN=(C(22)+DXPG1+DXPG2)/DXRS+1.99999
      FCT=DDXCH
      XN=FLOAT(N-1)*DXCH
      XR=TIME*C(30)
      IF(XN.LT.XR) GO TO 67
      XRN=DXCH-(XN-XR)
      FCT=DDXCH*XRN/DXCH
   67 DO 62 K=2,KN
      X=FLOAT(K-1)*DXRS
      X1=X-DXRS
      CALL GEOM(2,A1,H(N,K,1),R1,T1,D1,1,1,X)
      CALL GEOM(2,A2,H(N-1,K,1),R2,T2,D2,1,1,X)
      CALL GEOM(2,A3,H(N,K-1,1),R3,T3,D3,1,1,X1)
      CALL GEOM(2,A4,H(N-1,K-1,1),R4,T4,D4,1,1,X1)
      IF(K.EQ.KN) CALL GEOM(2,A1,HI(N,1),R1,T1,D1,1,1,XX)
      IF(K.EQ.KN) CALL GEOM(2,A2,HI(N-1,1),R2,T2,D2,1,1,XX)
      DX1=DXRS
      IF(K.EQ.KN) DX1=(XI(N,1)+XI(N-1,1)-2.*FLOAT(KN-2)*DXRS)/2.
      X12=X-DX1/2.
      CALL STORM(X12,TIME)
      VO=VO+(A1+A2+A3+A4)/4.*DX1*FCT/C(9)
   62 CONTINUE
   63 CONTINUE
      N=NCH
      CALL GEOM(2,A1,H(N,1,1),R1,T1,D1,1,1,0.)
      CALL GEOM(2,A2,H(N,2,1),R2,T2,D2,1,1,DXCH)
      CALL GEOM(2,A3,HL(N,NJJ,1),R3,T3,D3,1,1,XJ1)
      VO=VO+(A1+A2)/2.*DXCH/C(5)
```

```
      VO=VO+(A2+A3)/2.*(XJ1-DXCH)/C(5)
      GO TO 61
   53 VO=VT
   61 XR=(TIME-DT/2.)*C(30)
      VIN=B(32)/B(19)*XR*DT*C(19)*(B(22)+XPG1+XPG2)*B(11)/B(18)+C(28)*B(
     $12)/B(11)
      VT1=0.
      DO 56 N=2,NN
      IF(IWET(N).EQ.0.AND.IWET(N-1).EQ.0) GO TO 56
      CALL PREP
      IF(NK(N-1).LT.KN) KN=NK(N-1)
      FCT=DDXCH
      XN=FLOAT(N-1)*DXCH
      XR=TIME*C(30)
      IF(XN.LT.XR) GO TO 68
      XRN=DXCH-(XN-XR)
      FCT=DDXCH*XRN/DXCH
   68 DO 54 K=2,KN
      X=FLOAT(K-1)*DXRS
      X1=X-DXRS
      DX1=DXRS
      CALL GEOM(2,A1,H(N,K,2),R1,T1,D1,1,2,X)
      CALL GEOM(2,A2,H(N-1,K,2),R2,T2,D2,1,2,X)
      CALL GEOM(2,A3,H(N,K-1,2),R3,T3,D3,1,2,X1)
      CALL GEOM(2,A4,H(N-1,K-1,2),R4,T4,D4,1,2,X1)
      IF(K.LT.KN) GO TO 54
      DX1=(XI(N,2)-AINT(XI(N,2)/DXRS)*DXRS+XI(N-1,2)-AINT(XI(N,2)/DXRS )
     $*DXRS)/2.
      CALL GEOM(2,A1,HI(N,2),R1,T1,D1,1,2,XI(N,2))
      CALL GEOM(2,A2,HI(N-1,2),R2,T2,D2,1,2,XI(N-1,2))
   54 X12=X-DX1/2.
      CALL STORM(X12,TIME)
      VT1=VT1+(A1+A2+A3+A4)*DX1*FCT/4./C(9)
   56 CONTINUE
      N=NCH
      CALL PREP
      DO 64 K=2,K1
      XK=FLOAT(K-1)*DXCH
      XK1=X-DXCH
      XKA=(XK+XK1)/2.
      CALL STORM(XKA,TIME)
      CALL GEOM(2,AA,H(N,K-1,2),RA,TA,DA,1,2,XK1)
      CALL GEOM(2,AB,H(N,K,2),RB,TB,DB,1,2,XK)
      VT1=VT1+(AA+AB)*DXCH/2./C(9)
   64 CONTINUE
      CALL STORM(XJ1,TIME)
      GO TO 24
   57 XJ(NCH,NJJ,2)=XJ2
      NJ(NCH)=NJ(NCH)-1
      H(NCH,NN,2)=2.*H(NCH,NN-1,2)-H(NCH,NN-2,2)
      V(NCH,NN,2)=2.*V(NCH,NN-1,2)-V(NCH,NN-2,2)
      H(NCH,NN,1)=HMIN
      CT(NN,1)=ACCU
      CALL INBDY(2,XX,HH,TT,2)
      ITYPE=7
      RETURN
   59 CALL INPT
```

```
      NN1=NN-1
      DO 60 N=2,NN1
      CALL PREP
      CALL INBDY(1,XX,HH,TT,2)
   60 CONTINUE
      N=NCH
      CALL PREP
      CALL UBDY
      CALL INLET
      RETURN
      END
```

```
      SUBROUTINE CEQS(VD,DD,VE,DE,VP,HP,XD,XE,DTD,DTE,XP)
C     SOLVE TWO CHARACTERISTIC EQUATIONS TO OBTAIN VP AND HP
      COMMON /B1/ B(40),C(40),Z(10),TIME,OPH,NN,N,NCH,RSL,CURVE
      COMMON /B3/ NK(27),NJ(27),DX,DT,DIST,HMIN,VMIN,ITYPE,IO,OC(27,10),
     $S,DS
      COMMON/B4/II(27,2),XI(27,2),HI(27,2),VI(27,2),QI(27,2),WI(27,2),
     $CT(27,2),CH(27,2),CV(27,2)
      COMMON /B5/ NG(27,27),SG(27,27),FG(27,27),NF,SF,FF
      COMMON/B6/AA1,BB1,CC1,SNK,IDG,SP1,XPG1,SP2,XPG2
      COMMON /B7/ NL(27,10),NR(27,10),SL(27,10),SR(27,10),FL(27,10),
     $FR(27,10),NFJ,SFJ,FFJ
      COMMON /B8/ ACCU,ACCUX,ACCUY,HDRY,CC
      COMMON/B16/AAA,BBB,CCC,TD,RTO,RMN,RAV
      CALL RAIN(3,TIME)
      KP=XP/DX+1.99999
      IF(IDG.EQ.1.AND.N.EQ.NCH) CTMIN=HMIN*B(16)/C(5)/TAN(ASIN(SP2))/B(1
     $0)
C     CD AND CE ARE ENERGY COEFFICIENTS AT POINTS D AND E
      CD=1.
      CE=1.
      NF=0
      IF(DD.LT.HDRY.OR.DE.LT.HDRY) HP=HDRY
      IF(DD.LT.HDRY.OR.DE.LT.HDRY) GOTO 5
      CALL GEOM(5,AD,HD,RD,CTD,DD,1,1,XD)
      CALL GEOM(5,AE,HE,RE,CTE,DE,1,1,XE)
      TIM=TIME-DTD
      CALL STORM(XD,TIM)
      CALL OPHEAD
      CALL FRIC(VD,HD,FD,RD,RED,REC,IRD,1,XD)
      SFD=C(4)*FD*VD*ABS(VD)/(B(13)*RD)
      IF(ABS(XE-XD).LT.ACCUX) SFDE=C(8)
      IF(ABS(XE-XD).LT.ACCUX) GOTO 8
    7 SFDE=C(8)+(B(16)*(HD-HE)/C(5)+B(12)**2*(CD*VD*VD-CE*VE*VE)/64.4)/
     $((XE-XD)*B(11))*C(9)
    8 IF(ABS(SFD).LT.ABS(SFDE)) GOTO 12
    9 SFD=SFDE
      NF=1
   12 DSQ=SQRT(C(1)*(C(1)-1.)*VD*VD+C(1)*C(20)*(DD*C(9)/C(5)+OPH))
      A1=((1.-C(1))*VD+DSQ)*C(9)/C(5)/DD
      C7=C(7)*DTD/DT
      SFD=(SFD+SFDE)/2.
      C1=C(11)*DTD*(C(1)*C(20)*(C(8)-SFD)+C(26)/DD*C(19)*(C7*C(25)*C(6)
     $/C(9)-C(1)*VD+DSQ)*C(9)*C(5)+C(27)*C(19)/DD*(C(1)*VD-DSQ)*
     $C(9)*C(5)+C(29)/CTD/DD*(C(3)*C(2)*C(24)-C(1)*VD+DSQ)*B(16)/B(10)
     $)+HD*A1+VD
      TIM=TIME-DTE
      CALL STORM(XE,TIM)
      CALL OPHEAD
      CALL FRIC(VE,HE,FE,RE,REE,REC,IRE,1,XE)
      SFE=C(4)*FE*VE*ABS(VE)/(B(13)*RE)
      IF(ABS(XE-XD).LT.ACCUX) SFDE=C(8)
      IF(ABS(XE-XD).LT.ACCUX) GOTO 18
   17 SFDE=C(8)+(B(16)*(HD-HE)/C(5)+B(12)**2*(CD*VD*VD-CE*VE*VE)/64.4)/
     $((XE-XD)*B(11))*C(9)
   18 IF(ABS(SFE).LT.ABS(SFDE)) GOTO 22
   19 SFE=SFDE
```

```
      NF=1
   22 ESQ=SQRT(C(1)*(C(1)-1.)*VE*VE+C(1)*C(20)*(DE*C(9)/C(5)+CPH))
      A2=((1.-C(1))*VE-ESQ)*C(9)/C(5)/DE
      C7=C(7)*DTE/DT
      SFE=(SFE+SFDE)/2.
      C2=C(11)*DTE*(C(1)*C(20)*(C(8)-SFE)+C(26)/DE*C(19)*(C7*C(25)*C(6)
     $/C(9)-C(1)*VE-ESQ)*C(9)*C(5)+C(27)*C(19)/DE*(C(1)*VE+ESQ)*
     $C(9)*C(5)+C(29)/CTE/DE*(C(3)*C(2)*C(24)-C(1)*VE-ESQ)*B(16)/B(10))
     $+HE*A2+VE
      HP=(C1-C2)/(A1-A2)
      VP=(A1*C2-A2*C1)/(A1-A2)
      SFP=(SFD+SFE)/2.
      IF(SFP.GT.0..AND.VP.LT.0.) VP=(VD+VE)/2.
    5 CALL STORM(XP,TIME)
      SFO=C(8)
      IF(SFO.GT.0.) GOTO 37
      CC=0.
      GOTO 38
   37 CC=C(36)*SFO**C(37)
   38 IF(CC.LT.24.) CC=24.
      QFLOW=VP*B(12)*HP*B(16)/C(5)
      QRAIN=RMN/43200.*XP*B(11)
      IF(N.NE.NCH.AND.QFLOW.GT.1.10*QRAIN) GOTO 30
      IF(IDG.EQ.1.AND.N.EQ.NCH.AND.HP.LE.HMIN) GOTO 39
      GOTO 27
   39 HP=HMIN
      CT(KP,2)=CTMIN
      CALL GEOM(2,AP,HP,RP,CTP,DP,1,2,XP)
      VP=SFO*257.6*RP*RP*B(17)**2/(CC*B(24)*B(12))
      CALL FRIC(VP,HP,FP,RP,REP,REC,IRP,2,XP)
   26 FF=FP
      SF=C(4)*FP*VP*ABS(VP)/(B(13)*RP)
      FFJ=FF
      SFJ=SF
      NFJ=NF
      RETURN
   27 IF(HP.LE.HDRY) HP=HDRY
      CALL GEOM(2,AP,HP,RP,CTP,DP,1,2,XP)
      IF(RP.LE.B(2)*C(23).AND.XP.LT.DIST) VP=SFO*257.6*RP*RP*B(17)**2/
     $(CC*B(24)*B(12))
      CALL FRIC(VP,HP,FP,RP,REP,REC,IRP,2,XP)
      IF(N.EQ.NCH.OR.IRP.NE.6) GOTO 26
   30 IF(SFO.LE.0.) GOTO 28
      HMAX=(CC*B(24)*RMN*XP*B(11)/(257.6*43200.*SFO))**(1./3.)*C(5)/B(16
     $)
      GOTO 29
   28 HMAX=RMN/43200.*TIME*B(11)/B(12)*C(5)/B(16)
   29 IF(HP.GT.HMAX) HP=HMAX
      VMAX=RMN/43200.*XP*B(11)/(HP*B(16)/C(5))/B(12)
      IF(VP.GT.VMAX) VP=VMAX
      CALL GEOM(2,AP,HP,RP,CTP,DP,1,2,XP)
      CALL FRIC(VP,HP,FP,RP,REP,REC,IRP,2,XP)
      GOTO 26
      END
```

```
      SUBROUTINE CONJ(XJ2,J,VLL,HLL,VRR,HRR,$)
C     EVALUATE THE CONJUGATE DEPTHS AND VELOSITIES OF THE DISCONTINUITY
      COMMON /B1/ B(40),C(40),Z(10),TIME,OPH,NN,N,NCH,RSL,CURVE
      COMMON /B2/ H(27,27,2),V(27,27,2),HL(27,10,2),HR(27,10,2),
     $VR(27,10,2),VL(27,10,2),VJ(27,10,2),XJ(27,10,2),JI(27,27,2),KN,NJJ
      COMMON /B3/ NK(27),NJ(27),DX,DT,DIST,HMIN,VMIN,ITYPE,IO,OC(27,10),
     $S,DS
      COMMON /B7/ NL(27,10),NR(27,10),SL(27,10),SR(27,10),FL(27,10),
     $FR(27,10),NFJ,SFJ,FFJ
      K=XJ2/DX+1.99999
      CALL STORM(XJ2,TIME)
      CALL OPHEAD
      CALL GEOM(2,AL,HL(N,J,1),RL,TL,DL,1,1,XJ(N,J,1))
      CALL GEOM(2,AR,HR(N,J,1),RR,TR,DR,1,1,XJ(N,J,1))
      IF(AL.GT.AR) GO TO 3
      CALL JL(XJ2,J,VLL,HLL,$13,1)
      NL(N,J)=NFJ
      SL(N,J)=SFJ
      FL(N,J)=FFJ
      CALL JR1(XJ2,J,VLL,HLL,VRR,HRR,$13)
      RETURN
    3 CALL JR(XJ2,J,VRR,HRR,$13,1)
      NR(N,J)=NFJ
      SR(N,J)=SFJ
      FR(N,J)=FFJ
      CALL JL1(XJ2,J,VLL,HLL,VRR,HRR,$13)
      RETURN
   13 RETURN 7
      END
```

```
      SUBROUTINE CRISEC
C     LOCATE CRITICAL SECTIONS, IF ANY
      COMMON /B1/ B(40),C(40),Z(10),TIME,OPH,NN,N,NCH,RSL,CURVE
      COMMON /B2/ H(27,27,2),V(27,27,2),HL(27,10,2),HR(27,10,2),
     $VR(27,10,2),VL(27,10,2),VJ(27,10,2),XJ(27,10,2),JI(27,27,2),KN,NJ
      COMMON /B3/ NK(27),NJ(27),DX,DT,DIST,HMIN,VMIN,ITYPE,IO,OC(27,10),
     $S,DS
      COMMON/B6/AA1,BB1,CC1,SNK,IDG,SP1,XPG1,SP2,XPG2
      COMMON /B8/ ACCU,ACCUX,ACCUY,HDRY,CC
      KNM=KN
      IF(N.LT.NCH.AND.IDG.EQ.1) KNM=KN-1
      DO 9 K=2,KNM
      IF(JI(N,K,2).GT.0) GO TO 9
      IF(H(N,K,2).LT.HDRY*2.) GO TO 9
      KA=K-1
      IF(H(N,KA,2).LT.HDRY*2.) GO TO 9
      X=FLOAT(KA)*DX
      CALL STORM(X,TIME)
      CALL OPHEAD
      VB=V(N,K,2)
      VA=V(N,KA,2)
      CALL GEOM(2,AB,H(N,K,2),RB,TB,DB,1,2,X)
      FRB=FRTST(VB,DB,OPH,C(1),C(5),C(9),C(20),1)
      IF(FRB)9,2,3
    2 XCR=X
      GO TO 4
    3 X1=X-DX
      CALL STORM(X1,TIME)
      CALL OPHEAD
      CALL GEOM(2,AA,H(N,KA,2),RA,TA,DA,1,2,X1)
      FRA=FRTST(VA,DA,OPH,C(1),C(5),C(9),C(20),1)
      IF(FRA.GT.-ACCU) GO TO 9
      NCT=0
      XCR1=(X+X1)/2.
    5 CALL STORM(XCR1,TIME)
      CALL OPHEAD
      A1=((VB-VA)/DX)**2
      IF(A1.LT.ACCU) GO TO 9
      B1=2.*VA*(VB-VA)/DX-(DB-DA)*C(20)/DX*C(9)/C(5)
      C1=VA**2-C(20)*(DA*C(9)/C(5)+OPH)
      DXCR=(-B1+SQRT(B1*B1-4.*A1*C1))/(2.*A1)
      XCR=DXCR+X-DX
      IF(ABS(XCR1-XCR).LT.ACCUX) GOTO 4
      NCT=NCT+1
      IF(NCT.GT.20) WRITE(6,100) X1,X
  100 FORMAT(' NO CRITICAL SECTION SOLUTION BETWEEN SECTIONS',F7.4,' A D
     $',F7.4)
      IF(NCT.GT.20) GOTO 9
      XCR1=XCR
      GOTO 5
    4 WRITE(6,200) XCR
  200 FORMAT('  CRITICAL SECTION LOCATES AT X=',F7.4)
    9 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE CROSS(XB,J,ID,VV,DD,DXX,DTT,CS)
C     CALCULATE THE VALUE OF V AND H AT A POINT ON THE PATH OF DISCONTI
C     UITY IN THE X,T-PLANE WHEN A DISCONTINUITY CROSSES THE GRID POINT
C     ID=1 ON REGION 'R' OF THE DISCONTINUITY
C     ID=2 ON REGION 'L' OF THE DISCONTINUITY
      COMMON /B1/ B(40),C(40),Z(10),TIME,OPH,NN,N,NCH,RSL,CURVE
      COMMON /B2/ H(27,27,2),V(27,27,2),HL(27,10,2),HR(27,10,2),
     $VR(27,10,2),VL(27,10,2),VJ(27,10,2),XJ(27,10,2),JI(27,27,2),KN,NJ
      COMMON /B3/ NK(27),NJ(27),DX,DT,DIST,HMIN,VMIN,ITYPE,IO,OC(27,10),
     $S,DS
      COMMON /B8/ ACCU,ACCUX,ACCUY,HDRY,CC
      DIMENSION T(2),F(2)
      IF(ID.EQ.2) GO TO 1
      XB2=XB-XJ(N,J,2)
      XB1=XB-XJ(N,J,1)
      V1=VR(N,J,1)
      V2=VR(N,J,2)
      H2=HR(N,J,2)
      H1=HR(N,J,1)
      GO TO 2
    1 XB1=XJ(N,J,1)-XB
      XB2=XJ(N,J,2)-XB
      V1=VL(N,J,1)
      V2=VL(N,J,2)
      H2=HL(N,J,2)
      H1=HL(N,J,1)
    2 I=1
      NCT=0
      T(1)=(DXX-XB1)/(-XB1+XB2)
    3 VV=V1+(V2-V1)*T(I)
      HH=H1+(H2-H1)*T(I)
      DTT=(1.-T(I))*DT
      DXX=XB1+(XB2-XB1)*T(I)
      CALL GEOM(2,AA,HH,RR,TT,DD,1,1,XB)
      CALL STORM(XB,TIME)
      F(I)=DXX/C(9)-DTT*(C(1)*W+CS*SQRT(C(1)*(C(1)-1.)*VV*VV+C(1)*C(20
     $*(DD*C(9)/C(5)+OPH)))
      IF(ABS(F(I)).LT.ACCU) RETURN
      IF(I.EQ.2) GO TO 4
      I=2
      T(2)=T(1)+0.1*DT
      GO TO 3
    4 NCT=NCT+1
      IF(NCT.GT.20) SS=SQRT(-1.)
      TT=(F(1)*T(2)-F(2)*T(1))/(F(1)-F(2))
      T(1)=T(2)
      T(2)=TT
      F(1)=F(2)
      GO TO 3
      END
```

```
      SUBROUTINE CROWN
C     FORMULATE THE EQUATION OF THE TRANSVERSE PROFILE OF A ROAD SURFAC
      COMMON /B1/ B(40),C(40),Z(10),TIME,CPH,NN,N,NCH,RSL,CURVE
      COMMON /B2/ H(27,27,2),V(27,27,2),HL(27,10,2),HR(27,10,2),
     $VR(27,10,2),VL(27,10,2),VJ(27,10,2),XJ(27,10,2),JI(27,27,2),KN,NJJ
      COMMON/B6/AA1,BB1,CC1,SNK,IDG,SP1,XPG1,SP2,XPG2
      COMMON /B8/ ACCU,ACCUX,ACCUY,HDRY,CC
      COMMON /B10/ DXCH,DXRS,DDXCH,DDXRS
      DIMENSION Y(3),G(2)
      DATA G/' CURB','CHANL'/
      READ(5,100)NL,IDG,(Y(I),I=1,3),SUPEL,TRFCT,SPEED
  100 FORMAT(2I5,6F10.0)
C     NL      THE NUMBER OF TRAFFIC LANES
C     IDG     INDICATE THE TYPE OF GUTTER
C             1 CURB TYPE
C             2 CHANNEL TYPE
C     SUPEL=SUPERELEVATION,FT PER FT OF ROADWAY WIDTH
C     TRFCT=SIDE FRICTION (CORNERING RATIO) BETWEEN TIRES AND ROAD SURF.
C     SPEED=DESIGN SPEED FOR ROADWAY, MILES PER HOUR
C     RADIUS=RADIUS OF CURVATURE OF ROADWAY
      READ(5,101) SP1,XPG1,SP2,XPG2
C     SP1=CROSS SLOPE OF PAVED SHOULDER (3 TO 5 PERCENT)
C     XPG1=HORIZONTAL WIDTH OF PAVED SHOULDER (12 FT, 4 FT, OR 2FT FOR E
C     ACH LANE)
C     SP2=CROSS SLOPE OF GUTTER OR MEDIAN (1/12 OR 10 PERCENT)
C     XPG2=HORIZONTAL WIDTH OF GUTTER OR MEDIAN (3 FT OR (12-2*NO. OF
C     LANES) FT)
  101 FORMAT(8F10.0)
      IF(CURVE.LT.0.1E-5) GOTO 2
      RADIUS=0.067*SPEED*SPEED/(SUPEL+TRFCT)
      CURVE=1./RADIUS
      WRITE(6,150) SUPEL,TRFCT,RADIUS,CURVE,SPEED
  150 FORMAT(/' THIS IS A CURVED ROADWAY WITH SUPERELEVATION = ',F5.3,'
     $(FT/FT),SIDE FRICTION = ',F5.3,' RADIUS OF CURVATURE = ',F10.2,' (
     $FT)'/' AND CURVATURE = ',E8.3,' (RADIANS) FOR DESIGN SPEED = ',F5.
     $1,' (MPH)')
    2 NKTEMP=NL*12/INT(DDXRS+0.001)+1
    3 AA1=(Y(3)-2.*Y(2)+Y(1))/288.
      BB1=(-Y(3)+4.*Y(2)-3.*Y(1))/24.
      CC1=Y(1)
   10 TAN=-(2.*AA1*FLOAT(NKTEMP-1)*DDXRS+BB1)
C     SNK=BED SLOPE AT THE END OF OVERLAND FLOW ON ROADWAY
      THETA=ATAN(TAN)
      SNK=SIN(THETA)
      KN=NKTEMP+INT((XPG1+XPG2)/DDXRS+0.9999)
      IF(INT(XPG1).EQ.0) GOTO 30
      GOTO 31
   30 SP2=SNK
      GOTO 12
   31 IF(SP1.LT.SNK) SP1=SNK
      IF(IDG.EQ.1) GOTO 32
      GOTO 12
   32 IF(SP2.LT.SP1) SP2=SP1
      GOTO 12
   12 WRITE(6,200) NL,G(IDG),(Y(I),I=1,3)
  200 FORMAT(/I2,' TRAFFIC LANES HIGHWAY WITH ',A6,'TYPE GUTTER FLOW'/
```

```
     $'  Y(1)=',F5.3,'  Y(2)=',F5.3,'  Y(3)=',F5.3)
      WRITE(6,202) SP1,XPG1,SP2,XPG2
  202 FORMAT(' SP1 = ',F6.4,' XPG1 = ',F8.3,' SP2 = ',F6.4,' XPG2 = ', 8
     $.3)
      WRITE(6,203) AA1,BB1,CC1,SNK
  203 FORMAT(/'  THE COEFFICIENTS OF CROWN CURVE EQUATION ARE:'/
     $'   A =',F9.6,'  B =',F9.6,'  C =',F9.6,'  SNK =',F9.6)
      RETURN
      END
```

```
      SUBROUTINE CS(SS,X1,X2,XC,XP,D1,D2,DC,V1,V2,VC)
C     COMPUTE D,V,AND LOCATION OF C+ OR C- CHARACTERISTIC CURVE
C     SS=+1.  FOR C+
C     SS=-1.  FOR C-
      COMMON /B1/ B(40),C(40),Z(10),TIME,OPH,NN,N,NCH,RSL,CURVE
      COMMON /B3/ NK(27),NJ(27),DX,DT,DIST,HMIN,VMIN,ITYPE,IO,OC(27,10),
     $S,DS
      COMMON /B8/ ACCU,ACCUX,ACCUY,HDRY,CC
      COMMON /B12/ NDEPTH
      DIMENSION F(2),X(2)
      C1=DT/(X2-X1)*C(9)
      C2=(X2-XP)/(X2-X1)
      NCT=0
      NDEPTH=0
      I=1
C     X(I)=(X2-XC)/(X2-X1), XC=X2-X(I)*(X2-X1)
      X(1)=0.4
    1 XX=X(I)
      VC=V2-XX*(V2-V1)
      DC=D2-XX*(D2-D1)
      XC=X2-XX*(X2-X1)
      IF(ITYPE.EQ.2.OR.ITYPE.EQ.3) GOTO 3
      GOTO 5
    3 IF(DC.LT.0.) NDEPTH=1
      IF(DC.LT.0.) RETURN
    5 IF(DC.LT.HDRY) DC=HDRY
      DSQ=SQRT(C(1)*(C(1)-1.)*VC*VC+C(1)*C(20)*(DC*C(9)/C(5)+OPH))
      F(I)=C1*(C(1)*VC+SS*DSQ)+C2-XX
      IF(ABS(F(I)).LT.ACCU) RETURN
      IF(I.EQ.1) GO TO 2
      NCT=NCT+1
      IF(NCT.GT.20) GO TO 4
      IF(ABS(F(1)-F(2)).LT.ACCU*ACCU) GO TO 4
      XX=(F(1)*X(2)-F(2)*X(1))/(F(1)-F(2))
      X(1)=X(2)
      X(2)=XX
      IF(ABS(X(1)-X(2)).LT.ACCU) RETURN
      F(1)=F(2)
      GO TO 1
    2 I=2
      X(2)=0.6
      GO TO 1
    4 IF(ABS(F(I)).GT..1E-4) WRITE(6,200) F(I)
  200 FORMAT(/'  AT CS F(1)=F(2)=',E12.7)
      END
```

```
      SUBROUTINE DBDY
C     SET UP DOWMSTREAM BOUNDARY CONDITION
      COMMON /B1/ B(40),C(40),Z(10),TIME,OPH,NN,N,NCH,RSL,CURVE
      COMMON /B2/ H(27,27,2),V(27,27,2),HL(27,10,2),HR(27,10,2),
     $VR(27,10,2),VL(27,10,2),VJ(27,10,2),XJ(27,10,2),JI(27,27,2),KN,NJJ
      COMMON /B3/ NK(27),NJ(27),DX,DT,DIST,HMIN,VMIN,ITYPE,IO,OC(27,10),
     $S,DS
      IF(ITYPE.NE.1.AND.N.EQ.1) GO TO 90
      KN1=KN-1
      IF(NJJ.EQ.0) GO TO 5
      DO 1 JJ=1,NJJ
      J=NJJ-JJ+1
      IF(XJ(N,J,2).GT.DIST-DX.AND.XJ(N,J,2).LT.DIST) GO TO 2
    1 CONTINUE
      GO TO 5
    2 JI(N,KN,2)=1
    5 IF(JI(N,KN,1).EQ.1) GO TO 20
      IF(JI(N,KN,2).EQ.1) GO TO 10
      DX1=DIST-FLOAT(KN-2)*DX
      CALL DPT(H(N,KN,1),V(N,KN,1),H(N,KN1,1),V(N,KN1,1),H(N,KN1,2),
     $V(N,KN1,2),DX1)
      RETURN
   10 X=DIST-XJ(N,J,2)
      H2=H(N,KN,1)+(H(N,KN1,1)-H(N,KN,1))*X/DX
      V2=V(N,KN,1)+(V(N,KN1,1)-V(N,KN,1))*X/DX
   15 CALL DPT(H(N,KN,1),V(N,KN,1),H2,V2,HR(N,J,2),VR(N,J,2),X)
      RETURN
   20 IF(JI(N,KN,2).EQ.0) GO TO 22
      X=DIST-XJ(N,J,2)
      IF(J.LT.NJJ) GO TO 21
      X1=DIST-XJ(N,J,1)
      H2=H(N,KN,1)+(HR(N,J,1)-H(N,KN,1))*X/X1
      V2=V(N,KN,1)+(VR(N,J,1)-V(N,KN,1))*X/X1
      GO TO 15
   21 X1=DX-(DIST-XJ(N,NJJ,1))
      H1=H(N,KN1,1)+(HL(N,NJJ,1)-H(N,KN1,1))*DX/X1
      V1=V(N,KN1,1)+(VL(N,NJJ,1)-V(N,KN1,1))*DX/X1
      H2=H(N,KN1,1)+(HL(N,NJJ,1)-H(N,KN1,1))*(DX-X)/X1
      V2=V(N,KN1,1)+(VL(N,NJJ,1)-V(N,KN1,1))*(DX-X)/X1
      CALL DPT(H1,V1,H2,V2,HR(N,J,2),VR(N,J,2),X)
      RETURN
   22 IF(VJ(N,NJJ,1).LT.0.) GO TO 23
      H1=H(N,KN1,1)+(HL(N,NJJ,1)-H(N,KN1,1))*DX/(DX-DIST+XJ(N,NJJ,1))
      V1=V(N,KN1,1)+(VL(N,NJJ,1)-V(N,KN1,1))*DX/(DX-DIST+XJ(N,NJJ,1))
      CALL DPT(H1,V1,H(N,KN1,1),V(N,KN1,1),H(N,KN1,2),V(N,KN1,2),DX)
      RETURN
   23 H2=H(N,KN,1)+(HR(N,NJJ,1)-H(N,KN,1))*DX/(DIST-XJ(N,NJJ,1))
      V2=V(N,KN,1)+(VR(N,NJJ,1)-V(N,KN,1))*DX/(DIST-XJ(N,NJJ,1))
      CALL DPT(H(N,KN,1),V(N,KN,1),H2,V2,H(N,KN1,2),V(N,KN1,2),DX)
      RETURN
   90 H(N,KN,2)=H(N,KN,1)
      V(N,KN,2)=V(N,KN,1)
      RETURN
      END
```

```
      SUBROUTINE DPT(H1,V1,H2,V2,H3,V3,X)
C     COMPUTE V AND H AT THE DOWNSTREAM GRID POUNT
      COMMON /B1/ B(40),C(40),Z(10),TIME,OPH,NN,N,NCH,RSL,CURVE
      COMMON /B2/ H(27,27,2),V(27,27,2),HL(27,10,2),HR(27,10,2),
     $VR(27,10,2),VL(27,10,2),VJ(27,10,2),XJ(27,10,2),JI(27,27,2),KN,NJJ
      COMMON /B3/ NK(27),NJ(27),DX,DT,DIST,HMIN,VMIN,ITYPE,IO,OC(27,10),
     $S,DS
      COMMON/B4/II(27,2),XI(27,2),HI(27,2),VI(27,2),QI(27,2),WI(27,2),
     $CT(27,2),CH(27,2),CV(27,2)
      COMMON /B5/ NG(27,27),SG(27,27),FG(27,27),NF,SF,FF
      COMMON/B6/AA1,BB1,CC1,SNK,IDG,SP1,XPG1,SP2,XPG2
      COMMON /B8/ ACCU,ACCUX,ACCUY,HDRY,CC
      DIMENSION HH(2),F(2)
      IF(IDG.EQ.1.AND.N.EQ.NCH) CTMIN=HMIN*B(16)/C(5)/TAN(ASIN(SP2))/B(1
     $0)
      TIM=TIME-DT
      CALL STORM(DIST,TIM)
      CALL OPHEAD
      CALL GEOM(2,A1,H1,R1,T1,D1,1,1,DIST)
      X1=DIST-X
      CALL STORM(X1,TIM)
      CALL OPHEAD
      CALL GEOM(2,A2,H2,R2,T2,D2,1,1,X1)
      CALL STORM(X1,TIME)
      CALL OPHEAD
      CALL GEOM(2,A3,H3,R3,T3,D3,1,2,X1)
      FRN3=FRTST(V3,D3,OPH,C(1),C(5),C(9),C(20),1)
      IF(FRN3.LE.0.) GOTO 9
      CALL CS(1.,X1,DIST,XD,DIST,D2,D1,DD,V2,V1,VD)
      CALL CS(-1.,X1,DIST,XE,DIST,D2,D1,DE,V2,V1,VE)
C     FOR SUPERCRITICAL FLOW
      CALL CEGS(VD,DD,VE,DE,V(N,KN,2),H(N,KN,2),XD,XE,DT,DT,DIST)
      NG(N,KN)=NF
      FG(N,KN)=FF
      SG(N,KN)=SF
      HCH=H(N,KN,2)
      IF(N.EQ.NCH.AND.NK(NN).GT.2.AND.IDG.EQ.1) CALL INBDY(2,DIST,HCH,T,
     $2)
      CALL STORM(DIST,TIME)
      CALL GEOM(2,A,H(N,KN,2),R,T,D,1,2,DIST)
      FRN=FRTST(V(N,KN,2),D,OPH,C(1),C(5),C(9),C(20),1)
      IF(FRN.GT.0.) RETURN
C     FOR SUBCRITICAL FLOW, OVERFALL CONDITION CONTROL THE H AND V
    9 CALL STORM(DIST,TIM)
      C9=C(9)
      C26=C(26)
      C27=C(27)
      C29=C(29)
      CALL STORM(X1,TIM)
      C9=C(9)+C9
      C26=C(26)+C26
      C27=C(27)+C27
      C29=C(29)+C29
      CALL STORM(X1,TIME)
      CALL GEOM(2,A3,H3,R3,T3,D3,1,2,X1)
      C9=C(9)+C9
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```
      C26=C(26)+C26
      C27=C(27)+C27
      C29=C(29)+C29
      CALL STORM(DIST,TIME)
      C9=(C(9)+C9)/4.
      C26=(C(26)+C26)/4.
      C27=(C(27)+C27)/4.
      C29=(C(29)+C29)/4.
   10 I=1
      NCT=0
      HH(1)=H1
   11 IF(N.EQ.NCH.AND.IDG.EQ.1.AND.HH(I).LT.HMIN) HH(I)=HMIN
      IF(HH(I).LT.HDRY) HH(I)=HDRY
      H(N,KN,2)=HH(I)
      IF(N.EQ.NCH.AND.NK(NN).GT.2.AND.IDG.EQ.1) CALL INBDY(2,DIST,HH(I),
     $TTT,2)
      IF(N.EQ.NCH.AND.IDG.EQ.1.AND.HH(I).LE.HMIN) CT(NN,2)=CTMIN
      CALL GEOM(2,A,HH(I),R,T,D,1,2,DIST)
      CALL STORM(DIST,TIME)
      T=(T1+T2+T3+T )/4.
      RIQL=B(11)*(T*B(10)*C9*(C26-C27)*C(19)/B(18)+C29/(B(10)*C(5)))
      VV=SQRT(C(20)*(D*C(9)/C(5)+OPH))
      F(I)=A3-A2+A-A1+DT/X*(V1*A1-V2*A2+VV*A-V3*A3)*C 9 -2.*DT*RIQL
      IF(ABS(F(I)).LT.ACCU) GO TO 13
      IF(I.EQ.1) GO TO 12
      IF(ABS(F(1)-F(2)).LT.ACCU*ACCU)GO TO 13
      NCT=NCT+1
      IF(NCT.GT.20) GO TO 20
      HHH=(F(1)*HH(2)-F(2)*HH(1))/(F(1)-F(2))
      HH(1)=HH(2)
      HH(2)=HHH
      F(1)=F(2)
      GO TO 11
   12 I=2
      HH(2)=H3
      GO TO 11
   20 SSS=-1.
      WRITE(6,100) N
  100 FORMAT(' NO SOLUTION AT THE DOWNSTREAM END OF SECTION',I3)
      IF(N.EQ.NCH) GO TO 13
      IF(ABS(F(I)).GT.0.1E-4) SS=SQRT(SSS)
   13 H(N,KN,2)=HH(I)
      V(N,KN,2)=VV
      NG(N,KN)=2
      CALL GEOM(2,A,H(N,KN,2),R,T,D,1,2,DIST)
      CALL FRIC(V(N,KN,2),H(N,KN,2),FF,R,RE,REC,IR,2,DIST)
      FG(N,KN)=FF
      SG(N,KN)=C(4)*FF*V(N,KN,2)*ABS(V(N,KN,2))/(B(13)*R)
      RETURN
      END
```

```
      SUBROUTINE ERR(ID)
C     COMPUTE THE COMPUTATIONAL ERROR
      COMMON /B1/ B(40),C(40),Z(10),TIME,OPH,NN,N,NCH,RSL,CURVE
      COMMON /B2/ H(27,27,2),V(27,27,2),HL(27,10,2),HR(27,10,2),
     $VR(27,10,2),VL(27,10,2),VJ(27,10,2),XJ(27,10,2),JI(27,27,2),KN,N J
      COMMON /B3/ NK(27),NJ(27),DX,DT,DIST,HMIN,VMIN,ITYPE,IO,OC(27,10),
     $S,DS
      COMMON /B4/ II(27,2),XI(27,2),HI(27,2),VI(27,2),QI(27,2),WI(27,2),
     $CT(27,2),CH(27,2),CV(27,2)
      COMMON /B8/ ACCU,ACCUX,ACCUY,HDRY,CC
      COMMON /B10/ DXCH,DXRS,DDXCH,DDXRS
      COMMON /B14/ IWET(27)
      COMMON /B15/ VO1,VT1,VIN1,VOUT1
      DATA TTTT/-1./
      DATA VIN,VOUT,VO,VT,ER1/0.,0.,0.,0.,0./
C     VO=ACCUMULATED VOLUME OF WATER RETAINING ON THE GROUND AT NT=1
C     VT=ACCUMULATED VOLUME OF WATER RETAINING ON THE GROUND AT NT=2
C     VIN=ACCUMULATED VOLUME OF WATER FLOWING IN FROM THE UPSTREAM END OF
C     GUTTER PLUS LATERAL INFLOW INCLUDING RAINFALL AND INFILTRATION
C     VOUT=ACCUMULATED VOLUME OF WATER FLOWING OUT FROM THE DOWNSTREAM
C     END OF GUTTER
C     ID=INDEX FOR OPTION OF COMPUTING ERROR
C         1,  COMPUTE ASSUMED INTIAL VOLUME OF WATER RETAINING ON THE
C             GROUND ONLY
C         2,  COMPUTE INFLOW, OUTFLOW, AND FINAL VOLUME OF WATER RETAIN-
C             ING ON THE GROUND
C         3,  FOR ITYPE 3 ADVANCING WAVE PROBLEM
C         4,  FOR ITYPE 2 ADVANCING WAVE PROBLEM
      NS=NCH+1
      GOTO (41,11,21,31),ID
   41 IF(ITYPE.EQ.1) GOTO 1
      IF(ITYPE.EQ.3) GO TO 30
      IF(ITYPE.EQ.5) GO TO 1
      RETURN
   30 N=1
      CALL PREP
      XJ2=XJ(N,NJJ,1)/2.
      CALL STORM(XJ2,TIME)
      CALL GEOM(2,A1,H(N,1,1),R1,T1,D1,1,1,0.)
      CALL GEOM(2,A2,HL(N,1,1),R2,T2,D2,1,1,XJ(N,NJJ,1))
      VO=(A1+A2)*XJ(N,NJJ,1)*B(21)/2.*B(16)/B(18)/C(9)
      VO1=VO/B(21)/B(16)*B(18)
      RETURN
    1 DO 25 N=1,NS
      FCT=1.
      IF(N.LT.NCH) FCT=DDXCH*B(16)/B(18)
      IF(N.EQ.1.OR.N.EQ.NN) FCT=DDXCH/2.*B(16)/B(18)
      IF(N.EQ.NS) FCT=B(21)*B(16)/B(18)
      IF(NN.EQ.1) FCT=1.
      CALL PREP
      IF(KN.LE.2) GOTO 40
      DO 10 K=2,KN
      DX1=DX
      H2=H(N,K,1)
      X=FLOAT(K-1)*DX
      IF(N.EQ.NCH.OR.K.LT.KN) GO TO 9
```

```
      IF(NN.EQ.1) GO TO 9
      IF(N.LT.NCH) H2=HI(N,1)
      X=XI(N,1)
      DX1=XI(N,1)-AINT(XI(N,1)/DX)*DX
    9 IF(H(N,K-1,1).LT.HDRY*1.01.AND.H2.LT.HDRY*1.01) GO TO 10
      X1=X-DX1
    2 IF(JI(N,K,1).EQ.1) GO TO 4
    3 X12=(X+X1)/2.
      CALL STORM(X12,TIME)
      CALL GEOM(2,A1,H(N,K-1,1),R1,T1,D1,1,1,X1)
      CALL GEOM(2,A2,H2,R2,T2,D2,1,1,X)
      VO=VO+(A1+A2)/2./C(9)*DX1*FCT
      GO TO 10
    4 J=1
      H1=H(N,K-1,1)
    5 DO 6 JJ=J,NJJ
      IF(XJ(N,JJ,1).GT.X1.AND.XJ(N,JJ,1).LE.X) GOTO 7
    6 CONTINUE
      X2=X
      H2=H(N,K,1)
      IF(NN.EQ.1) GO TO 8
      IF(N.LT.NCH.AND.K.EQ.KN) H2=HI(N,1)
      GO TO 8
    7 X2=XJ(N,JJ,1)
      H2=HL(N,JJ,1)
    8 X12=(X1+X2)/2.
      CALL STORM(X12,TIME)
      CALL GEOM(2,A1,H1,R1,T1,D1,1,1,X1)
      CALL GEOM(2,A2,H2,R2,T2,D2,1,1,X2)
      VO=VO+(A1+A2)/2./C(9)*(X2-X1)*FCT
      IF(X-X2.LT.ACCU) GO TO 10
      X1=X2
      H1=HR(N,JJ,1)
      J=JJ+1
      GO TO 5
   10 CONTINUE
   40 IF(NN.EQ.1) RETURN
   25 CONTINUE
      RETURN
   11 VT=0.
      VIN2=0.
      IF(ITYPE.EQ.3) GO TO 35
      N=NCH
      KX=NN
      IF(NN.EQ.1) N=1
      IF(NN.EQ.1) KX=KN
      CALL GEOM(2,A1,H(N,KX,1),R1,T1,D1,1,1,C(21))
      CALL GEOM(2,A2,H(N,KX,2),R2,T2,D2,1,2,C(21))
      VOUT=VOUT+(V(N,KX,1)*A1+V(N,KX,2)*A2)*DT/2.
   35 DO 24 N=1,NS
      IF(ITYPE.EQ.2.AND.IWET(N).EQ.0) GOTO 24
      IF(ITYPE.EQ.5.AND.IWET(N).EQ.0) GO TO 24
      FCT=1.
      IF(N.LT.NCH) FCT=DDXCH*B(16)/B(18)
      IF(N.EQ.1.OR.N.EQ.NN) FCT=DDXCH/2.*B(16)/B(18)
      IF(N.EQ.NS) FCT=B(21)*B(15)/B(18)
      IF(NN.EQ.1) FCT=1.
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```
      IOO=IO
      IO=0
      CALL PREP
      IF(N.EQ.NCH) C28=C(28)
      IF(NN.EQ.1) C28=C(28)
      IO=IOO
      VIN=VIN+C28*DT
      IF(KN.LE.2) GOTO 50
      DO 20 K=2,KN
      X=FLOAT(K-1)*DX
      DX1=DX
      H2=H(N,K,2)
      IF(N.EQ.NCH.OR.K.LT.KN) GO TO 18
      IF(NN.EQ.1) GO TO 18
      IF(ITYPE.EQ.3) GO TO 18
      DX1=XI(N,2)-AINT(XI(N,2)/DX)*DX
      IF(N.LT.NCH) H2=HI(N,2)
      X=XI(N,2)
   18 IF(H(N,K-1,2).LT.HDRY*1.01.AND.H2.LT.HDRY*1.01) GO TO 20
      X1=X-DX1
      IF(JI(N,K,2).EQ.1) GO TO 16
      X12=(X1+X)/2.
      CALL STORM(X12,TIME)
      CALL GEOM(2,A1,H(N,K-1,2),R1,T1,D1,1,2,X1)
      CALL GEOM(2,A2,H2,R2,T2,D2,1,2,X)
      VT=VT+(A1+A2)/2./C(9)*DX1*FCT
      GO TO 17
   16 J=1
      H1=H(N,K-1,2)
   12 DO 13 JJ=J,NJJ
      IF(XJ(N,JJ,2).GT.X1.AND.XJ(N,JJ,2).LE.X) GO TO 14
   13 CONTINUE
      X2=X
      H2=H(N,K,2)
      IF(NN.EQ.1) GO TO 15
      IF(N.LT.NCH.AND.K.EQ.KN) H2=HI(N,2)
      GO TO 15
   14 X2=XJ(N,JJ,2)
      H2=HL(N,JJ,2)
   15 X12=(X1+X2)/2.
      CALL STORM(X12,TIME)
      CALL GEOM(2,A1,H1,R1,T1,D1,1,2,X1)
      CALL GEOM(2,A2,H2,R2,T2,D2,1,2,X2)
      VT=VT+(A1+A2)/2./C(9)*(X2-X1)*FCT
      IF(X-X2.LT.ACCU) GO TO 17
      X1=X2
      H1=HR(N,JJ,2)
      J=JJ+1
      GO TO 12
   17 X1=X-DX1
      CALL STORM(X1,TIME)
      CALL GEOM(2,A,H(N,K-1,2),R,T,D,1,2,X1)
      TT=T
      C26=C(26)
      C27=C(27)
      CALL STORM(X,TIME)
      H2=H(N,K,2)
```

```
      IF(NN.EQ.1) GOTO 22
      IF(N.LT.NCH.AND.K.EQ.KN) H2=HI(N,2)
   22 CALL GEOM(2,A,H2,R,T,D,1,2,X)
      TT=TT+T
      C26=C26+C(26)
      C27=C27+C(27)
      TIM=TIME-DT
      CALL STORM(X1,TIM)
      CALL GEOM(2,A,H(N,K-1,1),R,T,D,1,1,X1)
      TT=TT+T
      C26=C26+C(26)
      C27=C27+C(27)
      CALL STORM(X,TIM)
      H2=H(N,K,1)
      IF(NN.EQ.1) GO TO 19
      IF(N.LT.NCH.AND.K.EQ.KN) H2=HI(N,1)
   19 CALL GEOM(2,A,H2,R,T,D,1,1,X)
      TT=(TT+T)/4.
      C26=(C26+C(26))/4.
      C27=(C27+C(27))/4.
      VIN2=VIN2+(C26-C27)*TT*DT*DX1*C(19)*B(10)*B(11)/B(18)*FCT
   20 CONTINUE
   50 IF(NN.EQ.1) GOTO 27
      IF(ITYPE.EQ.3) GO TO 26
   24 CONTINUE
      VIN=VIN+VIN2
      GO TO 27
   26 VOUT1=0.
      VT1=VT/FCT
      VIN1=VIN2/FCT
   21 VT=VT1*B(21)*B(16)/B(18)
      VIN=VIN+VIN1*B(21)
      VOUT=VOUT+VOUT1*B(21)
      GO TO 27
   31 IF(TTTT.LT.0.) VO=VO1
      TTTT=1.
      VT=VT1
      VIN=VIN+VIN1
      VOUT=VOUT+VOUT1
   27 ER=(VT+VOUT-VIN-VO)/(VIN+VO)*100.
      CER=ER-ER1
      IF(IO.EQ.1) WRITE(6,200) ER,CER,VO,VT,VIN,VOUT
  200 FORMAT(/'  ACC COMP ERR =',F8.2,'%, CURR COMP ERR =',F8.2,'%, WITH
     $ VO =',F7.3,' VT =',F7.3,' VIN =',F7.3,' VOUT =',F7.3)
      IF(ID.EQ.2) ER1=ER
      TTTT=TIME
      RETURN
      END
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      SUBROUTINE EVDT
C     EVALUATE THE TIME INTERVAL 'DT'
      COMMON /B1/ B(40),C(40),Z(10),TIME,OPH,NN,N,NCH,RSL,CURVE
      COMMON /B2/ H(27,27,2),V(27,27,2),HL(27,10,2),HR(27,10,2),
     $VR(27,10,2),VL(27,10,2),VJ(27,10,2),XJ(27,10,2),JI(27,27,2),KN,NJ
      COMMON /B3/ NK(27),NJ(27),DX,DT,DIST,HMIN,VMIN,ITYPE,IO,OC(27,10),
     $S,DS
      COMMON /B8/ ACCU,ACCUX,ACCUY,HDRY,CC
      COMMON /B10/ DXCH,DXRS,DDXCH,DDXRS
      COMMON /B13/ STR
      COMMON /B14/ IWET(27)
      DATA NCT /0/
      IF(NCT.GT.0) GO TO 2
      TFCT=0.1/(TIME+ACCU)
      IF(ITYPE.NE.1) GO TO 1
      IF(C(4).LT.0.01.OR.B(26).LT.9.) TFCT=0.5
    1 IF(TFCT.GT.1.) TFCT=1.
      CALL OPHEAD
      DTEQ=DXCH/(1.+SQRT(C(20)*(1.+OPH)))/C(5)
    2 DTMAX=DTEQ*TIME*TFCT
      DTMIN=1.0E6
      FACTOR=0.9
      IF(NCT.GT.1.AND.TIME.GT.STR) DTMAX=(TIME-STR+.2)/20.
      NCT=NCT+1
      IOO=IO
      IO=0
      NS=NCH+1
      DO 10 N=1,NS
      IF(ITYPE.EQ.2.AND.IWET(N).EQ.0) GO TO 10
      IF(ITYPE.EQ.5.AND.IWET(N).EQ.0) GO TO 10
      CALL PREP
      IF(KN.LE.2) GOTO 8
      DO 5 K=1,KN
      IF(H(N,K,1).LT.1.1*HDRY) GO TO 5
      X=FLOAT(K-1)*DX
      CALL STORM(X,TIME)
      CALL OPHEAD
      CALL GEOM(2,A,H(N,K,1),R,T,D,1,1,X)
      TAN=C(1)*V(N,K,1)+SQRT(C(1)*(C(1)-1.)*V(N,K,1)**2+C(1)*C(20)*(D*
     $C(9)/C(5)+OPH))
      IF(ABS(TAN).LT.ACCU) GOTO 5
      DTT=DX/TAN/C(9)
      IF(DTT.LT.DTMIN) DTMIN=DTT
    5 CONTINUE
    8 IF(NN.EQ.1) GOTO 11
      IF(ITYPE.EQ.3) GO TO 11
   10 CONTINUE
   11 DT=DTMIN*FACTOR
      IF(DT.GT.DTMAX) DT=DTMAX
      IF(DT.GT.DTEQ) DT=DTEQ
      IO=IOO
      IF(DT.LT.ACCU) SS=SQRT(-1.)
      RETURN
      END
```

```
      SUBROUTINE FRIC(VV,HH,F,R,RE,REC,IR,NT,X)
C     EVALUATE THE FRICTIONAL COEFICIENT
      COMMON /B1/ B(40),C(40),Z(10),TIME,OPH,NN,N,NCH,RSL,CURVE
      COMMON /B3/ NK(27),NJ(27),DX,DT,DIST,HMIN,VMIN,ITYPE,IO,OC(27,10)
     $S,DS
      COMMON /B8/ ACCU,ACCUX,ACCUY,HDRY,CC
C     IR=REGIONS OF FRICTION COEFFICIENT VS. REYNOLDS NUMBER
      SF=C(8)
      CC=C(36)*SF**C(37)
      IF(CC.LT.24.) CC=24.
      FMAX=1./ACCU**3
      IF(HH.GT.HDRY*1.01) GOTO 1
   20 IR=0
      F=FMAX
      REC=0.
      RE=CC/FMAX
      RETURN
    1 RE=ABS(VV*R*B(14))
      IF(RE.LT.ACCU) GOTO 20
      FB2=1./(2.*ALOG10(2.*B(2))+1.74)**2
      IF(R.LE.B(2)*C(23)) GOTO 15
C     RELS IS THE SOLUTION OF F=C/RE AND 1/SQRT(F)=2*ALOG10(RE*
C     SQRT(F))+0.404
      IF(CC.LE.24.) RELS=478.22
      IF(CC.LE.24.) GOTO 4
      RE1=500.
      NCT=0
    2 F1=RE1-CC*(ALOG10(RE1)+ALOG10(CC)+0.404)**2
      F2=1.-2.*SQRT(CC)/(ALOG(10.)*SQRT(RE1))
      RE2=RE1-F1/F2
      IF(RE2.LT.1.) RE2=1.
      IF(ABS(RE1-RE2).LT.ACCU) GO TO 3
      NCT=NCT+1
      IF(NCT.GT.20) SS=SQRT(-1.)
      RE1=RE2
      GO TO 2
    3 RELS=RE2
    4 IF(C(23).LT.ACCU) GO TO 7
C     RELR IS THE SOLUTION OF F=C/RE AND 1/SQRT(F)=I*ALOG10(2*R/K)+1.74
      RELR=CC*(2.*ALOG10(2.*R/C(23))+1.74)**2
C     CHECK THE EXISTENCE OF RELS
      IF(RELS.GT.RELR) GO TO 6
C     THERE EXIST BOTH RELS AND RESR
C     RESR IS THE SOLUTION OF 1/SQRT(F)=2*ALOG10(RE*SQRT(F))+0.404 AND
C     1/SQRT(F)=2*ALOG10(2*R/K)+1.74
      RESR=2.*R/C(23)*(2.*ALOG10(2.*R/C(23))+1.74)*10.**0.668
      IF(RE.LT.RESR) GO TO 7
C     F FOR TURBULENT FLOW ON ROUGH SURFACE
      IR=3
      REC=RESR
    5 F=1./(2.*ALOG10(2.*R/C(23))+1.74)**2
      RETURN
C     THERE EXISTS RELR ONLY
    6 REC=RELR
      IF(RE.LT.RELR) GO TO 10
      IR=5
```

```
      GO TO 5
    7 REC=RELS
      IF(RE.LT.RELS) GO TO 11
C     TURBULENT FLOW ON SMOOTH SURFACE
      IR=2
      F=0.1E-3
      NCT=0
    8 F1=-1./F+2.*ALOG10(RE*F)+0.404
      F2=1./F**2+2./(F*ALOG(10.))
      FNEW=F-F1/F2
      IF(FNEW.LT.ACCU) FNEW=ACCU
      IF(ABS(F-FNEW).LT.ACCU) GO TO 9
      NCT=NCT+1
      IF(NCT.GT.20) SS=SQRT(-1.)
      F=FNEW
      GO TO 8
    9 F=FNEW*FNEW
      RETURN
C     LAMINAR FLOW
   10 IR=4
      F=CC/RE
      IF(F.GT.FMAX) F=FMAX
      RETURN
   11 IR=1
      F=CC/RE
      IF(F.GT.FMAX) F=FMAX
      RETURN
   15 IR=6
      REC=CC/FB2
      F=CC/RE
      IF(F.GT.FMAX) F=FMAX
      RETURN
      END
```

```
      FUNCTION FRTST(V,D,OP,C1,C5,C9,C20,ID)
C     THE EQUATION OF FROUDE NUMBER
C     ID=1 TO TEST FROUDE NUMBER
C     ID=2 TO FIND FROUDE NUMBER
      T1=C1*ABS(V)
      T2=SQRT(C1*(C1-1.)*V*V+C1*C20*(D*C9/C5+OP))
      GO TO (1,2),ID
    1 FRTST=T1-T2
      RETURN
    2 FRTST=T1/T2
      RETURN
      END
```

```
      SUBROUTINE GEOM(ID,A,Y,R,T,D,IDIM,NT,X)
C     COMPUTE THE MAGNITUDES OF CHANNEL GEOMETRIES
C     ID
C       1  A IS GIVEN
C       2  Y IS GIVEN
C       3  R IS GIVEN
C       4  T IS GIVEN
C       5  D IS GIVEN
C       6  Y IS GIVEN TO FIND CENTROID HD (RETURNED BY R)
C     IDIM
C       1  FOR DIMENSIONLESS VARIABLES
C       2  FOR DIMENSIONAL VARIABLES
      COMMON /B1/ B(40),C(40),Z(10),TIME,OPH,NN,N,NCH,RSL,CURVE
      COMMON /B2/ H(27,27,2),V(27,27,2),HL(27,10,2),HR(27,10,2),
     $VR(27,10,2),VL(27,10,2),VJ(27,10,2),XJ(27,10,2),JI(27,27,2),KN,NJJ
      COMMON /B3/ NK(27),NJ(27),DX,DT,DIST,HMIN,VMIN,ITYPE,IO,OC(27,10),
     $S,DS
      COMMON /B4/ II(27,2),XI(27,2),HI(27,2),VI(27,2),QI(27,2),WI(27,2),
     $CT(27,2),CH(27,2),CV(27,2)
      COMMON/B6/AA1,BB1,CC1,SNK,IDG,SP1,XPG1,SP2,XPG2
      COMMON /B8/ ACCU,ACCUX,ACCUY,HDRY,CC
      COMMON /B9/ TL(10,2),TR(10,2)
      COMMON /B10/DXCH,DXRS,DDXCH,DDXRS
      GA(A1,A2,A3,U)=-(A1*U**3./3.+A2*U*U/2.+A3*U)
      GY(A1,A2,A3,U)=-(A1*U*U+A2*U+A3)
      GS(A1,A2,    U)=(2.*A1*U+A2)/(4.*A1)*SQRT(4.*A1*A1*U*U+4.*A1*A2*U+A
     $2*A2+1.)+1./(4.*SQRT(A1*A1))*ALOG(8.*A1*A1*U+4.*A1*A2+4.*SQRT(A1*A
     $1)*SQRT(4.*A1*A1*U*U+4.*A1*A2*U+A2*A2+1.))-A2/(4.*A1)*SQRT(A2*A2+
     $1.)-1./(4.*SQRT(A1*A1))*ALOG(4.*A1*A2+4.*SQRT(A1*A1)*SQRT(A2*A2+1.
     $))
      GH(A1,A2,A3,U)=A1*A1*U**5./5.+A1*A2*U**4./2.+(A2*A2+2.*A1*A3)*U**3
     $./3.+A2*A3*U*U+A3*A3*U
      IF(N.EQ.NCH) GO TO 20
C     FOR OVERLAND FLOW (N.LT.NCH.AND.N=NCH+1)
      IF(IDIM.EQ.2) GO TO 6
      GO TO(1,2,3,4,5,2),ID
C     CHANGE DIMENSIONLESS PATAMETERS TO DIMENSIONAL HYDRAULIC DEPTH D
    1 D=A*B(18)
      GO TO 11
    2 D=Y*B(16)*C(9)/C(5)
      GO TO 11
    3 D=R*B(17)
      GO TO 11
    4 SS=SQRT(-1.)
    5 D=D*B(16)
      GO TO 11
C     CHANGE ALL DIMENSIONAL PARAMETERS TO DIMENSIONAL HYDRAULIC DEPTH D
    6 GO TO (7,8,9,10,11,8),ID
    7 D=A
      GO TO 11
    8 D=Y*C(9)
      GO TO 11
    9 D=R
      GO TO 11
   10 SS=SQRT(-1.)
   11 A=D
```

```
      Y=D/C(9)
      R=D
      T=1.
      IF(ID.EQ.6) R=Y/2.
      IF(IDIM.EQ.2) RETURN
      A=A/B(18)
      Y=Y*C(5)/B(16)
      R=R/B(17)
      T=T/B(10)
      D=D/B(16)
      IF(ID.EQ.6) R=Y/2.
      RETURN
C     FOR GUTTER FLOW
   20 IF(IDG.EQ.1) GO TO 40
C     CHANNEL TYPE GUTTER FLOW CROSS-SECTION OF CHANNEL IS 2FT OF
C     BOTTEM WITH 1:1 SIDE SLOPE 1FT HIGH
      IF(IDIM.EQ.2) GO TO 26
      GO TO (21,22,23,24,25,22),ID
   21 Y=(SQRT(1.+A*B(18))-1.)/C(5)
      GO TO 31
   22 Y=Y*B(16)/C(5)
      GO TO 31
   23 R=R*B(17)
      GO TO 29
   24 Y=(T*B(10)/2.-1.)/C(5)
      GO TO 31
   25 D=D*B(16)
      GO TO 28
   26 GO TO (27,31,29,30,28,31),ID
   27 Y=(SQRT(1.+A)-1.)/C(5)
      GO TO 31
   28 Y=((D-1.)+SQRT(D*D+1.))/C(5)
      GO TO 31
   29 Y=(1.414*R-1.+SQRT((1.-1.414*R)**2+2.*R))/C(5)
      GO TO 31
   30 Y=(T/2.-1.)/C(5)
   31 DD=Y*C(5)
      A=(2.+DD)*DD
      Y=DD/C(5)
      R=A/(2.+2.828*DD)
      T=2.+2.*DD
      D=A/T
      IF(ID.EQ.6) R=DD*DD*(1.+DD/3.)/A
      IF(IDIM.EQ.2) RETURN
      A=A/B(18)
      Y=Y*C(5)/B(16)
      R=R/B(17)
      T=T/B(10)
      D=D/B(16)
      IF(ID.EQ.6) R=DD*DD*(1.+DD/3.)/(A*B(18))
      RETURN
C     CURB TYPE GUTTER FLOW
   40 XJJ=XJ(N,NJJ,NT)
      IF(NJ(NCH).LT.1) GO TO 54
      IF(ITYPE.EQ.2.AND.X.LT.XJJ) GO TO 54
      IF(ITYPE.EQ.2.AND.X.GE.XJJ) GOTO 52
   54 XDX=X/DXCH
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```
      DDX=XDX-AINT(XDX-0.00001)
      K=XDX+1.99999
      IF(K.GT.NN) K=NN
      IF(K.EQ.1) GOTO 59
      IF(NJJ.EQ.0) GO TO 58
      IF(JI(N,K,NT).EQ.0) GO TO 58
      XK=FLOAT(K-1)*DXCH
      XK1=XK-DXCH
      DO 55 J=1,NJJ
      XJJ=XJ(N,J,NT)
      IF(XJJ.GT.XK1.AND.XJJ.LT.XK) GO TO 56
   55 CONTINUE
      GO TO 58
   56 IF(XJJ.LE.X) GOTO 57
      IF((XJJ-XK1).LT.ACCU) GOTO 81
      T=TL(J,NT)+(CT(K-1,NT)-TL(J,NT))*(XJJ-X)/(XJJ-XK1)
      GOTO 61
   81 T=TL(J,NT)
      GO TO 61
   57 IF((XK-XJJ).LT.ACCU) GOTO 82
      T=TR(J,NT)+(CT(K,NT)-TR(J,NT))*(XJJ-X)/(XJJ-XK)
      GOTO 61
   82 T=TR(J,NT)
      GOTO 61
   58 K1=K-1
      T=CT(K1,NT)+(CT(K,NT)-CT(K1,NT))*DDX
      GOTO 61
   59 T=CT(1,NT)
   61 DXPG1=XPG1/B(11)
      DXPG2=XPG2/B(11)
      XXI=C(22)+DXPG1+DXPG2-T*B(10)/B(11)
      IF(XXI.GE.C(22)) GOTO 62
      XXID=XXI*B(11)
      HY=GY(AA1,BB1,CC1,B(22))
      AS=GA(AA1,BB1,CC1,B(22))-GA(AA1,BB1,CC1,XXID)
      HS=(GH(AA1,BB1,CC1,B(22))-GH(AA1,BB1,CC1,XXID))/AS
      SX=RSL-GS(AA1,BB1,XXID)
   62 T=T*B(10)
      TAN1=TAN(ASIN(SP1))
      TAN2=TAN(ASIN(SP2))
      SEC1=1./COS(ASIN(SP1))
      SEC2=1./COS(ASIN(SP2))
      IF(IDIM.EQ.2) GOTO 46
C     CHANGE DIMENSIONLESS PARAMETERS TO DIMENSIONAL ONES
      A=A*B(18)
      Y=Y*B(16)/C(5)
      R=R*B(17)
      D=D*B(16)
C     THE FOLLOWING EXPRESSIONS ARE ALL DIMENSIONAL
   46 GO TO (47,48,49,50,51,48),ID
   47 D=A/T
      GO TO 51
   48 IF(T.LE.XPG2) D=Y*C(5)-T/2.*TAN2
      IF(T.GT.XPG2.AND.T.LE.(XPG1+XPG2)) D=(2.*Y*C(5)-XPG2*TAN2)*XPG2/T/
     $2.+(2.*Y*C(5)-2.*XPG2*TAN2-(T-XPG2)*TAN1)*(T-XPG2)/T/2.
      IF(T.GT.(XPG1+XPG2))D=(2.*Y*C(5)-XPG2*TAN2)*XPG2/T/2.+(2.*Y*C(5)-2
     $.*XPG2*TAN2-XPG1*TAN1)*XPG1/T/2.+AS/T+(Y*C(5)-XPG2*TAN2-XPG1*TAN1-
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```
      $HY)*(T-XPG1-XPG2)/T
       GOTO 51
    49 IF(T.LE.XPG2) D=R*(TAN2/2.+SEC2)/(1.-R/T)
       IF(T.GT.XPG2.AND.T.LE.(XPG1+XPG2))D=((T-XPG2/2.)/T*XPG2*TAN2+(T-XP
      $G2)/(2.*T)*(T-XPG2)*TAN1+XPG2*SEC2+(T-XPG2)*SEC1)*R/(T-R)
       IF(T.GT.(XPG1+XPG2))D=((T-XPG2/2.)/T*XPG2*TAN2+(T-XPG1/2.-XPG2)/T*
      $XPG1*TAN1+(T-XPG1-XPG2)/T*HY+AS/T+XPG2*SEC2+XPG1*SEC1+SX)*R/(T-R)
       GOTO 51
    50 SS=SQRT(-1.)
    51 A=T*D
       IF(T.LE.XPG2) Y=(D+T/2.*TAN2)/C(5)
       IF(T.GT.XPG2.AND.T.LE.(XPG1+XPG2))Y=(D+(T-XPG2/2.)/T*XPG2*TAN2+(T-
      $XPG2)/(2.*T)*(T-XPG2)*TAN1)/C(5)
       IF(T.GT.(XPG1+XPG2))Y=(D+(T-XPG2/2.)/T*XPG2*TAN2+(T-XPG1/2.-XPG2)/
      $T*XPG1*TAN1+(T-XPG1-XPG2)/T*HY-AS/T)/C(5)
       IF(T.LE.XPG2) R=A/(Y*C(5)+T*SEC2)
       IF(T.GT.XPG2.AND.T.LE.(XPG1+XPG2))R=A/(Y*C(5)+XPG2*SEC2+(T-XPG2)*S
      $EC1)
       IF(T.GT.(XPG1+XPG2))R=A/(Y*C(5)+XPG2*SEC2+XPG1*SEC1+SX)
       IF(ID.EQ.6) GOTO 70
       GOTO 71
    70 IF(T.LE.XPG2) R=((Y*C(5)-T*TAN2)**2.+T*TAN2*(Y*C(5)-2./3.*T*TAN2))
      $/(2.*Y*C(5)-T*TAN2)
       IF(T.GT.XPG2.AND.T.LE.(XPG1+XPG2))R=(XPG2*(Y*C(5)-XPG2*TAN2)**2+XP
      $G2*XPG2*TAN2*(Y*C(5)-2./3.*XPG2*TAN2)+(T-XPG2)*(Y*C(5)-XPG2*TAN2-(
      $T-XPG2)*TAN1)**2.+(T-XPG2)**2.*TAN1*(Y*C(5)-XPG2*TAN2-2./3.*(T-XPG
      $2)*TAN1))/(2.*A)
       IF(T.GT.(XPG1+XPG2))R=(XPG2*(Y*C(5)-XPG2*TAN2)**2/2.+XPG2*XPG2*TAN
      $2*(Y*C(5)-2./3.*XPG2*TAN2)/2.+XPG1*(Y*C(5)-XPG1*TAN1-XPG2*TAN2)**2
      $./2.+XPG1*XPG1*TAN1*(Y*C(5)-2./3.*XPG1*TAN1-XPG2*TAN2)/2.+(T-XPG1-
      $XPG2)*(Y*C(5)-XPG1*TAN1-XPG2*TAN2-HY)**2./2.+AS*(Y*C(5)-XPG1*TAN1-
      $XPG2*TAN2-HY+HS))/A
       HCTD=R
    71 IF(IDIM.EQ.2) RETURN
       A=A/B(18)
       Y=Y*C(5)/B(16)
       R=R/B(17)
       T=T/B(10)
       D=D/B(16)
       IF(ID.EQ.6) R=HCTD*C(5)/B(16)
       RETURN
    52 IF(ID.EQ.5) Y=2.*D
       T=Y*B(16)/C(5)*COS(ASIN(SP2))/SP2/B(10)
       A=Y*B(16)/C(5)*T*B(10)/2./B(18)
       D=A*B(18)/(T*B(10))/B(16)
       P=Y/SP2+Y
       R=A*B(18)/P/B(17)
       IF(ID.EQ.6) R=Y/3.
       IF(IDIM.EQ.1) RETURN
       T=T*B(10)
       A=A*B(18)
       D=D*B(16)
       R=R*B(17)
       RETURN
       END
```

```
      SUBROUTINE GOON
C     SUBSTITUTE THE VALUES OF ALL VARIABLES OBTAINED AT TIME LEVEL 2
C     INTO THE CORRESPONDING VARIABLES AT TIME LEVEL 1
      COMMON /B1/ B(40),C(40),Z(10),TIME,OPH,NN,N,NCH,RSL,CURVE
      COMMON /B2/ H(27,27,2),V(27,27,2),HL(27,10,2),HR(27,10,2),
     $VR(27,10,2),VL(27,10,2),VJ(27,10,2),XJ(27,10,2),JI(27,27,2),KN,NJJ
      COMMON /B3/ NK(27),NJ(27),DX,DT,DIST,HMIN,VMIN,ITYPE,IO,OC(27,10),
     $S,DS
      COMMON /B4/ II(27,2),XI(27,2),HI(27,2),VI(27,2),QI(27,2),WI(27,2),
     $CT(27,2),CH(27,2),CV(27,2)
      COMMON /B8/ ACCU,ACCUX,ACCUY,HDRY,CC
      COMMON /B9/ TL(10,2),TR(10,2)
      NS=NCH+1
      DO 10 N=1,NS
      KN=NK(N)
      DO 1 K=1,KN
      H(N,K,1)=H(N,K,2)
      V(N,K,1)=V(N,K,2)
      JI(N,K,1)=JI(N,K,2)
      IF(H(N,K,1).LT.HDRY) H(N,K,1)=HDRY
    1 CONTINUE
      IF(N.EQ.NS) GOTO 8
      II(N,1)=II(N,2)
      HI(N,1)=HI(N,2)
      QI(N,1)=QI(N,2)
      WI(N,1)=WI(N,2)
      XI(N,1)=XI(N,2)
      VI(N,1)=VI(N,2)
      CT(N,1)=CT(N,2)
      CH(N,1)=CH(N,2)
      CV(N,1)=CV(N,2)
      IF(CT(N,1).LT.ACCU) CT(N,1)=ACCU*0.99
    8 DO 2 J=1,10
      XJ(N,J,1)=XJ(N,J,2)
      VJ(N,J,1)=VJ(N,J,2)
      VL(N,J,1)=VL(N,J,2)
      VR(N,J,1)=VR(N,J,2)
      HR(N,J,1)=HR(N,J,2)
      HL(N,J,1)=HL(N,J,2)
    2 CONTINUE
      IF(NN.EQ.1) GO TO 5
   10 CONTINUE
      DO 30 J=1,10
      TL(J,1)=TL(J,2)
      TR(J,1)=TR(J,2)
   30 CONTINUE
    5 DO 20 N=1,NS
      KN=NK(N)
      DO 11 K=1,KN
      H(N,K,2)=0.
      V(N,K,2)=0.
      JI(N,K,2)=0
   11 CONTINUE
      IF(N.EQ.NS) GOTO 9
      CV(N,2)=0.
      CH(N,2)=0.
```

```
      CT(N,2)=CT(N,1)
      XI(N,2)=XI(N,1)
      WI(N,2)=0.
      QI(N,2)=0.
      VI(N,2)=0.
      HI(N,2)=0.
      II(N,2)=0
    9 DO 12 J=1,10
      HL(N,J,2)=0.
      HR(N,J,2)=0.
      VR(N,J,2)=0.
      VL(N,J,2)=0.
      VJ(N,J,2)=0.
      XJ(N,J,2)=0.
   12 CONTINUE
      IF(NN.EQ.1) RETURN
   20 CONTINUE
      DO 21 J=1,10
      TL(J,2)=TL(J,1)
      TR(J,2)=TR(J,1)
   21 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE INBDY(ID,XCH,HCH,TCH,NT)
C     SOLVE THE INTERNAL BOUNDARY-VALUE PROBLEM BETWEEN ROAD SURFACE
C     FLOW AND GUTTER FLOW
C     ID=INDEX FOR COMPUTING INTERNAL BOUNDARY FLOW CONDITIONS
C      1 FOR GRID POINT
C      2 DOWNSTREAM
C      3 UPSTREAM
      COMMON /B1/ B(40),C(40),Z(10),TIME,OPH,NN,N,NCH,RSL,CURVE
      COMMON /B2/ H(27,27,2),V(27,27,2),HL(27,10,2),HR(27,10,2),
     $VR(27,10,2),VL(27,10,2),VJ(27,10,2),XJ(27,10,2),JI(27,27,2),KN,NJJ
      COMMON /B3/ NK(27),NJ(27),DX,DT,DIST,HMIN,VMIN,ITYPE,IO,OC(27,10),
     $S,DS
      COMMON /B4/ II(27,2),XI(27,2),HI(27,2),VI(27,2),QI(27,2),WI(27,2),
     $CT(27,2),CH(27,2),CV(27,2)
      COMMON/B6/AA1,BB1,CC1,SNK,IDG,SP1,XPG1,SP2,XPG2
      COMMON /B8/ ACCU,ACCUX,ACCUY,HDRY,CC
      COMMON /B10/ DXCH,DXRS,DDXCH,DDXRS
      COMMON /B14/ IWET(27)
      DIMENSION F(2),X(2)
      DATA TMIN/0.01/
C     IFA=INDEX FOR ASSUMPTION OF INTERNAL BOUNDARY
C         1, ASSUME CONTINUOUS WATER SURFACE
C         2, ASSUME DISCONTINUOUS WATER SURFACE, IF ANY
      IFA=1
      DXPG1=XPG1/B(11)
      DXPG2=XPG2/B(11)
      IF(ITYPE.EQ.2.AND.ID.EQ.1.AND.H(NCH,N,2).LT.HDRY*1.01) RETURN
      IF(ITYPE.NE.5.OR.ID.EQ.2) GO TO 1
      XW=TIME*C(30)
      PW=C(21)-XW
      N1=N
      IF(ID.EQ.3) N1=1
      XN=FLOAT(N1-1)*DXCH
      IF(XN.LT.PW) CT(N1,2)=ACCU*0.99
      IF(XN.LT.PW) RETURN
    1 IF(NN.EQ.1) SSS=-1.
      IF(NN.EQ.1) SSS=SQRT(SSS)
      NNN=N
      DISTT=DIST
      GO TO (7,6,8),ID
    8 N=1
      GOTO 7
    6 N=NN
    7 IF(IDG.EQ.2) GO TO 30
      K=NK(N)-1
      M=K
      XK=FLOAT(K-2)*DXRS
      CALL STORM(XK,TIME)
      HKKK=H(N,K-1,2)
      VKKK=V(N,K-1,2)
      NKKK=0
      IF(B(26).LT.ACCU.AND.H(N,K-1,1).LT.1.1*HDRY) NKKK=1
      IF(NKKK.EQ.1) H(N,K-1,2)=H(N,K,2)
      IF(NKKK.EQ.1) V(N,K-1,2)=V(N,K,2)
    5 XK=FLOAT(K-1)*DXRS
      XK1=XK-DXRS
```

```
      HH=H(NCH,N,2)
      Y22=AA1*(C(22)*B(11))**2.+BB1*C(22)*B(11)+CC1
      IF(IFA.EQ.1) GOTO 10
      IF(II(N,1).EQ.0) GO TO 15
C     THERE IS A DISCONTINUITY BETWEEN ROADSURFACE FLOW AND CHANNEL FLO
      XI(N,2)=XI(N,1)+DT*WI(N,1)
      YXI=AA1*(XI(N,2)*B(11))**2.+BB1*XI(N,2)*B(11)+CC1
      YH=YXI-Y22
      CALL STORM(XI(N,2),TIME)
      IF(XI(N,2).GE.(C(22)+DXPG1)) HRR=HH-TAN(ASIN(SP2))*(C(22)+DXPG1+DX
     $PG2-XI(N,2))*B(11)*C(5)/B(16)
      IF(XI(N,2).GE.C(22).AND.XI(N,2).LT.(C(22)+DXPG1)) HRR=HH-TAN(ASIN(
     $SP1))*(C(22)+DXPG1-XI(N,2))*B(11)*C(5)/B(16)-TAN(ASIN(SP2))*DXPG2*
     $B(11)*C(5)/B(16)
      IF(XI(N,2).LT.C(22)) HRR=HH-YH*C(5)/B(16)-TAN(ASIN(SP1))*DXPG1*B(1
     $1)*C(5)/B(16)-TAN(ASIN(SP2))*DXPG2*B(11)*C(5)/B(16)
      CALL GEOM(6,ARR,HRR,HHR,TRR,DRR,1,2,XI(N,2))
      DXK=XI(N,2)-XK
      HLL=H(N,K,2)+(H(N,K,2)-H(N,K-1,2))*DXK/DXRS
      VLL=V(N,K,2)+(V(N,K,2)-V(N,K-1,2))*DXK/DXRS
      CALL GEOM(6,ALL,HLL,HHL,TLL,DLL,1,2,XI(N,2))
      IF(ALL*ARR.LT.0.) GO TO 10
      VRR=VLL-ABS(ALL-ARR)*SQRT(C(1)*C(20)/(ALL*ARR)*((ALL*HHL-ARR*HHR)
     $/(ALL-ARR)*(C(9)/C(5))**2+OPH))
      XJT=(ALL*VLL-ARR*VRR)/(ALL-ARR)
      IF(HRR-HLL) 9,10,3
    3 FRL=FRTST((VLL-XJT),DLL,OPH,C(1),C(5),C(9),C(20),1)
      FRR=FRTST((VRR-XJT),DRR,OPH,C(1),C(5),C(9),C(20),1)
      IF(FRL.LT.0..OR.FRR.GT.0.) GO TO 10
    4 HI(N,2)=HLL
      VI(N,2)=VLL
      WI(N,2)=XJT
      QI(N,2)=ALL*VLL
      II(N,2)=1
      CH(N,2)=HRR
      CV(N,2)=VRR
      GO TO 12
    9 FRL=FRTST((XJT-VLL),DLL,OPH,C(1),C(5),C(9),C(20),1)
      FRR=FRTST((XJT-VRR),DRR,OPH,C(1),C(5),C(9),C(20),1)
      IF(FRL.GT.0..OR.FRR.LT.0.) GOTO 10
      GOTO 4
C     FOR CONTINUOUS WATER SUUFACE
   10 YXK=AA1*(XK*B(11))**2.+BB1*XK*B(11)+CC1
      YK=YXK-Y22
      IF(XK.GE.(C(22)+DXPG1)) HK=H(N,K,2)+TAN(ASIN(SP2))*(C(22)+DXPG1+DX
     $PG2-XK)*B(11)*C(5)/B(16)-HH
      IF(XK.GE.C(22).AND.XK.LT.(C(22)+DXPG1)) HK=H(N,K,2)+TAN(ASIN(SP1))
     $*(C(22)+DXPG1-XK)*B(11)*C(5)/B(16)+TAN(ASIN(SP2))*DXPG2*B(11)*C(5)
     $/B(16)-HH
      IF(XK.LT.C(22)) HK=H(N,K,2)+YK*C(5)/B(16)+TAN(ASIN(SP1))*DXPG1*B(1
     $1)*C(5)/B(16)+TAN(ASIN(SP2))*DXPG2*B(11)*C(5)/B(16)-HH
      YXK1=AA1*(XK1*B(11))**2.+BB1*XK1*B(11)+CC1
      YK1=YXK1-Y22
      IF(XK1.GE.(C(22)+DXPG1)) HK1=H(N,K-1,2)+TAN(ASIN(SP2))*(C(22)+DXPG
     $1+DXPG2-XK1)*B(11)*C(5)/B(16)-HH
      IF(XK1.GE.C(22).AND.XK1.LT.(C(22)+DXPG1)) HK1=H(N,K-1,2)+TAN(ASIN(
     $SP1))*(C(22)+DXPG1-XK1)*B(11)*C(5)/B(16)+TAN(ASIN(SP2))*DXPG2*B(11
```

```
     $)*C(5)/B(16)-HH
      IF(XK1.LT.C(22)) HK1=H(N,K-1,2)+YK1*C(5)/B(16)+TAN(ASIN(SP1))*DXPG
     $1*B(11)*C(5)/B(16)+TAN(ASIN(SP2))*DXPG2*B(11)*C(5)/B(16)-HH
      IF(HK.LT.0.) K=K-1
      IF(K.LE.0) GOTO 19
      IF(HK.LT.0.) GO TO 5
   19 DXK=HK*DXRS/(HK1-HK)
      XI(N,2)=XK+DXK
      CTMIN=HMIN*B(16)/C(5)/TAN(ASIN(SP2))/B(10)
      IF(XI(N,2).LE.0.) XI(N,2)=ACCU
      IF(XI(N,2).GE.(C(22)+DXPG1+DXPG2-CTMIN*B(10)/B(11))) XI(N,2)=C(22)
     $+DXPG1+DXPG2-CTMIN*B(10)/B(11)
      DXK=XI(N,2)-XK
      HI(N,2)=H(N,K,2)-DXK*(H(N,K-1,2)-H(N,K,2))/DXRS
      IF(HI(N,2).LT.H(N,K,2)) HI(N,2)=H(N,K,2)
      CALL GEOM(2,AI,HI(N,2),RI,TI,DI,1,2,XI(N,2))
      VI(N,2)=V(N,K,2)-DXK*(V(N,K-1,2)-V(N,K,2))/DXRS
      IF(VI(N,2).LT.V(N,K,2)) VI(N,2)=V(N,K,2)
   11 WI(N,2)=0.
      QI(N,2)=VI(N,2)*AI
      II(N,2)=0
   12 CT(N,2)=(C(22)+DXPG1+DXPG2-XI(N,2))*B(11)/B(10)
  121 DIST=XI(N,2)
      NK(N)=DIST/DXRS+1.99999
      KN=NK(N)
      KN1=KN-1
      DO 13 K=3,KN1
      IF(H(N,K,2).GT.HDRY/2.) GOTO 13
      DXK=XI(N,2)-FLOAT(K-2)*DXRS
      H(N,K,2)=H(N,K-1,2)+(HI(N,2)-H(N,K-1,2))*DXRS/DXK
      V(N,K,2)=V(N,K-1,2)+(VI(N,2)-V(N,K-1,2))*DXRS/DXK
   13 CONTINUE
   14 IF(NKKK.EQ.1) H(N,M-1,2)=HKKK
      IF(NKKK.EQ.1) V(N,M-1,2)=VKKK
      N=NNN
      KN=NK(N)
      IF(N.EQ.NCH) DIST=DISTT
      RETURN
C     FOR GENERATION OF DISCONTINUITY
   15 I=1
      NCT=0
      X(1)=XI(N,1)-XK
   16 HLL=H(N,K,2)-(H(N,K-1,2)-H(N,K,2))*X(I)/DXRS
      VLL=V(N,K,2)-(V(N,K-1,2)-V(N,K,2))*X(I)/DXRS
      XE=XK+X(I)
      YXE=AA1*(XE*B(11))**2.+BB1*XE*B(11)+CC1
      YE=YXE-Y22
      IF(XE.GE.(C(22)+DXPG1+DXPG2).OR.XE.LE.0.) GOTO 10
      IF(XE.GE.(C(22)+DXPG1)) HRR=HH-TAN(ASIN(SP2))*(C(22)+DXPG1+DXPG2-X
     $E)*B(11)*C(5)/B(16)
      IF(XE.GE.C(22).AND.XE.LT.(C(22)+DXPG1)) HRR=HH-TAN(ASIN(SP1))*(C(2
     $2)+DXPG1-XE)*B(11)*C(5)/B(16)-TAN(ASIN(SP2))*DXPG2*B(11)*C(5)/B(16
     $)
      IF(XE.LT.C(22)) HRR=HH-YE*C(5)/B(16)-TAN(ASIN(SP1))*DXPG1*B(11)*C(
     $5)/B(16)-TAN(ASIN(SP2))*DXPG2*B(11)*C(5)/B(16)
      CALL GEOM(6,ALL,HLL,HHL,TLL,DLL,1,2,XX)
      CALL GEOM(6,ARR,HRR,HHR,TRR,DRR,1,2,XX)
```

```
      CALL STORM(XE,TIME)
      CALL OPHEAD
      IF(ALL*ARR.LT.0.) GO TO 10
      VRR=VLL-ABS(ALL-ARR)*SQRT(C(1)*C(20)/(ALL*ARR)*((ALL*HHL-ARR*HHR)
     $/(ALL-ARR)*(C(9)/C(5))**2+OPH))
      XJT=(ALL*VLL-ARR*VRR)/(ALL-ARR)
      IF(HRR-HLL)25,10,25
   25 F(I)=XI(N,1)+DT*XJT/2.-XE
      IF(ABS(F(I)).LT.ACCU) GO TO 18
      IF(I.EQ.1) GO TO 17
      NCT=NCT+1
      IF(NCT.GT.20) GO TO 10
      IF(ABS(F(1)-F(2)).LT.ACCU*ACCU) GO TO 20
      XX=(F(1)*X(2)-F(2)*X(1))/(F(1)-F(2))
      X(1)=X(2)
      X(2)=XX
      F(1)=F(2)
      GO TO 16
   17 I=2
      X(2)=X(1)*1.1
      GO TO 16
   20 IF(ABS(F(I)).GT.10.*ACCU) WRITE(6,202) F(I)
  202 FORMAT(/'  AT INBDY F(1)=F(2)=',E15.8)
   18 IF(HLL.GT.HRR) GOTO 26
      FRL=FRTST((VLL-XJT),DLL,OPH,C(1),C(5),C(9),C(20),1)
      FRR=FRTST((VRR-XJT),DRR,OPH,C(1),C(5),C(9),C(20),1)
      IF(FRL.LT.0..OR.FRR.GT.0.) GO TO 10
      GOTO 27
   26 FRL=FRTST((XJT-VLL),DLL,OPH,C(1),C(5),C(9),C(20),1)
      FRR=FRTST((XJT-VRR),DRR,OPH,C(1),C(5),C(9),C(20),1)
      IF(FRL.GT.0..OR.FRR.LT.0.) GOTO 10
   27 IF(XE.GE.(C(22)+DXPG1+DXPG2).OR.XE.LE.0.) GOTO 10
      XI(N,2)=XE
      GO TO 4
C     FOR CHANNEL TYPE GUTTER FLOW
   30 CALL PREP
      CALL DBDY
      XI(N,2)=XI(N,1)
      HI(N,2)=H(N,KN,2)
      VI(N,2)=V(N,KN,2)
      CALL GEOM(2,AI,HI(N,2),RI,TI,DI,1,2,DIST)
      QI(N,2)=AI*VI(N,2)
      II(N,2)=0
      N=NNN
      KN=NK(N)
      IF(N.EQ.NCH) DIST=DISTT
      RETURN
      END
```

```
      SUBROUTINE INFLT(ID,TMLS)
C     COMPUTE INFILTRATION RATE
      COMMON /B1/ B(40),C(40),Z(10),TIME,OPH,NN,N,NCH,RSL,CURVE
      COMMON /B8/ ACCU,ACCUX,ACCUY,HDRY,CC
      COMMON/B16/AAA,BBB,CCC,TD,RTO,RMN,RAV
      COMMON/B17/FINF,BETTA,ALPHA,TO,TP,VSF,SPI
C     INDEX ID=1, READ AND WRITE THE INPUT DATA FOR SOIL INFILT. PARAMTS
C               2, COMPUTE INSTANT INFILTRATION RATE
C               3, COMPUTE CUMULATIVE INFILTRATION
C     USE THE GENERALIZED KOSTIAKOV INFILTRATION EQUATION
C     FRATE=FINF+BETTA*(TIME-TO)**(-ALPHA)
C     FOR FRATE TO BE ALWAYS ZERO, SET FINF=0. AND BETTA=0., REGARDLESS
C     OF TO AND ALPHA VALUES
C     FRATE=INFILTRATION RATE,IN./HR
C     FINF=FINAL INFILTRATION RATE, IN./HR
C     SPI=POTENTIAL INFILTRATION, INCHES
C     BETTA, TO, ALPHA=INFILTRATION PARAMETERS
C     TP=TIME OF PONDING, MINUTES
C     TP MUST BE GREATER THAN TO, OTHERWISE INVALID
C     ALPHA VALUE MUST BE LESS THAN UNITY AND GREATER THAN ZERO, EXCLUS.
C     TMLS=DIMENSIONLESS TIME
C     RMN=TEMPORAL MEAN RAINFALL INTENSITY, IN./HR
C     VSF=CUMULATIVE INFILTRATION VOLUME PER UNIT SURFACE AREA, INCHES
      GO TO(1,2,3),ID
    1 READ(5,100) FINF,BETTA,ALPHA,TO,SPI
  100 FORMAT(8F10.0)
C     COMPUTE TP AND TO FROM RAINSTORM AND SOIL INFILTRATION PARAMETERS
      DDT=TD*60.*B(12)/B(11)/20.
      TFPDL=DDT
   16 CALL RAIN(3,TFPDL)
      IF((RMN-FINF).LE.0.) GOTO 15
      IF(0.2*SPI*(1.-ALPHA).GT.0.) GOTO 25
      BETTA=0.
      TTRY=0.
      GOTO 26
   25 BETTA=(0.2*SPI*(1.-ALPHA))**ALPHA*(RMN-FINF)**(1.-ALPHA)
      TTRY=1./(1.-ALPHA)*(BETTA/(RMN-FINF))**(1./ALPHA)
   26 IF(TTRY*60.*B(12)/B(11).GT.TFPDL) GOTO 15
      NCT=0
      T1=TFPDL-DDT
      T2=TFPDL
   14 TFPDL=T1+(T2-T1)/2.
      NCT=NCT+1
      IF(NCT.GT.50) SS=SQRT(-1.)
      IF((T2-T1).LT.100.*ACCU) GOTO 18
      CALL RAIN(3,TFPDL)
      IF((RMN-FINF).LE.0.) GOTO 17
      IF(0.2*SPI*(1.-ALPHA).GT.0.) GOTO 35
      BETTA=0.
      TTRY=0.
      GOTO 36
   35 BETTA=(0.2*SPI*(1.-ALPHA))**ALPHA*(RMN-FINF)**(1.-ALPHA)
      TTRY=1./(1.-ALPHA)*(BETTA/(RMN-FINF))**(1./ALPHA)
   36 IF(ABS(TTRY*60.*B(12)/B(11)-TFPDL).LT.100.*ACCU) GOTO 18
      IF(TTRY*60.*B(12)/B(11).GT.TFPDL) GOTO 17
      T2=TFPDL
```

```
      GOTO 14
   17 T1=TFPDL
      GOTO 14
   15 IF(TFPDL.GE.TD*60.*B(12)/B(11)) GOTO 13
      TFPDL=TFPDL+DDT
      GOTO 16
   18 TP=TFPDL*B(11)/B(12)/60.
      GOTO 20
   13 WRITE(6,150)
  150 FORMAT(/' THERE IS NO RUNOFF ON SIDESLOPE')
      TP=1./ACCU*ACCU
   20 TO=ALPHA*TP
      WRITE(6,200) FINF,BETTA,ALPHA,TO,TP,SPI
  200 FORMAT(/' SOIL INFILTRATION PARAMETERS ARE FINF = ',F8.2,' (IN./HR
     $) BETTA = ',F8.2,' ALPHA = ',F8.2,' TO = ',E10.4,' (MIN.) TP = ',E
     $10.4/' (MIN.) SPI = ',F8.2,' (INCHES)')
      RETURN
    2 TST=TMLS*B(11)/B(12)/60.
      CALL RAIN(2,TMLS)
      IF(TST.LE.TP) B(27)=B(32)
      IF(TST.GT.TP) B(27)=FINF+BETTA*(TST-TO)**(-ALPHA)
      RETURN
    3 CALL RAIN(3,TMLS)
      RMNS=RMN
      TPL=TP*60.*B(12)/B(11)
      CALL RAIN(3,TPL)
      RMNP=RMN
      TST=TMLS*B(11)/B(12)/60.
      IF(TST.LE.TP) VSF=RMNS*TST/60.
      IF(TST.GT.TP) VSF=RMNP*TP/60.+(FINF*(TST-TP)+BETTA/(1.-ALPHA)*((TS
     $T-TO)**(1.-ALPHA)-(TP-TO)**(1.-ALPHA)))/60.
      RETURN
      END
```

```
      SUBROUTINE INPT
C     COMPUTE V AND H AT INTERIOR GRID POINTS
      COMMON /B1/ B(40),C(40),Z(10),TIME,OPH,NN,N,NCH,RSL,CURVE
      COMMON /B2/ H(27,27,2),V(27,27,2),HL(27,10,2),HR(27,10,2),
     $VR(27,10,2),VL(27,10,2),VJ(27,10,2),XJ(27,10,2),JI(27,27,2),KN,NJJ
      COMMON /B3/ NK(27),NJ(27),DX,DT,DIST,HMIN,VMIN,ITYPE,IO,OC(27,10),
     $S,DS
      COMMON /B4/ II(27,2),XI(27,2),HI(27,2),VI(27,2),QI(27,2),WI(27,2),
     $CT(27,2),CH(27,2),CV(27,2)
      COMMON /B5/ NG(27,27),SG(27,27),FG(27,27),NF,SF,FFF
      COMMON/B6/AA1,BB1,CC1,SNK,IDG,SP1,XPG1,SP2,XPG2
      COMMON /B8/ ACCU,ACCUX,ACCUY,HDRY,CC
      COMMON /B10/ DXCH,DXRS,DDXCH,DDXRS
      COMMON /B14/ IWET(27)
      DIMENSION VV(2),FF(2)
C     LOCATE THE MOVING DISCONTINUITIES, IF ANY
      IF(ITYPE.EQ.1) GO TO 1
      IF(ITYPE.EQ.2.AND.N.LT.NCH) GO TO 30
      IF(ITYPE.EQ.5.AND.N.LT.NCH) GO TO 30
      GOTO 1
   30 IF(IWET(N).EQ.1) GO TO 1
      XN=FLOAT(N-1)*DXCH
      XW=TIME*C(30)
      PW=C(21)-XW
      IF(XW.LT.XN.AND.ITYPE.EQ.2) GO TO 32
      IF(ITYPE.EQ.5.AND.PW.GT.XN) GO TO 32
      HO=TIME*C(26)*C(19)*B(11)*C(5)/B(16)
      HN=HO*(XW-XN)/XW
      IF(ITYPE.EQ.5) HN=HO*(XN-PW)/XW
      IF(HN.LT.B(31)*HMIN) GO TO 32
      DO 31 K=1,KN
      H(N,K,2)=HN
      XK=FLOAT(K-1)*DXRS
      CALL STORM(XK,0.)
      NCT=0
      I=1
      VV(1)=0.1
      CALL GEOM(2,A,HN,R,T,D,1,1,XK)
   35 VN=VV(I)
   36 CALL FRIC(VN,HN,F,R,RE,REC,IR,1,XK)
      FF(I)=C(8)-C(4)*F/B(13)*ABS(VN)*VN/R
      IF(ABS(FF(I)).LT.ACCU)GO TO 38
      IF(I.EQ.1) GO TO 37
      NCT=NCT+1
      IF(NCT.GT.50) GO TO 38
      VN=(FF(1)*VV(2)-FF(2)*VV(1))/(FF(1)-FF(2))
      VV(1)=VV(2)
      VV(2)=VN
      FF(1)=FF(2)
      GO TO 36
   37 I=2
      VV(2)=0.0001
      GO TO 35
   38 V(N,K,2)=VN
   31 CONTINUE
      IWET(N)=1
```

```
      IF(N.EQ.NN.AND.ITYPE.EQ.2) ITYPE=1
      IF(ITYPE.EQ.5.AND.N.EQ.1) ITYPE=1
      RETURN
   32 DO 33 K=1,KN
      H(N,K,2)=HDRY
      V(N,K,2)=0.
   33 CONTINUE
      IWET(N)=0
      XI(N,2)=XI(N,1)
      HI(N,2)=HI(N,1)
      VI(N,2)=VI(N,1)
      RETURN
    1 NJP=NJJ
      IF(NJP.EQ.0) GO TO 4
    2 DO 3 J=1,NJP
      CALL JUMP(J)
    3 CONTINUE
C     COMPUTE V AND H AT GRID POINT
    4 KUP=2
      KNN=KN-1
      DO 23 K=2,KNN
      IF(H(N,K,2).GT.HDRY/2.) GO TO 23
      XB=FLOAT(K-1)*DX
      TIM=TIME-DT
      CALL STORM(XB,TIM)
      IF(C(26).GT.ACCU) GO TO 5
      IF(ITYPE.NE.1.AND.JI(N,2,1).GT.0) GO TO 5
      IF(K.EQ.KUP.AND.H(N,K,1).LT.HDRY*2.) GO TO 22
    5 CALL OPHEAD
      CALL GEOM(2,AB,H(N,K,1),RB,TB,DB,1,1,XB)
      TSTK=FRTST(V(N,K,1),DB,OPH,C(1),C(5),C(9),C(20),1)
      IF(N.EQ.1.OR.N.GE.NCH) GOTO 51
      IF(ITYPE.EQ.2) GO TO 51
      IF(ABS(H(N,K,1)-H(N-1,K,1)).GT.ACCU) GO TO 51
      IF(ABS(V(N,K,1)-V(N-1,K,1)).GT.ACCU) GO TO 51
      IF(H(N-1,K,2).LT.HDRY) GO TO 51
      IF(TSTK.GT.0.) GO TO 25
   51 XA=XB-DX
      XC=XB+DX
      HC=H(N,K+1,1)
      VC=V(N,K+1,1)
      IF(K.LT.KNN) GOTO 34
      IF(N.GE.NCH) XC=DIST
      IF(N.GE.NCH) GOTO 34
      IF(NN.EQ.1) GO TO 34
      XC=XI(N,1)
      HC=HI(N,1)
      VC=VI(N,1)
   34 CALL GEOM(2,AA,H(N,K-1,1),RA,TA,DA,1,1,XA)
      CALL GEOM(2,AC,HC,RC,TC,DC,1,1,XC)
      IF(NJJ.EQ.0) GO TO 17
      DO 6 J=1,NJJ
      IF(XJ(N,J,1).GT.XB.AND.XJ(N,J,2).GT.0.) GO TO 7
    6 CONTINUE
      GO TO 20
    7 DO 8 J2=1,NJJ
      IF(XJ(N,J2,2).GT.XB) GO TO 9
```

```
    8 CONTINUE
      J2=NJJ+1
      GOTO 15
    9 IF(J2-J) 10,11,15
   10 CALL JL(XB,J2,V(N,K,2),H(N,K,2),$23,2)
      GO TO 24
   11 IF(XJ(N,J,1)-DX.LT.XB) GO TO 10
      IF(J.EQ.1) GO TO 17
      J1=J-1
   12 DO 13 JJ=1,J1
      J3=J1-JJ+1
      IF(XJ(N,J3,2).GT.0.) GO TO 14
   13 CONTINUE
      GO TO 17
   14 IF((J2-J).GT.0) GOTO 26
      IF((XJ(N,J3,1)+DX).LT.XB) GOTO 17
   26 J1=J3
      GO TO 16
   15 J1=J2-1
      GO TO 12
   16 CALL JR(XB,J1,V(N,K,2),H(N,K,2),$23,2)
      GO TO 24
   17 CALL CS(1.,XA,XB,XD,XB,DA,DB,DD,V(N,K-1,1),V(N,K,1),VD)
      IF(TSTK.LT.0.) GO TO 18
      CALL CS(-1.,XA,XE,XE,XB,DA,DB,DE,V(N,K-1,1),V(N,K,1),VE)
      GO TO 19
   18 CALL CS(-1.,XB,XC,XE,XB,DC,DC,DE,V(N,K,1),VC,VE)
   19 CALL CEQS(VD,DD,VE,DE,V(N,K,2),H(N,K,2),XD,XE,DT,DT,XB)
   24 NG(N,K)=NF
      SG(N,K)=SF
      FG(N,K)=FFF
      GO TO 23
   25 N1=N-1
      H(N,K,2)=H(N1,K,2)
      V(N,K,2)=V(N1,K,2)
      NG(N,K)=NG(N1,K)
      FG(N,K)=FG(N1,K)
      SG(N,K)=SG(N1,K)
      GO TO 23
   20 DO 21 J2=1,NJJ
      IF(XJ(N,J2,2).GT.XB) GO TO 10
   21 CONTINUE
      IF(XJ(N,NJJ,1)+DX.LT.XB.OR.XJ(N,NJJ,2).LT.ACCU) GO TO 17
      J1=NJJ
      GO TO 16
   22 H(N,K,2)=HDRY
      V(N,K,2)=0.
      KUP=KUP+1
   23 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE INTAL
C     SET UP INITIAL CONDITIONS
      COMMON /B1/ B(40),C(40),Z(10),TIME,OPH,NN,N,NCH,RSL,CURVE
      COMMON /B2/ H(27,27,2),V(27,27,2),HL(27,10,2),HR(27,10,2),
     $VR(27,10,2),VL(27,10,2),VJ(27,10,2),XJ(27,10,2),JI(27,27,2),KN,NJJ
      COMMON /B3/ NK(27),NJ(27),DX,DT,DIST,HMIN,VMIN,ITYPE,IO,OC(27,10),
     $S,DS
      COMMON /B4/ II(27,2),XI(27,2),HI(27,2),VI(27,2),QI(27,2),WI(27,2),
     $CT(27,2),CH(27,2),CV(27,2)
      COMMON/B6/AA1,BB1,CC1,SNK,IDG,SP1,XPG1,SP2,XPG2
      COMMON /B8/ ACCU,ACCUX,ACCUY,HDRY,CC
      COMMON /B9/ TL(10,2),TR(10,2)
      COMMON /B10/ DXCH,DXRS,DDXCH,DDXRS
      COMMON /B11/ HRR,VRR
      COMMON /B14/ IWET(27)
      COMMON/B16/AAA,BBB,CCC,TD,RTO,RMN,RAV
      DIMENSION  VV(2),F(2),VVV(27),TMT(2)
      DXCH=DDXCH/B(11)
      DXRS=DDXRS/B(11)
      DX=DXRS
      DXPG1=XPG1/B(11)
      DXPG2=XPG2/B(11)
      DT=0.
      NKK=(C(22)+DXPG1+DXPG2)/DX+1.99999
      DO 4 N=1,NN
      NJ(N)=0
      NK(N)=NKK
      IWET(N)=0
      DO 4 NT=1,2
      XI(N,NT)=C(22)+DXPG1+DXPG2
      II(N,NT)=0
      HI(N,NT)=0.
      VI(N,NT)=0.
      QI(N,NT)=0.
      WI(N,NT)=0.
      CT(N,NT)=ACCU*0.99
      DO 1 K=1,27
      H(N,K,NT)=0.
      V(N,K,NT)=0.
      JI(N,K,NT)=0
    1 CONTINUE
      DO 4 J=1,10
      XJ(N,J,NT)=0.
      VJ(N,J,NT)=0.
      VL(N,J,NT)=0.
      VR(N,J,NT)=0.
      HR(N,J,NT)=0.
      HL(N,J,NT)=0.
    4 CONTINUE
      NK(NCH)=NN
      NJ(NCH)=0
      DO 3 NT=1,2
      XI(NCH,NT)=C(21)
      DO 2 K=1,NN
      H(NCH,K,NT)=0.
      V(NCH,K,NT)=0.
```

```
      JI(NCH,K,NT)=0
    2 CONTINUE
      DO 3 J=1,10
      XJ(NCH,J,NT)=0.
      VJ(NCH,J,NT)=0.
      VL(NCH,J,NT)=0.
      VR(NCH,J,NT)=0.
      HR(NCH,J,NT)=0.
      HL(NCH,J,NT)=0.
    3 CONTINUE
C     INITIAL CONDITIONS FOR FLOW ON SIDESLOPE
      NS=NCH+1
      NJ(NS)=0
      NK(NS)=C(33)/DXRS+1.99999
      NKS=NK(NS)
      DO 33 NT=1,2
      XI(NS,NT)=C(33)
      DO 32 K=1,NKS
      H(NS,K,NT)=0.
      V(NS,K,NT)=0.
      JI(NS,K,NT)=0.
   32 CONTINUE
      DO 33 J=1,10
      XJ(NS,J,NT)=0.
      VJ(NS,J,NT)=0.
      VL(NS,J,NT)=0.
      VR(NS,J,NT)=0.
      HR(NS,J,NT)=0.
      HL(NS,J,NT)=0.
   33 CONTINUE
      CALL RAIN(3,0.1)
      N=1
      IF(B(23).LT.ACCU) GO TO 6
      HMIN=B(23)*C(5)/B(16)
      ST=B(23)
      CALL PREP
      IF(ITYPE.EQ.3) GO TO 60
      IF(ITYPE.EQ.6) GO TO 80
      CALL STORM(DXRS,0.1)
      Q0=DDXRS*RAV/43200.
      ST1=(CC/8.*Q0*B(24)/(32.2*C(8)))**(1./3.)
      ST1=ST1/5.
      IF(ST.GT.ST1) ST=ST1
      GO TO 7
C     ST IS DIMENSIONAL STARTING DEPTH
C     SH IS DIMENSIONLESS STARTING DEPTH
C     SV IS DIMENSIONLESS STARTING VELOCITY
    6 HMIN=HDRY
      ST=0.1*B(11)*C(19)*RMN/B(19)
    7 TIME=ST/(B(11)*C(19)*RMN/B(19))
      NCT=0
      I=1
      TMT(I)=TIME
   42 CALL RAIN(3,TMT(I))
      F(I)=TMT(I)-ST/(B(11)*C(19)*RMN/B(19))
      IF(ABS(F(I)).LT.ACCU) GOTO 44
      IF(I.EQ.1) GOTO 43
```

```
      NCT=NCT+1
      IF(NCT.GT.20) GOTO 99
      IF(ABS(F(1)-F(2)).LT.ACCU) GOTO 44
      TMM=(F(1)*TMT(2)-F(2)*TMT(1))/(F(1)-F(2))
      TMT(1)=TMT(2)
      TMT(2)=TMM
      F(1)=F(2)
      GOTO 42
   43 I=2
      TMT(2)=1.1*TIME
      GOTO 42
   44 TIME=TMT(I)
      SH=ST*C(5)/B(16)
      SV=0.
      IF(SH.LT.HMIN) HMIN=SH
      VMIN=SV
      CHH=2.*SH
      IF(IDG.EQ.2) CHH=SH
      IF(NN.EQ.1) GO TO 10
      CX=(CHH-SH)/SP2*B(16)/C(5)
      CTT=CX*SQRT(1.-SP2**2)/B(10)
      IF(IDG.EQ.2) CTT=0.
    9 DIST=XI(N,1)-CTT*B(10)/B(11)
      NM=NN
      IF(ITYPE.EQ.2) NM=2
      IF(ITYPE.EQ.5) GOTO 5
C     FOR UNIFORM RAINFALL (ITYPE=1)
      DO 8 N=1,NM
      HI(N,1)=SH
      XI(N,1)=DIST
      CT(N,1)=CTT
      IWET(N)=1
    8 CONTINUE
      GO TO 10
    5 CT(NN,1)=CTT
C     COMPUTE H AND V FOR ALL N AND K AT NT=1
   10 IF(IDG.EQ.1) NKK=NKK-1
      DO 15 K=1,NKK
      XK=FLOAT(K-1)*DXRS
      CALL STORM(XK,TIME)
      NCT=0
      I=1
      VV(1)=0.1
      SSH=SH
      CALL GEOM(2,A,SSH,R,T,D,1,1,XK)
   11 SV=VV(I)
   12 CALL FRIC(SV,SSH,FF,R,RE,REC,IR,1,XK)
      F(I)=C(8)-C(4)*FF/B(13)*ABS(SV)*SV/R
      IF(ABS(F(I)).LT.ACCU) GO TO 14
      IF(I.EQ.1) GO TO 13
      NCT=NCT+1
      IF(NCT.GT.50) GO TO 99
      SV=(F(1)*VV(2)-F(2)*VV(1))/(F(1)-F(2))
      VV(1)=VV(2)
      VV(2)=SV
      F(1)=F(2)
      GO TO 12
```

```
   13 I=2
      VV(2)=0.0001
      GO TO 11
   14 VVV(K)=SV
   15 CONTINUE
      N=NCH
      CALL STORM(1.,TIME)
      NCT=0
      I=1
      VV(1)=0.1
      CALL GEOM(2,A,CHH,R,T,D,1,1,1.)
      IF(ITYPE.EQ.2) CALL GEOM(2,A,CHH,R,T,D,1,1,0.)
   16 SV=VV(I)
   17 CALL FRIC(SV,CHH,FF,R,RE,REC,IR,1,1.)
      F(I)=C(8)-C(4)*FF/B(13)*ABS(SV)*SV/R
      IF(ABS(F(I)).LT.ACCU) GOTO 19
      IF(I.EQ.1) GOTO 18
      NCT=NCT+1
      IF(NCT.GT.50) GOTO 99
      SV=(F(1)*VV(2)-F(2)*VV(1))/(F(1)-F(2))
      VV(1)=VV(2)
      VV(2)=SV
      F(1)=F(2)
      GOTO 17
   18 I=2
      VV(2)=0.0001
      GOTO 16
   19 SVV=SV
      IF(ITYPE.EQ.5) GOTO 70
   20 DO 22 N=1,NM
      DO 21 K=1,NKK
      H(N,K,1)=SH
      V(N,K,1)=VVV(K)
   21 CONTINUE
      IF(NN.EQ.1) GO TO 24
      DXK=XI(N,1)-FLOAT(NKK-1)*DXRS
      VI(N,1)=V(N,NKK,1)+(V(N,NKK,1)-V(N,NKK-1,1))*DXK/DXRS
      CALL GEOM(2,A,HI(N,1),R,T,D,1,1,XI(N,1))
      QI(N,1)=VI(N,1)*A
   22 CONTINUE
      DO 23 K=1,NM
      H(NCH,K,1)=CHH
      V(NCH,K,1)=SVV
   23 CONTINUE
      IF(ITYPE.EQ.2) GOTO 50
      N=NS
      CALL STORM(0.,TIME)
      NCT=0
      I=1
      VV(1)=0.1
      SSH=SH
      CALL GEOM(2,A,SSH,R,T,D,1,1,0)
   26 SV=VV(I)
   27 CALL FRIC(SV,SSH,FF,R,RE,REC,IR,1,0)
      F(I)=C(8)-C(4)*FF/B(13)*ABS(SV)*SV/R
      IF(ABS(F(I)).LT.ACCU) GOTO 29
      IF(I.EQ.1) GOTO 23
```

```
      NCT=NCT+1
      IF(NCT.GT.50) GOTO 99
      SV=(F(1)*VV(2)-F(2)*VV(1))/(F(1)-F(2))
      VV(1)=VV(2)
      VV(2)=SV
      F(1)=F(2)
      GOTO 27
   28 I=2
      VV(2)=0.0001
      GOTO 26
   29 SVS=SV
      DO 25 K=1,NKS
      H(NS,K,1)=SH
      V(NS,K,1)=SVS
   25 CONTINUE
   24 GOTO 90
C     FOR MOVING RAINSTORM THE DIRECTION OF MOVING RAINSTORM COINCIDES
C     WITH THAT OF CHANNEL FLOW (ITYPE=2)
   50 HRR=B(31)*HMIN
      VRR=0.
      XINTAL=1.5
      CNK=SQRT(1.-SP2**2)
      NKKK=NKK
      DO 501 N=3,NCH
      IF(N.EQ.NCH) NKKK=NN
      DO 500 K=1,NKKK
      H(N,K,1)=HDRY
      V(N,K,1)=0.
  500 CONTINUE
      IF(N.EQ.NCH) GOTO 501
      HI(N,1)=HDRY
      VI(N,1)=0.
      CT(N,1)=HRR*CNK/SP2*B(16)/B(10)/C(5)
      XI(N,1)=C(22)+DXPG1+DXPG2-CT(N,1)*B(10)/B(11)
  501 CONTINUE
      HL(NCH,1,1)=CHH
      VL(NCH,1,1)=SVV
      HR(NCH,1,1)=HRR
      VR(NCH,1,1)=VRR
      VJ(NCH,1,1)=SVV
      XJ(NCH,1,1)=XINTAL*DXCH
      JI(NCH,3,1)=1
      NJ(NCH)=1
      IWET(NCH)=1
      TL(1,1)=CTT
      TR(1,1)=HRR*CNK/SP2*B(16)/B(10)/C(5)
      C(26)=1.
      TIME=SQRT(SH*XINTAL*DXCH*B(16)/(0.5*C(5)*C(26)*C(19)*C(30)*B(11) )
      GOTO 90
C     FOR TYPE 3 MOVING RAINSTORM, THE DIRECTION OF MOVING STORM IS THE
C     SAME AS THAT OF ROAD SURFACE FLOW
   60 TIME=DXRS/C(30)
      H1=TIME*RMN/B(19)*C(19)*B(11)*C(5)/B(16)
      XINTAL=1.5
      V0=H1*DXRS/2.
      HH=V0/(XINTAL*DXRS)
      DO 61 K=1,3
```

```
      XK=FLOAT(K-1)*DXRS
      IF(K.EQ.3) XK=XINTAL*DXRS
      CALL STORM(XK,TIME)
      CALL GEOM(2,A,HH,R,T,D,1,1,XK)
      V(N,K,1)=C(8)*8.*32.2*R*R*B(17)**2/(CC*B(24)*B(12))
      H(N,K,1)=HH
   61 CONTINUE
      HRR=B(31)*HMIN
      VRR=0.
      HL(N,1,1)=HH
      VL(N,1,1)=V(N,3,1)
      CALL GEOM(6,ARR,HRR,HHR,TRR,DRR,1,1,XJJ)
      VJ(N,1,1)=(A*VL(N,1,1)-ARR*VRR)/(A-ARR)
      XJ(N,1,1)=XINTAL*DXRS
      NJ(N)=1
      JI(N,3,1)=1
      VR(N,1,1)=VRR
      HR(N,1,1)=HRR
   63 DO 64 K=3,NKK
      H(N,K,1)=HDRY
      V(N,K,1)=0.
   64 CONTINUE
      GO TO 90
C     FOR TYPE 5 MOVING STORM
   70 N=NN
      DO 71 K=1,NKK
      H(N,K,1)=SH
      V(N,K,1)=VVV(K)
   71 CONTINUE
      H(NCH,NN,1)=CHH
      V(NCH,NN,1)=SVV
      CT(NN,1)=CTT
      IF(IDG.EQ.2) CTT=0.
      XI(NN,1)=C(22)+DXPG1+DXPG2-CTT*B(10)/B(11)
      HI(NN,1)=SH
      DXK=XI(NN,1)-FLOAT(NKK-1)*DXRS
      VI(NN,1)=V(NN,NKK,1)+(V(NN,NKK,1)-V(NN,NKK-1,1))*DXK/DXRS
      CALL GEOM(2,A,HI(N,1),R,T,D,1,1,XI(N,1))
      QI(NN,1)=VI(NN,1)*A
      NM=NN-1
      DO 73 N=1,NM
      DO 72 K=1,NKK
      H(N,K,1)=HDRY
      V(N,K,1)=0.
   72 CONTINUE
      H(NCH,N,1)=HDRY
      V(NCH,N,1)=0.
      CT(N,1)=ACCU*0.99
      IF(IDG.EQ.2) CT(N,1)=0.
   73 CONTINUE
      IWET(NN)=1
      IWET(NCH)=1
      GO TO 90
C     FOR TYPE 6 MOVINC STORM
   80 CONTINUE
      DX1=C(22)+DXPG1+DXPG2-AINT((C(22)+DXPG1+DXPG2)/DXRS)*DXRS
      IF(DX1.LE.ACCU.OR.IDC.EQ.2) DX1=DXRS
```

```
      TIME=DX1/C(30)
      N=NCH
      CALL STORM(DXCH,TIME)
      CC=C(36)*C(8)**C(37)
      IF(CC.LT.24.) CC=24.
      H1=TIME*RMN/B(19)*C(19)*B(11)*C(5)/B(16)
      A=H1*B(16)/C(5)*DX1*B(11)/2./B(18)
      CNK=SQRT(1.-SP2**2)
      HH=SQRT(2.*A*B(18)*SP2/CNK)*C(5)/B(16)
      T=HH*CNK/SP2/C(5)*B(16)/B(10)
      XRS=C(22)+DXPG1+DXPG2-T*B(10)/B(11)
      NKK=XRS/DXRS+1.99999
      P=HH/C(5)*B(16)*(1.+1./SP2)
      R=A*B(18)/P/B(17)
      IF(IDG.EQ.2) CALL GEOM(1,A,HH,R,T,D,1,1,DXCH)
  401 VCH=C(8)*8.*32.2*R*R*B(17)**2/(CC*B(24)*B(12))
      DO 81 K=1,NN
      H(NCH,K,1)=HH
      V(NCH,K,1)=VCH
      IF(IDG.EQ.2) GOTO 402
      XI(K,1)=XRS
      HI(K,1)=HDRY
      VI(K,1)=0.
      CT(K,1)=T
      CH(K,1)=HDRY
      CV(K,1)=0.
      GOTO 81
  402 XI(K,1)=C(22)+DXPG1+DXPG2
      HI(K,1)=H(K,NKK,1)
      VI(K,1)=V(K,NKK,1)
      CT(K,1)=0.
   81 CONTINUE
      DO 83 N=1,NN
      DO 82 K=1,NKK
      H(N,K,1)=HDRY
      V(N,K,1)=0.
   82 CONTINUE
   83 CONTINUE
      ITYPE=1
  90  CALL ERR(1)
      CALL OPHEAD
      WRITE(6,200) HMIN,VMIN,OPH,CC
  200 FORMAT('  HMIN =',F9.5,' VMIN =',F9.5,' OPH =',E10.4,' C =',E11.6
      TDIM=TIME*B(11)/B(12)
      WRITE(6,201) TIME,TDIM
  201 FORMAT(1H1' THE INITIAL CONDITIONS ARE :'/'  TIME =',F9.3,5X,
     $'(DIMENSIONAL TIME =',F9.3,' SEC.)')
      IO=1
      IF(NN.EQ.1) GO TO 96
      IF(ITYPE.EQ.2) N=NCH
      IF(ITYPE.EQ.2) KJ=3
      TL(1,2)=TL(1,1)
      TR(1,2)=TR(1,1)
      XJ(N,1,2)=XJ(N,1,1)
      VJ(N,1,2)=VJ(N,1,1)
      VL(N,1,2)=VL(N,1,1)
      VR(N,1,2)=VR(N,1,1)
```

```
      HR(N,1,2)=HR(N,1,1)
      HL(N,1,2)=HL(N,1,1)
      JI(N,KJ,2)=JI(N,KJ,1)
      IF(ITYPE.EQ.3) GO TO 96
      DO 95 IN=1,NN
      XI(IN,2)=XI(IN,1)
      HI(IN,2)=HI(IN,1)
      VI(IN,2)=VI(IN,1)
      QI(IN,2)=QI(IN,1)
      WI(IN,2)=WI(IN,1)
      II(IN,2)=II(IN,1)
      CT(IN,2)=CT(IN,1)
      CH(IN,2)=CH(IN,1)
      CV(IN,2)=CV(IN,1)
   95 CONTINUE
   96 DO 93 I=1,3
      IF(I.EQ.1) N=1
      IF(ITYPE.EQ.5.AND.I.EQ.1) N=NN
      IF(I.EQ.2) N=NCH
      IF(I.EQ.3) N=NS
      CALL PREP
      IF(N*ITYPE.EQ.1) WRITE(6,202)
  202 FORMAT(10X,'ALSO FOR ALL SECTIONS OF ROAD SURFACE FLOW')
      DO 91 K=1,KN
      H(N,K,2)=H(N,K,1)
      V(N,K,2)=V(N,K,1)
   91 CONTINUE
      Z(3)=1.
      IF(N.EQ.NCH) Z(3)=0.
      IF(N.EQ.NS) Z(3)=0.
      IF(ITYPE.EQ.3) Z(3)=0.
      CALL OUPT
      DO 92 K=1,KN
      H(N,K,2)=0.
      V(N,K,2)=0.
   92 CONTINUE
      IF(NN.EQ.1) RETURN
      XJ(N,1,2)=0.
      VJ(N,1,2)=0.
      VL(N,1,2)=0.
      VR(N,1,2)=0.
      HR(N,1,2)=0.
      HL(N,1,2)=0.
      JI(N,KJ,2)=0
      IF(ITYPE.EQ.3) RETURN
   93 CONTINUE
      TL(1,2)=TL(1,1)
      TR(1,2)=TR(1,1)
      DO 94 IN=1,NN
      XI(IN,2)=XI(IN,1)
      HI(IN,2)=0.
      VI(IN,2)=0.
      QI(IN,2)=0.
      WI(IN,2)=0.
      II(IN,2)=0.
      CT(IN,2)=CT(IN,1)
      CH(IN,2)=0.
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      CV(IN,2)=0.
   94 CONTINUE
      RETURN
   99 SSS=-1.
      SS=SQRT(SSS)
      END
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```
      SUBROUTINE JL(XP,J,VLL,HLL,S,ID)
C     COMPUTE V AND H ON REGION 'L' OF THE DISCONTINUITY
C     ID=1 COMPUTE VL, HL AT DISCONTINUITY WHEN AL IS LESS THAN AR
C     ID=2 COMPUTE V, H AT GRID POINT IN LEFT-HAND SIDE OF DISCONTINUI Y
      COMMON /B1/ B(40),C(40),Z(10),TIME,OPH,NN,N,NCH,RSL,CURVE
      COMMON /B2/ H(27,27,2),V(27,27,2),HL(27,10,2),HR(27,10,2),
     $VR(27,10,2),VL(27,10,2),VJ(27,10,2),XJ(27,10,2),JI(27,27,2),KN,NJJ
      COMMON /B3/ NK(27),NJ(27),DX,DT,DIST,HMIN,VMIN,ITYPE,IO,OC(27,10),
     $S,DS
      COMMON /B8/ ACCU,ACCUX,ACCUY,HDRY,CC
C     SS=1. FOR C+
C     SS=-1. FOR C-
      DTD=DT
      DTE=DT
      SS=-1.
      XJ1=XJ(N,J,1)
      K=XJ1/DX+1.99999
      X2=XJ1
      X1=FLOAT(K-1)*DX
      XJ2=0.
      JJ=J
   16 IF(JJ.LE.0) GO TO 15
      IF(XJ(N,JJ-1,2).GT.0..AND.XJ(N,JJ-1,2).LT.DIST) XJ2=XJ(N,JJ-1,1)
      IF(XJ2.GT.0.) GO TO 15
      JJ=JJ-1
      GO TO 16
   15 V2=VL(N,J,1)
      CALL GEOM(2,A2,HL(N,J,1),R2,T2,D2,1,1,XJ1)
      IF(X2-X1.LT.ACCUX) GOTO 4
    1 IF(XJ2.GT.X1) GO TO 5
      V1=V(N,K-1,1)
      CALL GEOM(2,A1,H(N,K-1,1),R1,T1,D1,1,1,X1)
    2 CALL CS(SS,X1,X2,XC,XP,D1,D2,DC,V1,V2,VC)
   14 IF(ID.EQ.2) GO TO 10
   13 IF(XC.LT.XJ2.AND.XJ(N,JJ-1,2).GT.0.) GOTO 12
      IF(XC.GT.X2) GOTO 6
      IF(XC.LT.X1) GOTO 4
    3 IF(SS.LT.0.) GO TO 8
    9 CALL CEQS(VC,DC,VE,DE,VLL,HLL,XC,XE,DTD,DTE,XP)
      IF(ID.EQ.1.OR.ITYPE.EQ.1) RETURN
      DX1=XJ(N,J,2)-X1
      VLL1=V(N,K-1,2)+(V(N,K-1,2)-V(N,K-2,2))*DX1/DX
      HLL1=H(N,K-1,2)+(H(N,K-1,2)-H(N,K-2,2))*DX1/DX
      IF(VLL.LT.VLL1) VLL=VLL1
      IF(HLL.GT.HLL1) HLL=HLL1
      RETURN
    4 K=K-1
      X1=X1-DX
      GO TO 1
    5 X1=XJ2
      IF(ABS(X1-X2).LT.ACCUX) RETURN 5
      V1=VR(N,JJ-1,1)
      CALL GEOM(2,A1,HR(N,JJ-1,1),R1,T1,D1,1,1,X1)
      GO TO 2
    6 XC=X2
      DC=D2
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      VC=V2
      GO TO 3
    8 SS=1.
      XE=XC
      VE=VC
      DE=DC
      DTE=DTD
      GO TO 2
   10 IF(XC.GT.XJ1) GOTO 11
      GOTO 13
   11 XPC=XP-XC
      CALL CROSS(XP,J,2,VC,DC,XPC,DTD,SS)
      XC=XP-XPC
      IF(SS.LT.0.) GOTO 8
      GOTO 9
   12 XPC=XP-XC
      JM=JJ-1
      CALL CROSS(XP,JM,1,VC,DC,XPC,DTD,SS)
      XC=XP-XPC
      IF(SS.LT.0.) GOTO 8
      GO TO 9
      END
```

```
      SUBROUTINE JL1(XP,J,VLL,HLL,VRR,HRR,$)
C     USE C+ CHARACTERISTIC EQUATION AND ONE OF THE EQUATIONS OF
C     DISCONTINUITY TO SOLVE VL AND HL
      COMMON /B1/ B(40),C(40),Z(10),TIME,OPH,NN,N,NCH,RSL,CURVE
      COMMON /B2/ H(27,27,2),V(27,27,2),HL(27,10,2),HR(27,10,2),
     $VR(27,10,2),VL(27,10,2),VJ(27,10,2),XJ(27,10,2),JI(27,27,2),KN,NJ
      COMMON /B3/ NK(27),NJ(27),DX,DT,DIST,HMIN,VMIN,ITYPE,IO,OC(27,10),
     $S,DS
      COMMON /B7/ NL(27,10),NR(27,10),SL(27,10),SR(27,10),FL(27,10),
     $FR(27,10),NFJ,SFJ,FFJ
      COMMON /B9/ ACCU,ACCUX,ACCUY,HDRY,CC
      DIMENSION F(2),HH(2)
      DTD=DT
      CALL GEOM(6,ARR,HRR,HHR,TRR,DRR,1,2,XP)
      XJ1=XJ(N,J,1)
      NL(N,J)=0
      K=XJ1/DX+1.99999
      X2=XJ1
      X1=FLOAT(K-1)*DX
      XJ2=0.
      JJ=J
   16 IF(JJ.LE.1) GOTO 15
      IF(XJ(N,JJ-1,2).GT.0..AND.XJ(N,JJ-1,2).LT.DIST) XJ2=XJ(N,JJ-1,1)
      IF(XJ2.GT.0..AND.XJ2.LT.DIST) GOTO 15
      JJ=JJ-1
      GOTO 16
   15 V2=VL(N,J,1)
      CALL GEOM(2,A2,HL(N,J,1),R2,T2,D2,1,1,XJ(N,J,1))
      IF(X2-X1.LT.ACCUX) GOTO 8
    1 IF(XJ2.GT.X1) GO TO 9
      V1=V(N,K-1,1)
      CALL GEOM(2,A1,H(N,K-1,1),R1,T1,D1,1,1,X1)
    2 CALL CS(1.,X1,X2,XD,XP,D1,D2,DD,V1,V2,VD)
      IF(DD.LT.HDRY) DD=HDRY
      IF(XD.GT.X2) GO TO 10
      IF(XD.LT.X1) GOTO 12
    3 CALL GEOM(5,AD,HD,RD,TD,DD,1,1,XD)
      T=TIME-DTD
      CALL STORM(XD,T)
      CALL FRIC(VD,HD,FD,RD,RED,REC,KD,1,XD)
      CALL OPHEAD
      SFDD=C(4)*FD*VD*ABS(VD)/(B(13)*RD)
C     SD, S2 ARE ENERGY COEFICIENTS AT POINTS D AND 2
      SD=1.
      S2=1.
      DXD2=X2-XD
      IF(ABS(DXD2).LT.ACCUX) SFD2=C(8)
      IF(ABS(DXD2).LT.ACCUX) GOTO 20
      SFD2=C(8)+(B(16)*(HD-HL(N,J,1))/C(5)+B(12)**2*(SD*VD*VD-S2*V2*V2
     $/64.4)/(DXD2*B(11))*C(9)
   20 IF(ABS(SFDD).LT.ABS(SFD2)) GOTO 4
   31 SFD=SFD2
      NL(N,J)=1
      GO TO 14
    4 SFD=(SFDD+SFD2)/2.
   14 DSQ=SQRT(C(1)*(C(1)-1.)*VD*VD+C(1)*C(20)*(DD*C(9)/C(5)+OPH))
```

```
      C7=C(7)*DTD/DT
      C1=C(11)*DTD*(C(1)*C(20)*(C(8)-SFD)+C(26)/DD*C(19)*(C7*C(25)*C(6)
     $/C(9)-C(1)*VD+DSQ)*C(9)*C(5)+C(27)/DD*C(19)*(C(1)*VD-DSQ)*C(9)*
     $C(5)+B(16)/B(10)*C(29)/(TD*DD)*(C(3)*C(2)*C(24)-C(1)*VD+DSQ))
      I=1
      NCT=0
      HH(1)=HL(N,J,1)*1.1
    5 HLL=HH(I)
      CALL GEOM(6,ALL,HLL,HHL,TLL,DLL,1,1,XP)
      ALR=ALL-ARR
      AHLR=ALL*HHL-ARR*HHR
      HSQ=SQRT(C(1)*C(20)/(ALL*ARR)*(AHLR/ALR*(C(9)/C(5))**2+OPH))
      F(I)=C(9)/(C(5)*DD)*((1.-C(1))*VD+DSQ)*(HLL-HD)+VRR+ALR*HSQ-VD-C1
      IF(ABS(F(I)).LT.ACCU) GO TO 7
      IF(I.EQ.1) GO TO 6
      IF(ABS(F(1)-F(2)).LT.ACCU*ACCU) GO TO 7
      NCT=NCT+1
      IF(NCT.GT.20) SS=SQRT(-1.)
      HLL=(F(1)*HH(2)-F(2)*HH(1))/(F(1)-F(2))
      HH(1)=HH(2)
      HH(2)=HLL
      F(1)=F(2)
      GO TO 5
    6 I=2
      HH(2)=HL(N,J,1)*1.05
      GO TO 5
    7 VLL=VRR+ALR*HSQ
      CALL GEOM(2,ALL,HLL,RLL,TLL,DLL,1,2,XP)
      CALL FRIC(VLL,HLL,FLL,RLL,REL,REC,IRL,2,XP)
      FL(N,J)=FLL
      SL(N,J)=C(4)*FLL*VLL*ABS(VLL)/(B(13)*RLL)
      RETURN
    8 K=K-1
      X1=X1-DX
      GO TO 1
    9 X1=XJ2
      IF(ABS(X1-X2).LT.ACCUX) RETURN 7
      V1=VR(N,JJ-1,1)
      CALL GEOM(2,A1,HR(N,JJ-1,1),R1,T1,D1,1,1,X1)
      GO TO 2
   10 XD=X2
      DD=D2
      VD=V2
      GO TO 3
   12 IF(XJ2.LT.X1) GOTO 8
      XPD=XP-XD
      JM=JJ-1
      CALL CROSS(XP,JM,1,VD,DD,XPD,DTD,1)
      XD=XP-XPD
      GOTO 3
      END
```

```
      SUBROUTINE JR(XP,J,VRR,HRR,$,ID)
C     COMPUTE V AND H ON REGION 'R' OF THE DISCONTINUITY
C      ID=1 COMPUTE VR AND HR AT DISCONTINUITY WHEN AL IS GREATER THAN  R
C      ID=2 COMPUTE V AND H AT GRID POINT IN RIGHT-HAND SIDE OF DISCONTI.
      COMMON /B1/ B(40),C(40),Z(10),TIME,OPH,NN,N,NCH,RSL,CURVE
      COMMON /B2/ H(27,27,2),V(27,27,2),HL(27,10,2),HR(27,10,2),
     $VR(27,10,2),VL(27,10,2),VJ(27,10,2),XJ(27,10,2),JI(27,27,2),KN,NJJ
      COMMON /B3/ NK(27),NJ(27),DX,DT,DIST,HMIN,VMIN,ITYPE,IO,OC(27,10),
     $S,DS
      COMMON /B8/ ACCU,ACCUX,ACCUY,HDRY,CC
      IQQ=0
C     SS=1.  FOR C+
C     SS=-1. FOR C-
      DTD=DT
      DTE=DT
      SS=1.
      XJ1=XJ(N,J,1)
      K=XJ1/DX+1.99999
      X1=XJ1
      X2=FLOAT(K)*DX
      XJ2=DIST
      JJ=J
   16 IF(JJ.GE.NJJ) GO TO 15
      IF(XJ(N,JJ+1,2).GT.0..AND.XJ(N,JJ+1,2).LT.DIST) XJ2=XJ(N,JJ+1,1)
      IF(XJ2.LT.DIST-ACCUX) GO TO 15
      JJ=JJ+1
      GO TO 16
   15 V1=VR(N,J,1)
      CALL GEOM(2,A1,HR(N,J,1),R1,T1,D1,1,1,XJ1)
      IF(X2-X1.LT.ACCUX) GOTO 4
    1 IF(XJ2.LT.X2) GO TO 5
      V2=V(N,K,1)
      CALL GEOM(2,A2,H(N,K,1),R2,T2,D2,1,1,X2)
    2 CALL CS(SS,X1,X2,XC,XP,D1,D2,DC,V1,V2,VC)
   14 IF(ID.EQ.2) GO TO 10
   13 IF(XC.GT.XJ2.AND.XJ(N,JJ+1,2).GT.0.) GOTO 12
      IF(XC.LT.X1) GOTO 6
      IF(XC.GT.X2) GOTO 4
    3 IF(SS.GT.0.) GO TO 8
    9 CALL CEQS(VD,DD,VC,DC,VRR,HRR,XD,XC,DTD,DTE,XP)
      RETURN
    4 X2=X2+DX
      K=K+1
      GO TO 1
    5 X2=XJ2
      IF(ABS(X1-X2).LT.ACCUX) RETURN 5
      V2=VL(N,JJ+1,1)
      CALL GEOM(2,A2,HL(N,JJ+1,1),R2,T2,D2,1,1,X2)
      GO TO 2
    6 XC=X1
      VC=V1
      DC=D1
      GO TO 3
    8 SS=-1.
      XD=XC
      VD=VC
```

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      DD=DC
      DTD=DTE
      GO TO 2
   10 IF(XC.LT.XJ1) GOTO 11
      GOTO 13
   11 XPC=XP-XC
      CALL CROSS(XP,J,1,VC,DC,XPC,DTE,SS)
      XC=XP-XPC
      IF(SS.GT.0.) GOTO 8
      GOTO 9
   12 XPC=XP-XC
      JP=JJ+1
      CALL CROSS(XP,JP,2,VC,DC,XPC,DTE,SS)
      XC=XP-XPC
      IF(SS.GT.0.) GOTO 8
      GO TO 9
      END
```

```
      SUBROUTINE JR1(XP,J,VLL,HLL,VRR,HRR,S)
C     USE C- CHARACTERISTIC EQUATION AND ONE OF THE EQUATIONS OF
C     DISCONTINUITY TO SOLVE VR AND HR
      COMMON /B1/ B(40),C(40),Z(10),TIME,OPH,NN,N,NCH,RSL,CURVE
      COMMON /B2/ H(27,27,2),V(27,27,2),HL(27,10,2),HR(27,10,2),
     $VR(27,10,2),VL(27,10,2),VJ(27,10,2),XJ(27,10,2),JI(27,27,2),KN,NJ
      COMMON /B3/ NK(27),NJ(27),DX,DT,DIST,HMIN,VMIN,ITYPE,IO,OC(27,10),
     $S,DS
      COMMON /B7/ NL(27,10),NR(27,10),SL(27,10),SR(27,10),FL(27,10),
     $FR(27,10),NFJ,SFJ,FFJ
      COMMON /B8/ ACCU,ACCUX,ACCUY,HDRY,CC
      DIMENSION F(2),HH(2)
      DTE=DT
      CALL GEOM(6,ALL,HLL,HHL,TLL,DLL,1,2,XP)
      XJ1=XJ(N,J,1)
      NR(N,J)=0
      K=XJ1/DX+1.99999
      X1=XJ1
      X2=FLOAT(K)*DX
      XJ2=DIST
      JJ=J
   16 IF(JJ.GE.NJJ) GOTO 15
      IF(XJ(N,JJ+1,2).GT.0..AND.XJ(N,JJ+1,2).LT.DIST) XJ2=XJ(N,JJ+1,1)
      IF(XJ2.GT.0..AND.XJ2.LT.DIST) GOTO 15
      JJ=JJ+1
      GOTO 16
   15 V1=VR(N,J,1)
      CALL GEOM(2,A1,HR(N,J,1),R1,T1,D1,1,1,XJ1)
      IF(X2-X1.LT.ACCUX) GOTO 8
    1 IF(XJ2.LT.X2) GO TO 9
      V2=V(N,K,1)
      CALL GEOM(2,A2,H(N,K,1),R2,T2,D2,1,1,X2)
    2 CALL CS(-1.,X1,X2,XE,XP,D1,D2,DE,V1,V2,VE)
      IF(DE.LT.HDRY) DE=HDRY
      IF(XE.LT.X1) GO TO 10
      IF(XE.GT.X2) GOTO 12
    3 CALL GEOM(5,AE,HE,RE,TE,DE,1,1,XE)
      T=TIME-DTE
      CALL STORM(XE,T)
      CALL FRIC(VE,HE,FE,RE,REE,REC,KE,1,XE)
      CALL OPHEAD
      SFEE=C(4)*FE*VE*ABS(VE)/(B(13)*RE)
C     SE,S1 ARE THE ENERGY COEFICIENTS OF POINTS E AND 1
      SE=1.
      S1=1.
      DX1E=XE-X1
      IF(ABS(DX1E).LT.ACCUX) SF1E=C(8)
      IF(ABS(DX1E).LT.ACCUX) GOTO 20
      SF1E=C(8)+(B(16)*(H(N,K,1)-HE)/C(5)+B(12)**2*(S1*V1*V1-SE*VE*VE)
     $/64.4)/(DX1E*B(11))*C(9)
   20 IF(ABS(SFEE).LT.ABS(SF1E)) GOTO 4
   31 SFE=SF1E
      NR(N,J)=1
      GO TO 14
    4 SFE=(SFEE+SF1E)/2.
   14 DSQ=SQRT(C(1)*(C(1)-1.)*VE*VE+C(1)*C(20)*(DE*C(9)/C(5)+OPH))
```

```
      C7=C(7)*DTE/DT
      C1=C(11)*DTE*(C(1)*C(20)*(C(8)-SFE)+C(26)/DE*C(19)*(C7*C(25)*C(6
     $/C(9)-C(1)*VE-DSQ)*C(9)*C(5)+C(27)/DE*C(19)*(C(1)*VE+DSQ)*C(9)*
     $C(5)+B(16)/B(10)*C(29)/(TE*DE)*(C(3)*C(2)*C(24)-C(1)*VE-DSQ))
      I=1
      NCT=0
      HH(1)=HR(N,J,1)
    5 HRR=HH(I)
      CALL GEOM(6,ARR,HRR,HHR,TRR,DRR,1,1,XP)
      ALR=ALL-ARR
      AHLR=ALL*HHL-ARR*HHR
      HSQ=SQRT(C(1)*C(20)/(ALL*ARR)*(AHLR/ALR*(C(9)/C(5))**2+OPH))
      F(I)=C(9)/(C(5)*DE)*((1.-C(1))*VE-DSQ)*(HRR-HE)+VLL+ALR*HSQ-VE-C1
      IF(ABS(F(I)).LT.ACCU) GO TO 7
      IF(I.EQ.1) GO TO 6
      IF(ABS(F(1)-F(2)).LT.ACCU*ACCU) GO TO 7
      NCT=NCT+1
      IF(NCT.GT.20) SS=SQRT(-1.)
      HRR=(F(1)*HH(2)-F(2)*HH(1))/(F(1)-F(2))
      HH(1)=HH(2)
      HH(2)=HRR
      F(1)=F(2)
      GO TO 5
    6 I=2
      HH(2)=HH(1)*1.01
      GO TO 5
    7 VRR=VLL+ALR*HSQ
      CALL GEOM(2,ARR,HRR,RRR,TRR,DRR,1,2,XP)
      CALL FRIC(VRR,HRR,FRR,RRR,RER,REC,IRR,2,XP)
      FR(N,J)=FRR
      SR(N,J)=C(4)*FRR*VRR*ABS(VRR)/(B(13)*RRR)
      RETURN
    8 X2=X2+DX
      K=K+1
      GO TO 1
    9 X2=XJ2
      IF(ABS(X1-X2).LT.ACCUX) RETURN 7
      V2=VL(N,JJ+1,1)
      CALL GEOM(2,A2,HL(N,JJ+1,1),R2,T2,D2,1,1,X2)
      GO TO 2
   10 XE=X1
      DE=D1
      VE=V1
      GO TO 3
   12 IF(XJ2.GT.X2) GOTO 8
      XPE=XP-XE
      JP=JJ+1
      CALL CROSS(XP,JP,2,VE,DE,XPE,DTE,-1)
      XE=XP-XPE
      GOTO 3
      END
```

```
      SUBROUTINE JUMP(J)
C     COMPUTE XJ AND VJ OF THE DISCONTINUITY
      COMMON /B1/ B(40),C(40),Z(10),TIME,CPH,NN,N,NCH,RSL,CURVE
      COMMON /B2/ H(27,27,2),V(27,27,2),HL(27,10,2),HR(27,10,2),
     $VR(27,10,2),VL(27,10,2),VJ(27,10,2),XJ(27,10,2),JI(27,27,2),KN,NJ
      COMMON /B3/ NK(27),NJ(27),DX,DT,DIST,HMIN,VMIN,ITYPE,IO,OC(27,10),
     $S,DS
      COMMON /B8/ ACCU,ACCUX,ACCUY,HDRY,CC
      COMMON/B9/ TL(10,2),TR(10,2)
      DATA NAME/'JUMP'/
      IF(J.EQ.1) J2=0
      IF(J2.GT.0) GO TO 50
      IF(ABS(HL(N,J,1)-HR(N,J,1)).LT.ACCU) RETURN
      J1=J
      J3=J
      K1=XJ(N,J1,1)/DX+1.99999
      XE2=XJ(N,J1,1)+VJ(N,J1,1)*DT
      IF(XE2.LT.0.) GO TO 7
      IF(J1.EQ.NJJ) GO TO 1
      XE3=XJ(N,J1+1,1)+VJ(N,J1+1,1)*DT
      IF(XE2.LT.XE3) GO TO 1
C     TWO DISCONTINUITIES CROSS EACH OTHER TO PRODUCE A NEW DISCONTINUITY
      J2=J1+1
      J3=J2
      DTT=DT
      DT=(XJ(N,J2,1)-XJ(N,J1,1))/(VJ(N,J1,1)-VJ(N,J2,1))
      TIME=TIME-DTT+DT
      XE2=XJ(N,J2,1)+VJ(N,J2,1)*DT
      KK2=XE2/DX+1.99999
      KK1=KK2-1
      H1=H(N,KK1,1)
      V1=V(N,KK1,1)
      XJ1=XJ(N,J1,1)
      VJ1=VJ(N,J1,1)
      VL1=VL(N,J1,1)
      VR1=VR(N,J1,1)
      HR1=HR(N,J1,1)
      HL1=HL(N,J1,1)
      HL2=HL(N,J2,1)
      HR2=HR(N,J2,1)
      VR2=VR(N,J2,1)
      VL2=VL(N,J2,1)
      VJ2=VJ(N,J2,1)
      XJ2=XJ(N,J2,1)
      V2=V(N,KK2,1)
      H2=H(N,KK2,1)
      CALL GEOM(2,AL1,HL1,RL1,TL1,DL1,1,1,XJ1)
      CALL GEOM(2,AR2,HR2,RR2,TR2,DR2,1,1,XJ2)
      IF(AL1.GT.AR2) GO TO 19
      CALL JL(XE2,J1,VLL,HLL,$25,1)
      CALL JR1(XE2,J2,VLL,HLL,VRR,HRR,$26)
      GO TO 20
   19 CALL JR(XE2,J2,VRR,HRR,$26,1)
      CALL JL1(XE2,J1,VLL,HLL,VRR,HRR,$25)
   20 XKK2=FLOAT(KK2-1)*DX
      XKK1=XKK2-DX
```

```
      CALL JL(XKK1,J1,V(N,KK1,2),H(N,KK1,2),$49,2)
      CALL JR(XKK2,J2,V(N,KK2,2),H(N,KK2,2),$49,2)
      CALL GEOM(2,ALL,HLL,RLL,TLL,DLL,1,2,XE2)
      CALL GEOM(2,ARR,HRR,RRR,TRR,DRR,1,2,XE2)
      XJT=(ALL*VLL-ARR*VRR)/(ALL-ARR)
      DT=DTT-DT
      TIME=TIME+DT
      HL(N,J2,1)=HLL
      HR(N,J2,1)=HRR
      VR(N,J2,1)=VRR
      VL(N,J2,1)=VLL
      VJ(N,J2,1)=XJT
      XJ(N,J2,1)=XE2
      XJ(N,J1,1)=0.
      XE2=XE2+XJT*DT
      IF(XE2.GT.DIST) GO TO 11
      CALL CONJ(XE2,J2,VLL,HLL,VRR,HRR,$7)
      DT=DTT
      V(N,KK1,1)=V1
      H(N,KK1,1)=H1
      H(N,KK2,1)=H2
      V(N,KK2,1)=V2
      XJ(N,J1,1)=XJ1
      VJ(N,J1,1)=VJ1
      VL(N,J1,1)=VL1
      VR(N,J1,1)=VR1
      HR(N,J1,1)=HR1
      HL(N,J1,1)=HL1
      HL(N,J2,1)=HL2
      HR(N,J2,1)=HR2
      VR(N,J2,1)=VR2
      VL(N,J2,1)=VL2
      VJ(N,J2,1)=VJ2
      XJ(N,J2,1)=XJ2
      GO TO 4
C     THERE IS SINGLE DISCONTINUITY
    1 J2=0
      J3=J
      IF(XE2.GT.DIST) GO TO 11
      CALL CONJ(XE2,J,VLL,HLL,VRR,HRR,$7)
    4 IF(VLL.LT.VRR) GO TO 7
      CALL GEOM(2,ALL,HLL,RLL,TLL,DLL,1,2,XE2)
      CALL GEOM(2,ARR,HRR,RRR,TRR,DRR,1,2,XE2)
      XJT=(ALL*VLL-ARR*VRR)/(ALL-ARR)
      CALL STORM(XE2,TIME)
      CALL OPHEAD
      IF(ALL.GT.ARR) GOTO 6
      FRR=FRTST((VRR-XJT),DRR,OPH,C(1),C(5),C(9),C(20),1)
      FRL=FRTST((VLL-XJT),DLL,OPH,C(1),C(5),C(9),C(20),1)
      IF(FRL.GT.0..AND.FRR.LT.0.) GOTO 8
      GOTO 7
    6 FRR=FRTST((XJT-VRR),DRR,OPH,C(1),C(5),C(9),C(20),1)
      FRL=FRTST((XJT-VLL),DLL,OPH,C(1),C(5),C(9),C(20),1)
      IF(FRL.LT.0..AND.FRR.GT.0.)GO TO 8
    7 DO 9 JJ=J1,J3
      XJ(N,JJ,2)=0.
    9 CONTINUE
```

```
      RETURN
    8 DO 10 JJ=J1,J3
      XJ(N,JJ,2)=XE2
      VJ(N,JJ,2)=XJT
      VL(N,JJ,2)=VLL
      VR(N,JJ,2)=VRR
      HR(N,JJ,2)=HRR
      HL(N,JJ,2)=HLL
      IF(N.EQ.NCH) TL(JJ,2)=TLL
      IF(N.EQ.NCH) TR(JJ,2)=TRR
      OC(N,JJ)=NAME
   10 CONTINUE
      RETURN
   25 CALL CONJ(XE2,J2,VLL,HLL,VRR,HRR,$7)
      GO TO 20
   26 CALL CONJ(XE2,J1,VLL,HLL,VRR,HRR,$7)
      GO TO 20
   11 DO 15 JJ=J1,J3
      XJ(N,JJ,2)=DIST+1.
   15 CONTINUE
      RETURN
   49 SS=SQRT(-1.)
   50 J2=0
      RETURN
      END
```

```
      SUBROUTINE NEWJ
C     TO SEARCH NEW DISCONTINUITY, IF ANY
      COMMON /B1/ B(40),C(40),Z(10),TIME,OPH,NN,N,NCH,RSL,CURVE
      COMMON /B2/ H(27,27,2),V(27,27,2),HL(27,10,2),HR(27,10,2),
     $VR(27,10,2),VL(27,10,2),VJ(27,10,2),XJ(27,10,2),JI(27,27,2),KN,N J
      COMMON /B3/ NK(27),NJ(27),DX,DT,DIST,HMIN,VMIN,ITYPE,IO,OC(27,10),
     $S,DS
      COMMON /B4/ II(27,2),XI(27,2),HI(27,2),VI(27,2),QI(27,2),WI(27,2),
     $CT(27,2),CH(27,2),CV(27,2)
      COMMON/B6/AA1,BB1,CC1,SNK,IDG,SP1,XPG1,SP2,XPG2
      COMMON /B8/ ACCU,ACCUX,ACCUY,HDRY,CC
      COMMON /B9/ TL(10,2),TR(10,2)
      COMMON /B10/ DXCH,DXRS,DDXCH,DDXRS
      DIMENSION F(2),X(2)
      DATA NAME/'NEWJ'/
      KNN=KN-1
      DO 30 K=3,KNN
      IF(JI(N,K,2).GT.0) GO TO 30
      IF(V(N,K,2).GT.V(N,K-1,2)-ACCU) GO TO 30
      DXA=DX
      DXC=DX
      KA=K-1
      KAA=K-2
      KC=K+1
      HA=H(N,KA,2)
      VA=V(N,KA,2)
      HB=H(N,K,2)
      VB=V(N,K,2)
      HAA=H(N,KAA,2)
      VAA=V(N,KAA,2)
      HC=H(N,KC,2)
      VC=V(N,KC,2)
    1 IF(JI(N,KC,2).GT.0) GO TO 15
    2 IF(JI(N,KA,2).GT.0) GO TO 18
   21 I=1
      NCT=0
      X(1)=0.
    3 XX=X(I)
      HRR=HB+(HB-HC)*XX/DXC
      VRR=VB+(VB-VC)*XX/DXC
      HLL=HA+(HA-HAA)*(DX-XX)/DXA
      VLL=VA+(VA-VAA)*(DX-XX)/DXA
      XJ2=FLOAT(KA)*DX-XX
      CALL STORM(XJ2,TIME)
      CALL OPHEAD
      CALL GEOM(6,ARR,HRR,HHR,TRR,DRR,1,2,XJ2)
      CALL GEOM(6,ALL,HLL,HHL,TLL,DLL,1,2,XJ2)
      IF(ABS(ARR-ALL).LT.ACCU) GO TO 30
      IF(ALL*ARR.LT.0.) GOTO 30
      F(I)=EQDIS(ALL,VLL,HHL,ARR,VRR,HHR,OPH,C(1),C(5),C(9),C(20))
      IF(ABS(F(I)).LT.ACCU) GO TO 5
      IF(I.EQ.1) GO TO 4
      IF(NCT.EQ.0.AND.F(1)*F(2).GT.0.) GO TO 30
      NCT=NCT+1
      IF(NCT.GT.20) GO TO 30
      XX=(F(1)*X(2)-F(2)*X(1))/(F(1)-F(2))
```

```
      IF(XX.LT.0..OR.XX.GT.DX) GO TO 30
      X(1)=X(2)
      X(2)=XX
      F(1)=F(2)
      GO TO 3
    4 I=2
      X(2)=DX
      GO TO 3
    5 IF(HLL.LT.HMIN.OR.HRR.LT.HMIN) GO TO 30
      XJT=(ALL*VLL-ARR*VRR)/(ALL-ARR)
      IF(ALL.GT.ARR) GOTO 6
      FRL=FRTST((VLL-XJT),DLL,OPH,C(1),C(5),C(9),C(20),1)
      FRR=FRTST((VRR-XJT),DRR,OPH,C(1),C(5),C(9),C(20),1)
      IF(FRL.LT.0..OR.FRR.GT.0.) GOTO 30
      GOTO 7
    6 FRL=FRTST((XJT-VLL),DLL,OPH,C(1),C(5),C(9),C(20),1)
      FRR=FRTST((XJT-VRR),DRR,OPH,C(1),C(5),C(9),C(20),1)
      IF(FRL.GT.0..OR.FRR.LT.0.) GOTO 30
    7 JI(N,K,2)=1
      IF(NJJ.GT.0) GO TO 8
      J=1
      GO TO 12
    8 DO 9 J=1,NJJ
      IF(XJ(N,J,2).GT.XJ2) GO TO 10
    9 CONTINUE
      J=NJJ+1
      GO TO 12
   10 DO 11 JJJ=J,NJJ
      JJ=NJJ-JJJ+J
      XJ(N,JJ+1,2)=XJ(N,JJ,2)
      VJ(N,JJ+1,2)=VJ(N,JJ,2)
      VL(N,JJ+1,2)=VL(N,JJ,2)
      VR(N,JJ+1,2)=VR(N,JJ,2)
      HR(N,JJ+1,2)=HR(N,JJ,2)
      HL(N,JJ+1,2)=HL(N,JJ,2)
      OC(N,JJ+1)=OC(N,JJ)
   11 CONTINUE
   12 NJJ=NJJ+1
      NJ(N)=NJJ
      XJ(N,J,2)=XJ2
      VJ(N,J,2)=XJT
      VL(N,J,2)=VLL
      VR(N,J,2)=VRR
      HR(N,J,2)=HRR
      HL(N,J,2)=HLL
      OC(N,J)=NAME
      GO TO 30
   15 XK=FLOAT(K-1)*DX
      DO 16 J=1,NJJ
      IF(XJ(N,J,2).GT.XK) GO TO 17
   16 CONTINUE
   17 HC=HL(N,J,2)
      VC=VL(N,J,2)
      DXC=XJ(N,J,2)-XK
      GO TO 2
   18 XKA=FLOAT(KA-1)*DX
      DO 19 JJ=1,NJJ
```

```
      J=NJJ-JJ+1
      IF(XJ(N,J,2).LT.XKA) GO TO 20
   19 CONTINUE
   20 HAA=HR(N,J,2)
      VAA=VR(N,J,2)
      DXA=XKA-XJ(N,J,2)
      GO TO 21
   30 CONTINUE
C     TO CALCULATE THE TOP WIDTH OF DISCONTINUITIES OF GUTTRT FLOW
      IF(NN.EQ.1) RETURN
      IF(IDG.NE.1) RETURN
      IF(N.NE.NCH.OR.NJJ.EQ.0) RETURN
      DO 40 J=1,NJJ
      K=XJ(NCH,J,2)/DXCH+0.99999
      XK=FLOAT(K-1)*DXCH
      DXKJ=XJ(NCH,J,2)-XK
      IF(J.EQ.1) GO TO 31
      IF(XJ(NCH,J-1,2).LT.XK-DXCH) GO TO 31
      DXJ1K=XK-XJ(NCH,J-1,2)
      TL(J,2)=CT(K,2)+(CT(K,2)-TR(J-1,2))*DXKJ/DXJ1K
      GO TO 32
   31 TL(J,2)=CT(K,2)+(CT(K,2)-CT(K-1,2))*DXKJ/DXCH
   32 DXJK1=XK+DXCH-XJ(NCH,J,2)
      IF(J.EQ.NJJ) GO TO 33
      IF(XJ(NCH,J+1,2).GT.XK+2.*DXCH) GO TO 33
      DXK1J1=XJ(NCH,J+1,1)-XK-DXCH
      TR(J,2)=CT(K+1,2)+(CT(K+1,2)-TL(J+1,1))*DXJK1/DXK1J1
      GO TO 40
   33 TR(J,2)=CT(K+1,2)+(CT(K+1,2)-CT(K+2,2))*DXJK1/DXCH
      IF(K.GE.NN-1) TR(J,2)=TR(J,1)
   40 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE OPHEAD
C     COMPUTE THE OVERPRESSURE HEAD DUE TO RAINDROP IMPACT
      COMMON /B1/ B(35),C(35),Z(10),TIME,OPH,NN,N,NCH,RSL,CURVE
      B68=B(6)+B(8)
      OPH=C(7)*B(20)**2*C(26)*C(19)*C(25)*COS(B68)/C(1)
      RETURN
      END
```

```
      SUBROUTINE OUPT
C     OUTPUT THE RESULTS OF COMPUTATION
      COMMON /B1/ B(40),C(40),Z(10),TIME,OPH,NN,N,NCH,RSL,CURVE
      COMMON /B2/ H(27,27,2),V(27,27,2),HL(27,10,2),HR(27,10,2),
     $VR(27,10,2),VL(27,10,2),VJ(27,10,2),XJ(27,10,2),JI(27,27,2),KN,N J
      COMMON /B3/ NK(27),NJ(27),DX,DT,DIST,HMIN,VMIN,ITYPE,IO,OC(27,10),
     $S,DS
      COMMON /B4/ II(27,2),XI(27,2),HI(27,2),VI(27,2),QI(27,2),WI(27,2),
     $CT(27,2),CH(27,2),CV(27,2)
      COMMON /B5/ NG(27,27),SG(27,27),FG(27,27),NF,SF,FF
      COMMON/B6/AA1,BB1,CC1,SNK,IDG,SP1,XPG1,SP2,XPG2
      COMMON /B8/ ACCU,ACCUX,ACCUY,HDRY,CC
      IF(KN.LT.2) RETURN
      NS=NCH+1
      CALL RAIN(2,TIME)
      B(27)=0.
      IF(N.EQ.NCH.AND.B(5).GT.0.3) CALL INFLT(2,TIME)
      IF(N.GT.NCH.AND.B(35).GT.0.3) CALL INFLT(2,TIME)
      WRITE(6,100) B(32),B(27)
  100 FORMAT(/' RAINFALL INTENSITY = ',F6.2,' (IN./HR) INFILTRAION RAT
     $= ',E8.3,' (IN./HR)')
      CALL CRISEC
      IF(NJJ.GT.0) CALL WRITJ
      WRITE(6,200)
  200 FORMAT(/4X,'X',6X,'V',7X,'H',7X,'Q',5X,'FROUDE',2X,'REYNOLDS',2X,
     $'CRI RE',2X,'F',3X,'FRIC',4X,'SLOPE F',2X,'E',3X,'V(FPS)',3X,
     $'H(FT)',4X,'Q(CFS)')
      KNM=KN
      IF(N.LT.NCH.AND.IDG.EQ.1) KNM=KN-1
      DO 10 K=1,KNM
      IF(ITYPE.EQ.5.AND.N.EQ.NCH.AND.K.EQ.1) GO TO 10
      HH=H(N,K,2)
      IF(HH.LT.HDRY*1.01) GO TO 10
    1 VV=V(N,K,2)
      XK=FLOAT(K-1)*DX
      CALL GEOM(2,A,HH,R,T,D,1,2,XK)
      CALL STORM(XK,TIME)
      CALL OPHEAD
      Q=VV*A
      CALL FRIC(VV,HH,F,R,RE,REC,KF,2,XK)
      VEL=VV*B(12)
      HEI=HH*B(16)/C(5)
      FR=FRTST(VV,D,OPH,C(1),C(5),C(9),C(20),2)
      FLOW=VEL*A*B(18)
      IF(K.EQ.1) GO TO 14
      WRITE(6,201)XK,VV,HH,Q,FR,RE,REC,KF,FG(N,K),SG(N,K),NG(N,K),VEL
     $,HEI,FLOW
  201 FORMAT(F6.3,2F8.4,E9.3,F8.4,2E9.3,I3,2E9.3,I3,3E9.3)
      GO TO 10
   14 WRITE(6,207)XK,VV,HH,Q,FR,RE,REC,KF,VEL,HEI,FLOW
  207 FORMAT(F6.3,2F8.4,E9.3,F8.4,2E9.3,I3,4X,'--',7X,'--',5X,'-',3E9.3)
   10 CONTINUE
   16 IF(NN.EQ.1) RETURN
      IF(Z(3).LT.0.5) GO TO 15
      WRITE(6,202)
  202 FORMAT(/54(' *')/'  THE CONDITIONS ON INTER BOUNDARY ARE:'/'   N',
```

```
      $4X,'X',6X,'H',6X,'V',7X,'Q',7X,'FR L',5X,'FR R',3X,'CNJ H',2X,
      $'CNJ V',3X,'XJDOT',5X,'T')
       NNN=N
       DO 12 N=1,NN
       IF(CT(N,2).LT.ACCU)GO TO 12
       CALL STORM(XI(N,2),TIME)
       CALL OPHEAD
       CALL GEOM(2,A,HI(N,2),R,T,D,1,2,XI(N,2))
       CALL GEOM(2,A,CH(N,2),RRR,TRR,DRR,1,2,XI(N,2))
       FR=FRTST(VI(N,2),D,OPH,C(1),C(5),C(9),C(20),2)
       IF(II(N,2).EQ.0) GO TO 11
       IF(CH(N,2)-HI(N,2))9,11,3
     9 FRL=FRTST((WI(N,2)-VI(N,2)),D,OPH,C(1),C(5),C(9),C(20),2)
       FRR=FRTST((WI(N,2)-CV(N,2)),DRR,OPH,C(1),C(5),C(9),C(20),2)
       GOTO 4
     3 FRL=FRTST((VI(N,2)-WI(N,2)),D,OPH,C(1),C(5),C(9),C(20),2)
       FRR=FRTST((CV(N,2)-WI(N,2)),DRR,OPH,C(1),C(5),C(9),C(20),2)
     4 WRITE(6,203)N,XI(N,2),HI(N,2),VI(N,2),QI(N,2),FRL,FRR,
      $CH(N,2),CV(N,2),WI(N,2),CT(N,2)
   203 FORMAT(I4,3F7.4,2E9.3,E9.3,2F7.4,2F8.4)
       GO TO 12
    11 WRITE(6,205)N,XI(N,2),HI(N,2),VI(N,2),QI(N,2),FR,CT(N,2)
   205 FORMAT(I4,3F7.4,2E9.3,5X,'—',5X,'—',5X,'—',6X,'—',F10.4)
    12 CONTINUE
       N=NNN
       RETURN
    15 IF(N.NE.NCH) RETURN
       IF(V(NCH,NN,2).LT.ACCU) RETURN
       QINLET=Q-C(28)
       QDIN=FLOW-B(28)
       WRITE(6,204) QINLET,QDIN
   204 FORMAT(/'  FLOW THROUGH INLET IS Q =',E9.3,'  (DIMENSIONAL DISCH R
      $GE Q =',E9.3,' CFS)')
       RETURN
       END
```

```
      SUBROUTINE PACKJ
C     ELIMINATE ANY DISCONTINUITY WHICH DISAPPEARS
      COMMON /B1/ B(40),C(40),Z(10),TIME,OPH,NN,N,NCH,RSL,CURVF
      COMMON /B2/ H(27,27,2),V(27,27,2),HL(27,10,2),HR(27,10,2),
     $VR(27,10,2),VL(27,10,2),VJ(27,10,2),XJ(27,10,2),JI(27,27,2),KN,NJJ
      COMMON /B3/ NK(27),NJ(27),DX,DT,DIST,HMIN,VMIN,ITYPE,IO,OC(27,10),
     $S,DS
      COMMON /B7/ NL(27,10),NR(27,10),SL(27,10),SR(27,10),FL(27,10),
     $FR(27,10),NFJ,SFJ,FFJ
      COMMON /B8/ ACCU,ACCUX,ACCUY,HDRY,CC
      IF(NJJ.LT.1) RETURN
   20 IF(NJJ.EQ.1) GO TO 24
      NJP=NJJ-1
      DO 23 J=1,NJP
      IF(XJ(N,J,2).GT.DIST) GOTO 19
      IF(XJ(N,J,2).GT.0..AND.ABS(XJ(N,J+1,2)-XJ(N,J,2)).GT.ACCU)GO TO 2
   19 DO 21 JJ=J,NJP
      XJ(N,JJ,2)=XJ(N,JJ+1,2)
      VJ(N,JJ,2)=VJ(N,JJ+1,2)
      VL(N,JJ,2)=VL(N,JJ+1,2)
      VR(N,JJ,2)=VR(N,JJ+1,2)
      HR(N,JJ,2)=HR(N,JJ+1,2)
      HL(N,JJ,2)=HL(N,JJ+1,2)
      OC(N,JJ)=OC(N,JJ+1)
      NL(N,JJ)=NL(N,JJ+1)
      NR(N,JJ)=NR(N,JJ+1)
      FR(N,JJ)=FR(N,JJ+1)
      FL(N,JJ)=FL(N,JJ+1)
      SL(N,JJ)=SL(N,JJ+1)
      SR(N,JJ)=SR(N,JJ+1)
   21 CONTINUE
   22 NJJ=NJP
      IF(J.LT.NJP) GO TO 20
   23 CONTINUE
   24 NJ(N)=NJJ
      IF(XJ(N,NJJ,2).GT.DIST.OR.XJ(N,NJJ,2).LT.ACCUX) NJ(N)=NJ(N)-1
      NJJ=NJ(N)
      IF(NJ(N).EQ.0) RETURN
      DO 25 J=1,NJJ
      K=XJ(N,J,2)/DX+1.99999
      JI(N,K,2)=1
   25 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE PARA
C     COMPUTE VARIABLE C'S VALUES
      COMMON /B1/ B(40),C(40),Z(10),TIME,OPH,NN,N,NCH,RSL,CURVE
      COMMON/B6/AA1,BB1,CC1,SNK,IDG,SP1,XPG1,SP2,XPG2
      COMMON/B13/STR
      COMMON/B16/AAA,BB3,CCC,TD,RTO,RMN,RAV
      DIMENSION A1(80),A2(80)
      DATA A1/' BETA',' ',' EPSIL','ON',' BETA','L',' THETA',' O',2*' ',
     1' PHI Z',' ',' DELTA',' ',' THETA',' Z',2*' ',' T O',' ',' L O',
     2' ',' V O',' ',' F O',' ',' RE O',' ',' H O',' ',' D O',' ',' R O'
     3,' ',' A O',' ',' RAIN','O',' FR O',' ',' L CH',' ',' L RS',' ',
     4' K',' ',' NU',' ',' DAMDA',' ',' RAIN',' ',' I',' ',' Q IN',' ',
     5' Q L',' ',' W',' ',' HR/HM','IN',' R (FO','R  MS)',' FT',' ',' PE
     6RCE','NT',' FT',' ',8*' ',' IS IN',' '/
      DATA A2/' BETA',' ',' TAN P','SI',' BETA','L',' SIN B','4',
     1' COS B','4',' SIN B','6+S8',' C R',' ',' SIN B','8',' COS B','8',
     22*' ',' LO/DO','/C5',14*' ',' RO/43','2DD/VO',' 1/FRO','**2',
     3' L CH','*',' L RS','*',' K *',' ',' U *',' ',' DAMDA',' *',
     4'RAIN','*',' I *',' ',' Q IN','*',' Q L *',' ',' W *',5*' ',' LS *
     5',' ',' THETA',' S *',' KS *',' ',10*' '/
      GG(A,B,X)=SQRT(4.*A*A*X*X+4.*A*B*X+B*B+1.)
      IF(ABS(AA1).LT.0.1E-20) GOTO 12
      RSL=(2.*AA1*B(22)+BB1)/(4.*AA1)*GG(AA1,BB1,B(22))+1./(4.*SQRT(AA1*
     $AA1))*ALOG(8.*AA1*AA1*B(22)+4.*AA1*BB1+4.*SGRT(AA1*AA1)*GG(AA1,BB1
     $,B(22)))-BB1/(4.*AA1)*GG(AA1,BB1,0.)-1./(4.*SQRT(AA1*AA1))*ALOG(4.
     $*AA1*BB1+4.*SQRT(AA1*AA1)*GG(AA1,BB1,0.))
      GOTO 13
   12 RSL=SQRT(BB1**2+1.)*B(22)
   13 C(1)=B(1)
      C(2)=SIN(ATAN(SIN(B(4))/SP2))
      C(3)=B(3)
      C(7)=1.5*B(26)/(60.*60.*B(7))*0.01*B(11)/B(12)
      C(10)=B(9)/B(11)
      C(11)=B(11)/B(16)/C(5)
      C(12)=B(5)/B(17)
      C(19)=B(19)/(43200.*B(12))
      C(20)=1./B(20)**2
      C(21)=B(21)/B(11)
      C(22)=B(22)/B(11)
      C(23)=B(23)/B(17)
      C(25)=B(25)/B(12)
      C(26)=B(26)/B(19)
      C(27)=B(27)/B(19)
      C(28)=B(28)/(B(12)*B(18))
      C(29)=B(29)*C(5)/(B(12)*B(16))
      C(30)=B(30)/B(12)
      C(33)=B(33)/B(11)
      C(34)=ATAN(B(34))
      C(35)=B(35)/B(17)
      C(36)=B(36)
      C(37)=B(37)
      C(40)=B(40)*C(5)/B(16)
C     THE FOLLOWING TWO STATEMENTS ARE SET TO CHANGE TD BY STR (DIMENSI-
C     ONLESS TIME FOR RAIN TO STOP).
      STR=5.
      IF(TD*60.*B(12)/B(11).GT.STR) TD=STR*B(11)/B(12)/60.
```

```
      WRITE(6,200)
  200 FORMAT(/' TABLE OF INPUT DATA AND DIMENSIONLESS PARAMETERS:'
     $//5X,'I',11X,'B(I)',20X,'C(I)'/)
      DO 10 I=1,40
      IIII=2*I
      III=IIII-1
      WRITE(6,201)I,B(I),A1(III),A1(IIII),C(I),A2(III),A2(IIII)
  201 FORMAT(I6,2X,2(F11.4,1X,2A6))
      IF(I/5*5.EQ.I) WRITE(6,202)
  202 FORMAT(1X)
   10 CONTINUE
      WRITE(6,203) RSL
  203 FORMAT(/' RSL = ',F6.2,' FT')
      RETURN
      END
```

```
      SUBROUTINE PREP
C     SET UP THE VALUES OF THOSE PARAMETERS WHICH CHANGE WITH SECTION N
      COMMON /B1/ B(40),C(40),Z(10),TIME,OPH,NN,N,NCH,RSL,CURVE
      COMMON /B2/ H(27,27,2),V(27,27,2),HL(27,10,2),HR(27,10,2),
     $VR(27,10,2),VL(27,10,2),VJ(27,10,2),XJ(27,10,2),JI(27,27,2),KN,NJJ
      COMMON /B3/ NK(27),NJ(27),DX,DT,DIST,HMIN,VMIN,ITYPE,IO,OC(27,10),
     $S,DS
      COMMON /B4/ II(27,2),XI(27,2),HI(27,2),VI(27,2),QI(27,2),WI(27,2),
     $CT(27,2),CH(27,2),CV(27,2)
      COMMON/B6/AA1,BB1,CC1,SNK,IDG,SP1,XPG1,SP2,XPG2
      COMMON /B10/ DXCH,DXRS,DDXCH,DDXRS
      DIMENSION STAR(18)
      DATA STAR/18*' * * *'/
      DATA Z(2)/0./
      DATA IO/0/
      C(7)=1.5*B(26)/(60.*60.*B(7))*DT*B(11)/B(12)
      IF(Z(2).GT.0.) QIN=B(28)
      Z(2)=0.
      NJJ=NJ(N)
      IF(N-NCH)2,3,2
C     FOR CHANNEL FLOW
    3 DX=DXCH
      B(28)=QIN
      C(28)=B(28)/(B(12)*B(18))
      DIST=C(21)
      KN=NN
      IF(IO.EQ.1) WRITE(6,200) STAR
  200 FORMAT(/18A6/'  FOR CHANNEL FLOW')
      RETURN
C     FOR OVERLAND FLOW
    2 IF(N.GT.NCH) XI(N,2)=C(33)
      DIST=XI(N,2)
      DXPG1=XPG1/B(11)
      DXPG2=XPG2/B(11)
      IF(ITYPE.EQ.3) DIST=C(22)+DXPG1+DXPG2
      IF(NN.EQ.1) DIST=C(22)+DXPG1+DXPG2
      DX=DXRS
      KN=DIST/DX+1.99999
      B(28)=0.
      C(28)=0.
      IF(IO.EQ.1) WRITE(6,201) STAR,N
  201 FORMAT(18A6/'  FOR OVERLAND FLOW,SECTION',I3)
      IF(IO.EQ.0.OR.Z(1).LT.0.0001) RETURN
      DZ1=Z(1)*B(11)/B(12)
      WRITE(6,202)Z(1),DZ1
  202 FORMAT(/5X,76('.')/5X,'. AT TIME =',F9.3,5X,'(DIMENSIONAL TIME ='
     $F9.3,' SEC.) RAINFALL STOPS .'/5X,76('.'))
      Z(1)=-1.
      RETURN
      END
```

```
      SUBROUTINE RAIN(IR,TMDL)
C     COMPUTE RAINFALL INTENSITY
      COMMON /B1/ B(40),C(40),Z(10),TIME,CPH,NN,N,NCH,RSL,CURVE
      COMMON/B16/AAA,BBB,CCC,TD,RTO,RMN,RAV
C     INDEX IR=1, COMPUTE AVERAGE RAINFALL INTENSITY, RAV, IN./HR
C              2, COMPUTE INSTANT RAINFALL INTENSITY, RINT, IN./HR
C              3, COMPUTE TEMPORAL MEAN RAINFALL INTENSITY, RMN, IN./HR
C     USE THE RATE-DURATION-FREQUENCY FORMULA,
C     RAV=AAA/(TD+BBB)**CCC
C     RTO=SKEWNESS OF STORM PATTERN
C     TD=TIME DURATION, MINUTES
C     AAA, BBB, CCC=PARAMETERS
C     CCC MUST BE LESS THAN UNITY IN CASE THAT BBB IS LESS THAN ZERO
      GO TO(1,2,3),IR
    1 READ(5,100) AAA,BBB,CCC,TD,RTO
  100 FORMAT(8F10.0)
      WRITE(6,200) AAA,BBB,CCC,TD,RTO
  200 FORMAT(/' RAINFALL PARAMETERS ARE  A = ',F8.2,' B = ',F8.2,' C = '
     $,F8.2,' TIME DURATION (TD) = ',F8.2,' (MINUTES) RATIO (R) = ',F8.3
     $)
      IF(BBB.LE.0.) GOTO 11
      RAV=AAA/(TD+BBB)**CCC
      B(26)=RAV
      RETURN
   11 BBB=-BBB
      IF(CCC.GE.1.) SSS=SQRT(-1.)
      RAV=AAA/(TD-BBB)**CCC
      IF(TD.LE.2.*BBB/(1.-CCC)) RAV=AAA/BBB**CCC*((1.-CCC)/(1.+CCC))**CC
     $C
      B(26)=RAV
      RETURN
    2 TTT=TMDL*B(11)/B(12)/60.
      IF(TTT.LE.TD) GOTO 20
      RINT=0.
      B(32)=RINT
      RETURN
   20 IF(BBB.LE.0.) GOTO 21
      IF(RTO.LE.0.) RINT=AAA*((1.-CCC)*TTT+BBB)/(TTT +BBB)**(1.+CCC)
      IF(RTO.GE.1.) RINT=AAA*((1.-CCC)*(TD-TTT)+BBB)/((TD-TTT)+BBB)**(1.
     $+CCC)
      IF(RTO.GT.0..AND.RTO.LT.1..AND.TTT.LE.RTO*TD) RINT=AAA*((1.-CCC)*
     $(TD-TTT/RTO)+BBB)/((TD-TTT/RTO)+BBB)**(1.+CCC)
      IF(RTO.GT.0..AND.RTO.LT.1..AND.TTT.GT.RTO*TD.AND.TTT.LE.TD) RINT=
     $AAA*((1.-CCC)*(TTT-RTO*TD)/(1.-RTO)+BBB)/((TTT-RTO*TD)/(1.-RTO)+
     $BBB)**(1.+CCC)
      B(32)=RINT
      RETURN
   21 BBB=-BBB
      IF(CCC.GE.1.) SSS=SQRT(-1.)
      IF(RTO.LE.0.) GOTO 22
      IF(RTO.GE.1.) GOTO 23
      GOTO 24
   22 IF(TTT.LE.2.*BBB/(1.-CCC)) RINT=AAA/BBB**CCC*((1.-CCC)/(1.+CCC))**
     $CCC
      IF(TTT.GT.2.*BBB/(1.-CCC).AND.TTT.LE.TD) RINT=AAA*((1.-CCC)*TTT-
     $BBB)/(TTT-BBB)**(1.+CCC)
```

```
      B(32)=RINT
      RETURN
   23 IF(TTT.LE.(TD-2.*BBB/(1.-CCC))) RINT=AAA*((1.-CCC)*(TD-TTT)-BBB)/(
     $(TD-TTT)-BBB)**(1.+CCC)
      IF(TTT.GT.(TD-2.*BBB/(1.-CCC)).AND.TTT.LE.TD) RINT=AAA/BBB**CCC*
     $((1.-CCC)/(1.+CCC))**CCC
      B(32)=RINT
      RETURN
   24 IF(TTT.LE.(RTO*TD-2.*BBB*RTO/(1.-CCC))) RINT=AAA*((1.-CCC)*(TD-TTT
     $/RTO)-BBB)/((TD-TTT/RTO)-BBB)**(1.+CCC)
      IF(TTT.GT.(RTO*TD-2.*BBB*RTO/(1.-CCC)).AND.TTT.LE.(RTO*TD+2.*BBB*(
     $1.-RTO)/(1.-CCC))) RINT=AAA/BBB**CCC*((1.-CCC)/(1.+CCC))**CCC
      IF(TTT.GT.(RTO*TD+2.*BBB*(1.-RTO)/(1.-CCC)).AND.TTT.LE.TD) RINT=
     $AAA*((1.-CCC)*(TTT-RTO*TD)/(1.-RTO)-BBB)/((TTT-RTO*TD)/(1.-RTO)-
     $BBB)**(1.+CCC)
      B(32)=RINT
      RETURN
    3 TTT=TMDL*B(11)/B(12)/60.
      IF(TTT.LT.TD) GOTO 30
      RMN=AAA*TD/(TD+BBB)**CCC/TTT
      RETURN
   30 IF(TTT.LE.0.1E-6) GOTO 35
      IF(BBB.LE.0.) GOTO 31
      IF(RTO.LE.0.) RMN=AAA/(TTT+BBB)**CCC
      IF(RTO.GE.1.)RMN=(AAA*TD/(TD+BBB)**CCC-AAA*(TD-TTT)/(TD-TTT+BBB)**
     $CCC)/TTT
      IF(RTO.GT.0..AND.RTO.LT.1..AND.TTT.LE.RTO*TD) RMN=(AAA*RTO*TD/(TD+
     $BBB)**CCC-AAA*RTO*(TD-TTT/RTO)/(TD-TTT/RTO+BBB)**CCC)/TTT
      IF(RTO.GT.0..AND.RTO.LT.1..AND.TTT.GT.RTO*TD.AND.TTT.LE.TD) RMN=(
     $AAA*RTO*TD/(TD+BBB)**CCC+AAA*(TTT-RTO*TD)/((TTT-RTO*TD)/(1.-RTO)+
     $BBB)**CCC)/TTT
      RETURN
   31 BBB=-BBB
      IF(CCC.GE.1.) SSS=SQRT(-1.)
      IF(RTO.LE.0.) GOTO 32
      IF(RTO.GE.1.) GOTO 33
      GOTO 34
   32 IF(TTT.LE.2.*BBB/(1.-CCC)) RMN=AAA/BBB**CCC*((1.-CCC)/(1.+CCC))**C
     $CC
      IF(TTT.GT.2.*BBB/(1.-CCC).AND.TTT.LE.TD) RMN=AAA/(TTT-BBB)**CCC
      RETURN
   33 IF(TTT.LE.(TD-2.*BBB/(1.-CCC))) RMN=(AAA*TD/(TD-BBB)**CCC-AAA*(TD-
     $TTT)/(TD-TTT-BBB)**CCC)/TTT
      IF(TTT.GT.(TD-2.*BBB/(1.-CCC)).AND.TTT.LE.TD) RMN=(AAA*TD/(TD-BBB)
     $**CCC-AAA/BBB**CCC*((1.-CCC)/(1.+CCC))**CCC*(TD-TTT))/TTT
      RETURN
   34 IF(TTT.LE.(RTO*TD-2.*BBB*RTO/(1.-CCC))) RMN=(AAA*RTO*TD/(TD-BBB)**
     $CCC-AAA*RTO*(TD-TTT/RTO)/(TD-TTT/RTO-BBB)**CCC)/TTT
      IF(TTT.GT.(RTO*TD-2.*BBB*RTO/(1.-CCC)).AND.TTT.LE.(RTO*TD+2.*BBB*(
     $1.-RTO)/(1.-CCC))) RMN=(AAA*RTO*TD/(TD-BBB)**CCC+AAA/BBB**CCC*((1.
     $-CCC)/(1.+CCC))**CCC*(TTT-RTO*TD))/TTT
      IF(TTT.GT.(RTO*TD+2.*BBB*(1.-RTO)/(1.-CCC)).AND.TTT.LE.TD) RMN=
     $(AAA*RTO*TD/(TD-BBB)**CCC+AAA*(TTT-RTO*TD)/((TTT-RTO*TD)/(1.-RTO)-
     $BBB)**CCC)/TTT
      RETURN
   35 RMN=0.
      RETURN
```

```
114          END
```

```
      SUBROUTINE REF
C     COMPUTE THE REFERENCE PARAMETERS
      COMMON /B1/ B(40),C(40),Z(10),TIME,OPH,NN,N,NCH,RSL,CURVE
      COMMON/B6/AA1,BB1,CC1,SNK,IDC,SP1,XPG1,SP2,XPG2
      COMMON /B8/ ACCU,ACCUX,ACCUY,HDRY,CC
      DIMENSION F(2),Y(2),RR(2)
C     REFERENCE FLOW IS ASSUMED AS UNIFORM FLOW PER UNIT WIDTH AT THE
C     EQUILIBRIUM STATE AT THE INLET
      B(11)=B(21)
      N=1
      ACCU=0.1E-6
      HDRY=0.1E-4
      ACCUX=ACCU/B(11)
      B(4)=ASIN(B(4))
      B(8)=B(4)
      B(32)=B(26)
      C(4)=SIN(B(4))
      C(5)=COS(B(4))
      C(6)=SIN(B(6)+B(8))
      C(8)=SIN(B(8))
      C(9)=COS(B(8))
      SO=ABS(C(4))
      IF(C(4).GT.0.) GOTO 22
      CC=0.
      GOTO 23
   22 CC=B(36)*C(4)**B(37)
   23 IF(CC.LT.24.) CC=24.
      AREA=B(21)*(B(22)+XPG1+XPG2+B(33)+B(9))*C(5)
      Q0=B(26)*AREA/(12.*60.*60.)+B(28)
      B(19)=12.*60.*60./AREA*Q0
      IF(B(23).LT.ACCU) GO TO 4
C     WHEN ROUGHNESS SIZE K IS LARGER THAN ACCU, ASSUME TURBULENT FLOW
C     ON ROUGH SURFACE
      I=1
      NCT=0
      Y(1)=0.1
    1 H0=Y(I)
      CALL GEOM(2,A0,H0,R0,T0,D0,2,1,1)
      F1=2.*ALOG10(2.*R0/B(23))+1.74
      F(I)=257.6*A0*A0*R0*SO*F1*F1-Q0*Q0
      IF(ABS(F(I)).LT.ACCU) GO TO 3
      IF(I.EQ.1) GO TO 2
      NCT=NCT+1
      IF(NCT.GT.20) SS=SQRT(-1.)
      IF(ABS(F(1)-F(2)).LT.ACCU*ACCU) GO TO 3
      H0=(F(1)*Y(2)-F(2)*Y(1))/(F(1)-F(2))
      Y(1)=Y(2)
      Y(2)=H0
      F(1)=F(2)
      GO TO 1
    2 I=2
      Y(2)=0.5
      GO TO 1
    3 B(12)=Q0/A0
      B(14)=B(12)*R0/B(24)
C     CALCULATE THE CRITICAL RENOLDS NUMBER BETWEEN TURBULENT FLOW ON
```

```
C     SMOOTH SURFACE AND LAMINAR FLOW
    4 REC=500.
      NCT=0
    5 F1=REC-CC*(ALOG10(REC)+ALOG10(CC)+0.404)**2
      F2=1.-2.*SQRT(CC)/(ALOG(10.)*SQRT(REC))
      RECC=REC-F1/F2
      IF(ABS(RECC-REC).LT.ACCU) GO TO 6
      NCT=NCT+1
      IF(NCT.GT.20) SS=SQRT(-1.)
      REC=RECC
      GO TO 5
    6 RELS=RECC
      IF(B(23).LT.ACCU) GO TO 9
C     CALCULATE THE CRITICAL RENOLDS NUMBER BETWEEN TURBULENT FLOW ON
C     ROUGH SURFACE AND LAMINAR FLOW
      F1=2.*ALOG10(2.*RO/B(23))+1.74
      RELR=CC*F1*F1
      IF(RELS.GT.RELR) GO TO 7
C     RESR=THE CRITICAL REYNOLDS NO. BETWEEN TURBULENT FLOW ON SMOOTH
C     SURFACE AND THAT ON ROUGH SURFACE
      RESR=9.312*RO*F1/B(23)
      IF(RESR-B(14)) 8,8,9
    7 IF(RELR.GT.B(14)) GO TO 15
    8 B(13)=1./F1**2
      GO TO 20
C     ASSUME TURBULENT FLOW ON SMOOTH SURFACE
    9 I=1
      NCT=0
      RR(1)=(CC*Q0*Q0/(257.6*S0*RELS))**(1./3.)
   10 RO=RR(I)
      CALL GEOM(3,A0,H0,RO,T0,D0,2,1,1)
      F1=SQRT(257.6*RO*S0)*A0/Q0
      F(I)=2.*ALOG10(Q0*RO/(A0*B(24))*F1)+0.404-1./F1
      IF(ABS(F(I)).LT.ACCU) GO TO 12
      IF(I.EQ.1) GO TO 11
      NCT=NCT+1
      IF(NCT.GT.20) SS=SQRT(-1.)
      RO=(F(1)*RR(2)-F(2)*RR(1))/(F(1)-F(2))
      RR(1)=RR(2)
      RR(2)=RO
      F(1)=F(2)
      GO TO 10
   11 I=2
      RR(2)=RO*1.2
      GO TO 10
   12 B(12)=Q0/A0
      B(14)=B(12)*RO/B(24)
      IF(B(14).LT.RELS) GO TO 15
      B(13)=F1*F1
      GO TO 20
C     COMPUTE F AND R FOR LAMINAR FLOW, F=C/RE AND Q=8*G*S*R*R*A/(C*NU)
   15 RR(1)=(CC/8.*Q0*B(24)/(32.2*S0))**(1./3.)
      I=1
      NCT=0
   16 RO=RR(I)
      CALL GEOM(3,A0,H0,RO,T0,D0,2,1,1)
      F(I)=32.2*RO**2*S0*A0/(CC/8.*B(24))-Q0
```

```
      IF(ABS(F(I)).LT.ACCU) GO TO 18
      IF(I.EQ.1) GO TO 17
      NCT=NCT+1
      IF(NCT.GT.20) SS=SQRT(-1.)
      RO=(F(1)*RR(2)-F(2)*RR(1))/(F(1)-F(2))
      RR(1)=RR(2)
      RR(2)=RO
      F(1)=F(2)
      GO TO 16
   17 I=2
      RR(2)=RO*1.2
      GO TO 16
   18 B(12)=QO/AO
      B(14)=B(12)*RO/B(24)
      B(13)=CC/B(14)
      IF(RELS.LT.B(14)) SS=SQRT(-1.)
   20 B(15)=HO
      B(10)=TO
      B(16)=DO
      B(17)=RO
      B(18)=AO
      B(20)=B(12)/SQRT(32.2*B(16)*C(5)/B(1))
      ACCUY=ACCU*C(5)/B(16)
      RETURN
      END
```

```
      SUBROUTINE SLOPE
C     COMPUTE RUNOFF DISCHARGE FROM SIDESLOPE
      COMMON /B1/ B(40),C(40),Z(10),TIME,OPH,NN,N,NCH,RSL,CURVE
      COMMON /B2/ H(27,27,2),V(27,27,2),HL(27,10,2),HR(27,10,2),
     $VR(27,10,2),VL(27,10,2),VJ(27,10,2),XJ(27,10,2),JI(27,27,2),KN,NJJ
      COMMON /B3/ NK(27),NJ(27),DX,DT,DIST,HMIN,VMIN,ITYPE,IO,CC(27,10),
     $S,DS
      COMMON /B4/ II(27,2),XI(27,2),HI(27,2),VI(27,2),QI(27,2),WI(27,2),
     $CT(27,2),CH(27,2),CV(27,2)
C     IFC=INDEX FOR COMPUTATION OF NEWLY OCCURRING SHOCK WAVES
C         1, ASSUME NO NEW SHOCK WAVES
C         2, OTHERWISE
      IFC=1
      CALL PREP
      IF(KN.LT.2) RETURN
      CALL INPT
      CALL UBDY
      CALL DBDY
      IF(NJJ.GT.0) CALL PACKJ
      IF(IFC.EQ.2) CALL NEWJ
      CALL GEOM(2,AS,H(N,KN,2),RS,TS,DS,1,2,DIST)
      QS=V(N,KN,2)*AS
      DO 1 K=1,NN
      QI(K,1)=QI(K,1)+QS
    1 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE STORM(X,TTTT)
C     SET UP THE VALUES OF THOSE PARAMETERS WHICH CHANGE WITH THE
C     LONGITUDINAL COORDINATE
      COMMON /B1/ B(40),C(40),Z(10),TIME,OPH,NN,N,NCH,RSL,CURVE
      COMMON /B2/ H(27,27,2),V(27,27,2),HL(27,10,2),HR(27,10,2),
     $VR(27,10,2),VL(27,10,2),VJ(27,10,2),XJ(27,10,2),JI(27,27,2),KN,NJJ
      COMMON /B3/ NK(27),NJ(27),DX,DT,DIST,HMIN,VMIN,ITYPE,IO,OC(27,10),
     $S,DS
      COMMON /B4/ II(27,2),XI(27,2),HI(27,2),VI(27,2),QI(27,2),WI(27,2),
     $CT(27,2),CH(27,2),CV(27,2)
      COMMON/B6/AA1,BB1,CC1,SNK,IDG,SP1,XPG1,SP2,XPG2
      COMMON /B8/ ACCU,ACCUX,ACCUY,HDRY,CC
      COMMON /B10/ DXCH,DXRS,DDXCH,DDXRS
      COMMON/B16/AAA,BBB,CCC,TD,RTC,RMN,RAV
      COMMON/B17/FINF,BETTA,ALPHA,TO,TP,VSF,SPI
      DATA IITYPE/0/
      DATA Z(1)/0./
      GG(A,B,Y)=SQRT(4.*A*A*Y*Y+4.*A*B*Y+B*B+1.)
C     FCTA=AREA MODIFICATION FACTOR DUE TO CURVED ROADWAY
C     RADLS=DIMENSIONLESS RADIUS OF CURVATURE (RADIUS/B(11))
      IF(CURVE.GT.0.1E-5) RADLS=1./CURVE/B(11)
      DXPG1=XPG1/B(11)
      DXPG2=XPG2/B(11)
      IF(CURVE.GT.0.1E-5) FCTA=1.+(C(22)+DXPG1+DXPG2-X)/RADLS
      IF(IITYPE.EQ.0) IITYPE=ITYPE
      IF(TTTT.GT.TD*60.*B(12)/B(11).AND.ABS(Z(1)).LT.0.0001) Z(1)=TD*60.
     $*B(12)/B(11)
      K=X/DX+1.99999
      XRAIN=C(30)*TTTT
      IF(N-NCH) 2,10,13
    2 C(24)=0.
      B(29)=0.
      IF(X.GT.C(22)) GOTO 4
      XL=X*B(11)
      IF(ABS(AA1).LT.0.1E-20) GOTO 1
      SATO=BB1/(4.*AA1)*SQRT(BB1*BB1+1.)+1./(4.*SQRT(AA1*AA1))*ALOG(4.*A
     $A1*BB1+4.*SQRT(AA1*AA1)*SQRT(BB1*BB1+1.))
      RSX=(2.*AA1*XL+BB1)/(4.*AA1)*GG(AA1,BB1,XL)+1./(4.*SQRT(AA1*AA1))*
     $ALOG(8.*AA1*AA1*XL+4.*AA1*BB1+4.*SQRT(AA1*AA1)*GG(AA1,BB1,XL))-SAT
     $0
      GOTO 9
    1 RSX=SQRT(BB1**2+1.)*XL
    9 S=RSX/B(11)
    3 TAN=-(2.*AA1*XL+BB1)
      B(8)=ATAN(TAN)
      DS=DX/COS(B(8))
      GOTO 5
    4 IF(INT(XPG1).EQ.0) GOTO 7
      IF(X.LE.(C(22)+DXPG1)) GOTO 6
    7 B(8)=ASIN(SP2)
      S=RSL/B(11)+(X-C(22))/COS(B(8))
      DS=DX/COS(B(8))
      GOTO 5
    6 B(8)=ASIN(SP1)
      S=RSL/B(11)+(X-C(22))/COS(B(8))
      DS=DX/COS(B(8))
```

```
    5 IF(IITYPE.NE.6) GOTO 8
      PRAIN=C(22)+DXPG1+DXPG2-XRAIN
      KPR=PRAIN/DX+1.99999
      IF(KPR.GE.2) H(N,KPR-1,1)=HMIN
      IF(PRAIN.GT.DX) H(N,1,2)=HDRY
      IF(X-PRAIN) 15,15,16
    8 IF(ITYPE.NE.3) GO TO 16
      IF(XRAIN-X) 15,15,16
   16 B(8)=B(4)
      DX1=FLOAT(K-1)*DX-X
      IF(ITYPE.EQ.5) GO TO 14
      IF(ITYPE.NE.2) GO TO 12
      IF(XRAIN.GT.X) GO TO 11
      C(24)=0.
      B(29)=0.
      GOTO 15
   11 KRAIN=XRAIN/DX+1.99999
      IF(KRAIN.NE.K) GO TO 12
      IF(K.GE.2) GOTO 41
      B(29)=0.
      C(24)=0.
      GOTO 16
   41 DX2=XRAIN-X
      DX3=XRAIN-FLOAT(K-2)*DX
      B(29)=QI(K-1,1)*DX2/DX3*B(18)*B(12)
      C(24)=VI(K-1,1)*DX2/DX3
      GOTO 16
   12 IF(K.GE.2) GOTO 31
      B(29)=QI(K,1)*B(18)*B(12)
      C(24)=VI(K,1)
      GOTO 32
   31 B(29)=(QI(K,1)-(QI(K,1)-QI(K-1,1))*DX1/DX)*B(18)*B(12)
      C(24)=VI(K,1)-(VI(K,1)-VI(K-1,1))*DX1/DX
   32 IF(IITYPE.EQ.3.AND.XRAIN.GT.(C(22)+DXPG1+DXPG2)) GOTO 16
      IF(IITYPE.EQ.3.AND.XRAIN.LT.(C(22)+DXPG1+DXPG2)) GOTO 15
      IF(ITYPE.EQ.1) GO TO 16
      WT=CT(K,1)
      IF(K.GE.2) WT=CT(K,1)-DX1/DX*(CT(K,1)-CT(K-1,1))
      IF(XRAIN-WT) 15,15,16
   14 PRAIN=C(21)-XRAIN
      KPR=PRAIN/DX+1.99999
      IF(KPR.GE.2) H(N,KPR-1,1)=HMIN
      IF(PRAIN.GT.DX) H(N,1,2)=HDRY
      IF(PRAIN.LT.X) GO TO 21
      C(24)=0.
      B(29)=0.
      GOTO 15
   21 IF(KPR.NE.K) GOTO 22
      IF(K.GE.2) GOTO 51
      B(29)=0.
      C(24)=0.
      GOTO 23
   51 DX2=X-PRAIN
      DX3=FLOAT(K-1)*DX-PRAIN
      B(29)=QI(K,1)*DX2/DX3*B(18)*B(12)
      C(24)=VI(K,1)*DX2/DX3
      GOTO 23
```

```
   22 IF(K.GE.2) GOTO 61
      B(29)=QI(K,1)*B(18)*B(12)
      C(24)=VI(K,1)
      GOTO 23
   61 B(29)=(QI(K,1)-(QI(K,1)-QI(K-1,1))*DX1/DX)*B(18)*B(12)
      C(24)=VI(K,1)-(VI(K,1)-VI(K-1,1))*DX1/DX
   23 IF(X-PRAIN) 15,15,16
   15 B(26)=0.
      GO TO 17
   13 C(24)=0.
      B(29)=0.
   16 B(26)=B(32)
      IF(ITYPE.EQ.1) CALL RAIN(2,TTTT)
   17 C(26)=B(26)/B(19)
      C(23)=B(23)/B(17)
      IF(N.EQ.NCH) C(23)=C(12)
      IF(N.GT.NCH) C(23)=C(35)
      B(27)=0.
      IF(N.EQ.NCH.AND.B(5).GE.0.3) CALL INFLT(2,TTTT)
      IF(N.GT.NCH.AND.B(35).GE.0.3) CALL INFLT(2,TTTT)
      C(27)=B(27)/B(19)
      IF(N.NE.NCH) B(29)=0.
      C(29)=B(29)/(B(18)*B(12))
      IF(N.GT.NCH) B(8)=C(34)
      C(6)=SIN(B(6)+B(8))
      C(8)=SIN(B(8))
      C(9)=COS(B(8))
      C(2)=SIN(ATAN(SIN(B(4))/C(8)))
      C(36)=B(36)
      C(37)=B(37)
      IF(N.EQ.NCH.AND.B(5).GE.0.3) C(36)=B(38)
      IF(N.EQ.NCH.AND.B(5).GE.0.3) C(37)=B(39)
      IF(N.GT.NCH.AND.B(35).GE.0.3) C(36)=B(38)
      IF(N.GT.NCH.AND.B(35).GE.0.3) C(37)=B(39)
      IF(CURVE.GT.0.1E-5.AND.N.NE.NCH) C(26)=FCTA*C(26)
      IF(CURVE.GT.0.1E-5.AND.N.NE.NCH) C(27)=FCTA*C(27)
      RETURN
      END
```

```
      SUBROUTINE TYPE4
C     SET UP THE GUTTER FLOW CONDITIONS FOR TYPE 3 MOVING RAINSTORM
C     THE ADVANCING WAVEFRONT REACHES THE ROAD CURB
      COMMON /B1/ B(40),C(40),Z(10),TIME,OPH,NN,N,NCH,RSL,CURVE
      COMMON /B2/ H(27,27,2),V(27,27,2),HL(27,10,2),HR(27,10,2),
     $VR(27,10,2),VL(27,10,2),VJ(27,10,2),XJ(27,10,2),JI(27,27,2),KN,NJJ
      COMMON /B3/ NK(27),NJ(27),DX,DT,DIST,HMIN,VMIN,ITYPE,IO,OC(27,10),
     $S,DS
      COMMON /B4/ II(27,2),XI(27,2),HI(27,2),VI(27,2),QI(27,2),WI(27,2),
     $CT(27,2),CH(27,2),CV(27,2)
      COMMON /B8/ ACCU,ACCUX,ACCUY,HORY,CC
      COMMON /B10/ DXCH,DXRS,DDXCH,DDXRS
      DIMENSION VV(2),FF(2)
      ITYPE=1
      CALL INBDY(1,XX,HH,TT,2)
      N=NCH
      CALL STORM(0.,TIME)
      NCT=0
      HP=H(NCH,1,2)
      I=1
      VV(I)=0.1
      CALL GEOM(2,A,HP,R,T,D,1,2,0.)
   82 CALL FRIC(VV(I),HP,F,R,RE,REC,IR,2,0.)
      FF(I)=C(8)-C(4)*F/B(13)*ABS(VV(I))*VV(I)/R
      IF(ABS(FF(I)).LT.ACCU) GO TO 84
      IF(I.EQ.1) GO TO 83
      NCT=NCT+1
      IF(NCT.GT.20) SS=SQRT(-1.)
      VVV=(FF(1)*VV(2)-FF(2)*VV(1))/(FF(1)-FF(2))
      VV(1)=VV(2)
      VV(2)=VVV
      FF(1)=FF(2)
      GO TO 82
   83 I=2
      VV(2)=0.0001
      GO TO 82
   84 V(NCH,1,2)=VV(I)
      KN=XI(1,2)/DXRS+1.00001
      XI(1,1)=XI(1,2)
      DO 10 N=2,NN
      DO 9 K=1,KN
      H(N,K,2)=H(1,K,2)
      V(N,K,2)=V(1,K,2)
      JI(N,K,2)=JI(1,K,2)
    9 CONTINUE
      NK(N)=KN
      HI(N,2)=HI(1,2)
      VI(N,2)=VI(1,2)
      II(N,2)=II(1,2)
      CT(N,2)=CT(1,2)
      CH(N,2)=CH(1,2)
      CV(N,2)=CV(1,2)
      WI(N,2)=WI(1,2)
      XI(N,2)=XI(1,2)
      QI(N,2)=QI(1,2)
      XI(N,1)=XI(1,1)
```

```
      H(NCH,N,2)=H(NCH,1,2)
      V(NCH,N,2)=V(NCH,1,2)
      IF(NJJ.EQ.0) GO TO 10
      NJ(N)=NJJ
      DO 8 J=1,NJJ
      XJ(N,J,2)=XJ(1,J,2)
      VJ(N,J,2)=VJ(1,J,2)
      VR(N,J,2)=VR(1,J,2)
      VL(N,J,2)=VL(1,J,2)
      HL(N,J,2)=HL(1,J,2)
      HR(N,J,2)=HR(1,J,2)
    8 CONTINUE
   10 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE UBDY
C     SET UP UPSTREAM BOUNDARY CONDITIONS
      COMMON /B1/ B(40),C(40),Z(10),TIME,OPH,NN,N,NCH,RSL,CURVE
      COMMON /B2/ H(27,27,2),V(27,27,2),HL(27,10,2),HR(27,10,2),
     $VR(27,10,2),VL(27,10,2),VJ(27,10,2),XJ(27,10,2),JI(27,27,2),KN,NJ
      COMMON /B3/ NK(27),NJ(27),DX,DT,DIST,HMIN,VMIN,ITYPE,IO,OC(27,10),
     $S,DS
      COMMON /B8/ ACCU,ACCUX,ACCUY,HDRY,CC
      COMMON /B14/ IWET(27)
      IF(ITYPE.EQ.2.AND.IWET(N).EQ.0) H(N,1,2)=HDRY
      IF(ITYPE.EQ.5.AND.IWET(N).EQ.0) H(N,1,2)=HDRY
      CALL STORM(0.,TIME)
      IF(B(26).LT.ACCU.AND.H(N,1,1).LT.1.1*HDRY) H(N,1,2)=HDRY
      IF(H(N,1,2).GT.ACCUY) RETURN
      XJ2=XJ(N,1,2)
      IF(XJ2.GT.0..AND.XJ2.LT.DX) JI(N,2,2)=1
      IF(JI(N,2,1).EQ.1) GOTO 20
      IF(JI(N,2,2).EQ.1) GOTO 10
      IF(ITYPE.EQ.2) GO TO 5
      IF(N.EQ.1.OR.N.EQ.NCH) GO TO 5
      N1=N-1
      IF(ABS(H(N,1,1)-H(N1,1,1)).GT.ACCU) GO TO 5
      IF(ABS(V(N,1,1)-V(N1,1,1)).GT.ACCU) GO TO 5
      IF(ABS(V(N,2,1)-V(N1,2,1)).GT.ACCU) GO TO 5
      IF(ABS(H(N,2,1)-H(N1,2,1)).GT.ACCU) GO TO 5
      IF(ABS(H(N,2,2)-H(N1,2,2)).GT.ACCU) GO TO 5
      IF(ABS(V(N,2,2)-V(N1,2,2)).GT.ACCU) GO TO 5
      H(N,1,2)=H(N1,1,2)
      V(N,1,2)=V(N1,1,2)
      RETURN
    5 CALL UPT(H(N,1,1),V(N,1,1),H(N,2,1),V(N,2,1),H(N,2,2),V(N,2,2),
     $DX)
      RETURN
   10 IF(XJ2.LT.ACCUX) GO TO 12
      H2=H(N,1,1)+(H(N,2,1)-H(N,1,1))*XJ2/DX
      V2=V(N,1,1)+(V(N,2,1)-V(N,1,1))*XJ2/DX
   11 CALL UPT(H(N,1,1),V(N,1,1),H2,V2,HL(N,1,2),VL(N,1,2),XJ2)
      RETURN
   12 H(N,1,2)=HL(N,1,2)
      V(N,1,2)=VL(N,1,2)
      RETURN
   20 IF(JI(N,2,2).EQ.0) GOTO 22
      IF(XJ(N,1,1).LT.ACCUX) GO TO 21
      H2=H(N,1,1)+(HL(N,1,1)-H(N,1,1))*XJ2/XJ(N,1,1)
      V2=V(N,1,1)+(VL(N,1,1)-V(N,1,1))*XJ2/XJ(N,1,1)
      GO TO 11
   21 CALL UPT(HL(N,1,1),VL(N,1,1),0.,0.,HL(N,1,2),VL(N,1,2),XJ2)
      RETURN
   22 IF(VJ(N,1,1).LT.0.) GO TO 23
      H2=H(N,1,1)+(HL(N,1,1)-H(N,1,1))*DX/XJ(N,1,1)
      V2=V(N,1,1)+(VL(N,1,1)-V(N,1,1))*DX/XJ(N,1,1)
      CALL UPT(H(N,1,1),V(N,1,1),H2,V2,H(N,2,2),V(N,2,2),DX)
      RETURN
   23 H1=H(N,2,1)+(HR(N,1,1)-H(N,2,1))*DX/(DX-XJ(N,1,1))
      V1=V(N,2,1)+(VR(N,1,1)-V(N,2,1))*DX/(DX-XJ(N,1,1))
      CALL UPT(H1,V1,H(N,2,1),V(N,2,1),H(N,2,2),V(N,2,2),DX)
```

```
      RETURN
      END
```

```
      SUBROUTINE UPT(H1,V1,H2,V2,H3,V3,X)
C     COMPUTE V AND H AT THE UPSTREAM GRID POINT
      COMMON /B1/ B(40),C(40),Z(10),TIME,OPH,NN,N,NCH,RSL,CURVE
      COMMON /B2/ H(27,27,2),V(27,27,2),HL(27,10,2),HR(27,10,2),
     $VR(27,10,2),VL(27,10,2),VJ(27,10,2),XJ(27,10,2),JI(27,27,2),KN,NJJ
      COMMON /B3/ NK(27),NJ(27),DX,DT,DIST,HMIN,VMIN,ITYPE,IO,OC(27,10),
     $S,DS
      COMMON /B4/ II(27,2),XI(27,2),HI(27,2),VI(27,2),QI(27,2),WI(27,2),
     $CT(27,2),CH(27,2),CV(27,2)
      COMMON/B6/AA1,BB1,CC1,SNK,IDG,SP1,XPG1,SP2,XPG2
      COMMON /B8/ ACCU,ACCUX,ACCUY,HDRY,CC
      DATA C22/0./
      IF(IDG.EQ.1.AND.N.EQ.NCH) CTMIN=HMIN*B(16)/C(5)/TAN(ASIN(SP2))/B(1
     $0)
      IF(IDG.EQ.1.AND.N.EQ.NCH.AND.CT(1,2).LT.CTMIN) CT(1,2)=CTMIN
      IF(N.EQ.NCH) CALL GEOM(2,AMIN,HMIN,R,T,D,1,2,0.)
      CALL GEOM(2,ADRY,HDRY,R,T,D,1,2,0.)
      TIM=TIME-DT
      CALL STORM(0.,TIM)
      CALL GEOM(2,A1,H1,R1,T1,D1,1,1,0.)
      C1=C(28)
      IF(N.EQ.NCH) C1=C22
      C9=C(9)
      C26=C(26)
      C27=C(27)
      C29=C(29)
      CALL STORM(0.,TIME)
      C2=C(28)
      C9=C(9)+C9
      C26=C(26)+C26
      C27=C(27)+C27
      C29=C(29)+C29
      CALL STORM(X,TIME)
      CALL GEOM(2,A3,H3,R3,T3,D3,1,2,X)
      C9=C(9)+C9
      C26=C(26)+C26
      C27=C(27)+C27
      C29=C(29)+C29
      CALL STORM(X,TIM)
      CALL GEOM(2,A2,H2,R2,T2,D2,1,1,X)
      C9=(C(9)+C9)/4.
      C26=(C(26)+C26)/4.
      C27=(C(27)+C27)/4.
      C29=(C(29)+C29)/4.
      T=(T1+T2+T3)/3.
      A=A1+A2-A3+2.*DT*((C9*(C26-C27)*C(19)*T*B(11)*B(10)/B(18))+B(11)
     $*C29/(B(10)*C(5)))-(V2*A2+V3*A3-C1-C2)*(DT/X)
      IF(N.EQ.NCH.AND.IDG.EQ.1.AND.A.LT.AMIN) A=AMIN
      IF(A.LT.ADRY) A=ADRY
      CALL GEOM(1,A,H(N,1,2),R,T,D,1,2,0.)
      IF(N.EQ.NCH.AND.IDG.EQ.1.AND.H(N,1,2).LT.HMIN) H(N,1,2)=HMIN
      IF(H(N,1,2).LT.HDRY) H(N,1,2)=HDRY
      IF(N.EQ.NCH.AND.NK(1).GT.2) CALL INBDY(3,0.,H(N,1,2),T,2)
      CALL GEOM(2,A,H(N,1,2),R,T,D,1,2,0.)
      V(N,1,2)=C2/A
      IF(N.EQ.NCH) C22=C2
```

```
      RETURN
      END
```

```
      SUBROUTINE WRITJ
C     OUTPUT INFORMATION FOR DISCONTINUITIES
      COMMON /B1/ B(40),C(40),Z(10),TIME,OPH,NN,N,NCH,RSL,CURVE
      COMMON /B2/ H(27,27,2),V(27,27,2),HL(27,10,2),HR(27,10,2),
     $VR(27,10,2),VL(27,10,2),VJ(27,10,2),XJ(27,10,2),JI(27,27,2),KN,N J
      COMMON /B3/ NK(27),NJ(27),DX,DT,DIST,HMIN,VMIN,ITYPE,IO,OC(27,10),
     $S,DS
      COMMON /B7/ NL(27,10),NR(27,10),SL(27,10),SR(27,10),FL(27,10),
     $FR(27,10),NFJ,SFJ,FFJ
      WRITE(6,200)
  200 FORMAT(/'  DISCONTINUITIES:'/4X,'TYPE',5X,'XJ',4X,'VJ',13X,'V',6X,
     1'H',6X,'Q',6X,'FR',5X,'REL FR',4X,'RENOS',4X,'CRI RE',3X,'FRIC',
     26X,'SF',5X,'F',2X,'E',4X,'OCC.')
      DO 30 J=1,NJJ
      XJJ=XJ(N,J,2)
      VJJ=VJ(N,J,2)
      VLL=VL(N,J,2)
      VRR=VR(N,J,2)
      HRR=HR(N,J,2)
      HLL=HL(N,J,2)
      CALL STORM(XJJ,TIME)
      CALL OPHEAD
      CALL GEOM(2,ALL,HLL,PLL,TLL,DLL,1,2,XJJ)
      CALL GEOM(2,ARR,HRR,RRR,TRR,DRR,1,2,XJJ)
      QL=VLL*ALL
      QR=VRR*ARR
      CALL FRIC(VLL,HLL,FLL,RLL,REL,RCL,KL,2,XJJ)
      CALL FRIC(VRR,HRR,FRR,RRR,RER,RCR,KR,2,XJJ)
      FR1=FRTST((VLL-VJJ),DLL,OPH,C(1),C(5),C(9),C(20),2)
      FR2=FRTST((VRR-VJJ),DRR,OPH,C(1),C(5),C(9),C(20),2)
      F1=FRTST(VLL,DLL,OPH,C(1),C(5),C(9),C(20),2)
      F2=FRTST(VRR,DRR,OPH,C(1),C(5),C(9),C(20),2)
      IF(ARR.LT.ALL) GO TO 20
      WRITE(6,201)XJJ,VJJ,VLL,HLL,QL,F1,FR1,REL,RCL,FL(N,J),SL(N,J),KL
     $,NL(N,J),OC(N,J),VRR,HRR,QR,F2,FR2,RER,RCR,FR(N,J),SR(N,J),KR,
     $NR(N,J)
  201 FORMAT(/4X,'JUMP ',2F7.4,'  LEFT ',3F7.4,2E9.4,4E9.3,2I3,4X,A6/
     $25X,'RIGHT',3F7.4,2E9.4,4E9.3,2I3)
      GO TO 30
   20 FR1=FRTST((VJJ-VLL),DLL,OPH,C(1),C(5),C(9),C(20),2)
      FR2=FRTST((VJJ-VRR),DRR,OPH,C(1),C(5),C(9),C(20),2)
      WRITE(6,202)XJJ,VJJ,VLL,HLL,QL,F1,FR1,REL,RCL,FL(N,J),SL(N,J),KL
     $,NL(N,J),OC(N,J),VRR,HRR,QR,F2,FR2,RER,RCR,FR(N,J),SR(N,J),KR,
     $NR(N,J)
  202 FORMAT(/4X,'SURGE',2F7.4,'  LEFT ',3F7.4,2E9.4,4E9.3,2I3,4X,A6/
     $25X,'RIGHT',3F7.4,2E9.4,4E9.3,2I3)
   30 CONTINUE
      RETURN
      END
```

7. Test Data

7.1. Test input

Input data for run 1 on the roadway with curb-type gutter are:

Card No.								
	ITYPE	NOUT	NN	TEND	DDXCH	DDXRS	CURVE	
1	1	5	5	10.0	100.0	4.0	0.0	
	B(1)	B(2)	B(3)	B(4)	B(5)	B(6)	B(7)	B(8)
2	1.0	1.0	1.0	0.05	0.0034	0.0	0.1575	-*
	B(9)	B(10)	B(11)	B(12)	B(13)	B(14)	B(15)	B(16)
3	-	-	400.0	-	-	-	-	-
	B(17)	B(18)	B(19)	B(20)	B(21)	B(22)	B(23)	B(24)
4	-	-	-	-	400.0	24.0	0.0034	0.0000121
	B(25)	B(26)	B(27)	B(28)	B(29)	B(30)	B(31)	B(32)
5	28.5	-	-	-	-	-	-	-
	B(33)	B(34)	B(35)	B(36)	B(37)	B(38)	B(39)	B(40)
6	-	-	0.333	235.0	0.296	510000.0	0.662	0.0
	NL	IDG	Y(1)	Y(2)	Y(3)	SUPEL	TRFCT	SPEED
7	2	1	0.0	-0.250	-0.625	-	-	-
	SP1	XPG1	SP2	XPG2				
8	0.0	0.0	0.10	3.0				
	AAA	BBB	CCC	TD	RTO			
9	20.0	**	0.0	-	-			
	FINF	BETTA	ALPHA	TO	SPI			
10	-	-	-	-	-			
11	Punch any digit but 0 on column 3							

*blank
**any digit but 0

7.2. Test output

A sample of output data is shown on the following page.

* *

* * * TIME = 1.448 (DIMENSIONAL TIME = 41.343 SEC.) *

* *

FOR OVERLAND FLOW, SECTION 3

RAINFALL INTENSITY = 20.00 (IN./HR) INFILTRAION RATE = .000 (IN./HR)
CRITICAL SECTION LOCATES AT X= .0299

X	V	H	Q	FROUDE	REYNOLDS	CRI RE	F	FRIC	SLOPE F	E	V(FPS)	H(FT)	Q(CFS)
.000	.0000	.0107	.000	.0000	.686-19	.000	0	--	--	-	.000	.386-02	.000
.010	.0197	.0196	.336-03	.5693	.160+03	.646+03	4	.454+00	.184-01	0	.272+00	.708-02	.193-02
.020	.0303	.0236	.726-03	.8103	.302+03	.755+03	4	.253+00	.208-01	0	.425+00	.853-02	.362-02
.030	.0397	.0257	.102-02	1.0023	.424+03	.825+03	4	.188+00	.230-01	1	.548+00	.929-02	.509-02
.040	.0506	.0265	.134-02	1.2574	.559+03	.871+03	4	.148+00	.293-01	0	.699+00	.960-02	.670-02
.050	.0580	.0274	.159-02	1.4178	.661+03	.916+03	4	.130+00	.325-01	1	.800+00	.991-02	.793-02

* *

THE CONDITIONS ON INTER BOUNDARY ARE:

N	X	H	V	Q	FR L	FR R	CNJ H	CNJ V	XJDOT	T
1	.0623	.0268	.0755	.202-02	.187+01	--	--	--	--	2.0876
2	.0602	.0282	.0655	.185-02	.158+01	--	--	--	--	2.9324
3	.0587	.0281	.0644	.181-02	.155+01	--	--	--	--	3.5123
4	.0582	.0281	.0640	.180-02	.155+01	--	--	--	--	3.7099
5	.0580	.0281	.0639	.179-02	.154+01	--	--	--	--	3.7801

* *

FOR CHANNEL FLOW

RAINFALL INTENSITY = 20.00 (IN./HR) INFILTRAION RATE = .000 (IN./HR)
CRITICAL SECTION LOCATES AT X= .0824

X	V	H	Q	FROUDE	REYNOLDS	CRI RE	F	FRIC	SLOPE F	E	V(FPS)	H(FT)	Q(CFS)
.000	.0000	.2412	.000	.0000	.968-19	.000	0	--	--	-	.000	.873-01	.000
.250	.3019	.3527	.190+00	2.6354	.258+05	.244+04	5	.397-01	.362-01	0	.417+01	.131+00	.950+00
.500	.3124	.4127	.259+00	2.6045	.272+05	.245+04	5	.392-01	.367-01	0	.431+01	.149+00	.129+01
.750	.3180	.4297	.286+00	2.6127	.287+05	.249+04	5	.386-01	.361-01	0	.439+01	.156+00	.143+01
1.000	.3215	.4357	.298+00	2.6275	.293+05	.250+04	5	.385-01	.362-01	0	.444+01	.158+00	.149+01

FLOW THROUCH INLET IS Q = .298+00 (DIMENSIONAL DISCHARGE Q = .149+01 CFS)

* *

FOR OVERLAND FLOW, SECTION 7

ACC COMP ERR = -2.09%, CURR COMP ERR = -.46%, WITH V0 = .113 VT = 1.302 VIN = 1.331 VOUT = .112