IMPROVED ESTIMATES OF PEAK FLOW RATES USING MODIFIED SCS LAG EQUATIONS

by

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EXECUTIVE SUMMARY

BACKGROUND

Considerable effort has been expended in the Department of Agricultural Engineering at the University of Natal, Pietermaritzburg, at improving the estimation of runoff volume using the SCS technique, in an attempt to adapt the technique for more general use and for specific application to Southern Africa. Little attention has until recently been given to the peak flow rates, which are frequently estimated poorly by the SCS Model, despite accurate estimates of runoff volume. These poor peak flow rate estimates are due largely to the coarse estimation of catchment lag time in the SCS equations.

Research into improving the estimation of lag time was conducted using data obtained from twelve small ($<3,5 km^2$) agricultural catchments located in South Africa and in the United States of America. A review of the sensitivity of estimates of peak flow rate to changes in runoff response times and the role played by both physical catchment and rainfall characteristics in determining such response times was undertaken. Following this review, it was concluded that inter- and intra- catchment adjustments should be made to estimates of catchment lag time obtained using the SCS lag equation, according to the characteristics of the rainfall event.

METHODS

Three methods were used to estimate lag time from recorded data. First, linear runoff distributions of peak discharge regressed on runoff volume were developed for each catchment using single triangular approximations of recorded runoff events. The magnitude and variability of catchment lag time was determined from such distributions. The results of this analysis indicated that the standard SCS lag equation provided poor estimates of catchment lag time when compared with estimates of catchment lag time obtained using single triangular approximations of the recorded events. Such inaccuracies were attributed to the inability of the SCS lag equation to distinguish between dominant processes of runoff on different catchments. Indices of climate and regional rainfall characteristics were shown to provide a good indication of the dominant processes contributing to runoff and an equation including such indices was regressed to enable the prediction of lag times on ungauged catchments. An examination of the effects of several rainfall parameters on intra-catchment variations in lag time showed the most intense thirty-minute period of rainfall to be the dominant parameter.

Secondly, incremental hydrographs were convoluted with the recorded storm rainfall excess to form a compound hydrograph. The lag time for the incremental hydrograph was optimised to develop a compound hydrograph representative of the recorded hydrograph. Catchment lag times, averaged from the storm lag times optimised for the individual events of each catchment, proved to be closely matched with the catchment lag times obtained from the linear regression of peak discharge regressed against runoff volume. No rainfall parameter was, however, found to be satisfactory for the estimation of individual storm lag times due to the highly variable nature of the storm lag times, which were dependent upon and seemed highly sensitive to individual rainfall bursts within the storm event. It was hypothesised that adjustments to storm lag times due to rainfall characteristics would only prove practical when incremental hydrographs are applied in conjunction with generalised rainfall depth-duration relationships.

Finally, the time response between effective rainfall and runoff was runoff volume were developed for each catchment using single triangular approximations of recorded runoff events. The magnitude and variability of catchment lag time was determined from such distributions. The results of this analysis indicated that the standard SCS lag equation provided poor estimates of catchment lag time when compared with estimates of catchment lag time obtained using single triangular approximations of the recorded events. Such inaccuracies were attributed to the inability of the SCS lag equation to distinguish between dominant processes of runoff on different catchments. Indices of climate and regional rainfall characteristics were shown to provide a good indication of the dominant processes contributing to runoff and an equation including such indices was regressed to enable the prediction of lag times on ungauged catchments. An examination of the effects of several rainfall parameters on intra-catchment variations in lag time showed the most intense thirty-minute period of rainfall to be the dominant parameter.

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Finally, the time response between effective rainfall and runoff was

measured for individual events and averaged over the data of each catchment to determine an index of catchment lag time. A large scatter of individual storm lag times suggested that such measured lag times were impractical for peak flow rate predictions.

CONCLUSIONS

It was concluded that improved inter-catchment estimates of lag time could be obtained for unguaged catchments by incorporating indices of climate and regional rainfall characteristics into an empirical lag equation. Such an equation was developed for use on small agricultural catchments with the SCS Model and is given as

$$L = \frac{A^{0,35}\ MAP^{1,10}}{41,67\ y^{0,30}\ \bar{I}_{30}^{\ 0,87}}$$

where

L = catchment lag time (h),

A = catchment area (km^2),

y = average catchment slope (percent),

MAP = mean annual precipitation (mm) and

$\bar{I}_{30}$ = regional mean of the most intense thirty minute period of rainfall (mm.h^{-1}).

Intra-catchment variations in lag time may similarly be determined from storm characteristics, although not as yet on a generalised scale.

RECOMMENDATIONS FOR FURTHER RESEARCH

In view of the markedly improved estimates of peak flow rates that have been made following the procedures of this report, it can be concluded that similar research into the estimation of peak flow rate encompassing a wider variety of study regions, is warranted. Three areas where additional research is required have been recognised, the details and objectives of which are now summarised :

1. The proportion of the total volume of runoff under the rising limb of a recorded hydrograph varies with both rainfall and catchment characteristics. The shape of the triangular unit hydrograph used in the SCS Model is, however, constant for all catchments and storms with such catchments. Future research should be directed towards the provision of relationships between rainfall and physical catchment characteristics and the shape of the unit hydrograph.

2. For design applications two typical twenty-four hour storm distributions have been derived by the SCS. Future research should be directed towards the development of regional rainfall depth-duration curves together with indices describing such curves for application in empirical equations to estimate lag time according to localised conditions of rainfall duration and intensity.

3. An extensive study of the relationship of peak flow rate regressed against volume should be undertaken. Such distributions provide a simple and yet affective method for predicting peak flow rate when limited records are available.

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- Furthermore, by determining the slopes of linearly regressed runoff relationships a procedure can be adopted to provide accurate estimates of catchment lag time.

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The results presented in this report were submitted to the University of Natal by the senior author as an integral part of his M.Sc.Eng. degree, which was awarded in 1982. Valuable comments and suggestions made by members of the W.R.C. Steering Committee of the above project, Professor J.K. Mitchell (University of Illinois, Urbana-Champaign) and Professor G.G.S. Pegram (University of Natal, Durban) have been incorporated in this report.

1. INTRODUCTION

Estimates of peak flow rates are required for the design of a variety of engineering structures built on small agricultural catchments. Poor estimates of peak flow rate can lead to underdesign and thus a high risk of failure or to overdesign with resulting additional expense. An important approach used in estimating peak flow rate on unguaged catchments requires the development of a rainfall-runoff model, based on an investigation into the factors influencing the runoff response of the catchment to rainfall.

The runoff response of a catchment is affected by the spatial and temporal distribution of the rainfall and by catchment characteristics such as physiography, land use, soil type and moisture status. There is as yet no deterministic analysis which can account satisfactorily for the effect of the above factors on the runoff hydrograph. Empirical relations have thus been developed for hydrograph synthesis, starting with the Rational Method in the 19th century, progressing to the unit hydrograph in the 1930's and to the more recent use of dimensionless hydrographs where the time to peak and flow rate are used as basic units and the hydrograph is plotted in ratios of these units.

The United States Department of Agriculture (USDA) Soil Conservation Service hydrograph generating technique, or SCS Model, uses such a dimensionless unit hydrograph, which is considered to be an average characteristic of small agricultural catchments. The Model, which is described in detail in Volume Four of the USDA National Engineering Handbook (1972) is at the present time being adapted in the Department of Agricultural Engineering at the University of Natal in Pietermaritzburg for general use with individual storms. The SCS Model, which 20 years ago was first suggested for use in South Africa by Reich (1962), is practical to use since it is physically based and the equations developed are relatively simple and can be solved graphically.

Present day problems with hydrograph development using this Model are the precise estimation of runoff volume from rainfall and the determination of lag time between such runoff and the rainfall effective in its production. The Model has been adapted to Southern African conditions (Schulze and Arnold, 1979) and is undergoing continual improvement. Recently Hope (1980) and Arnold (1980) conducted research into the estimation of runoff volume by way of improvements to the standard SCS methods for estimating the catchment antecedent moisture status and the initial abstraction component of the Model.

The purpose of the research presented in this report is to develop alternative equations to those given in the National Engineering Handbook (1972) to estimate lag time, in order to estimate peak flow rate more accurately. Throughout the present study runoff volumes have been assumed to be estimated accurately; in fact, recorded volumes of runoff have been used. The existing SCS technique bases the estimation of a catchment lag time solely on physical catchment characteristics and uses an estimate of lag time to derive the catchment unit hydrograph. However, the derivation of such a unit hydrograph from catchment characteristics makes a number of assumptions pertaining to the consistency of the unit response to inconsistent rainfall inputs. Such assumptions impose limitations on the technique and thus an improvement was sought for the estimation of peak flow rate by providing both inter- and intra-catchment adjustments to estimates of lag time to account for variations in rainfall inputs.

Before the research procedure and results are discussed a general description of the SCS Model is given and an evaluation is made of the unit hydrograph used in estimating peak flow rates. Furthermore, relationships that have been established in research elsewhere between the unit hydrograph and physical catchment characteristics and the modifications to the unit hydrograph by rainfall characteristics are reviewed. Following this initial review chapter the experimental procedures, results and discussion of results are presented. Finally, proposals for future research are made.

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2. ESTIMATION OF PEAK FLOW RATE - THEORETICAL CONSIDERATIONS

2.1 The SCS runoff equations

The relationship used in the SCS Model to estimate direct runoff volume - which is required in the determination of peak flow rate - was derived experimentally for numerous soil and vegetative cover conditions using recorded rainfall and runoff data. An equation was developed for small agricultural catchments for which only daily rainfall and catchment data are normally available. This equation is given by

$$Q = \frac{(P - I_a)^2}{(P - I_a) + S} \quad , P > I_a \qquad \text{Eq. 2.1}$$

where

Q = accumulated direct runoff (mm),

P = accumulated rainfall (mm),

I_a = initial abstraction (mm), including surface storage, interception and infiltration prior to runoff and

S = potential maximum retention of the soil (mm).

A relationship between I_a and S was derived by the SCS from records of rainfall and runoff in order to remove the necessity for estimating initial abstraction. It is given by

$$I_a = 0{,}2\ S \qquad \text{Eq. 2.2}$$

The potential maximum retention, S, is related to soil, vegetative cover and antecedent soil moisture characteristics and is transformed into a runoff Curve Number, CN, by means of the equation

$$CN = \frac{25400}{S + 254} \qquad \text{Eq. 2.3}$$

Values of CN are listed in tables which indicate their association with various hydrological soil-cover complexes for "average" antecedent soil moisture conditions (National Engineering Handbook, 1972). The CNs have to be adjusted if moisture conditions are not "average". The SCS uses three soil moisture classes, "wet", "average", and "dry", based on the five day total rainfall preceding the storm to make adjustments for antecedent conditions where necessary (National Engineering Handbook, 1972).

Calculation of peak flow rate using direct runoff volume is made by means of a dimensionless unit hydrograph developed by Mockus (1957) from natural unit hydrographs and derived from catchments differing greatly in size and geographical location. A unit hydrograph is determined as the hydrograph of direct runoff, resulting from one inch (25,4mm) of effective rainfall generated uniformly over the catchment area at a uniform rate during a specified unit period of rainfall excess (National Engineering Handbook, 1972). In the SCS Model the unit hydrograph, shown in its dimensionless form in Figure 2.1, in terms of time, t, and flow rate, q, after the start of the hydrograph rise, is approximated by a triangular hydrograph, derived in Equations 2.4 to 2.7, having the same proportion (37,5 percent) of the total volume under the rising limb as the dimensionless unit hydrograph (National Engineering Handbook, 1972).

The triangular unit hydrograph is a practical representation of excess runoff with uniform rise, one peak and uniform recession and is described mathematically by the equation

$$Q = 0{,}5\, q_p\, (t_p + t_r) \qquad \text{Eq. 2.4}$$

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$$Q = 0{,}5\, q_p\, (t_p + t_r) \qquad \text{Eq. 2.4}$$

where

Q = direct runoff volume (mm),

q_p = peak flow rate ($mm.\ h^{-1}$),

t_p = time to peak (h) and

t_r = time of recession (h).

Substituting t_p for t_r in accordance with the proportion of runoff volume under the rising limb to runoff volume under the recession limb of the triangular unit hydrograph, gives

$$q_p = \frac{2\ Q}{(1 + 1{,}67)t_p}$$

or

$$q_p = \frac{K\ Q}{t_p} \qquad \text{Eq. 2.5}$$

where

K = a constant defining the shape of the hydrograph,

= 0,75.

As shown in Figure 2.1, time to peak is related to catchment lag and storm duration by the equation

$$t_p = \frac{D}{2} + L \qquad \text{Eq. 2.6}$$

where

D = effective storm duration (h) and

L = catchment lag (h).

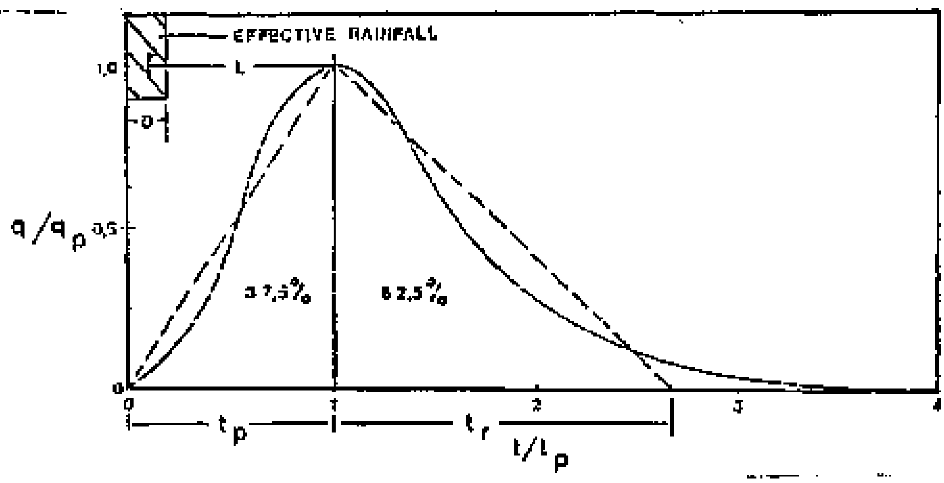
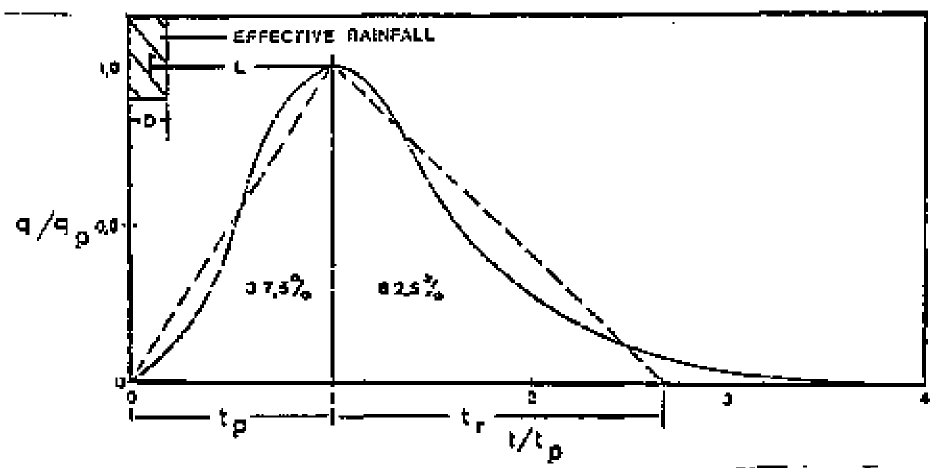


Figure 2.1 Dimensionless curvilinear unit hydrograph and approximated triangular hydrograph



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Combining Equations 2.5 and 2.6 the peak flow rate is therefore given by

$$q_p = \frac{0,75\ Q}{\frac{D}{2} + L} \qquad \text{Eq. 2.7}$$

Introducing catchment area, A in km^2, into the equation to convert the units of q_p from $mm.h^{-1}$ to $m^3.s^{-1}$ gives

$$q_{ps} = \frac{0,2083\ A\ Q}{\frac{D}{2} + L} \qquad \text{Eq. 2.8}$$

where

q_{ps} = peak flow rates ($m^3.s^{-1}$).

Lag may be envisaged as a weighted average of the time for runoff, from each point of the catchment to reach the catchment outlet. Lag is defined as the time from the centre of mass of effective rainfall to peak flow rate (National Engineering Handbook, 1972) and is related to the physical properties of a catchment by the SCS equation

$$L = \frac{l^{0,8}\ (S' + 25,4)^{0,7}}{7069\ y^{0,5}} \qquad \text{Eq. 2.9}$$

where

l = hydraulic length of the catchment (m),

y = average catchment slope (percent) and

$S' = \frac{25400}{CN'} - 254$ (mm).

where

CN' = measure of the retardance of surface conditions, and is approximated by the runoff Curve Number unadjusted for antecedent soil moisture.

Equation 2.9 was developed for areas smaller than 8 km^2 and spans a broad set of conditions extending from those with a high percent of the runoff resulting from subsurface flow to those where surface runoff predominates (National Engineering Handbook, 1972). For user convenience, a metricated graphical solution for the estimation of lag, as shown in Figure 2.2 was produced by Schulze and Arnold (1979).

Where runoff from a catchment approaches uniformity it is usually sufficient to relate lag to the catchment's time of concentration, which is defined as the time taken for runoff to travel from the hydraulically most distant part of the catchment to the catchment outlet (Kent, 1973). The relationship is given by Kent (1973) as

$$L = 0{,}6\ T_c \qquad \text{Eq. 2.10}$$

where

T_c = time of concentration (h).

The estimation of peak flow rate by Equation 2.8 assumes that a storm has a uniform areal and temporal rainfall distribution. Total storm rainfall rarely, if ever, occurs uniformly with respect to time and hence incremental unit hydrographs, derived for increments of storm duration, are employed in the Model to account for temporally varying rainfall intensities. The peak discharge for an increment of runoff is calculated by the equation

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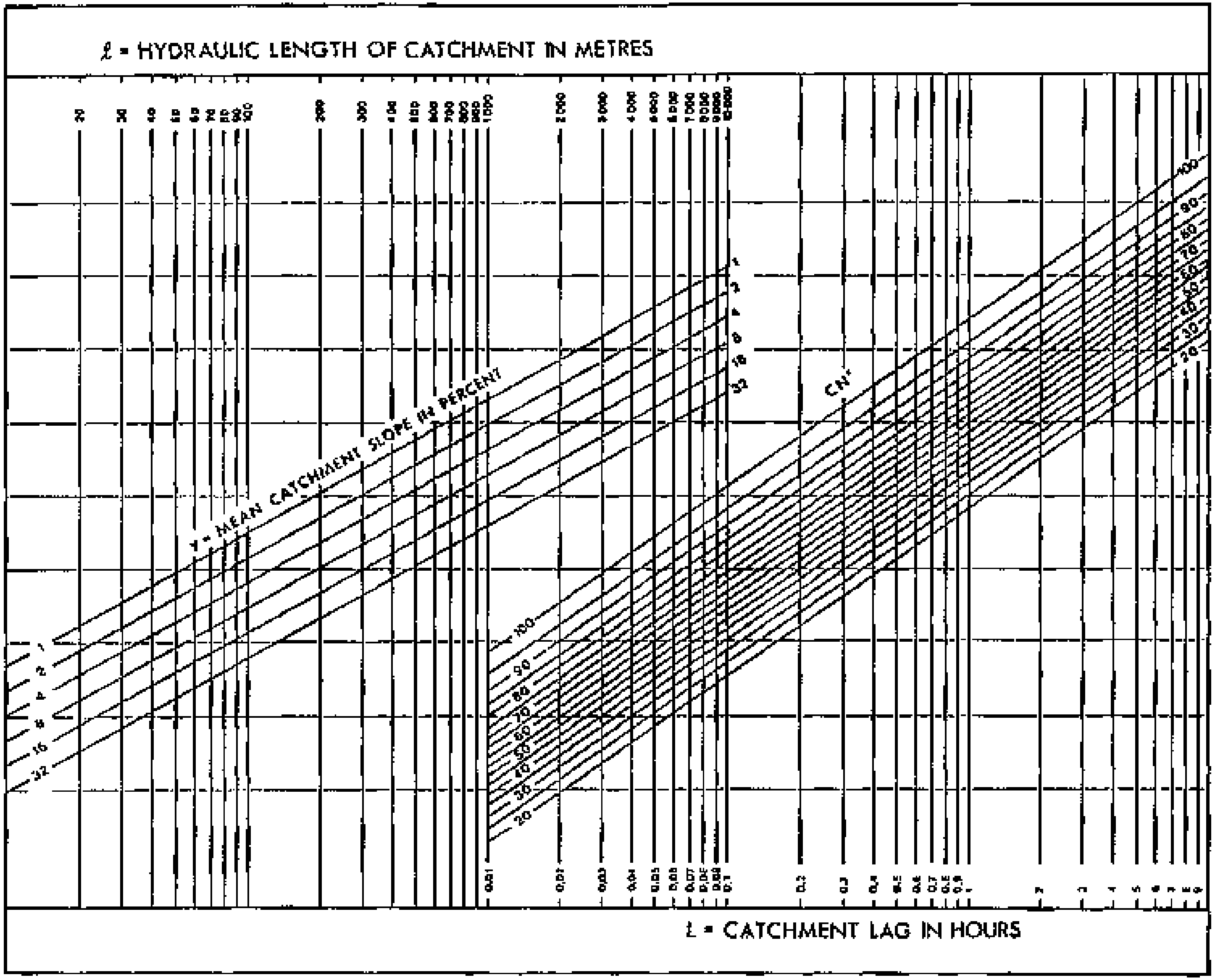

Figure 2.2 Nomograph solution to catchment lag (Schulze and Arnold, 1979)

$$\Delta q_{ps} = \frac{0.2083\ A\ \Delta Q}{\frac{\Delta D}{2} + L} \qquad \text{Eq. 2.11}$$

where

Δq_{ps} = peak flow rate of the incremental triangular hydrograph ($m^3.s^{-1}$),

ΔQ = increment of direct runoff volume (mm) and

ΔD = incremental duration of effective rainfall (h).

In applying incremental hydrographs the problem of choosing an appropriate storm duration is overcome by selecting a suitable incremental duration of effective rainfall and superimposing the resulting successive incremental hydrographs to form the complete runoff hydrograph. The recommended value of ΔD lies between 1/3 and 1/6 of the time to peak (Haan and Barfield, 1978).

The temporal distribution of storm rainfall for a particular event is not generally available. For this reason, two 24 hour design storm distributions (Type I and Type II) were developed from generalised rainfall depth-duration relationships (Kent 1973). The time distributions for the two storm types, which are associated with climatic regimes are shown in Figure 2.3. Summing incremental hydrograph ordinates, calculated from incremental rainfall depths determined from the design storm distributions, enables the development of the complete design hydrograph. Alternatively the use of only a sufficient number of incremental hydrographs to cover the peak producing period of the day's rainfall, enables the calculation of just the peak discharge without further development for the entire composite hydrograph.

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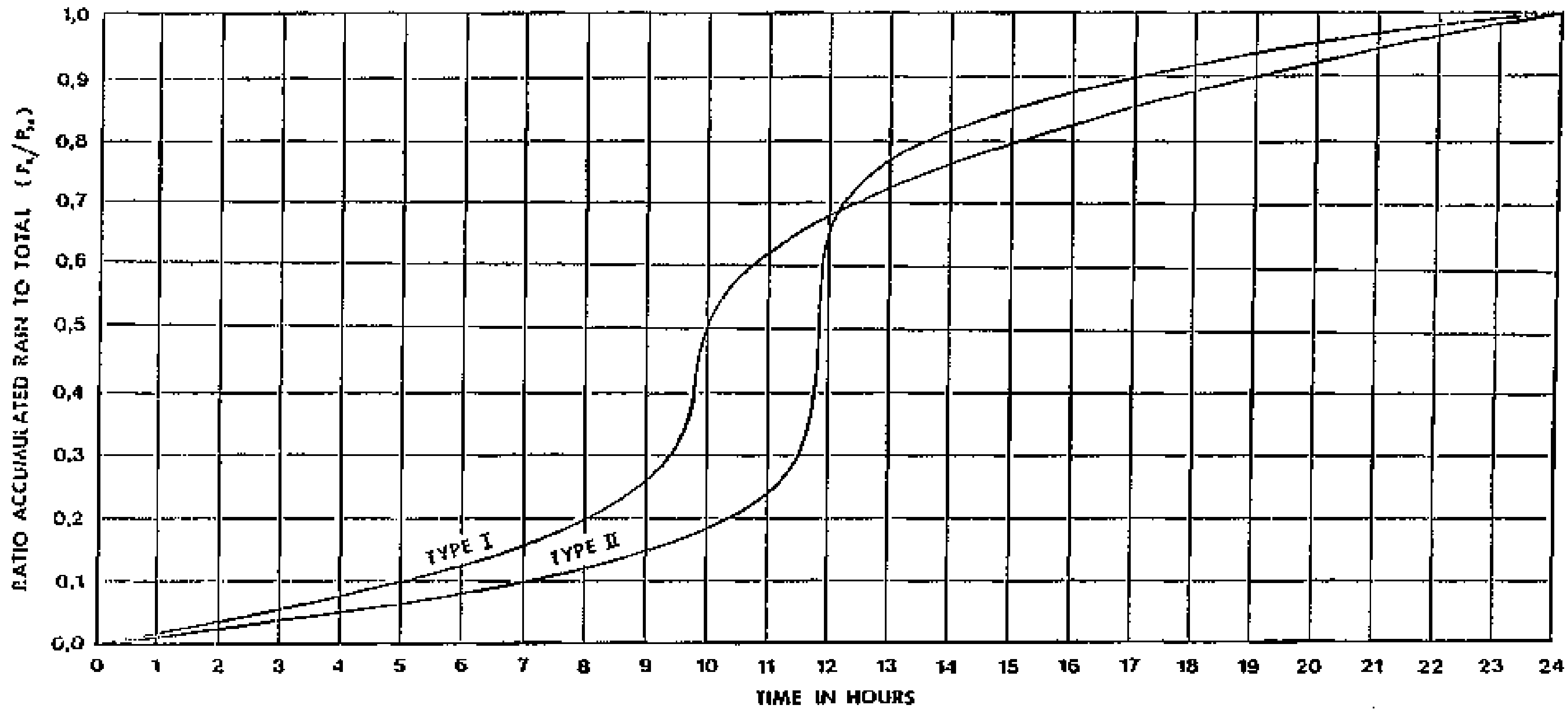

Figure 2.3 The SCS twenty-four hour rainfall distributions

Use of the SCS runoff equations enables the estimation of direct runoff volume together with peak discharge and if desired, the entire runoff hydrograph. The Model is conceptually based, simple to use and lends itself to graphical solution. The determination of peak flow rate however, relies on the linear concepts of unit hydrograph theory which limits the accuracy of the technique when aplied to processes which are essentially non-linear. Considerable research has been undertaken to evaluate the applicability of the unit hydrograph in hydrological modelling techniques and to assess the improvements that can be made to peak flow rate predictions when the unit hydrograph, derived for a catchment, is modified for non-linear processes. A review of such research will now be made.

2.2 Evaluation of the unit hydrograph used in estimating peak flow rate

In the SCS Model a unit hydrograph is derived by means of Equations 2.7 and 2.9 in order to determine peak flow rate and the temporal distribution of runoff. The basis of this method, proposed by Sherman (1932), is that since a stream hydrograph is described by many of the physical characteristics of the catchment area, similar hydrographs will be produced by similar rainfalls, assuming comparable antecedent conditions. Consequently, the determination of a unit hydrograph for certain clearly defined conditions, enables an estimate of runoff from a rainfall of any duration or intensity, by superimposing the required number of such unit hydrographs. Inherent in this technique is the simplification introduced by separating the direct response component from the unit hydrograph for total runoff by some arbitrary method of hydrograph separation. Unit hydrograph theory is based upon the following three postulates:

1. Constant baselength

For a given catchment the duration of runoff is essentially

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1. Constant baselength

For a given catchment the duration of runoff is essentially constant for all spatially and temporally uniform rainfalls of a given duration and is independent of the total volume of runoff.

2. Proportional ordinates

   It is assumed that for a given rainfall duration and catchment, the ordinates of the runoff hydrograph are proportional to the total volume of runoff or excess rainfall.

3. Superposition

   The catchment is assumed to operate as a linear system. Accordingly, the runoff hydrograph of a particular rainfall is assumed to be independent of, and can be superimposed on, concurrent runoff due to preceding rainfalls.

The postulates upon which unit hydrograph theory is based are theoretical and make a number of assumptions concerning the consistency of the unit response with constant physical catchment conditions, despite inconsistent rainfall inputs. These assumptions impose limitations on the accuracy of the technique (Nash, 1958). Criticisms of unit hydrograph methods commonly pertain to the assumption of linearity, which is the major assumption of unit hydrograph theory and is regarded as contrary to hydraulic theory applied to overland and channel flow (Nash, 1958). The need for a more mathematical determination of the unit hydrograph, encompassing non-linear relationships has been expressed by Barnes (1959), who emphasised that the flow of water is governed primarily by the laws of hydraulics rather than by imaginary units of water as suggested in unit hydrograph theory. Recent research (Natural Environment Research Council, 1975) reiterates the need for the incorporation of non-linear processes in unit hydrograph theory, with an adjustment of the unit hydrograph according to storm magnitude.

Since linear concepts can be more readily applied than non-linear ones, synthetic models using unit hydrograph techniques are preferred, provided they serve the purpose of a study with sufficient accuracy. In the light of the criticism that has been directed at the assumptions upon which the unit hydrograph is based, it is surprising that unit hydrograph techniques do, as sometimes indicated, serve the purposes for which they are set (Mostaghimi and Mitchell, 1979). Ward (1975) suggests that the reason they do so may be due to the fact that direct runoff is not predominantly overland flow or Hortonian as Sherman (1932) understood it, but follows rather the concept of partial area contributions (Betson, 1964). Such a concept reflects a situation where direct runoff producing areas within a catchment will remain more or less identical in size and that since infiltration capacity is effectively zero in these areas, the total volume of quickflow and its time base will be fairly constant for similar precipitation inputs.

A review of relevant research does, however, indicate that in general the non-linear nature of catchment response cannot be described adequately by linear theory, especially for small catchments subject to rainfall of varying intensities. It is apparent that modifications to the unit hydrograph procedure made to account for variations in rainfall inputs are needed to overcome the limitations of the approach while maintaining its simplicity. Synthetic relationships that have been established between unit hydrographs and various physical catchment characteristics and the modifications to the unit hydrograph which incorporate the effects of varying rainfall characteristics and flood magnitude, will now be reviewed.

2.3 Derivation of synthetic unit hydrographs

Unit hydrographs can be derived using rainfall and runoff data for isolated storms having a unit duration of constant rainfall

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Unit hydrographs can be derived using rainfall and runoff data for isolated storms having a unit duration of constant rainfall intensity, by adjusting the ordinates of the runoff hydrograph to correspond to a hydrograph of unit volume. Alternatively, the unit hydrograph may be determined by using iterative solutions and superimposing the unit hydrograph analytically to form a composite hydrograph representative of the recorded hydrograph (Mays and Coles, 1980).

Unit hydrograph theory is, however, generally applied to catchments with no streamflow recording facilities and hence it is of great practical importance to have a procedure whereby a synthetic unit hydrograph may be constructed for an ungauged catchment. Synthetic unit hydrographs are usually determined by deriving empirical relationships between parameters describing the unit hydrograph, such as its peak flow rate, time to peak or alternatively lag time and catchment and storm characteristics. A wide range of studies forming such relationships has been conducted.

Early work focussed on physical catchment characteristics and their influence upon the unit hydrograph for a particular catchment and gave indications of the need for non-linear effects to be incorporated into the unit hydrograph. Rainfall parameters were incroporated in later studies with correlations being done on a unit hydrograph for each storm within a catchment, thereby accounting for some of the non-linearities present due to storm variation. In keeping with historical developments this review is directed first at work incorporating relationships between the unit hydrograph and mainly catchment characteristics. Secondly, the effects of rainfall factors and the non-linearity of the rainfall-runoff processes on the unit hydrograph will be studied.

2.3.1 Derivation of synthetic unit hydrographs from catchment characteristics

During investigations into the effect of catchment characteristics on the unit hydrograph, variables such as the size, shape, slope and drainage network of the catchment have frequently been studied. In describing the significance of these factors the British Institute of Civil Engineers ascribes to catchment size, the scale of the flood process in each catchment; to the drainage pattern, a time distribution of floods; to slopes, the infiltration and velocity performance and considers that storage will modify the effect of all of these (Natural Environment Research Council, 1975). The choice of the catchment characteristics used in hydrological studies should be such that those used are both relevant hydrologically and easily measured for a large number of catchments. In addition, to simplify coefficient interpretation, the variables should be chosen to be uncorrelated (Natural Environment Research Council, 1975).

Snyder (1938) was a forerunner in the determination of synthetic unit hydrographs and derived Equations 2.12 and 2.13 to determine catchment lag time and peak flow rate of the unit hydrograph. The equations were given as

$$L = C_t \, (l_{ca} \cdot l_m)^{0,3} \qquad \text{Eq. 2.12}$$

$$q_{pm} = \frac{C_p \, 640}{L} \qquad \text{Eq. 2.13}$$

where

L = catchment lag time (h),

q_{pm} = peakflow rate of unit hydrograph ($ft^3.s^{-1}.mile^{-2}$),

l_{ca} = distance from gauging point to centre of catchment (mile),

l_m = length of catchment (mile) and

C_p and C_t are coefficents depending on the units being used and on catchment physiographic characteristics.

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C_p and C_t are coefficents depending on the units being used and on catchment physiographic characteristics.

The variable C_t was found to vary from 1,8 to 2,2 with an average value of 2,0. The coefficent C_p was obtained from Equation 2.14 and varied from 0,56 to 0,69 for Snyder's study area.

$$C_p = \frac{L}{t_d} \times \frac{A_{cm}}{A_m} \qquad \text{Eq. 2.14}$$

where

t_d = unit duration of surface-runoff producing rain (h),

A_{cm} = effective area contributing to the peak flow ($mile^2$),

A_m = catchment area ($mile^2$) and

$\frac{L}{t_d}$ = 5.

Snyder (1938) summarised his findings by suggesting that variations in the derived unit hydrographs were due mainly to variations in the duration and areal distribution of effective rainfall and that a different lag time should be used for different types of storms.

Taylor and Schwarz (1952) developed a nomograph to derive lag time and peak flow rate for a unit hydrograph from the indices of main stream slope, basin elongation and rainfall duration. The lag time was plotted against duration of effective rainfall as the first correlation step, which resulted in the equation.

$$L = c' e^{m' t_d} \qquad \text{Eq. 2.15}$$

where

m' = rate of change of lag time with storm duration (-) and

c' = lag of an instantaneous unit hydrograph, IUH (h) which is the hydrograph with an infinitesimal duration of effective rainfall.

The regression of m' on the product $(l_{ca}.l_m)$ was calculated as

$$m' = \frac{0,212}{(l_{ca}.l_m)^{0,36}} \qquad \text{Eq. 2.16}$$

The relationship of c' with catchment characteristics was investigated and the equation derived was

$$c' = \frac{0,6}{y_{st}} \qquad \text{Eq. 2.17}$$

where

y_{st} = slope of a uniform channel having the same length as the longest watercourse and an equal time to travel (-).

The peak flow rate of the unit hydrograph was determined from physiographic catchment characteristics and the unit duration of surface-runoff producing rain using the equation

$$q_{pm} = c'' e^{m'' t_d} \qquad \text{Eq. 2.18}$$

where

c'' = peak flow rate of an IUH ($ft^3.s^{-1}.mile^{-2}$) and

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c" = peak flow rate of an IUH $(ft^3.s^{-1}.mile^{-2})$ and

m" = rate of change of flow rate with storm duration (-).

m" and c" were determined from the equations

$$m'' = 0,121\ y_{st}^{0,142} - 0,05 \qquad \text{Eq. 2.19}$$

and

$$c'' = 382\ (l_{ca} \cdot l_m)^{-0,36} \qquad \text{Eq. 2.20}$$

Buil (1968) applied synthetic unit hydrograph data obtained from the graphical solution of the equations developed by Taylor and Schwarz (1952) to the equations derived by Snyder (1938) and obtained synthetic values of C_t and C_p. Main stream slope and a catchment elongation index were used to provide a correlation with the synthetic basin co-efficents C'_t and C'_p. Buil (1968) found that the unit hydrograph could be related to the location of the concentrated effective rainfall and took account of the storm areal distribution by sub-dividing the catchments into three equal sub-areas. Equations 2.21 to 2.23 were used to determine lag times for each sub-area. Subscripts 3, 2 and 1 refer to the lower, middle and upper sub-areas respectively.

$$L_3 = C'_t(l_{ca} \cdot l_m)^x - 6 \qquad \text{Eq. 2.21}$$

$$L_2 = L_3 + \Delta t_2 \qquad \text{Eq. 2.22}$$

$$L_1 = L_2 + \Delta t_1 \qquad \text{Eq. 2.23}$$

where

L = lag time for relevant sub-area (h),

Δt_1 & Δt_2 = regression constant terms (-) and

x = regression exponent (-).

Values of Δt_1, Δt_2 and x were determined from regression equations on the physiographic catchment characteristics l_m, l_{ca} and y_{st}. Hickok, Keppel and Rafferty (1959) also recognised the need to control the source area of runoff and found that the slope of the source area was important in determining lag times. The source area was defined by Hickock et al, (1959) as that half of the catchment with the highest average land slope and was used to define lag time as

$$L_{min} = \frac{23\ (l_{sa} + w_{sa})}{(y_{sa} + d_d)} \qquad \text{Eq. 2.24}$$

where

L_{min} = lag time (min),

l_{sa} = distance from gauge point to the centre of the source area (ft),

w_{sa} = average width of the source area (ft),

y_{sa} = average slope of the source area (-) and

d_d = drainage density for the entire catchment ($ft.acre^{-1}$).

The lag time derived from Equation 2.24 was used to determine peak flow rate for an assumed total volume of runoff using Equation 2.25.

$$q_{pr} = \frac{545\ Q_a}{L_{min}} \qquad \text{Eq. 2.25}$$

where

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Q_a = volume of runoff (acre.ft).

Hickock et al, (1959) concluded from hydrographs synthesised using Equations 2.24 and 2.25 that lag time was far more consistent than time to peak, which they found to vary from 74 to 145 percent of the lag time. Lag time was found to be significant in relating catchment influences to hydrogaph shape. The most important physiographic feature tested for inclusion in Equation 2.24 was land slope, which showed a higher correlation than channel slope. Reasons given for this were that for the intense convectional thunderstorm common to the arid region, momentum effects of abrupt translatory waves would dominate channel resistance effects. Drainage density was included in Equation 2.24, since it reflected the proportion of channel versus overland flow and provided a measure of the hydraulic efficiency of the catchment (Hickok et al, 1959).

Bell and OmKar (1969) derived dimensionless hydrographs for a number of catchments with widely differing catchment and climatic conditions. All the hydrogrpahs were similar and were approximated by Equation 2.26, which was shown to correspond closely to the dimensionless hydrographs described by Mockus (1957) and Hickok et al, (1959). The similarity between the three dimensionless unit hydrographs is shown in Figure 2.4.

Bell and OmKar (1969) gave

$$\frac{q_r}{q_{pr}} = \left(\frac{t_m}{t_{pm}}\right)^4 e^{\left(4 - 4\frac{t_m}{t_{pm}}\right)} \qquad \text{Eq. 2.26}$$

where

t_m = time after start of hydrograph rise (min),

q_r = flow rate at time t_m after start of hydrograph rise ($ft^3.s^{-1}$),

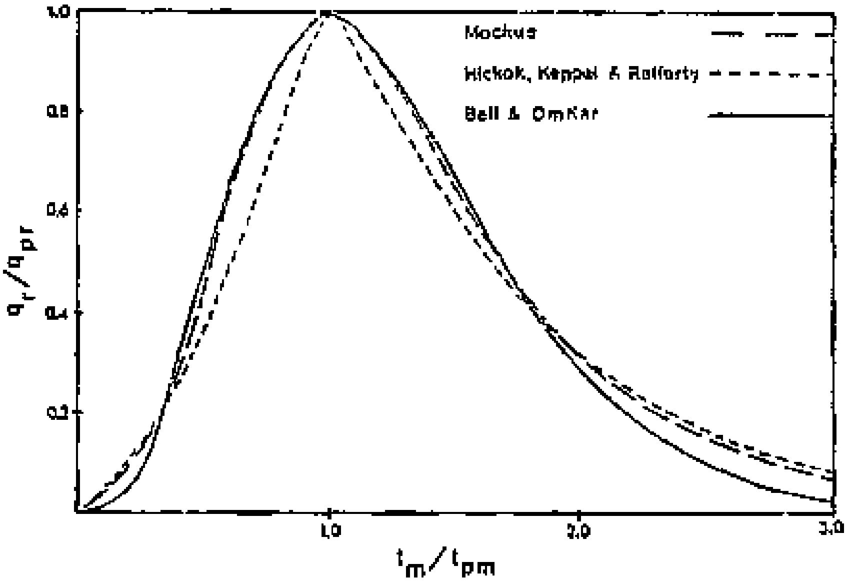


Figure 2.4 Comparison of dimensionless hydrographs (after Bell and OmKar, 1969)

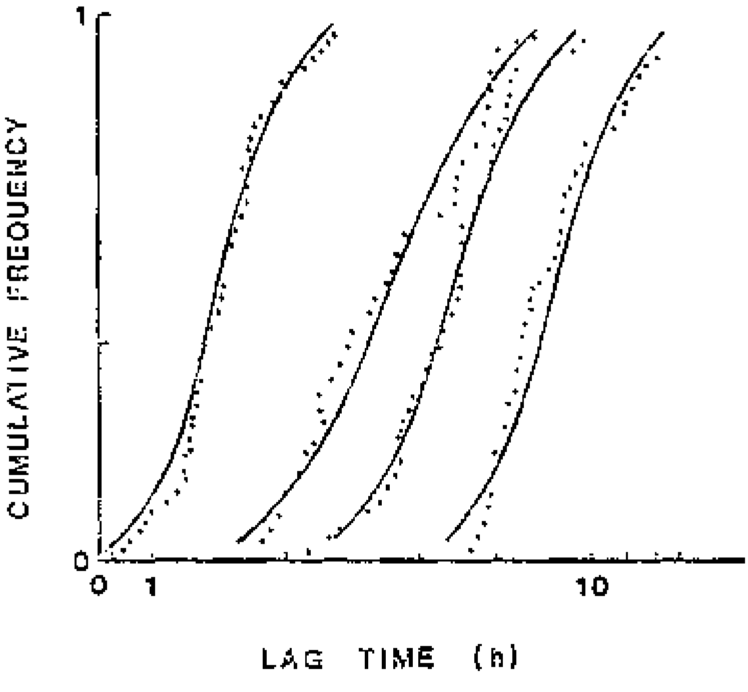
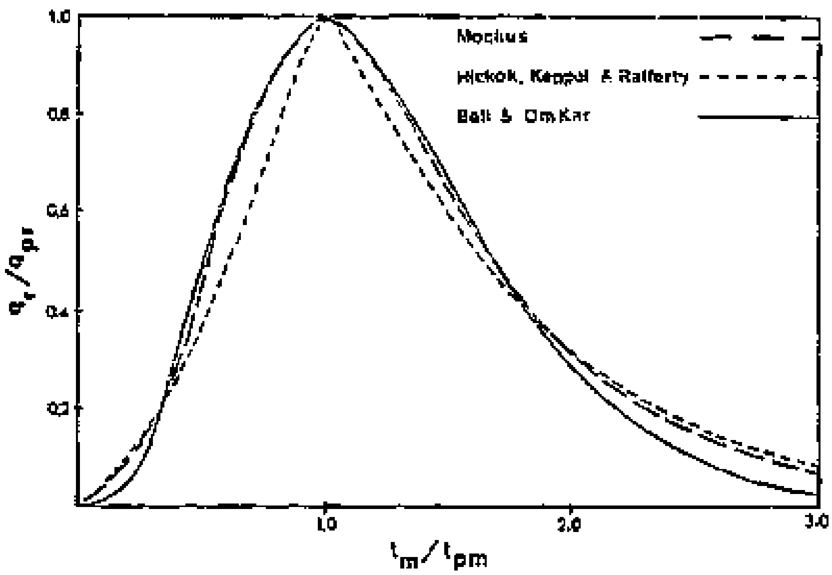


Figure 2.5 Distributions of lag time



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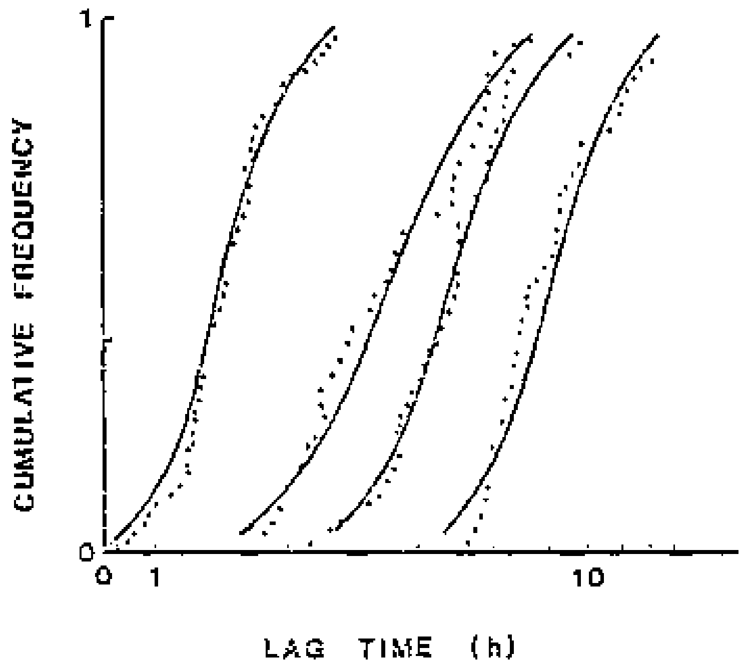

Figure 2.5 Distributions of lag time

q_{pr} = peak flow rate ($ft^3.s^{-1}$) and

t_{pm} = time to peak flow rate (min).

Bell and OmKar (1969) analysed relative catchment lag time, defined as the lag time for a particular flood divided by the median lag time for the catchment and found that it was more consistent than time to peak and was inversely related to flood magnitude. The following equation was derived to estimate lag time from the physical characteristics of the catchment.

$$L_c = a\ l_m^{0,77}\ y_1^{-0,39} \qquad \text{Eq. 2.27}$$

where

L_c = critical lag, or, average value of lag for extreme floods (h),

l_m = length of catchment (mile),

y_1 = slope of flow for l_m(-) and

a = constant to be evaluated.

Attempts were made to obtain correlations of the constant, a, with various catchment characteristics including channel slope, overland slope, drainage density, catchment shape, vegetation cover and precipitation factors. The only characteristic to show a relationship with the constant, a, was vegetation cover. Bell and OmKar (1969) suggest that such a result illustrates the influence of vegetation on the relative amounts of interflow and surface runoff contributing to the flood hydrograph.

Catchment lag and peak flow rates have been related to stream order, catchment area and network magnitude by Boyd (1978) and Gupta, Waymire and Wang (1980). Boyd (1978) found lag - defined in his study as the time from centre of mass of effective rainfall to the centre of mass of direct runoff - to be reasonably constant for a given catchment with some variation due to non-linear effects. The extent of lag variation is shown in Figure 2.5 where the frequency distributions of logarithmically transformed lag times for four catchments are plotted. Taking the average lag time for each catchment Boyd (1978) derived the following equation, described as a law of catchment lag, which has the same form as the stream order laws (Ward 1975), viz.

$$L_u = L_1 R_u^{u-1} \qquad \text{Eq. 2.28}$$

where

L_u = lag of basin of order u (h),

L_1 = lag of first order catchment (h) and

R_u = basin lag ratio (-)

= 1,737

Gupta <u>et al</u>, (1980) derived unit hydrographs using Horton's bifurcation ratio, stream length ratio, stream area ratio and a measure of catchment lag time. Peak flow rates, calculated on large catchments showed close agreement with those measured, but on smaller catchments peak flows were underestimated. The lack of agreement for the smaller catchments was used to question the validity of the assumption of linearity on the smaller catchments. Changming and Guangte (1980) differentiate between the mechanisms of peak discharge formation on small and large catchments, noted by Gupta <u>et al</u>, (1980). In smaller catchments vegetation, soil and geomorphology

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In the United Kingdom Flood Studies Report, time to peak is related to several catchment characteristics, one of which is a variable expressing a fraction of the catchment impervious to rainfall (Natural Environment Research Council, 1975). The equation proposed is

$$t_p = 46,6\ y_d^{-0,38}\ URBT^{-1,99}\ RSMD^{-0,4}\ l_s^{0,14} \qquad \text{Eq. 2.29}$$

where

t_p = time to peak (h),

y_d = stream slope between points located 10 percent and 85 percent of the distance along the length of the mainstream ($m.km^{-1}$),

l_s = stream length (km),

RSMD = climatic index of flood runoff potential (-), and

URBT = 1 + URBAN, where

URBAN = percentage of catchment impervious to rainfall.

Slope measurement was the most important variable explaining the variance of t_p in Equation 2.29. Streamlength was unexpectedly less critical, possibly due to the significant inverse correlation of streamlength with streamslope. The second most important independent variable is URBAN which affects the efficiency of the drainage network, the velocities of flow and the proportion of total runoff due to surface runoff. Research undertaken, for example, by Ragan, Root and Miller (1975) into the effect of percentage imperviousness on lag time was based mainly on the study of urban catchments. Such research, however, can be extended to natural catchments by means of variables such as the SCS Curve Number, an index which estimates relative proportions of surface and subsurface flow (National Engineering Handbook, 1972).

A comparative study of four synthetic unit hydrograph methods by Morgan and Johnson (1962) which included the SCS dimensionless unit hydrograph, indicated that the equations developed for the estimation of catchment lag time are the weak link in the application of synthetic unit hydrographs, especially when applied to small catchments. Figure 2.6 shows the improved estimate of peak flow rate and hydrograph shape obtained by the SCS Model when a value of lag time measured for the storm is used. The hydrograph obtained using a lag time estimated from the area of the catchment has a peak flow rate equal to 51 percent of the recorded peak flow rate, compared with a peak flow rate of 83 pecent of recorded peak flow rate obtained using a measured lag time.

A review of various methods used to synthesise parameters describing the unit hydrograph from catchment characteristics indicates the increased consistency in prediction obtained when using an index of catchment lag time rather than time to peak (Hickok et al, 1959; Bell and OmKar, 1969). Prediction of lag time and peak flow rate can be made using catchment characteristics, but careful consideration must be given to the amount of subsurface flow present (Bell and OmKar, 1969; Ward, 1975) and the source area contributing to runoff (Hickok et al, 1959; Bull 1968). The determination of the catchment runoff response to rainfall has been found to be critical for small catchments (Morgan and Johnson, 1962). It is, however, on such small catchments that non-linear processes have been found to dominate catchment runoff response (Changming and Guangte, 1980;

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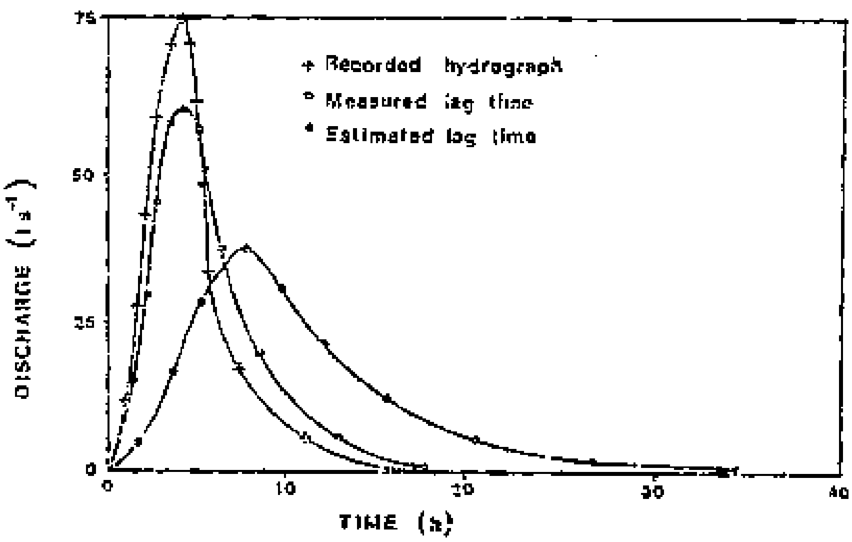

Figure 2.6 Comparison of the recorded unit hydrograph with those computed using a measured lag time and an estimated lag time (after Morgan and Johnson, 1962)

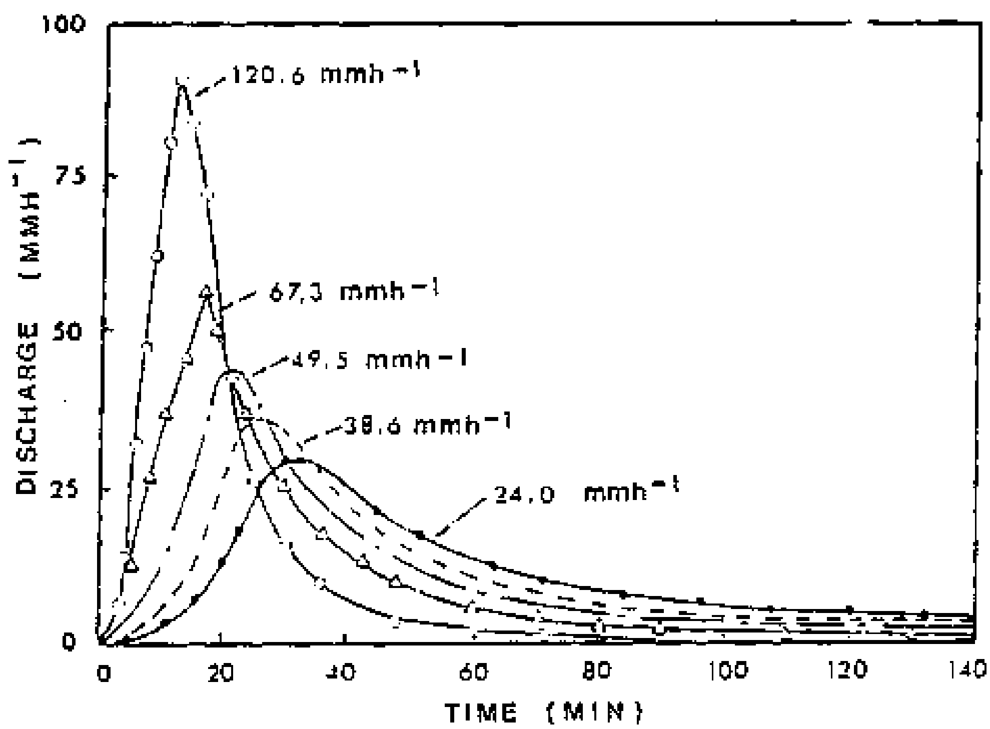

Figure 2.7 Unit hydrographs for a catchment with varying intensities of rainfall (after Dooge, 1977)

Gupta et al, 1980). With reference to the aforegoing the following section examines some methods of relating catchment runoff response and in particular lag time to rainfall characteristics and flood magnitude.

2.3.2 Rainfall characteristics and non-linearity of flood response.

Standard unit hydrograph techniques are based upon the assumption that a catchment has a constant lag time and responds as a linear system unaffected by changing rainfall characteristics. The need for improved accuracy and greater theoretical justification of hydrological techniques incorporating a non-linear time response is indicated in Figure 2.7, which shows various unit hydrographs derived for a single catchment from rainfalls of varying intensities (Dooge, 1977). Similar variations were attributed to antecedent conditions controlling the zones of satuation and overland flow (Anderson and Kneale, 1982) which were found to be most marked on hollow spur dominated catchments when compared with catchments having rectilinear slopes.

It has been suggested that it is possible to ignore the effects of rainfall intensity of the runoff hydrograph due to the dampening manifested upon these effects, as runoff passes through the catchment drainage network. Similar reasons may be advanced to account for areal distribution of rainfall. However, researchers such as Wilson (1979) dispute that runoff characterisitics reflecting rainfall intensity are significantly nullified during drainage processes and emphasize the importance of spatial and temporal distribution of rainfall and the accuracy of the precipitation input.

Theoretical reasons for a relationship between recorded characteristic times and some measure of storm intensity or magnitude are indicated by Manning's equation for turbulent flow (Chow ,1964), viz.

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$$V = \frac{R^{2/3}\, Y^{1/2}}{n} \qquad \text{Eq. 2.30}$$

where

V = velocity of flow ($m.s^{-1}$)

R = hydraulic radius (m),

= ratio of the cross-sectional area of the flow to the perimeter in contact with the fluid,

Y = slope (-) and

n = a friction coefficient (-).

High intensity rainfall would result in a greater flow depth, an increase in hydraulic radius and corresponding change of flow from laminar to turbulent flow, with a relative reduction of flow resistance and an increase in velocity. Gregory (1980) suggests that due to rilling, inherent in all runoff events on rural catchments, hydraulic radius will always be large and turbulent flow is ensured. Stephenson (1980) used kinematic flow theory to develop a T_c equation which included the effects of rainfall intensity and absolute surface roughness, while Gregory (1982) used Manning's equation to develop a T_c equation incorporating inter alia sixty minute rainfall intensity of a given return period and the catchment area.

Difficulties in determining times associated with peak discharge of a hydrograph are complicated by some uncertainties in the assumptions involved in calculating direct runoff and effective rainfall. By using an impervious catchment in a controlled laboratory experiment to avoid such difficulties Yen, Shen and Chow (1979) determined the effect of rainfall intensity, duration and catchment slope on time to peak. This relationship is shown in Figure 2.8 and described by the equation

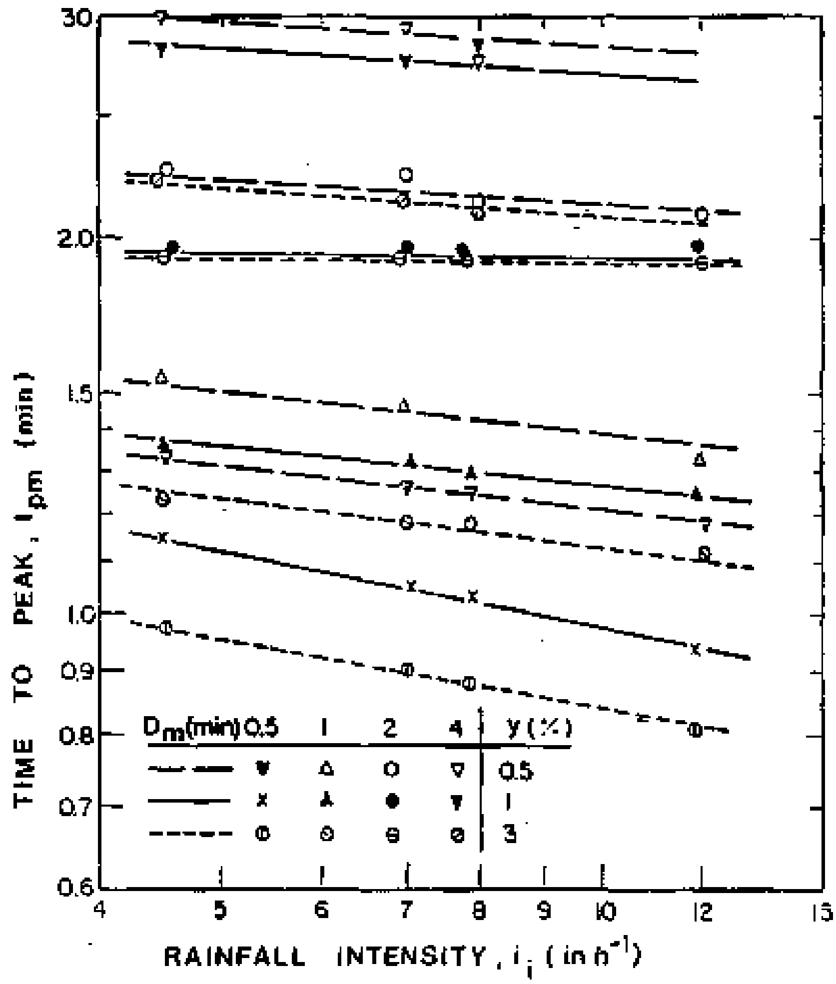


Figure 2.8 Variations of time to peak with intensity of effective rainfall (after Yen et al, 1979)

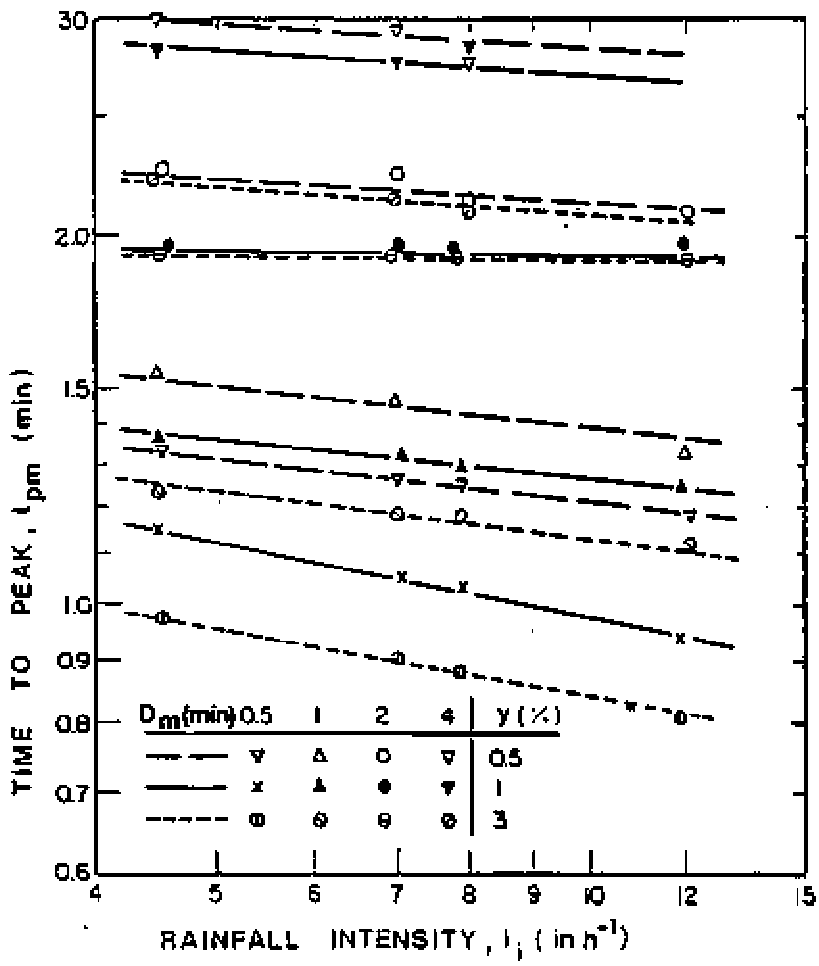


Figure 2.8 Variations of time to peak with intensity of effective rainfall (after Yen et al, 1979)

$$t_{pm} \alpha \; i_i^{-\lambda} \qquad \text{Eq. 2.31}$$

where

t_{pm} = time to peak (min),

i_i = rainfall intensity (in.h^{-1}) and

λ = a constant determined from catchment and rainfall characteristics

Figure 2.8 illustrates the increase in time to peak with an increase in rainfall duration, D_m(min) for a fixed rainfall intensity and catchment slope, y(%). This relationship supports unit hydrograph theory which envisages a constant lag time and a variation in time to peak corresponding to the variation in duration of rainfall excess. The decrease in time to peak with an increase in rainfall intensity, when y and D_m are held constant is, however, contrary to unit hydrograph theory and corresponds to a decrease in lag time with increasing rainfall intensity. The influence of rainfall intensity on time to peak and hence lag time generally decrease with increasing storm duration and slope (Yen et al, 1979).

Rastogi and Jones (1971) cite research similar to that done by Yen et al, (1979), which makes use of laboratory models to indicate the non-linear effects in the rainfall runoff processes. Rastogi and Jones (1971) stress that generally the degree of non-linearity found in laboratory models does not apply directly to natural catchments due to the scale differences present and make use of a mathematical surface flow model developed to be representative of a 0,65 km^2 catchment area.

The non-linearity of the catchment is indicated in Figure 2.9 where unit hydrograph peak flow rates are plotted against intensities of

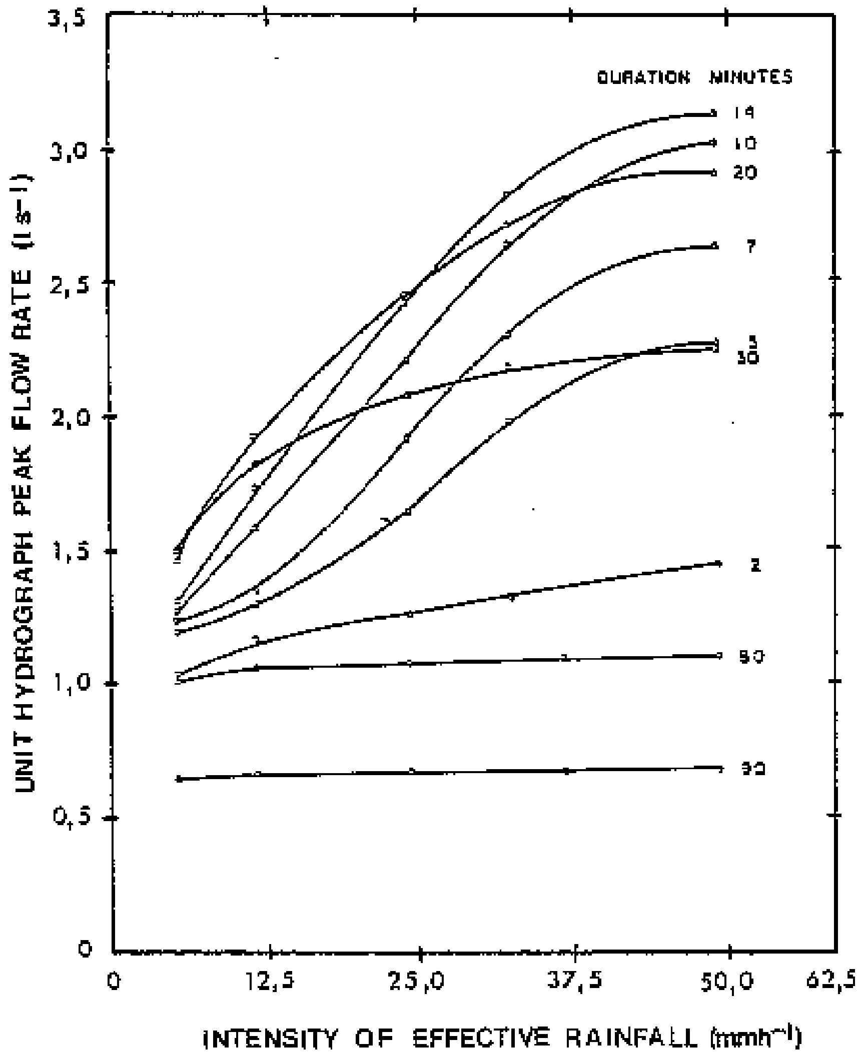


Figure 2.9 Effect of the intensity of effective rainfall on unit hydrograph peak discharge (after Rastogi and Jones, 1971)

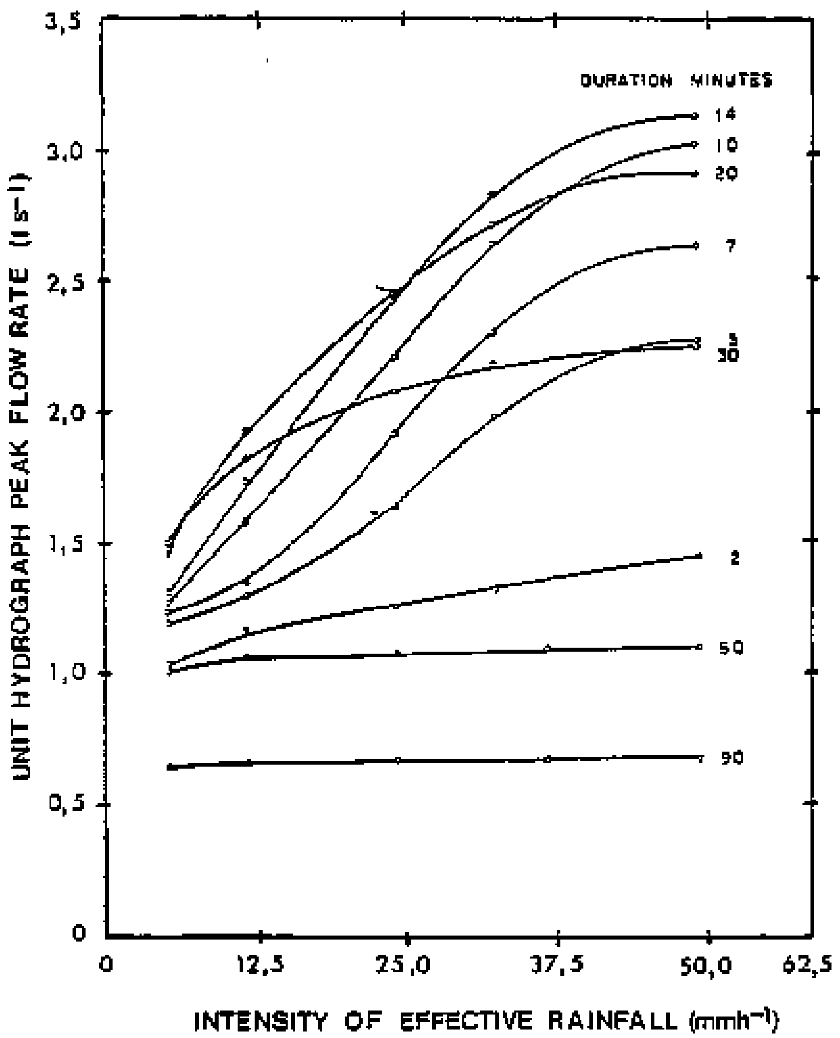


Figure 2.9 Effect of the intensity of effective rainfall on unit hydrograph peak discharge (after Rastogi and Jones, 1971)

effective rainfall for certain fixed durations of rainfall excess.

In accordance with unit hydrograph theory the peak flow rates for unit hydrographs of fixed duration and varying intensities should be constant and thus the curves plotted in Figure 2.9 should be horizontal. The curves show a non-linear relationship which only tend to linearity when the outflow rate from the catchment approximates the inflow rate to the catchment at a time known as the time of virtual equilibrium. The time of virtual equilibrium, which is related to lag time, was found to shorten with an increase in rainfall excess intensity (Rastogi and Jones, 1971).

Models of overland flow have been discussed comprehensively in the literature while other fields such as the expansion and contraction of the drainage network, together with subsurface flow are more sparsely documented. Roberts and Klingeman (1970) simulated permeability in a laboratory model to investigate the effects of non-linearity on runoff which is not purely surface runoff. Figure 2.10 shows the variation in hydrograph shape for storms of fixed intensity and varying rainfall duration when the catchment is a) impermeable and b) covered by a permeable layer of foam. For the impermeable surface the rainfalls corresponding to durations of 20, 30 and 45 seconds reached equilibrium, while the retardation effect of the simulated permeability prevented all except the 45 second duration rainfall from reaching equilibrium. The permeable surface resulted in a much longer lag time and a smaller rate of peak discharge per unit volume of runoff. Intensity of rainfall excess was found to be an important determinant of hydrograph shape, especially at low rainfall intensities (Roberts and Klingeman, 1970).

The importance of including variables describing rainfall intensity in regressions with a charactersitic travel time was indicated by Gregory (1980) as well as by Kadoya and Fukushima (1979), who incorporated intensity of rainfall in equations to calculate time of concentration. Kadoya and Fukushima (1979) developed a relationship between T_{cm} and rainfall intensity, which included the catchment area

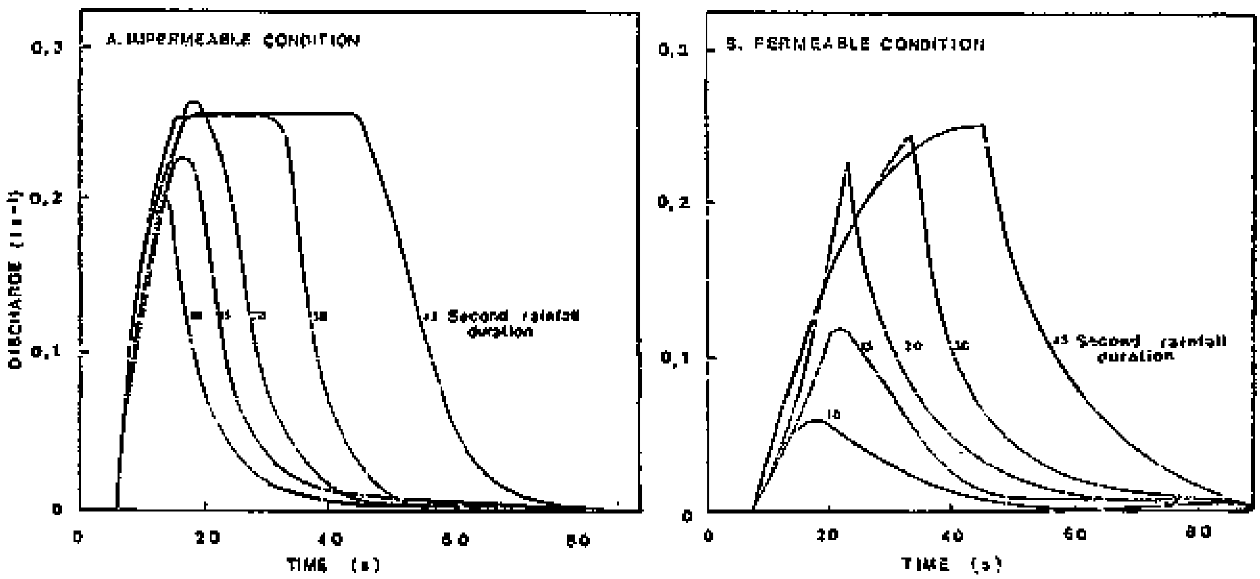


Figure 2.10 The effect of rainfall duration on a) impermeable and b) permeable catchments (after Roberts and Klingeman, 1970)

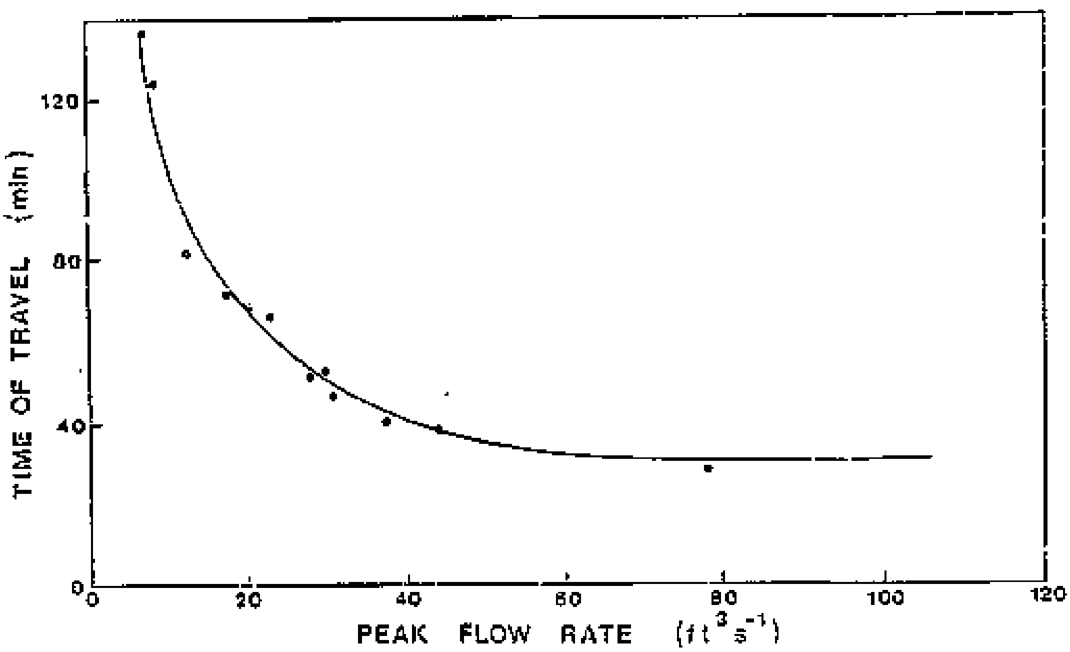
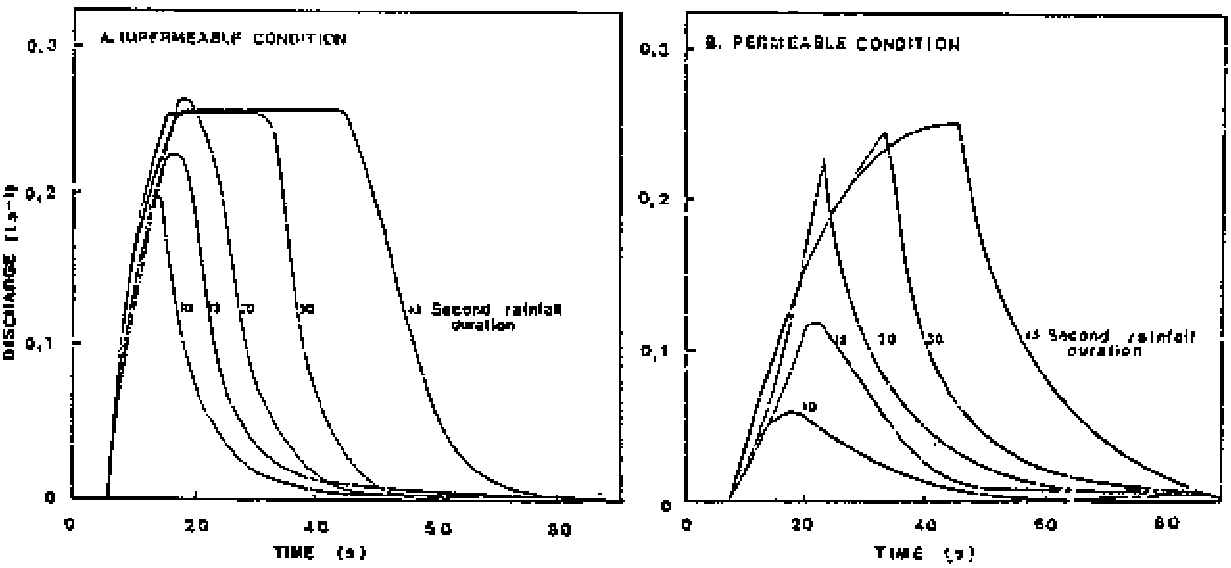


Figure 2.11 Relation of time of travel to peak flow rate (after Pilgrim, 1976)



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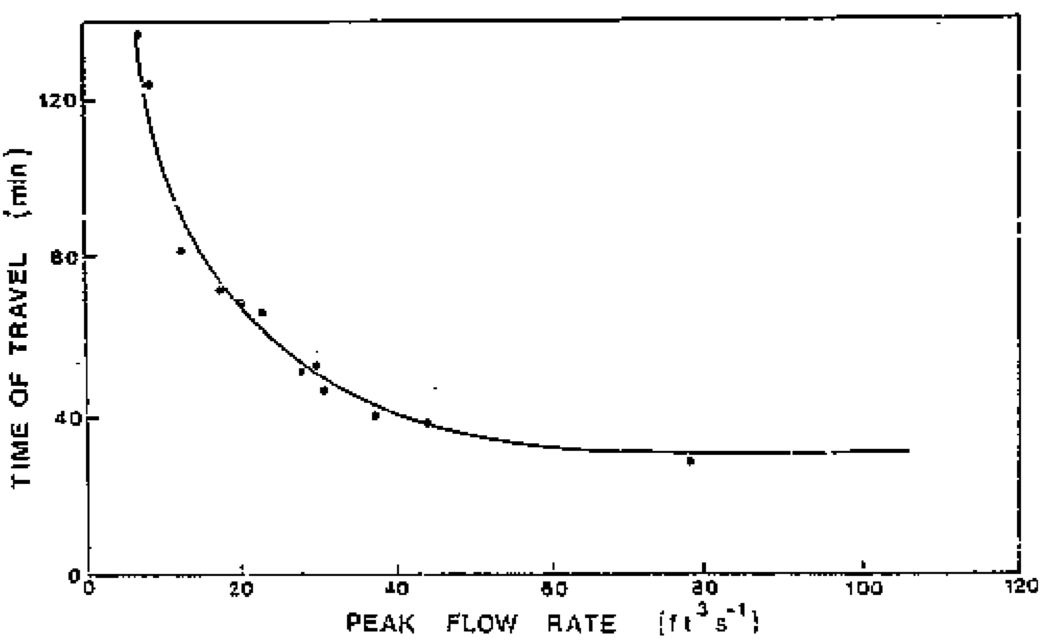

Figure 2.11 Relation of time of travel to peak flow rate (after Pilgrim, 1976)

and took the form

$$T_{cm} = c\ A^{0,22}\ i_m^{\ 0,385} \qquad \text{Eq. 2.32}$$

where

T_{cm} = time of concentration (min),

A = area (km^2),

i_m = rainfall intensity ($mm.h^{-1}$) and

c = a constant.

Average intensity of effective rainfall was used by Changming and Guangte (1980) in a study of flood peak discharge which incorporated a factor describing effective contributing catchment area. The equation to derive flood peak discharge was of the form

$$q_{ps} = (i_{av} \cdot A_c) \qquad \text{Eq. 2.33}$$

where

q_{ps} = flood peak discharge ($m^3.s^{-1}$),

i_{av} = average intensity of excess rainfall ($mm.h^{-1}$) and

A_c = effective area that contributes to the formation of the peak discharge (km^2).

Average intensity of excess rainfall was determined by adjusting the average total rainfall intensity, obtained from rainfall data, by an average losses intensity, determined from soil and soil flow properties. Effective contributing area was evaluated from a series of laboratory tests using simulated storms of different rainfall durations, intensities and distributions. The maximum peak discharge was calculated by differentiating the product of i_{av} and A_c and equating the product to zero.

Results of an investigation into the relationship between time to peak and mean rainfall intensity (Natural Environment Research Council, 1975) revealed little evidence to suggest non-linear relationships between runoff events. The dominance of subsurface flow and variable source area mechanisms, as depicted by Hewlett and Hibbert (1967), were suggested as a possible explanation of this lack of trend. The variable source area concept reflects an expanding area contributing to runoff, the extent of expansion being controlled by catchment moisture status. This increase in effective catchment size according to the Natural Environment Research Council (1975) would result in a longer travel time.

Pilgrim (1976) indicated the degree of non-linearity of rainfall runoff prcesses in an experiment using radio isotopes injected into streams at various sites on a 39 hectare catchment. Measurements of the base-length and variability of activity-time curves with peak flow rate for each site, gave an indication of the non-linearity of the processes on the catchment. A relationship between time of travel, defined as the difference between time from injection and time of the centre of mass of the activity time curve, and peak flow rate was determined for each injection point. The relationship for the prediction of time of travel from peak discharge for one site in the catchment, is shown in Figure 2.11. The results indicate that although the process is grossly non-linear at low flow rates, linearity is approximated at high flow rates. The relationship is represented by the equation

$$t_{com} = 286\, q_{pr}^{-0,492} \qquad \text{Eq. 2.34}$$

where

t_{com} = time of travel (min) and

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where

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q_{pr} = peak flow rate ($ft^3.s^{-1}$).

Askew (1970) found that variations in the temporal pattern of rainfall had little effect on lag time, defined in his study as the time from the centre of mass of effective rainfall to the centre of mass of direct runoff, and he found lag time to be correlated solely with weighted mean discharge rate. Weighted mean discharge rate is defined as the mean ratio of total discharge divided by the time of occurrence of direct runoff, weighted in proportion to the direct runoff discharge of the given rate. The regression equations determined had the form

$$L = a\, q_{wm}^{\ b} \qquad \text{Eq. 2.35}$$

where

L = catchment lag (h),

q_{wm} = weighted mean discharge rate ($m^3.s^{-1}$),

b = regression coefficient and

a = regression constant.

The magnitude of the regression coefficient b, was taken as a direct indication of the degree of non-linearity present in each catchment. The magnitude of b was found to vary between catchment areas, thereby implying different degrees of non-linearity. Little correlation was, however, found between the value of b and the physiographic characteristics of the catchments and a mean value of b of -0,23 was taken as the best estimate of the regression coefficeint. Using this constant exponent as a fixed regression coefficient, the data were re-examined to develop a means of predicting the constant term, a, which relects a measure of the lag time obtained for a linear model. A good correlation existed between the regression constant and catchment area, A in km^2, enabling the estimation of lag time using the equation

$$L = 2,12\ A^{0,57}\ q_{wm}^{-0,23} \qquad \text{Eq. 2.36}$$

Rogers (1980)[1)] conducted similar research to that done by Askew (1970) in order to identify the causes of catchment non-linearity and to model non-linear peak discharge distributions. Peak discharges were converted to a standardised value by taking the log of peak discharge divided by runoff volume squared. Regressions of standardised peak discharge were run against the log of runoff volume to form a standardised peak discharge distribution. The slope of this distribution is equal to negative one for catchments with linear response and is more positive for non-linearly responding catchments. Values of the coefficient of determination indicated that on average 86 percent of the variation in standardised peak discharge was accounted for by runoff volumes alone. The remaining 14 percent of the variation was attributed to variations in precipitation distribution, intensity and duration. Most drainage basins exhibited non-linear distributions but there appeared to be little correlation between the slopes of the distributions and conventional physical catchment characteristics (Rogers, 1980). The effect of rainfall characteristics on the slope of the standardised peak discharge distribution was suggested as being important but insufficient precipitation data were available to test this effect. Rogers (1980) speculated that drainage basin non-linearity was related to non-uniform infiltration capacity distributions. According to Rogers (1980) infiltration capacities are generally

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highest on the higher regions of the catchment and lowest in the channel valleys. The effect of this higher infiltration capacity around the basin perimeter results in most of the runoff for small to medium storms occurring near the catchment outlet, giving rise to short travel times, low storage effects and high peak flow rates in relation to runoff volume. For large storms runoff would be expected to originate from the entire catchment resulting in longer travel times and a lower peak for the volume of runoff distributed over the catchment. Rogers (1980) concluded from the study that the slope of the standardised peak discharge distribution was a unique characteristic of each catchment and was dependent largely upon drainage basin characteristics. In addition Rogers (1980) suggested that the standardised peak discharge distribution influenced the effects of precipitation duration and antecedent moisture condition, due to their inter-relationship with runoff volume.
Murray and Gorgens (1981) predicted peak discharge from linear equations of log of peak discharge vs log of runoff volume. The slope of the equations for their three semi-arid catchments, dominated by storms of low intensity and long duration, indicated a clear non-linear relationship between peak discharge and runoff volume. Only a weak association was found between peak flow rate and the most intense 60 minute rainfall amount, while seven day antecedent rainfall amount gave a fair correlation with runoff volume and hence peak discharge.

It has been proposed that the unit hydrograph is not only highly variable from storm to storm, but also from burst to burst within storms, particularly on small catchments (Betson, Bales and Pratt, 1980). A triangular unit hydrograph with a double recession limb, adjusted according to the precipitation excess distribution, was used by Betson et al, (1980) to route precipitation excess to form the storm hydrograph. The unit hydrograph, developed from the concept of partial area contributions to storm runoff, was varied by means of a lag time determined from a normalised precipitation excess intensity, which was related to the variation in intensity throughout the storm and the total rainfall amount. The equation used was

$$L = \frac{a\,(PEIN)^b}{1,6} \qquad \text{Eq. 2.27}$$

where

L = catchment lag (h),

PEIN = normalised precipitation excess intensity ($in.h^{-1}$) and

a & b = coefficients predicted from physiographic characteristics.

A similar triangular unit hydrograph with a double recession limb was incorporated by Ward, Bridges and Wilson (1981) into a model for predicting peak flow rates and for developing a storm hydrograph. Estimates of runoff volume were based on the SCS procedures (Equation 2.1) and the response time of the double triangle unit hydrograph was determined from parameters describing catchment slope, catchment hydraulic length and the percentage of the catchment covered by forest, grassland, crops and reclaimed surface mined lands. Wheater, Shaw and Rutherford (1982) included a change in slope in the recession limb of unit hydrograph of long duration but found a triangular shape was satisfactory for short steep unit hydrographs. Unit hydrograph shape was found to be influenced strongly by antecedent soil moisture conditions, which affected the area contributing to runoff.

Reed, Johnson and Firth (1975) varied lag for successive input elements of rainfall excess within a storm and superimposed the incremental hydrographs to fit an observed rainfall-runoff event. Preliminary results indicated that by catering for a variable lag from rainfall burst to burst within the storm, the model provided improved representation of the observed events against which it had been assessed and that in general a shortened lag time corresponded

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The various methods of relating parameters describing synthetic hydrographs to rainfall characteristics and peak flow rate indicate the significant role played by rainfall characteristics, especially rainfall intensity and duration, in the timing and shape of the runoff hydrograph (Kadova and Fukushima, 1979; Pilgrim, 1976; Rastogi and Jones, 1971; Roberts and Klingeman, 1970; Yen, Shen and Chow, 1979) and the non-linear relationship between peak flow rate and catchment response time (Askew, 1970; Pilgrim, 1976). Incorporation of practical methods to improve the estimation of synthetic unit hydrographs determined from catchment characteristics seems justified and possible modifications to the equations defining the SCS triangular unit hydrographs (National Engineering Handbook, 1972) will now be considered.

2.4 Modifications to the equations defining the SCS triangular unit hydrograph

The triangular unit hydrograph used in the SCS Model to estimate peak flow rate is defined by Equations 2.7 and 2.9. The lag time, calculated from catchment characteristics using Equation 2.9, is combined with Equation 2.7 to calculate the peak flow rate for a unit volume of runoff, Q, and duration of rainfall excess of constant intensity, D. Considerable effort has been expended at improving the estimation of runoff volume using the SCS technique (Hawkins, 1978; Hope and Schulze, 1981; Schulze, 1982). Little attention has however, been given to the peak flow rates which are frequently estimated poorly by the SCS Model, despite accurate estimates of runoff volume. These poor peak flow rate estimates are most likely due to inadequate representation of the shape and baselength of the triangular hydrograph. Improvements to the triangular hydrograph accounting for changing storm characteristics and catchment conditions are thus required if more accurate estimates of peak flow rate are to be made.

The shape of the triangular hydrograph is assumed to be constant for all catchments and storms within catchments, with 37,5 percent of the total volume of runoff being under the rising limb of the hydrograph. Such a basic shape is a simplifying assumption and should be linked to physical catchment parameters and rainfall characteristics. The proportion of the total volume of the hydrograph under the rising limb may be varied by means of adjustments to the shape factor, K (Equation 2.5). The factor K, has been shown to vary with different catchment characteristics (National Engineering Handbook, 1972) and an adjustment for different rainfall characteristics would improve the accuracy of the SCS technique.

The baselength of the triangular hydrograph is given in terms of the hydrograph time to peak which is related to effective storm duration, D and catchment lag time L by Equation 2.6. Unrealistic estimates of either D or L result in inaccurate estimates of peak flow rate. The determination of catchment lag time is considered by Morgan and Johnson (1962) to be the weak link in the application of synthetic unit hydrograph techniques and has been the subject of much research (Askew, 1970; Bell and OmKar, 1969; Betson et al, 1980; Boyd, 1978; Buil, 1978; Hickok et al, 1959, Reed et al, 1975). Equation 2.9 reflects the influence of catchment size and slope on lag time by means of the catchment hydraulic length and the catchment slope. A description of catchment condition is included in the equation by inclusion of the retardance factor (CN') unadjusted for antecedent soil moisture (Equation 2.9). An approximation of the retardance factor by the CN adjusted for antecedent soil moisture could be made. Such an equation would reflect the actual catchment condition, an index more applicable that the "average" catchment condition reflected by CN'. The lag time determined from Equation 2.9 depends entirely on catchment characteristics and does not include indices of rainfall intensity or temporal distribution of rainfall. The inadequacies of similar equations which are unable to account for the non-linearity of runoff response found with variations in storm magnitude have been indicated in Section 2.3. A means to include indices into the SCS lag equation which describe

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Calculation of duration of rainfall excess for ungauged catchments may be made by means of the relationship between effective duration of rainfall excess and average annual rainfall amount (National Engineering Handbook, 1972). Alternatively, duration of rainfall excess may be approximated by the catchment time of concentration (T_c), since this represents the duration after which all parts of the catchment contribute to the flow at the catchment outlet (National Engineering Handbook, 1972). The establishment of incremental unit hydrographs for incremental time periods of constant rainfall intensity enables calculation of the peak rate of runoff for temporally varying rainfall, without choosing an appropriate storm duration, while adhering to the requirements of constant rainfall intensity inherent in unit hydrograph theory. It should be stressed, however, that the incremental hydrographs represent a constant linear response function to rainfall inputs of varying intensity, which remain linearly superimposed.

Ideally the lag time and the shape of the triangular hydrograph should change for each incremental storm duration, according to the intensity of rainfall and moisture status of the catchment at the onset of the incremental period. In such a manner a varying incremental lag and hydrograph shape, corresponding to the rainfall distribution can be envisaged. Alternatively, as a simplification, the lag time and hydrograph shape could be determined for the total rainfall, but with due consideration being placed upon a characteristic rainfall intensity and the temporal variation of the rainfall.

Procedures to improve the equations defining the triangular unit hydrograph, by incorporating modifications to account for the effects of varying rainfall distribution and intensity on the unit hydrograph, have been suggested. These procedures provide a basis for the research, the aims of which are discussed in the ensuing section.

2.5 Aims

The present research has been undertaken to improve the estimation of peak flow rate for individual storms using the SCS triangular unit hydrograph. Investigations are restricted to the lag equation defining the baselength and hence peak flow rate of the triangular unit hydrograph and the shape of the unit hydrograph is held constant following SCS procedures. The main aim of the study is to test the accuracy of the estimation of lag time calculated for a catchment using the SCS lag equation. Variations in the lag times for individual storms within a catchment will also be examined and where possible, equations to predict both the catchment lag times and their variability will be determined.

Testing the accuracy of an empirically determined catchment lag time poses numerous problems since lag time varies with each runoff event recorded on the catchment and thus has to be determined for a number of events and then averaged in order to obtain a representative catchment estimate. The lag time for an individual event cannot always be measured directly from autographic records owing to difficulties in determining the start time, end time and temporal and areal distribution of the effective rainfall. Problems are further compounded by poorly synchronised rainfall and runoff recorders which contribute to inaccurate estimates of the storm lag time. Owing to the complexity associated with determining the centre of mass of rainfall.

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The time response calculated to provide the best estimates of peak flow rate for all the storms within a particular catchment would similarly be regarded as the best estimate of catchment lag time. Various approaches can thus be used to estimate lag time from recorded data. In this report, the investigations will be restricted to the following methods:

1. A triangular approximation of each runoff hydrograph for all the catchments used in the study will be made and the relationship between peak flow rate and runoff volume for the hydrographs of a catchment investigated to determine the magnitude and variability of catchment lag time. Such relationships will then be correlated with catchment and rainfall characteristics.

2. Incremental triangular hydrographs will be convoluted with the storm precipitation excess for the test storms and the resulting storm hydrograph produced. The value of lag time required to superimpose the incremental hydrographs to give an accurate estimation of recorded peak flow rate for each storm will determine the correct storm lag time, and this value is then explained in terms of catchment and rainfall characteristics.

3. The time response between effective rainfall and runoff will be measured from the autographic records for each test storm. Effective rainfall will be calculated following SCS procedures by separating an initial abstraction from the total storm rainfall. Initial abstraction will be obtained from recorded rainfall and runoff data.

The first two methods are orientated towards the runoff hydrograph with prediction of an accurate peak flow rate being the criterion for the determination of storm lag time. The third method bases the estimation of lag time on the measured time difference between effective rainfall and runoff response. Only the first method will be applied to all the catchments used in the study. Owing to the large amount of computational work involved, the second and third methods will be applied to a smaller sample of selected catchments, enabling comparison to be made between the three methods used.

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3. CATCHMENT AND DATA DESCRIPTIONS

Data from twelve small catchments covering a wide range of climatic and physiographic conditions were selected to study the effect rainfall and catchment characteristics have on inter- and intra-catchment variations in lag time. The catchments, from South Africa and the United States of America, were selected to be less than 3,5 km^2 in area to minimize areal variations in precipitation distribution.

The catchment locations are shown in Figures 3.1 and 3.2. Details regarding the location, climate, vegetation and lithology of these catchments are summarised in Table 3.1. Seven catchments from the USA were selected (Figure 3.1): two are located at Stillwater (Oklahoma), two at Safford (Arizona), one at Coshocton (Ohio), one at Hastings (Nebraska) and one at Albuquerque (New Mexico). Five South African catchments were used, three catchments being located at the DeHoek and two at the Zululand hydrological research stations (Figure 3.2). The catchment identification codes together with relevant physiographic catchment characteristics and the weighted mean catchment Curve Numbers are given in Table 3.2. The values of the catchment Curve Numbers are based on field observations and various surveys done by Arnold (1980) for the South African catchments and Schulze (1982) for the USA catchments. Catchment hydraulic length and average catchment slope were determined by computer from the available maps.

A total of 291 storms was selected for the study, with the criteria for selection being that the hydrograph resulting from storm rainfall should have an isolated, clearly defined single peak. A consistent method of separating stormflow from baseflow was applied using a line of constant slope of 1,13 mm. $day^{-1}.day^{-1}$, projected from the beginning of the hydrograph rise to the point where it intersected the recession limb of the hydrograph (Hewlett and Hibbert, 1967). The relevant hydrological data for the selected storms is listed in Appendix 1.

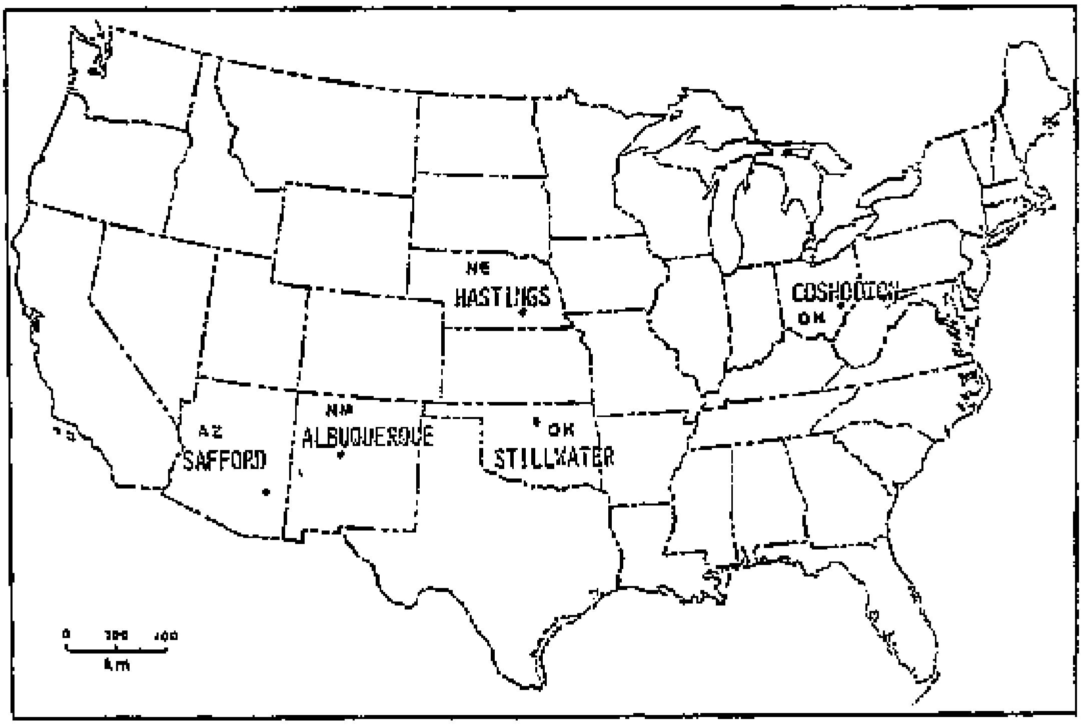

Figure 3.1 Location of USA catchments

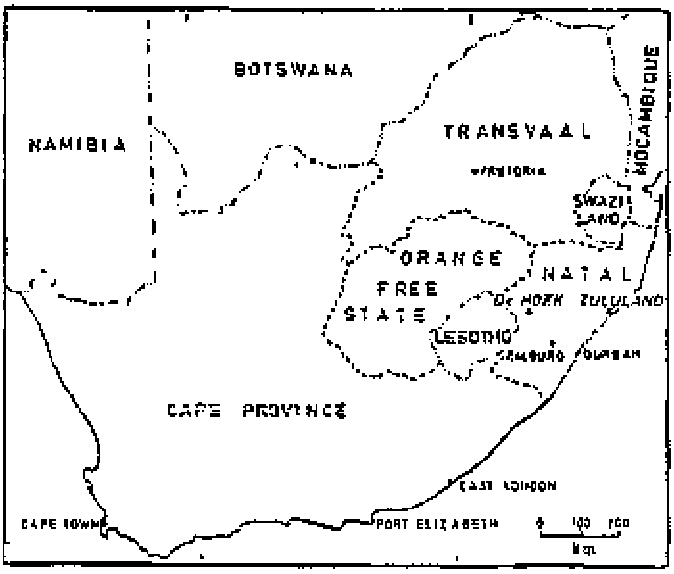

Figure 3.2 Location of South African catchments

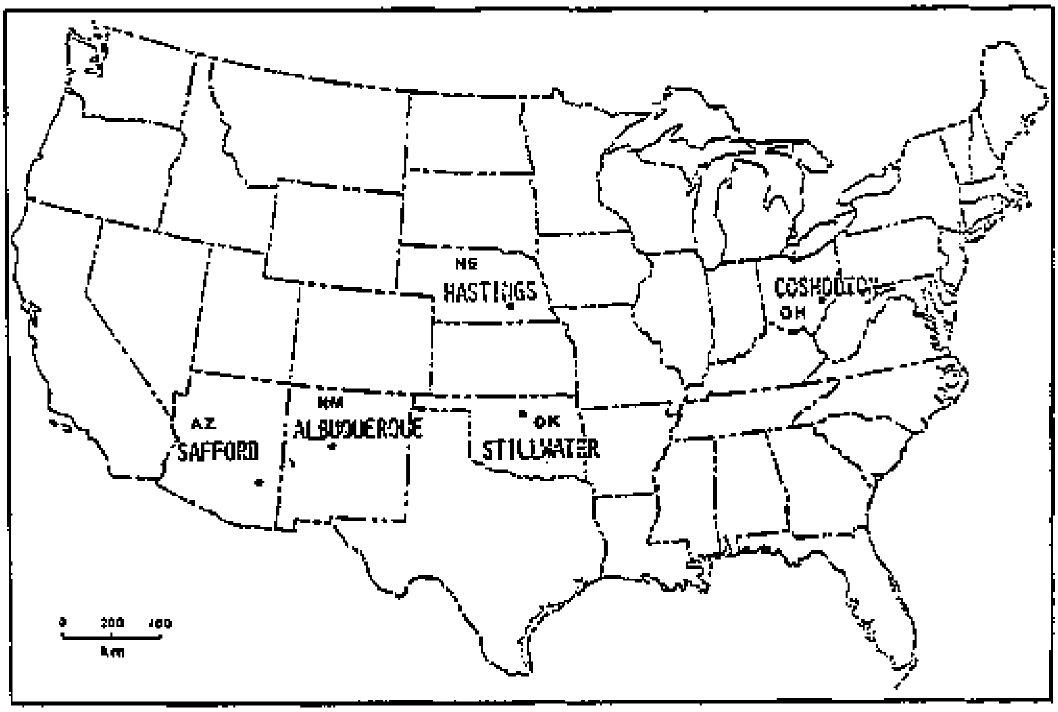

Figure 3.1 Location of USA catchments

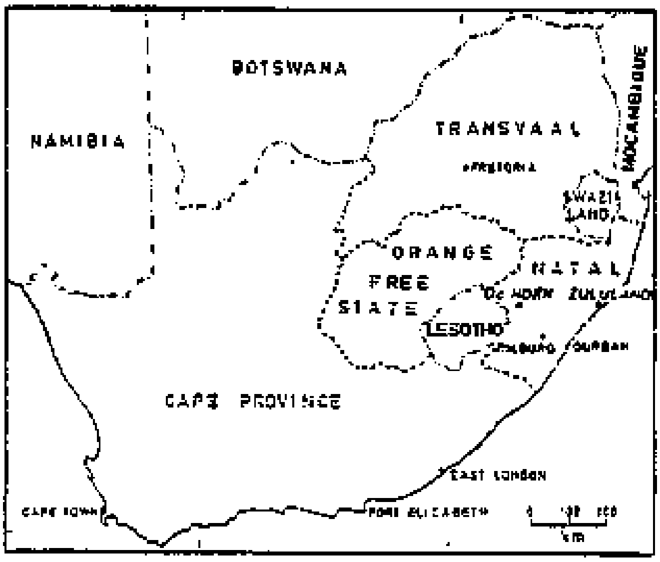

Figure 3.2 Location of South African catchments

Table 3.1 Summary of location, climate, vegetation and lithology of the study regions

Country	Location	Latitude	Longtitude	Altitude (m)	Climate	Mean Annual Precipitation (mm)	Vegetation	Lithology
USA	Coshocton, OH	40°22'N	82°01'W	372	Sub-humid	975	Grassland	Shales, and Silstones overlying sandstone
	Stillwater, OK	36°27'N	97°25'W	293	Sub-humid	725	Grassland	Shales with interbedded
	Hastings, NE	40°16'N	98°35'W	597	Sub-humid	600	Grassland	Loess
	Safford, AZ	32°51'N	110°00'W	1090	Arid	225	Sparse shrub, 85% bare	Basalt and calcareous granite
	Albuquerque, NM	35°05'N	106°50'W	1805	Arid	175	Shrub and short grass, 80% bare	Sandstone and shade
South Africa	DeHoek	29°01'S	29°10'E	1450	Sub-humid	850	Grassland	Mudstone, shale and sandstone
	Zululand	28°50'S	31°46'E	250	Humid	1450	Grassland	Biotite granite, gneiss

Sources : Arnold (1980) ; Schulze (1982)

Table 3.2 Summary of catchment physiographic characteristics and catchment Curve Numbers

Catchment Identification	Location	Area (km^2)	Hydraulic length of catchment (m)	Average Catchment Slope (%)	CN
26003	Coshocton	0,011	125	18,4	73
37001	Stillwater	0,068	445	4,3	80
37002		0,372	959	4,7	80
44005	Hastings	0,015	140	7,2	69
45001	Safford	2,100	4530	6,6	79
45002		2,760	5898	7,8	79
47002	Albuquerque	0,164	802	11,0	87
V1M12	DeHoek	0,500	726	20,0	74
V1M28		0,410	808	10,0	68
V7M03		0,450	938	15,2	74
W1M16	Zululand	3,222	3632	19,5	77
W1M17		0,669	700	18,9	63

Sources : Arnold (1980) ; Schulze (1982)

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Sources : Arnold (1980) ; Schulze (1982)

No depth-storage relationships were available for the measuring sites in the USA and no runoff backrouting could therefore be simulated. Runoff was backrouted for a sample of events from the South African weirs but the peaks of the inflow hydrographs did not differ to any marked extent from the observed peaks as the stilling basins are all relatively small. In order to maintain uniformity, no runoff routing was therefore performed and recorded peak flow rates were used to approximate the inflow peaks (Appendix 1). Duration of rainfall, D_u, was frequently difficult to determine owing to periods of low intensity rainfall leading up to, during or following the main storm period. This applied particularly to the Zululand catchments where low intensity rainfalls of long durations are common.

Rainfall duration, D_u was therefore approximated to the nearest hour for the Zululand storms. No rainfall falling more than two hours before the hydrograph initiation or after the termination of storm flow by the 1,13 $mm.day^{-1}.day^{-1}$ slope was included in the storm rainfall. In addition, continuous periods of rainfall intensity of less than 1 $mm.h^{-1}$ falling before or after the main event were excluded from the rainfall amount. The most intense 30-minute period of rainfall, I_{30}, was chosen as an indicator of the rainfall intensity during each storm. A parameter of storm kinetic energy, E, was calculated using the equation developed by Wischmeier and Smith (1958) :

$$E = \sum_{j=1}^{n} (11,19 - 8,73 \log_{10} I_j) P_j$$

where

E = the total kinetic energy ($J.m^{-2}$),

I = the mean rainfall intensity during the jth storm period ($mm.h^{-1}$)

and

P_j = the rainfall amount in the jth storm period (mm).

In order to characterise storms regionally, mean values of I_{30} and D_u were obtained for each location from the data in Appendix 1. These parameters together with a description of the 'typical' rainfall event for each region are given in Table 3.3.

The aims of this research having been outlined and the relevant data presented, attention is now turned to the procedures by which inter- and intra-catchment variations in lag times were studied and to the results obtained.

Table 3.3 Regional storm characteristics for the selected events

Region	$\bar{I}_{30}$ (mm h^{-1})	$\bar{D}_u$ (h)	Storm Description
Coshocton	36,5	1,8	Medium intensity rainfall, short duration
Stillwater	29,7	3,9	Medium intensity rainfall, medium duration
Hastings	48,6	1,0	High intensity rainfall, short duration
Safford	32,6	1,4	Medium intensity rainfall, short duration
Albuquerque	25,2	2,2	Medium intensity rainfall, short duration
DeHoek	29,8	2,2	Medium intensity rainfall, short duration
Zululand	13,2	12,0	Low intensity rainfall, long duration

and

P_j = the rainfall amount in the jth storm period (mm).

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4. DERIVATION OF LAG TIME USING TRIANGULAR APPROXIMATIONS OF THE RUNOFF HYDROGRAPH

4.1 Background

Although computer models are frequently used to superimpose numerous incremental hydrographs to obtain a compound hydrograph, it is often preferable, and in the absence of autographic rainfall records necessary, to assume a single triangular approximation of the runoff hydrograph. Such simplifications, which assume uniform rainfall distribution, are commonly made prior to conducting extensive analyses (Natal Provincial Administration Roads Department, 1981). In this chapter, simplified procedures have been utilized to form a triangular approximation of each runoff hydrograph which has the same peak flow rate and volume of runoff as the recorded hydrograph, but with 37,5 per cent of the total volume of runoff falling under the rising limb. Such triangular hydrographs are considered to be representative of the triangular unit hydrograph for each event and in this chapter relationships between peak flow rate and volume of runoff for the hydrographs for each catchment are used to calculate the magnitude and variability of catchment lag time.

The use of a hydrograph of non-unit volume to represent a unit hydrograph must not be regarded as contradictory to the assumptions upon which unit hydrograph theory is based. Such assumptions apply equally well when non-standard units are used (Rogers, 1980). The term 'unit' actually refers to a depth of uniform effective rainfall falling uniformly over a given time period. Triangular approximations of the total runoff hydrographs may be used to represent triangular unit hydrographs provided the effective rainfall is temporally and spatially uniform over a specified period of time. Under natural conditions uniform effective rainfall seldom occurs since both areal and temporal variations affect the generated runoff. Approximate unit hydrographs may, however, be determined from the runoff hydrographs of small catchments, where areal variations in the distribution of effective rainfall are minimized, by using isolated single peaked runoff events resulting from rainfalls of approximately uniform temporal distribution.

Such approximate unit hydrographs are not directly comparable with one another since they originate from storms of different durations of effective rainfall. It is difficult to determine the actual duration of effective rainfall for each storm using the recorded rainfall data since both the temporal distribution of the rainfall and catchment storage recharge rates influence this duration. For this reason a duration of effective rainfall for each catchment can be approximated by the catchment time of concentration, T_c, consistent with the procedure usually applied when design hydrographs are being determined (National Engineering Handbook, 1972), which is considered to be the best approximation available for the purposes of the present study.

4.2 Experimental procedures

According to the linear assumptions upon which the SCS hydrograph theory is based, the lag time for all storms on a catchment is constant and furthermore, the peak flow rate of the hydrograph for all storms of the same duration of effective rainfall will vary in proportion with the enclosed volume of runoff. . The actual relationship between peak flow rate and runoff volume for a series of triangular hydrographs, considered to be representative of triangular unit hydrographs with a duration of effective rainfall equal to the catchment time of concentration, were used to establish a procedure to determine the magnitude and variability of the lag time for each catchment. A logarithmic regression analysis of peak flow rate against runoff volume was initially undertaken for each catchment to provide equations of the form since both areal and temporal variations affect the generated runoff. Approximate unit hydrographs may, however, be determined from the runoff hydrographs of small catchments, where areal variations in the distribution of effective rainfall are minimized, by using isolated single peaked runoff events resulting from rainfalls of approximately uniform temporal distribution.

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$$\log q_p = a + b \log Q \qquad \text{Eq. 4.1}$$

where

q_p = peak flow rate ($mm.h^{-1}$),

Q = direct runoff volume (mm) and

a & b = regression coefficients.

The slope, b, of the line best fitting the data gave an indication of the degree of non-linearity of the runoff distribution and hence the consistency of lag time for each catchment. A slope of unity indicated a linear relationship between peak flow rate and runoff volume and enabled Equation 4.1 to be re-written as

$$q_p = 10^a Q^1 \qquad \text{Eq. 4.2}$$

Following the approximation of the duration of effective rainfall for each catchment to be equal to the catchment time of concentration, Equation 2.19 was re-written as

$$D = 1{,}66 \cdot L$$

and combined with Equation 2.7 to give

$$q_p = \frac{0{,}75 \ Q}{1{,}83 \ 10^a} \qquad \text{Eq. 4.3}$$

Assuming the runoff hydrographs to be represented adequately by triangular hydrographs, the equation describing the runoff distribution (Equation 4.2) was combined with Equation 4.3, which describes the shape of a triangular hydrograph to yield

$$L = \frac{0,75}{1,83 \; 10^{a}} \qquad \text{Eq. 4.4}$$

Equation 4.4 indicates that lag time is constant for a catchment with linear responses and its magnitude depends only on the regression constant, a. A regression slope, b, not equal to unity indicates a non-linear relationship between peak flow rate and runoff volume, the extent of the non-linearity being indicated by the deviation of the slope of the regression equation from unity. Lag for a non-linear catchment can be determined by substituting the relation

$$q_p = 10^{a} \, Q^{b}$$

into Equation 4.3 to yield

$$L = \frac{0,75 \, Q^{(1-b)}}{1,83 \; 10^{a}} \qquad \text{Eq. 4.5}$$

Equation 4.5 indicates the dependence of lag time for a catchment with non-linear response on the size of the runoff event. Similar equations can be derived, relating catchment lag time to peak flow rate.

The logarithmic regression equations of peak flow rate on runoff volume enabled an evaluation to be made of the applicability of the linear assumptions used in the SCS Model when applied to the catchments under study. Although similar equations have been used for prediction purposes (Askew, 1970; Rogers, 1980), it was decided to relate any non-linear variations in lag time to the characteristics of the rainfall event rather than the size of the runoff event, which is to a large extent itself related to rainfall characteristics. In order to do this the lag times for each catchment were re-calculated assuming a linear catchment response function using regression equations of peak flow rate on runoff volume similar to Equation 4.2 and having the form

$$L = \frac{0,75}{1,83\ 10^{a}} \qquad \text{Eq. 4.4}$$

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$$q_p = c\,Q \qquad \text{Eq. 4.6}$$

where

c = a regression constant.

Substituting Equation 4.6 into Equation 4.3 gave

$$L = \frac{0{,}75}{1{,}83\ c} \qquad \text{Eq. 4.7}$$

which enabled the calculation of that lag time, for a catchment with an assumed linear response, providing the most accurate estimates of peak flow rate for the runoff events of the particular catchment. Such estimated catchment lag times, L_{cs} (subscripts refer to a catchment lag time estimated using procedures incorporating single triangular approximations of recorded hydrographs) were compared with corresponding lag times determined by the defined SCS lag equation and a regression equation for catchment lag time prediction was developed.

The Coefficient of Determination (r^2) of Equation 4.6 indicated the extent to which the variability in peak flow rate was proportional to variations in runoff volume when a constant catchment lag time was employed. Over or under estimation of peak flow rates for individual events on a particular catchment, using such a linear relationship, generally occurred due to the non-linear changes in the rainfall pattern and catchment condition between individual events. Deviations of the peak flow rates calculated using the estimated catchment lag time from the observed peak flow rates, were related to the non-linear variations of the individual rainfall events for each catchment. Regression equations accounting for such deviations were calculated as

$$\frac{q_{pe}}{q_{po}} = f(x_1, \ldots\ldots, x_n) \qquad \text{Eq. 4.8}$$

where

q_{pe} = peak flow rate calculated using the estimated catchment lag time, obtained from Equation 4.7 ($mm.h^{-1}$),

q_{po} = observed peak flow rate ($mm.h^{-1}$) and

$x_1,...,x_n$ = indices describing the rainfall event.

Owing to the inverse relationship between peak flow rate and catchment lag time (Equation 4.3), the non-linear deviations of the observed peak flow rates from peak flow rates calculated using a linearly estimated catchment lag time were equated with deviations of the storm lag times from the linearly estimated catchment lag time to form the relationship

$$\frac{L_{ss}}{L_{cs}} = f(x_1,........, x_n) = \frac{q_{pe}}{q_{po}} \qquad \text{Eq. 4.9}$$

where

L_{ss} = lag time for the storm (h) when using a single triangular approximation of the runoff hydrograph and

L_{cs} = estimated catchment lag time (h) calculated using Equation 4.7.

An estimate of the lag time for a particular runoff event, L_{ess} (subscripts refer to an estimated storm lag time calculated using procedures incorporating single triangular approximations of recorded hydrographs) could thus be obtained by multiplying the linearly

where

q_{pe} = peak flow rate calculated using the estimated catchment lag time, obtained from Equation 4.7 ($mm.h^{-1}$),

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where

L_{ss} = lag time for the storm (h) when using a single triangular approximation of the runoff hydrograph and

L_{cs} = estimated catchment lag time (h) calculated using Equation 4.7.

An estimate of the lag time for a particular runoff event, L_{ess} (subscripts refer to an estimated storm lag time calculated using procedures incorporating single triangular approximations of recorded hydrographs) could thus be obtained by multiplying the linearly estimated catchment lag time (Equation 4.7) by a correction factor, determined from the non-linear rainfall characteristics of the relevant runoff event (Equation 4.9) to give

$$L_{ess} = \frac{0,75}{1,83\ c} \times f(x_1, \ldots\ldots, x_n) \qquad \text{Eq. 4.10}$$

A simple procedure, using non-linear runoff distribution, was thus established to assess the applicability of intra-catchment variations in lag time for the study catchments. In addition, linear runoff distributions were determined, enabling the estimation of a catchment lag time which could be adjusted by means of individual storm characteristics to provide estimates of individual storm lag times. The results of such procedures applied to the research catchments under study are shown in the following sections.

4.3 Results and discussion

4.3.1 Catchment lag times estimated from non-linear runoff distributions

The results of the logarithmic regression analysis of peak flow rate against runoff volume, which in agreement with other researchers (Murray and Görgens, 1981; Rogers, 1980) provided the best fit to the distributions, are shown in Table 4.1 which provides the regression equations, Coefficients of Determinatin and Variance Ratios for each of the catchments. The level of significance of the regression equations is indicated in brackets behind each Variance Ratio, consistent with the notation used by Rayner (1965), which is used throughout the text. The double asterisk (**) and single asterisk (*) denot significance at the 0,01 and 0,05 levels respectively.

Table 4.1 Logarithmic regression analysis of peak flow rate against runoff volume

Catchment	Regression Equation	Coefficient of Determination (r^2)	Variance Ratio (F)
26003	$\log q_p = 0,651 + 0,754 \log Q$	0,52	23,174 (**)
37001	$\log q_p = -0,224 + 1,032 \log Q$	0,69	60,600 (**)
37002	$\log q_p = -0,416 + 1,110 \log Q$	0,88	94,230 (**)
44005	$\log q_p = 0,710 + 0,888 \log Q$	0,96	840,509 (**)
45001	$\log q_p = 0,236 + 0,825 \log Q$	0,94	588,310 (**)
45002	$\log q_p = 0,455 + 0,876 \log Q$	0,95	679,924 (**)
47002	$\log q_p = 0,492 + 0,910 \log Q$	0,86	101,585 (**)
V1M12	$\log q_p = -0,334 + 0,964 \log Q$	0,96	415,690 (**)
V1M28	$\log q_p = -0,238 + 0,701 \log Q$	0,79	45,080 (**)
V7M03	$\log q_p = -0,440 + 0,926 \log Q$	0,81	88,710 (**)
W1M16	$\log q_p = -0,964 + 0,934 \log Q$	0,97	1068,703 (**)
W1M17	$\log q_p = -0,621 + 0,925 \log Q$	0,73	29,690 (**)

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W1M17	$\log q_p = -0{,}621 + 0{,}925 \log Q$	0,73	29,690 (**)

The Variance Ratios for all the catchments indicate a high degree of association between peak flow rate and volume of runoff. Non-linearity in the runoff distributions is, however, illustrated in two ways. First, the Coefficients of Determination in Table 4.1 indicate that for twelve catchments, on average, 16 percent of the variations of the dependent variable are not accounted for by the independent variable. Such variations are most likey due to changes in the distribution, intensity and duration of each rainfall event together with variations in the catchment antecedent moisture status at the onset of the storm. The regression equations are likely to incorporate to some extent the effects of rainfall characteristics and catchment antecedent conditions which are interrelated with runoff volume. Rainfall characteristics and catchment antecedent condition may thus play a more important role in determining peak flow rate than suggested by the Coefficient of Determination alone. Secondly, non-linearity is identified by the deviations of the distribution slopes from unity. All catchments exhibited non-linearity, as evidenced by their slopes being unequal to unity, which suggests that a lag time varying with event magnitude may be present for each catchment. Askew (1970) and Rogers (1980) identified similar non-linear regression slopes which were attributed to the catchments' physiographic characteristics, but attempts to determine the causes of the non-linearity proved unsuccessful. The effects of rainfall factors on the regression slopes were not tested by Askew (1970) nor by Rogers (1980), but were considered to be of importance.

Student's t-values were used to establish whether the slopes of the regression lines in Table 4.1 were significantly different from unity. The t-values are shown in Table 4.2. Of the twelve catchments, five have regression slopes that differ from unity at least at the five percent level. A method of describing empirically the slopes of these regression equations, enabling an extrapolation to be made to ungauged catchments, would provide an important improvement to existing unit hydrograph methods, which assume regression slopes of unity.

Table 4.2 Significance of deviations of regression slopes from unity.

Catchment	Standard Error of Coefficient	Student's t-value
26003	0,155	1,59
37001	0,133	-0,24
37002	0,114	-0,96
44005	0,031	3,61 (**)
45001	0,034	5,15 (**)
45002	0,034	3,65 (**)
47002	0,090	1,00
V1M12	0,047	1,00
V1M28	0,104	2,88 (*)
V7M03	0,098	0,76
W1M16	0,029	2,28 (*)
W1M17	0,170	0,44

Table 4.2 Significance of deviations of regression slopes from unity.

Catchment	Standard Error of Coefficient	Student's t-value
26003	0,155	1,59
37001	0,133	-0,24
37002	0,114	-0,96
44005	0,031	3,61 (**)
45001	0,034	5,15 (**)
45002	0,034	3,65 (**)
47002	0,090	1,00
V1M12	0,047	1,00
V1M28	0,104	2,88 (*)
V7M03	0,098	0,76
W1M16	0,029	2,28 (*)
W1M17	0,170	0,44

Variations in storm type might play an important role in determining the slope of the runoff distribution as well as in accounting for deviations of individual events from the catchment runoff distribution. Rogers (1980) propounds the most positive slope possible for the runoff distribution to be unity, which represents the linear runoff distribution for an impervious or uniformly pervious catchment. The regession slopes for catchments 37001 and 37002 in the Stillwater region oppose this proposition, thereby providing a possible illustration of the modifying effect the typical rainfall patterns of the Stillwater region (Table 3.3) have on the runoff distribution.

In order to distinguish between the two sources of non-linear variations, the runoff distributions were re- calculated assuming a linear relationship between peak flow rate and runoff volume. The linear runoff distributions enabled the estimation of a constant catchment lag time comparable with the lag time calculated using the SCS lag equation.

4.3.2 Catchment lag times estimated from linear runoff distributions

The approximation of a constant catchment lag time, as represented by the SCS lag equation is sometimes a necessary simplification. Linear equations of peak flow rate were regressed on runoff volume in order to estimate a constant catchment lag time, L_{cs}, providing the best estimates of peak flow rate for the recorded hydrographs of each catchment.

The regression equations were calculated without an intercept term, in order to facilitate the calculation of a constant value of lag time and are shown in Table 4.3. Since the regression packages available at the University of Natal in Pietermaritzburg automatically included an intercept term, an intercept-free fitted regression had to be obtained by entering each pair of data twice - as the pair (y_i, x_i) and as the pair ($-y_i$, $-x_i$) as suggested by

Table 4.3 Linear regression analysis of peak flow rate against runoff volume

Catchment	Regression Equation	Coefficient of Determination (r^2)	Variance Ratio (F)
26003	$q_p = 3,042\ Q$	0,77	80,206 (**)
37001	$q_p \approx 0,779\ Q$	0,88	213,769 (**)
37002	$q_p \approx 0,556\ Q$	0,94	242,499 (**)
44005	$q_p = 3,706\ Q$	0,84	193,764 (**)
45001	$q_p = 1,245\ Q$	0,97	263,401 (**)
45002	$q_p = 2,065\ Q$	0,95	667,548 (**)
47002	$q_p = 2,666\ Q$	0,97	591,130 (**)
V1M12	$q_p \approx 0,545\ Q$	0,98	1082,985 (**)
V1M28	$q_p = 0,384\ Q$	0,92	149,743 (**)
V7M03	$q_p = 0,310\ Q$	0,82	102,165 (**)
W1M16	$q_p = 0,097\ Q$	0,99	6477,778 (**)
W1M17	$q_p = 0,209\ Q$	0,94	620,398 (**)

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44005	$q_p = 3{,}706\ Q$	0,84	193,764 (**)
45001	$q_p = 1{,}245\ Q$	0,97	263,401 (**)
45002	$q_p = 2{,}065\ Q$	0,95	667,548 (**)
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W1M16	$q_p = 0{,}097\ Q$	0,99	6477,778 (**)
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Hawkins (1980). There was no bias in the resultant regression coefficients from which the lag time for each catchment was determined, but minor post analyses adjustments had to be made to the Variance Ratios which according to Hawkins (1980) are 'approximately' double the correct values, shown in Table 4.3, for the intercept free regression.

The Variance Ratios in Table 4.3 cannot be compared with those in Table 4.1, since the former were regressed to have no intercept term and the latter were logarithmically transformed. The highly significant linear association between peak flow rate and volume of runoff can, however, be gauged from the significance of the Variance Ratios presented in Table 4.3.

The estimated catchment lag times calculated by substituting the equations of Table 4.3 into Equation 4.3 and solving for L, are compared with the SCS lag times in Table 4.4. Owing to the short lag times obtained for some of the small catchments, lag times are compared in minutes. A scatter diagram of the lag times is shown in Figure 4.1 which indicates an under-estimation of lag time using the SCS equation for all catchments except those situated in the arid regions of Safford (45001/2) and Albuquerque (47002).

An evaluation of the estimates of peak flow rate obtained for the hydrographs of each catchmet using the SCS lag time and the estimated catchment lag time was made by way of the Coefficient of Determination, D_1 (r^2) and the Coefficient of Efficiency, E_1, (Aitken, 1973). The Coefficient of Efficiency is expressed as

$$E_1 = \frac{\Sigma(q_o - \bar{q}_o)^2 - \Sigma(q_o - q_e)^2}{\Sigma(q_o - \bar{q}_o)^2} \qquad \text{Eq. 4.11}$$

where

q_o = observed peak flow rate,

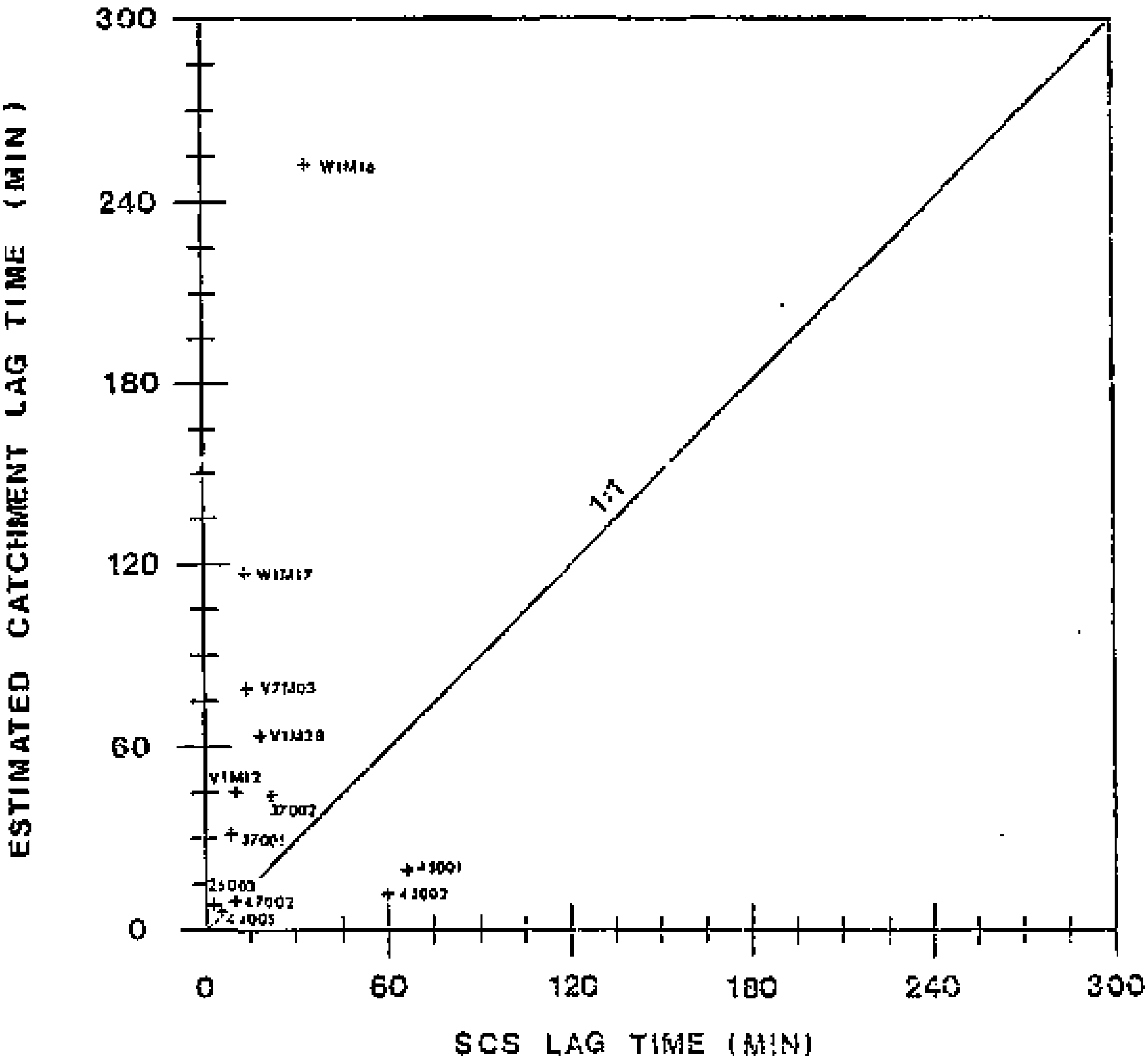

Figure 4.1 Catchment lag times estimated using single triangular procedures versus SCS lag times

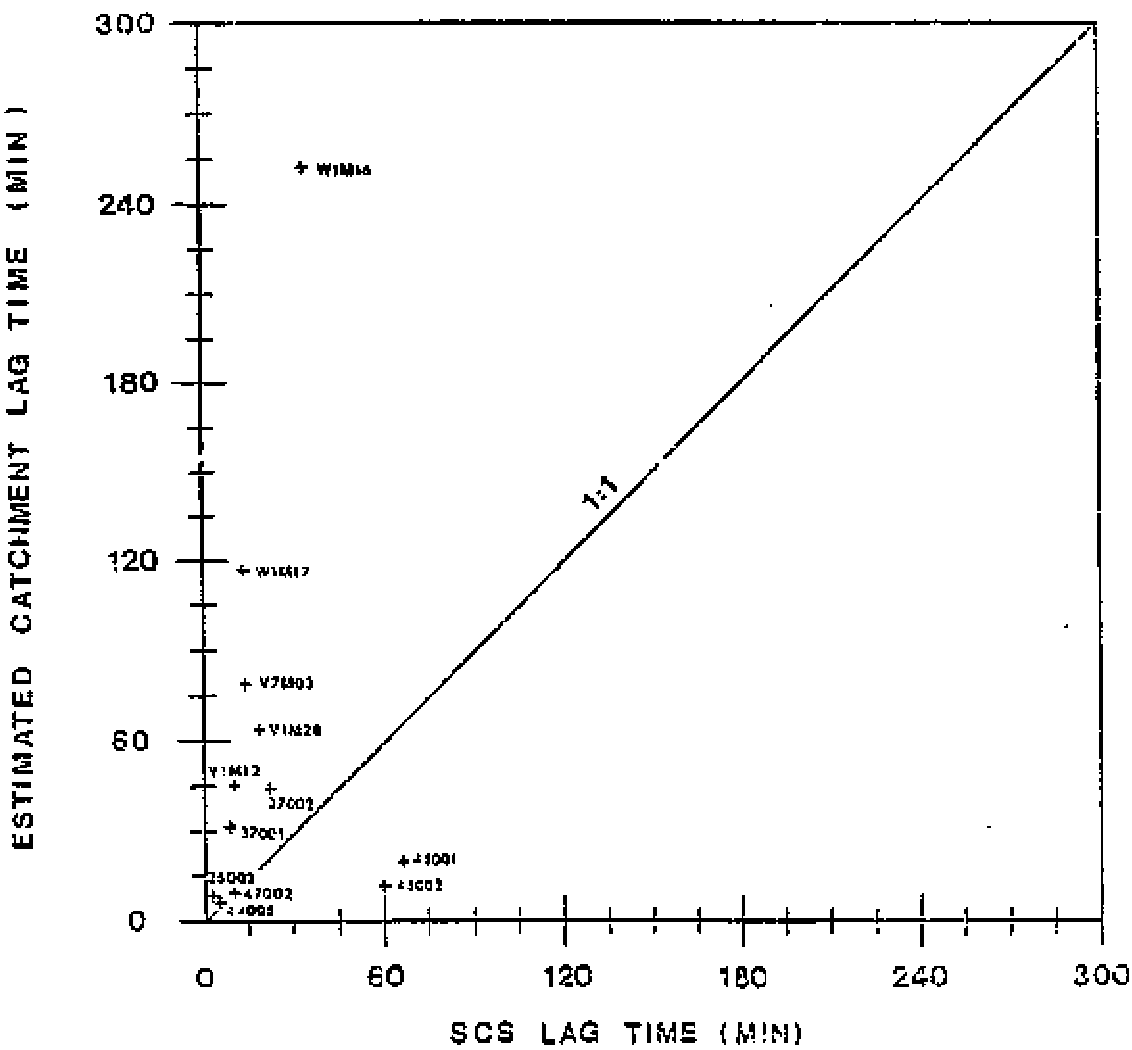

Figure 4.1 Catchment lag times estimated using single triangular procedures versus SCS lag times

$\bar{q}_o$ = mean of the observed peak flow rates and

q_e = the estimate of peak flow rate obtained using the relevant catchment lag time.

The Coefficient of Determination is defined as

$$D_1 = \frac{\Sigma q_o - \bar{q}_o)^2 - \Sigma (q_o - q_{est})^2}{\Sigma (q_o - \bar{q}_o)^2} \qquad \text{Eq. 4.12}$$

where

q_{est} = the estimate of peak flow rate as obtained from the linear regression of q_o on q_e.

Both D_1 and E_1 will always be less than unity, with values tending to unity indicating accurate estimations of peak flow rate. The Coefficient of Efficiency may be used as an absolute measure of the efficiency of peak flow rate prediction when comparing two catchment lag times. Furthermore, by considering D_1 and E_1 together it is possible to ascertain whether systematic error is present, the value of E_1 being lower than D_1 when this is so. The error function F_1 is defined as the difference between D_1 and E_1 (Aitken, 1973). Thus the closer F_1 is to zero, the less systematic error occurs in prediction. Values D_1, E_1 and F_1 associated with the SCS lag time and the estimated catchment lag time for each of the twelve catchments are shown in Table 4.5.

The results of Table 4.5 illustrate the considerably improved estimates of peak flow rate on all the catchments when using the estimated catchment lag times calculated from the linear runoff distributions. When approximating each runoff hydrograph by a single triangular hydrograph, the estimated peak flow rate is inversely proportional to the lag time. The estimates of peak flow rate for corresponding storms using different catchment lag times are thus direct multiples of one another. Consequently the error function D_1

Table 4.4 Comparison of catchment lag times estimated using single triangular procedures with SCS lag times

Catchment	Estimated catchment lag time (min)	SCS lag time (min)
26003	8,0	2,6
37001	31,4	8,5
37002	44,0	21,9
44005	6,6	5,2
45001	19,6	66,3
45002	11,8	60,0
47002	9,2	9,8
V1M12	44,9	10,2
V1M28	63,7	18,5
V7M03	78,9	14,3
W1M16	252,1	34,3
W1M17	117,0	13,7

Table 4.4 Comparison of catchment lag times estimated using single triangular procedures with SCS lag times

Catchment	Estimated catchment lag time (min)	SCS lag time (min)
26003	8,0	2,6
37001	31,4	8,5
37002	44,0	21,9
44005	6,6	5,2
45001	19,6	66,3
45002	11,8	60,0
47002	9,2	9,8
V1M12	44,9	10,2
V1M28	63,7	18,5
V7M03	78,9	14,3
W1M16	252,1	34,3
W1M17	117,0	13,7

Table 4.5 Error functions for predicted peak flow rates obtained using the standard SCS catchment lag time and the estimated catchment lag time

Catchment	Procedure	Error Function D_1	E_1	F_1
26003	SCS lag time	0,489	-7,107	7,596
	Estimated lag time	0,489	0,460	0,029
37001	SCS lag time	0,704	-4,958	5,662
	Estimated lag time	0,704	0,676	0,028
37002	SCS lag time	0,824	-1,405	2,229
	Estimated lag time	0,824	0,815	0,009
44005	SCS lag time	0,759	0,590	0,169
	Estimated lag time	0,759	0,711	0,048
45001	SCS lag time	0,941	-0,312	1,253
	Estimated lag time	0,941	0,934	0,007
45002	SCS lag time	0,901	-0,542	1,443
	Estimated lag time	0,901	0,890	0,011
47002	SCS lag time	0,900	0,483	0,417
	Estimated lag time	0,900	0,899	0,001
V1M12	SCS lag time	0,976	-16,060	17,036
	Estimated lag time	0,976	0,975	0,001
V1M28	SCS lag time	0,853	-5,437	6,290
	Estimated lag time	0,853	0,766	0,087
V7M03	SCS lag time	0,703	-28,661	29,364
	Estimated lag time	0,703	0,686	0,017
W1M16	SCS lag time	0,995	-50,251	51,246
	Estimated lag time	0,995	0,994	0,001
W1M17	SCS lag time	0,747	-112,381	113,128
	Estimated lag time	0,747	0,737	0,010

is the same for a particular catchment regardles of lag time used. It is thus the error function E_1 which provides a better measure of the efficiency of peak flow rate prediction when comparing the two catchment lag times. From Table 4.5 it is clear that poor estimates of peak flow rate are obtained from the lag times calculated using the SCS lag equation. The values of F_1, which are greater than 1,0 on all except catchments 44005 and 47002 indicate the high systematic error associated with the SCS lag times. The values of F_1 are less than 0,088 for all catchments when using the estimated catchment lag times, indicating minimal systematic errors in peak flow rate prediction. Significant improvements to estimations of peak flow rate, obtained using the estimated catchment lag times, can therefore only be made by eliminating 'random' errors - indicated by the deviation of the error function D_1 from unity- which are to a large extent related to variations in the individual storm characteristics.

A principal factor affecting catchment lag time appears to be the type of runoff produced in each region. Unpublished research results for the humid Zululand catchments have indicated that up to 70 percent of direct runoff can be due to sub-surface flow (Hope, 1981). The long estimated catchment lag times for catchments W1M16 and W1M17, where hydrographs typically have a low peak flow rate per volume of runoff indicate the high retardance for such sub-surface flow. On the other hand, overland flow is generally a major contributor to the runoff of arid catchments where shallow soils are frequently underlain by impervious rock strata and do not support sufficient vegetation to promote infiltration or prevent surface sealing. The inability of the SCS lag equation to simulate the corresponding short travel times is indicated in Table 4.4 where the lag times for catchments 45001 and 45002 are considerably over-estimated when using the SCS lag equation.

The SCS lag equation is based on overland flow criteria and the retardance factor CN is envisaged as a measure of the retardance of surface conditions on the rate of runoff (National Engineering Handbook, 1972). The inclusion of CN' into the SCS lag equation is the same for a particular catchment regardles of lag time used. It is thus the error function E_1 which provides a better measure of the efficiency of peak flow rate prediction when comparing the two catchment lag times. From Table 4.5 it is clear that poor estimates of peak flow rate are obtained from the lag times calculated using the SCS lag equation. The values of F_1, which are greater than 1,0 on all except catchments 44005 and 47002 indicate the high systematic error associated with the SCS lag times. The values of F_1 are less than 0,088 for all catchments when using the estimated catchment lag times, indicating minimal systematic errors in peak flow rate prediction. Significant improvements to estimations of peak flow rate, obtained using the estimated catchment lag times, can therefore only be made by eliminating 'random' errors - indicated by the deviation of the error function D_1 from unity- which are to a large extent related to variations in the individual storm characteristics.

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The SCS lag equation is based on overland flow criteria and the retardance factor CN is envisaged as a measure of the retardance of surface conditions on the rate of runoff (National Engineering Handbook, 1972). The inclusion of CN' into the SCS lag equation seems inadequate to account for either the high percentage of sub-surface flow present in the humid and sub-humid regions or the dominant surface runoff found in the arid areas. Estimates of CN' are derived from field surveys of soil type, vegetation type and condition of the catchment for average antecedent conditions. Such estimates are often highly inaccurate when compared with the 'actual' catchment Curve Number for each runoff event which is obtained by solving for S in the stormflow equation shown below using recorded rainfall and runoff data, viz.

$$Q = \frac{(P - 0,2S)^2}{(P - 0,8S)}$$

from which

$$S = \frac{(0,8Q + 0,4P) \pm \sqrt{(0,8Q + 0,4P)^2 - 0,16(P^2 - QP)}}{0,08}$$

Eq. 4.13

Since the condition that P 0,2S must be satisfied, only the square root term preceded by the negative is meaningful in Equation 4.13. Substituting measured values of Q and P into Equation 4.13 to determine S and hence CN enables the determination of the actual catchment Curve Number for each storm. A wide range of CNs calculated for the events of each catchment using Equation 4.13 are obtained. The results for catchment 45001 typify such variability with values of CN ranging from 72,0 to 97,7 and having a mean of 86,8 (c.f. Table 5.1). A mean catchment Curve Number calculated using recorded data (86,8) provides a more representative indication of catchment response than a field estimated value (79,0) which assumes antecedent moisture conditions to be average and is based on subjective applications of empirically quantified field classifications. The SCS lag equation is highly sensitive to CN' and a change from the measured value of 79,0 to 86,8 represents a decrease in lag time of 23 percent. Precision in the determination of CN' is thus critical for accurate estimates of lag time. Such precision is seldom attained.

The relationships between the estimated catchment lag time of Table 4.4 show strong regional trends, suggesting that lag time is affected by climatic conditions. Climate has a major influence on both the soils and the type and condition of vegetation in a region and has been found to be closely related to various drainage characteristics (Bedient, Huber and Heaney, 1978). Both soils and vegetation affect the retardance and proportions of surface and subsurface flow, suggesting a link between climate and lag time.

The temporal distribution and intensity of rainfall has a dominating influence on runoff production which modifies the effect due to soils and vegetation. The precipitation rate of short intense storms frequently exceeds soil infiltration rates, resulting in a large proportion of overland runoff. Low intensity rainfall of long durations frequently initiates subsurface flow. Although storm characteristics will vary widely within a catchment, thereby affecting individual storm lag times, the average catchment response time can be expected to depend, in part, on the typical characteristics of rainfall for the region.

Owing to the inaccurate estimates of catchment lag time obtained using the SCS lag equation, a multiple regression analysis was undertaken to provide improved estimates of catchment lag time for ungauged catchments.

4.3.3 Empirical relationships to determine catchment lag time

The relationship was investigated between estimated catchment lag time, L (h) and :

1. catchment area, A (km^2),

2. catchment hydraulic length, l (m),

precision is seldom attained.

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4.3.3 Empirical relationships to determine catchment lag time

The relationship was investigated between estimated catchment lag time, L (h) and :

1. catchment area, A (km^2),

2. catchment hydraulic length, l (m),

3. average catchment slope, y (%),

4. potential maximum retention, S (mm),

5. regional most intense 30-minute period of rainfall $\bar{I}_{30}$(mm.h^{1}),

6. regional storm duration, $\bar{D}_{u}$(h), and

7. mean annual precipitation, MAP (mm).

The values of the physical catchment characteristics may be obtained from Table 3.2, while catchment mean annual precipitation and regional rainfall indices, obtained by averaging the storm maximum thirty-minute rainfall intensities and durations for each region, have been presented in Tables 3.1 and 3.3 respectively. Potential maximum retention was transformed by the addition of a constant term to form the variable (S + 25,4), according to the procedures followed in the SCS National Engineering Handbook (1972) to enable the calculation of lag time for a potential maximum retention of zero millimetres, which corresponds with an impervious catchment. The regression equation obtained when combining all the independent variables is given in Table 4.6 together with other relevant statistics pertaining to the equation.

The results of Table 4.6 indicate a high degree of association between lag time and the independant variables used. However, the use of seven independent variables in the regression analysis, which is based on the results from only twelve catchments, leaves only four degrees of freedom for random error. In addition, the total correlation coefficient matrix shown in Table 4.7 indicates a high degree of inter-correlation between independent variables.

In order to reduce the number of independent variables, l and (S + 25,4) which had the smallest corresponding t-values, were omitted from the analyses to form a five parameter model. The regression

Table 4.6 Statistic's relating to the seven parameter multiple regression analysis of catchment lag times estimated using single triangular procedures.

Regression Equation	Coefficient of Determination (r^2)	Variance Ratio (F)
$L_{sc} = \dfrac{2{,}0\ A^{0,40}\ I^{0,04}\ MAP^{2,10}}{y^{0,91}\ (S + 25{,}4)^{0,36}\ \bar{T}_{30}^{\ 2,87}\ \bar{D}_{u}^{\ 1,26}}$	,980	28,400**

Independent variable	A	I	y	S+25,4	$\bar{T}_{30}$	$\bar{D}_u$	MAP
Student's t-value	1,302	0,087	3,065**	0,655	2,906*	2,595	4,906**

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Regression Equation	Coefficient of Determination (r^2)	Variance Ratio (F)
$L_{sc} = \dfrac{2,0\ A^{0,40}\ l^{0,04}\ MAP^{2,10}}{y^{0,91}\ (S + 25,4)^{0,36}\ \bar{T}_{30}^{\ 2,87}\ \bar{D}_u^{\ 1,26}}$	,980	28,400**

Independent variable	A	l	y	S+25,4	$\bar{T}_{30}$	$\bar{D}_u$	MAP
Student's t-value	1,302	0,007	3,065**	0,655	2,906*	2,595	4,906**

Table 4.7 Correlation matrix relating independent variables to lag time

	A	l	y	S+25.4	$\bar{I}_{30}$	$\bar{D}_u$	MAP	L_{cs}
A	1.00							
l	.95	1.00						
y	.11	-.07	1.00					
S+25.4	-.14	-.35	.40	1.00				
$\bar{I}_{30}$	-.49	-.33	-.50	-.09	1.00			
$\bar{D}_u$	.35	.18	.28	.30	-.84	1.00		
MAP	-.13	-.36	.46	.67	-.44	.71	1.00	
L_{cs}	.58	.37	.36	.31	-.77	.81	.66	1.00

equation for the reduced analysis with the relevant statistical information is shown in Table 4.8.

The results of Table 4.8 provide an accurate means of predicting catchment lag time with all the variables making a significant contribution to the prediction equation. However, as indicated by Hewlett (1981), a model that predicts adequately does not always explain well. Generally it is accepted that intense storms correspond with storms of short duration and give rise to short lag times. The regression equation in Table 4.8, however, indicates that as $\bar{D}_u$ increases lag time will decrease. Conversely the positive sign of the correlation between $\bar{D}_u$ and lag time (Table 4.7) indicates that as $\bar{D}_u$ increases catchment lag time increases. In an attempt to simplify coefficient interpretation, $\bar{D}_u$ which was significantly related to both $\bar{I}_{30}$ and MAP, was dropped from the regression analysis. The results of the four parameter regression model are shown in Table 4.9.
The regression equation in Table 4.9 is both statistically significant and is based on meaningful and simply defined variables. In Table 4.10, catchment lag times regressed from the equation in Table 4.9 are compared with catchment lag times estimated using single triangular procedures and SCS lag times (c.f. Table 4.4.). A scatter diagram of regressed versus estimated catchment lag time is given in Figure 4.2. The closer approximation of the point distribution to the 1:1 line in Figure 4.2 when compared with that in Figure 4.1 gives an indication of the improved estimation of lag time obtained using the equation in Table 4.9.

The estimated catchment lag times presented in Table 4.10 provide the best estimates of peak flow rate for the recorded hydrographs of each catchment, when intra-catchment variations in lag time are ignored. In order to estimate individual storm lag times, an attempt is made in the next section to provide non-linear adjustments to such constant catchment lag times by considering the storm characteristics of the individual events.

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The estimated catchment lag times presented in Table 4.10 provide the best estimates of peak flow rate for the recorded hydrographs of each catchment, when intra-catchment variations in lag time are ignored. In order to estimate individual storm lag times, an attempt is made in the next section to provide non-linear adjustments to such constant catchment lag times by considering the storm characteristics of the individual events.

Table 4.8 Statistics relating to the fine parameter multiple regression analysis of catchment lag times estimated using singular triangular procedures

Regression Equation					Coefficient of Determination (r^2)	Variance Ratio (F)
$L_{cs} = \dfrac{1{,}9\ A^{0,42}\ MAP^{2,10}}{y^{0,95}\ \bar{I}_{30}^{\ 3,00}\ \bar{D}_u^{\ 1,25}}$					,977	30,320 **
Independent variable	A	y	$\bar{I}_{30}$	$\bar{D}_u$	MAP	
Student's t-value	7,555**	3,927**	4,405**	3,526*	7,130**	

Table 4.9 Statistics relating to the four parameter multiple regression analysis of catchment lag times estimated using single triangular procedures

Regression Equation				Coefficient of Determination (r^2)	Variance Ratio (F)
$L_{cs} = \dfrac{A^{0,35}\ MAP^{1,10}}{41{,}67\ y^{0,30}\ \bar{I}_{30}^{\ 0,87}}$				,928	22,700**
Independent variable	A	y	$\bar{I}_{30}$	MAP	
Student's t-value	4,278**	1,173	1,697	5,253**	

Table 4.10 Comparison of catchment lag times estimated using single triangular procedures with regressed catchment lag times and SCS lag times

Catchment	Estimated lag time (min)	Regressed lag time (min)	SCS lag single time (min)
26003	8,0	11,6	2,6
37001	31,4	27,5	8,5
37002	44,0	48,4	21,9
44005	6,6	7,2	5,2
45001	19,6	19,1	66,3
45002	11,8	20,0	60,0
47002	9,2	6,9	9,8
V1M12	44,9	41,7	10,2
V1M28	63,7	47,7	18,5
V7M03	78,9	43,6	14,3
W1M16	252,1	265,0	34,3
W1M17	117,0	155,2	13,7

Table 4.10 Comparison of catchment lag times estimated using single triangular procedures with regressed catchment lag times and SCS lag times

Catchment	Estimated lag time (min)	Regressed lag time (min)	SCS lag time (min)
26003	8,0	11,6	2,6
37001	31,4	27,5	8,5
37002	44,0	48,4	21,9
44005	6,6	7,2	5,2
45001	19,6	19,1	66,3
45002	11,8	20,0	60,0
47002	9,2	6,9	9,8
V1M12	44,9	41,7	10,2
V1M28	63,7	47,7	18,5
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W1M16	252,1	265,0	34,3
W1M17	117,0	155,2	13,7

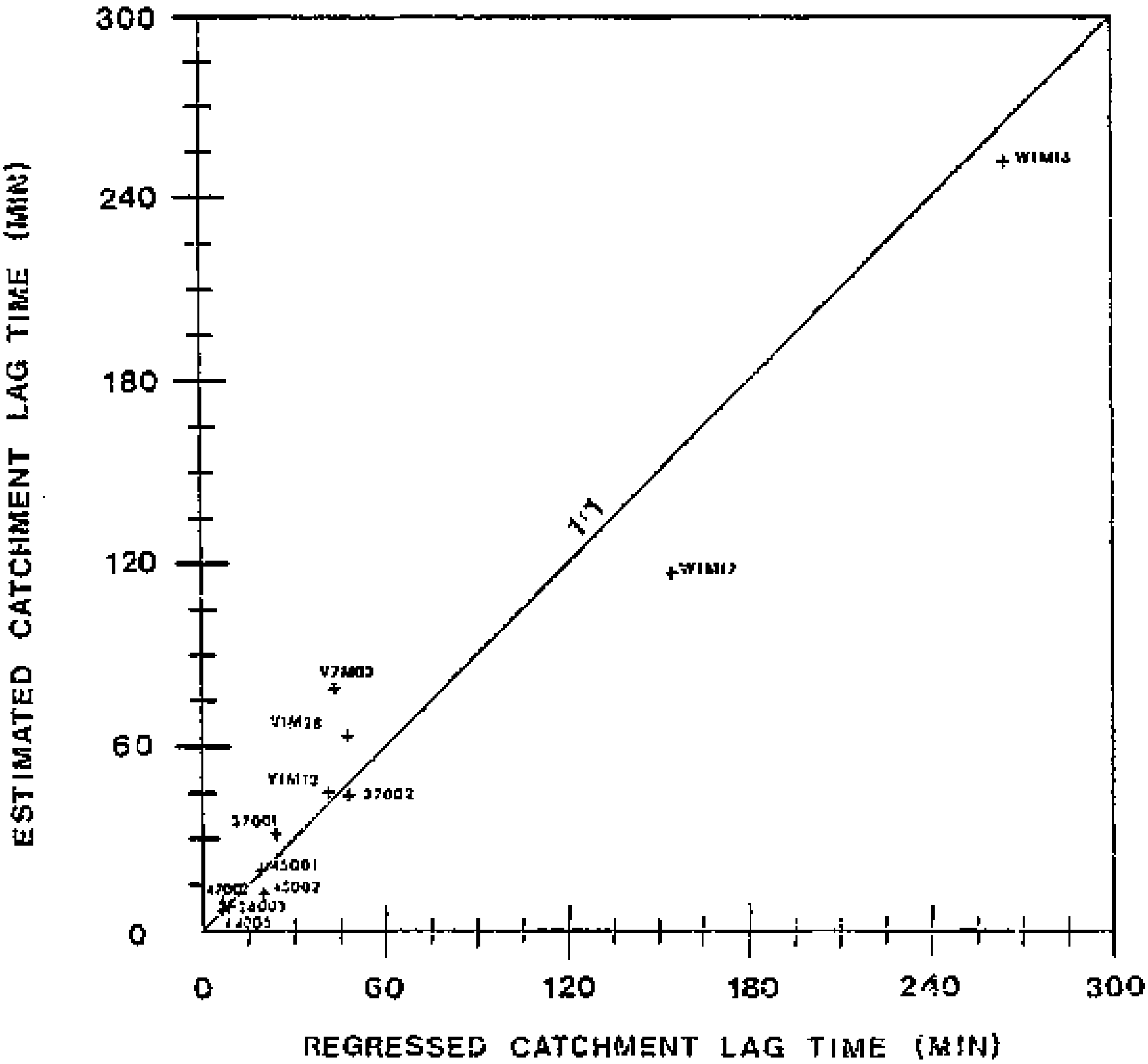

Figure 4.2 Catchment lag times estimated using single triangular procedures versus regressed catchment lag times using four parameters

4.3.4 Lag times for individual events determined from non-linear rainfall characteristics

The relationship between individual storm lag times and the estimated catchment lag time was determined from a multiple regression analysis between the ratio of estimated peak flow rate divided by observed peak flow rate q_{pe}/q_{po} and :

1. five day rainfall total preceding the event, API (mm),

2. storm rainfall amount, P (mm),

3. storm duration, D_u (mm),

4. kinetic energy of the rainfall event, E ($J.m^{-2}$),

5. most intense 30-minute period of rainfall, I_{30} ($mm.h^{-1}$).

The API was transformed by the addition of a constant term to give the variable (API + 1), in order to enable the regression equation to be calculated when zero values occurred in the data set. The results for the five parameter regression analysis are summarised in Table 4.11.

For eight of the catchments the Variance Ratios differ significantly from unity indicating a high degree of association between errors in the estimated peak flow rates and the storm characteristics considered. The relative importance of the various storm characteristics is given in Table 4.12.

The most important variables affecting the deviation in estimated peak flow rates from observed peak flow rates for individual events are I_{30}, E and D_u. The variable I_{30} is significantly correlated with q_{pe}/q_{po} for seven of the catchments, one of which (45002) shows an increase in q_{pe}/q_{po} with increase in I_{30}. A high value of I_{30} should produce a recorded peak flow rate higher than

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Table 4.11 Regression equations for the five parameter multiple regression analysis of q_{pe}/q_{po} with storm characteristics for individual events

Catchment	Regression Equation	Coefficient of Determination (r^2)	Variance Ratio (F)
26003	$\frac{q_{pe}}{q_{po}} = \frac{179{,}95\ P^{0{,}44} D_u^{0{,}18}}{(API+1)^{0{,}17} E^{0{,}33} I_{30}^{1{,}15}}$	0,71	9,019 (**)
37001	$\frac{q_{pe}}{q_{po}} = \frac{32{,}76\ (API+1)^{0{,}04}\ P^{0{,}70}}{D_u^{0{,}18}\ E^{0{,}61}\ I_{30}^{0{,}50}}$	0,66	9,010 (**)
37002	$\frac{q_{pe}}{q_{po}} = \frac{21{,}66\ (API+1)^{0{,}01}\ P^{0{,}62}\ D_u^{0{,}08}}{E^{0{,}79}\ I_{30}^{0{,}63}}$	0,82	8,460 (**)
44005	$\frac{q_{pe}}{q_{po}} = \frac{0{,}73\ (API+1)^{0{,}01}\ P^{0{,}16}\ D_u^{0{,}01}}{E^{0{,}03}\ I_{30}^{0{,}06}}$	0,04 0,04	0,201 0,201
45001	$\frac{q_{pe}}{q_{po}} = \frac{0{,}10 (API+1)^{0{,}02}\ D_u^{0{,}09}\ E^{0{,}63}}{P^{0{,}37}\ I_{30}^{0{,}19}}$	0,14	0,934
45002	$\frac{q_{pe}}{q_{po}} = \frac{0{,}63\ P^{0{,}61}\ I_{30}^{0{,}07}}{(API+1)^{0{,}08}\ D_u^{0{,}17}\ E^{0{,}25}}$	0,41	3,930 (**)
47002	$\frac{q_{pe}}{q_{po}} = \frac{1{,}90 (API+1)^{0{,}06}\ P^{0{,}80}}{Du^{0{,}03} E^{0{,}13}\ I_{30}^{0{,}66}}$	0,49	2,091
V1M12	$\frac{q_{pe}}{q_{po}} = \frac{2{,}44 (API+1)^{0{,}01}\ P^{0{,}51}\ E^{0{,}04}}{D_u^{0{,}24}\ I_{30}^{0{,}80}}$	0,65	5,280 (**)
V1M28	$\frac{q_{pe}}{q_{po}} = \frac{1{,}70\ (API+1)^{0{,}06}\ D_u^{0{,}15}\ E^{0{,}33}}{P^{0{,}21}\ I_{30}^{0{,}82}}$	0,43	1,076
V7M03	$\frac{q_{pe}}{q_{po}} = \frac{2{,}58\ P^{1{,}01}\ D_u^{0{,}01}}{(API+1)^{0{,}05}\ E^{0{,}29}\ I_{30}^{0{,}76}}$	0,62	5,530 (**)
W1M16	$\frac{q_{pe}}{q_{po}} = \frac{0{,}44\ (API+1)^{0{,}01} P^{0{,}09}\ D_u^{0{,}23}}{E^{0{,}02}\ I_{30}^{0{,}05}}$	0,54	6,010 (**)
W1M17	$\frac{q_{pe}}{q_{po}} = \frac{4{,}94\ P^{0{,}36}\ D_u^{0{,}07}}{(API+1)^{0{,}17}\ E^{0{,}31}\ I_{30}^{0{,}26}}$	0,75	4,230 (*)

Table 4.12 Statistics relating to the five parameter multiple regression analysis of q_{pe}/q_{po} with storm characteristics for individual events

Catchment		Independent Variable				
		-(API+1)	P	D_U	E	I_{30}
26003	Student's t-value, t	1,869	0,355	0,969	0,256	3,254**
	Correlation coefficient, r	0,061	0,088	0,484*	-0,112	-0,693**
37001	t	1,318	1,330	0,891	1,735	1,774
	r	0,312	-0,422*	0,388*	-0,693**	-0,756**
37002	t	0,616	1,567	0,499	2,340*	0,249
	r	0,230	-0,090	0,630*	-0,620*	-0,830**
44005	t	0,304	0,657	0,057	0,191	0,523
	r	0,074	0,139	0,129	0,019	-0,030
45001	t	1,614	0,495	0,752	0,920	0,974
	r	0,053	0,281	0,203	0,257	0,100
45002	t	1,788	2,055*	2,139*	1,028	0,556
	r	-0,272	0,537**	0,157	0,486**	0,378**
47002	t	1,109	1,100	0,179	0,308	1,812
	r	0,378	0,197	0,383	0,069	-0,167
V1M12	t	0,210	1,069	1,736	0,104	3,142**
	r	-0,210	-0,450*	0,270	-0,620**	-0,740**
V1M28	t	0,517	0,281	0,772	0,460	1,268
	r	0,260	-0,149	0,409	-0,293	-0,549
V7M03	t	0,814	1,566	0,082	0,633	2,806*
	r	-0,120	-0,180	0,384	-0,450*	-0,710**
W1M16	t	0,393	1,051	3,760**	0,340	0,727
	r	-0,020	0,195	0,716**	-0,019	-0,322
W1M17	t	1,120	0,835	0,418	1,000	0,850
	r	-0,100	0,090	0,740**	-0,510	-0,310**

Table 4.12 Statistics relating to the five parameter multiple regression analysis of q_{pe}/q_{po} with storm characteristics for individual events

Catchment		Independent Variable				
		-(API+1)	P	D_u	E	I_{30}
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	r	0,312	-0,422*	0,388*	-0,693**	-0,756**
37002	t	0,616	1,567	0,499	2,340*	0,249
	r	0,230	-0,090	0,630*	-0,620*	-0,830**
44005	t	0,304	0,657	0,057	0,191	0,523
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that estimated using an average catchment lag time and hence should correspond with a low value of q_{pe}/q_{po}. No reason for the disagreement of the results of catchment 45002 with this expected trend could be found. The variable, E is significantly correlated with q_{pe}/q_{po} for five catchments. As with I_{30}, catchment 45002 shows a positive sign for the correlation coefficient between E and q_{pe}/q_{po}, which is contrary to what would be expected. The variable, D_u has a significant positive correlation with q_{pe}/q_{po} for five catchments, indicating a decrease in observed peak flow rate relative to the estimated peak flow rate with increase in storm duration. The variable (API + 1) was not significantly correlated with q_{pe}/q_{po} for any catchment while P showed a significant correlation for only three catchments. Student's t-values confirm the domination of I_{30}, E and D_u in determining peak flow rate and suggest the use of a reduced model incorporating only the three dominant variables.

Since a high degree of intercorrelation exists between I_{30} and E, they were combined as EI_{30}, which was found by Wischmeier and Smith (1958) to be a good indicator of rainstorm classification in terms of erosion producing capacity. The results of the reduced two parameter multiple regression analyses are shown in Tables 4.13 and 4.14. The same eight catchments have F values significantly different from unity in the reduced model as in the five parameter model, confirming that minor contributions only are made by P and (API + 1) in determining q_{pe}/q_{po}. It is evident from the results of Table 4.12 that I_{30} is the major contributor to the regression equations for the reduced model shown in Table 4.13. Further studies could therefore investigate a one parameter regression equation using I_{30} as the only rainfall variate. It was decided, however, that for the present study, both D_u and E showed sufficient association with the dependant variable to be included in the analysis.

Multiplying the appropriate lag times estimated for each catchment using the linear regression equations (Table 4.3) by the equations of Table 4.13, introduces a non-linear correction to the linearly estimated catchment lag time and provides an estimate of the

Table 4.13 Regression equations for the two parameter multiple regression analysis of q_{pe}/q_{po} with storm characteristics for individual events

Catchment	Regression Equation	Coefficient of Determination (r^2)	Variance Ratio (F)
26003	$\frac{q_{pe}}{q_{po}} = \frac{64,71\ D_u^{0,42}}{EI_{30}^{0,43}}$	0,54	12,450(**)
37001	$\frac{q_{pe}}{q_{po}} = \frac{23,06\ D_u^{0,07}}{EI_{30}^{0,31}}$	0,60	19,601(**)
37002	$\frac{q_{pe}}{q_{po}} = \frac{11,15\ D_u^{0,13}}{EI_{30}^{0,26}}$	0,76	18,617(**)
44005	$\frac{q_{pe}}{q_{po}} = \frac{0,94\ D_u^{0,05}}{EI_{30}^{0,01}}$	0,02	0,253
45001	$\frac{q_{pe}}{q_{po}} = 0,52\ EI_{30}^{0,06}\ D_u^{0,08}$	0,08	1,344
45002	$\frac{q_{pe}}{q_{po}} = 0,31\ EI_{30}^{0,11}\ D_u^{0,02}$	0,21	4,185 (*)
47002	$\frac{q_{pe}}{q_{po}} = \frac{2,05\ D_u^{0,14}}{EI_{30}^{0,08}}$	0,20	1,747
V1M12	$\frac{q_{pe}}{q_{po}} = \frac{7,33}{EI_{30}^{0,19}\ D_u^{0,01}}$	0,49	8,160(**)
V1M28	$\frac{q_{pe}}{q_{po}} = \frac{6,02\ D_u^{0,24}}{EI_{30}^{0,26}}$	0,33	2,489
V7M03	$\frac{q_{pe}}{q_{po}} = \frac{9,31\ D_u^{0,17}}{EI_{30}^{0,27}}$	0,44	7,850(**)
W1M16	$\frac{q_{pe}}{q_{po}} = \frac{0,47\ D_u^{0,27}}{EI_{30}^{0,01}}$	0,52	14,910(**)
W1M17	$\frac{q_{pe}}{q_{po}} = \frac{2,19\ D_u^{0,22}}{EI_{30}^{0,14}}$	0,66	9,660(**)

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Catchment	Regression Equation	Coefficient of Determination (r^2)	Variance Ratio (F)
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W1M17	$\frac{q_{pe}}{q_{po}} = \frac{2,19\ D_u^{0,22}}{EI_{30}^{0,14}}$	0,56	9,660(**)

Table 4.14 Statistics relating to the two parameter multiple regression analysis of q_{pe}/q_{po} with storm characteristics for individual events

Catchment		Independent variable	
		εI_{30}	D_u
26003	Student's t-value, t	3,758**	4,078**
	Correlation coefficient, r	-0,424*	0,484*
37001	t	5,420**	0,839
	r	-0,768**	0,388*
37002	t	4,190**	1,872
	r	-0,828**	0,630*
44005	t	0,111	0,710
	r	0,008	0,129
45001	t	1,117	1,222
	r	0,185	0,203
45002	t	2,719*	0,463
	r	0,455**	0,157
47002	t	0,965	1,864
	r	-0,034	0,383
V1M12	t	3,725**	0,150
	r	-0,699**	0,270
V1M28	t	1,572	1,438
	r	-0,441	0,409
V7M03	t	3,230**	1,591
	r	-0,607**	0,384
W1M16	t	0,324	5,348**
	r	-0,146	0,716**
W1M17	t	1,792	2,074
	r	-0,716**	0,740**

individual storm lag time. The calculation of such an intra-catchment lag time thus includes the effects of both the physiographic and climatic characteristics of the catchment and the rainfall characteristics of the storm.

It is interesting to note that of the four catchments shown in Table 4.13 to have non-significant F values (44005,45001,47002 and V1M28), three catchments (44005, 45001 and V1M28) have runoff distribution regression slopes different at the five percent level from unity (Table 4.2). Furthermore, catchment 45002, which together with catchment 45001 shows an unexpected increase in q_{pe}/q_{po} with increase in EI_{30}, also has a runoff regression slope different at the five percent level from unity. Such non-linear regression slopes have been attributed to physiographic catchment characteristics (Askew, 1970; Rogers, 1980), which appear to dominate the effect rainfall characteristics have on the runoff distribution when the runoff distribution slopes differ significantly from unity. The conflicting role played by catchment and rainfall characteristics in determining the runoff distribution and deviation of individual events from this distribution must be separated if the contribution made by individual processes is to be better understood. Attempts to describe empirically the relationships between catchment characteristics and the runoff distribution have been unsuccessful (Askew, 1970; Rogers, 1980). The results of Tables 4.13 and 4.14 indicate that the effect rainfall characteristics have on the direct runoff distribution can to a large extent be evaluated.

The improvements to estimates of peak flow rate, obtained using the estimated catchment lag time, when modifications to such a lag time due to individual storm characteristics are introduced, are indicated graphically in Figure 4.3 for four selected catchments. The reduction in scatter of the point distribution about the 1:1 line when individual storm characteristics are introduced into the determination of lag time may be seen clearly by drawing connecting vectors between corresponding points.

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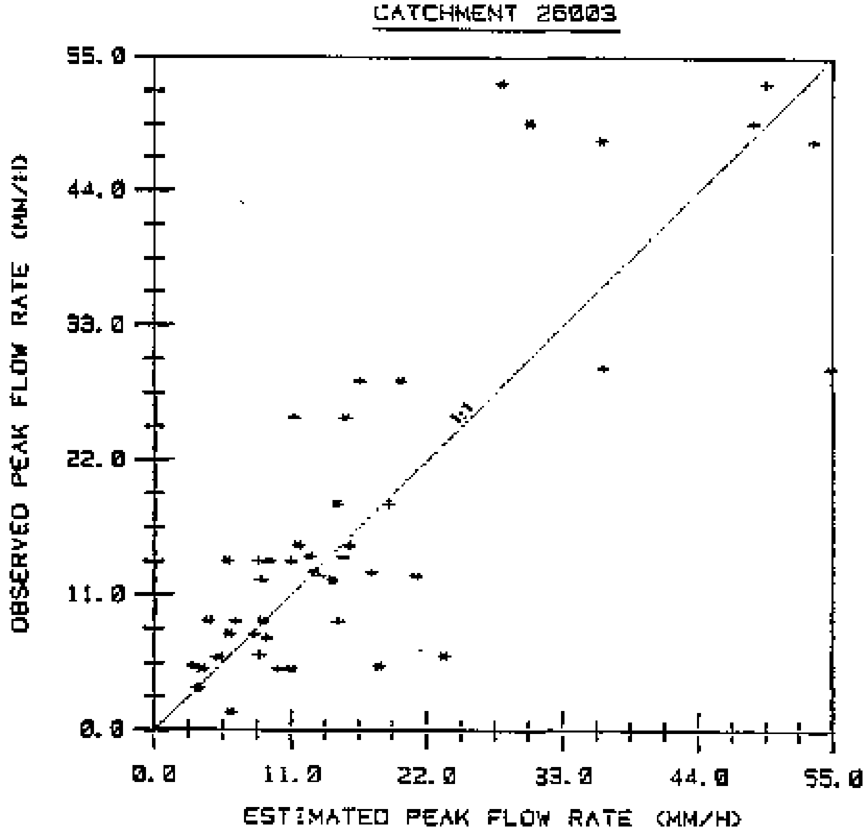
There is evidence which suggests that catchment non-linearity is related to non-uniform infiltration capacity distribution, which exists on most catchments and which modifies the effects rainfall characteristics will have on the hydrograph shape and lag time (Natural Environment Research Council, 1975; Rogers, 1980). Frequently, according to Rogers (1980), infiltration capacities are highest on the catchment divide and decrease down the topographic slope to the flood plains where runoff producing areas are permanently moist, approximately identical in size and infiltration capacity is effectively zero (Betson, 1964). The effect of high infiltration capacity around the catchment perimeter would result in most of the runoff from small to medium storms originating from near the catchment outlet with a corresponding short lag time and high peak flow rate in relation to volume of runoff. For a large storm a greater percentage of the catchment area would contribute to direct runoff with sub-surface flow and variable source area mechanisms dominating in the upland areas, where higher infiltration capacities and storage effects occur. The effect of this increase in effective catchment size contributing to runoff for larger storms is for a relatively lower peak to be produced with corresponding longer lag times.

It appears therefore that the expected decrease in lag time with increase in storm size for a catchment where runoff generation is spatially uniform, is affected to a large extent by the physical characteristics of the catchment and in particular, its soil properties. However, the results of Tables 4.13 and 4.14 indicate that the effects of rainfall characteristics on the runoff hydrograph are nevertheless significant. Such non-linearity introduced by changes in rainfall pattern is shown in Table 4.15 to be most accurately modelled in humid and sub-humid regions. From Table 4.15 it can be concluded, however, that although regionalisation yields satisfactory regression equations for the estimation of individual storm lag times, the determination of a pooled equation must await re-examination until further data become available.



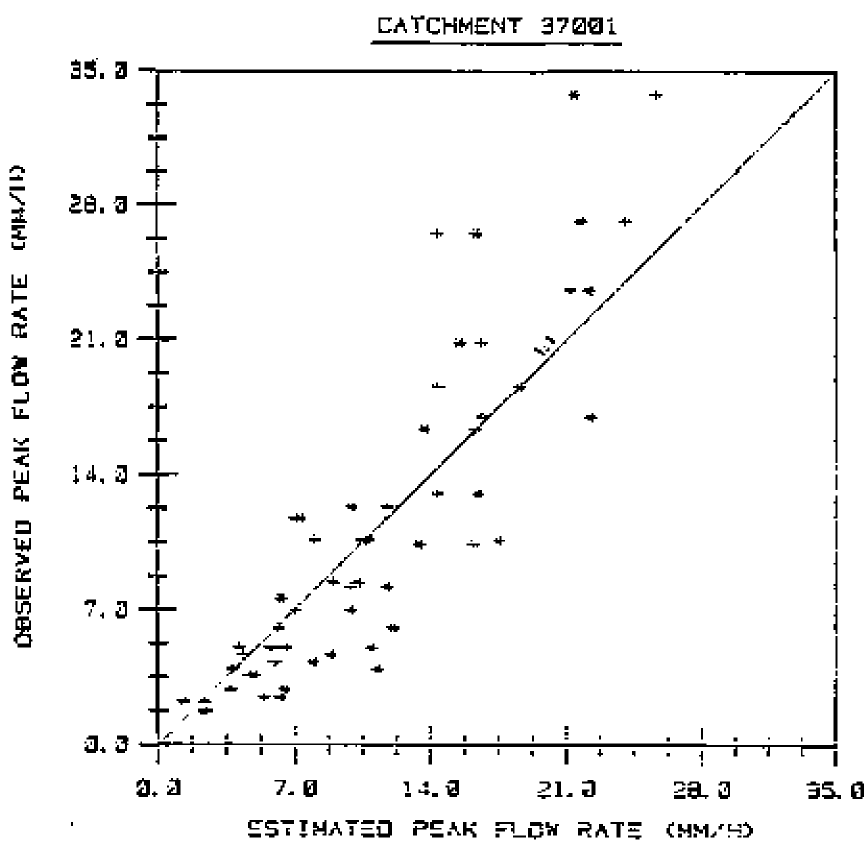
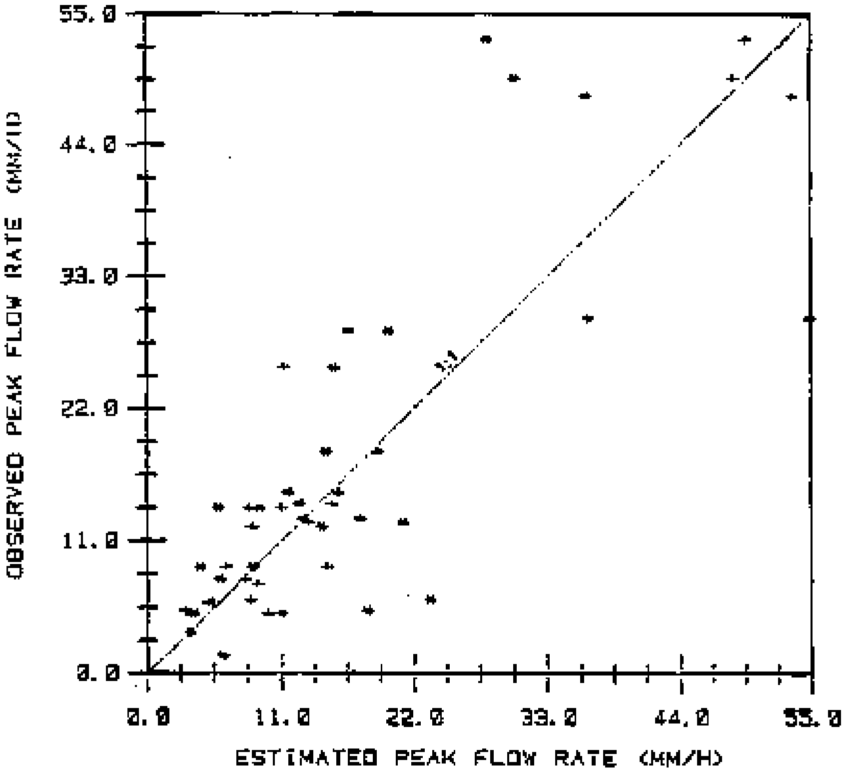
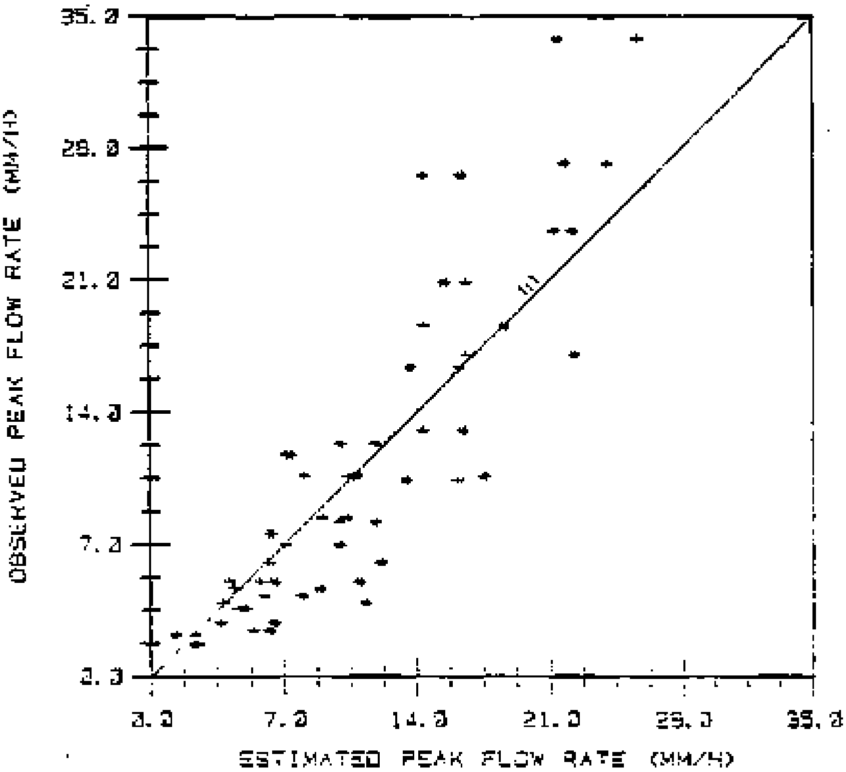


Figure 4.3 Observed peak flow rate versus estimates of peak flow rate for four selected catchments using an estimated catchment lag time (*) and estimated storm lag times (+)

CATCHMENT 28003



CATCHMENT 37001



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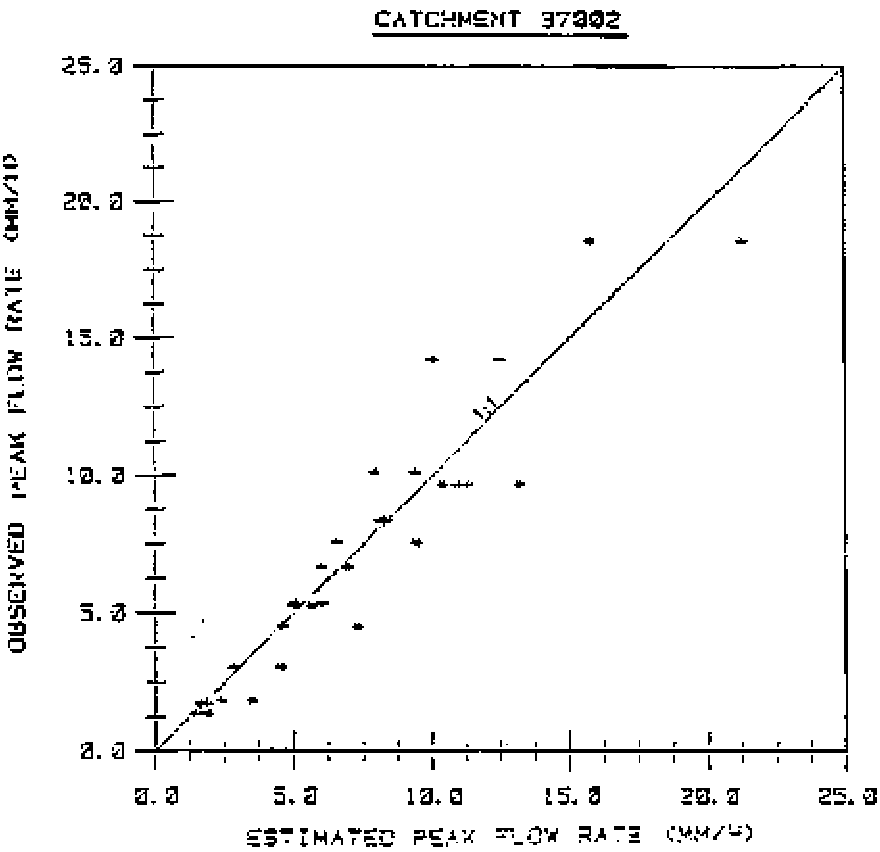

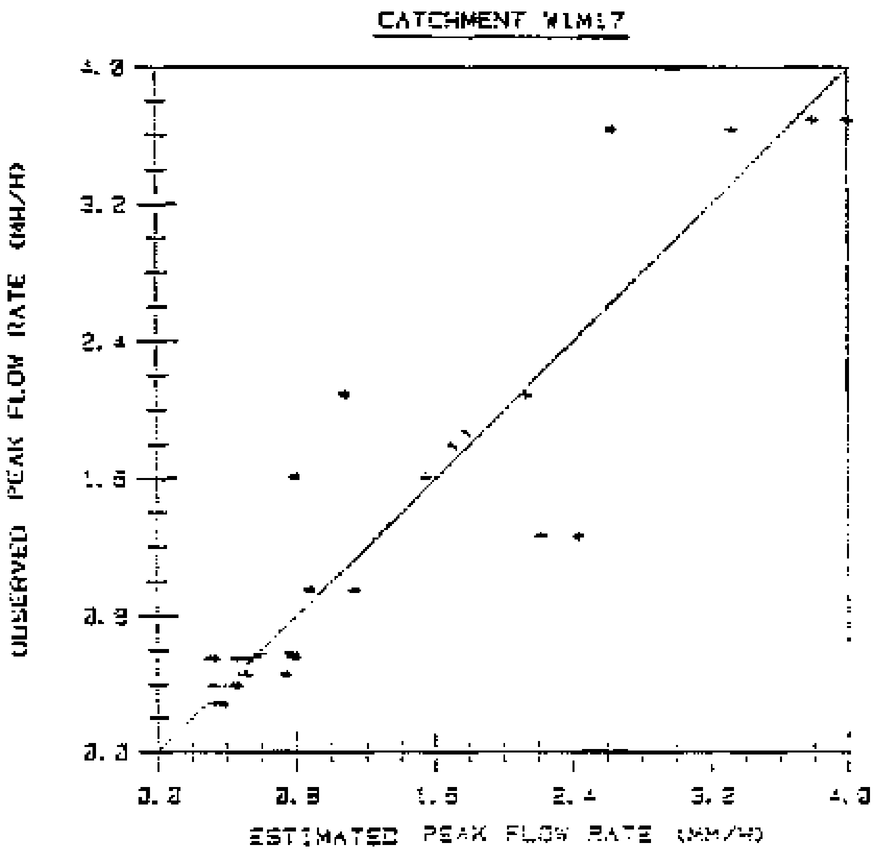

Figure 4.3 continued

Table 4.15 Regional regression equations for the two parameter multiple regression analysis of q_{pe}/q_{po} with storm characteristics for individual events

Region	Regression Equation	Coefficient of Determination (r^2)	Variance Ratio (F)
USA (sub-humid)	$\frac{7,97\ D_u^{0,16}}{EI_{30}^{0,22}}$	0,40	33,079(**)
USA (arid)	$0,49\ EI_{30}^{0,06}\ D_u^{0,04}$	0,08	3,517(*)
USA (pooled)	$\frac{1,79\ D_u^{0,16}}{EI_{30}^{0,07}}$	0,19	21,532(**)
SA (sub-humid)	$\frac{4,75\ D_u^{0,02}}{EI_{30}^{0,18}}$	0,16	4,975(*)
SA (humid)	$\frac{0,47\ D_u^{0,28}}{EI_{30}^{0,0003}}$	0,44	16,255(**)
SA (pooled)	$\frac{1,36\ D_u^{0,03}}{EI_{30}^{-0,05}}$	0,07	3,845(*)

Humid : MAP > 1100mm Sub-humid : MAP 300mm - 1100mm
Arid : MAP < 300mm

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SA (sub-humid)	$\frac{4,75\ D_u^{0,02}}{EI_{30}^{0,18}}$	0,16	4,975(*)
SA (humid)	$\frac{0,47\ D_u^{0,28}}{EI_{30}^{0,0003}}$	0,44	16,255(**)
SA (pooled)	$\frac{1,36\ D_u^{0,03}}{EI_{30}^{-0,05}}$	0,07	3,845(*)

Humid : MAP > 1100mm Sub-humid : MAP 300mm - 1100mm
Arid : MAP < 300mm

4.4 Conclusions

The SCS lag equation, while unable to account for intra-catchment variations in lag time, has been shown to estimate inter-catchment lag times inaccurately. These inaccuracies are believed due mainly to difficulties in differentiating between the mechanisms generating runoff in different catchments. Climatic and regional rainfall indices provide an indication of the dominant processes contributing to runoff and hence they can be used to estimate an average catchment lag time. Ultimately, however, it is the characteristics of the individual rainfall event which affect the areal distribution and extent of surface and subsurface runoff and thus intra-catchment adjustments to catchment lag times determined from regional climatic indices and the catchment physiographic characteristics must be made.

The results presented in this chapter indicate the improved estimates of lag time and hence peak flow rates obtained when incorporating indices describing inter- and intra-catchment variations in rainfall characteristics.

These results are based upon simplified assumptions of a temporally uniform rainfall distribution and single triangular approximates of the runoff hydrograph. In the following chapter a more complex approach using the recorded hyetograph and incremental triangular hydrographs will be used to enable comparisons to be made with the results already obtained.

5. DERIVATION OF LAG TIME USING INCREMENTAL TRIANGULAR HYDROGRAPHS

Superimposing incremental hydrographs determined from incremental periods of effective rainfall enables the synthesis of peak flow rate and the total time distribution of runoff for a recorded storm event. The accuracy with which the synthesised runoff hydrograph approximates the recorded runoff hydrograph produced by the given storm, depends on the shape and lag time of the incremental hydrograph used in the synthesising process.

It is widely accepted that the incremental hydrograph which analytically superimposes to form a representative estimate of the recorded runoff event typifies the unit hydrograph for the runoff event (Levi and Valdes, 1964; Mays and Coles, 1980; Mawdsley and Tagg, 1981). In the previous chapter such procedures were applied in a simplified form when the shape of the recorded hydrograph was used to approximate a single incremental hydrograph which was assumed to result from a rainfall distributed uniformly over an empirically determined duration of effective rainfall. The procedures of the present chapter are not restricted by such assumptions and are used to ascertain the reliability of the relationships, obtained in Chapter 4, describing inter- and intra- catchment variations in lag time.

5.1 Experimental procedures

5.1.1 Background

The incremental hydrograph lag times required to superimpose incremental triangular hydrographs to form 'representative estimates' of the recorded runoff events were determined for the storms of catchments 26003, 37001, 44005, 45002 and W1M17. Following the procedures of Chapter 4, synthetic volumes of runoff are assumed to

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The incremental hydrograph lag times required to superimpose incremental triangular hydrographs to form 'representative estimates' of the recorded runoff events were determined for the storms of catchments 26003, 37001, 44005, 45002 and W1M17. Following the procedures of Chapter 4, synthetic volumes of runoff are assumed to be predicted accurately and are given by the recorded volume of runoff for each event. The shape of the incremental triangular hydrographs were held constant with 37,5 percent of the total volume of runoff falling under the rising limb of the hydrograph.

Since this research was aimed at providing accurate estimates of peak flow rate the criterion for 'representative estimate' of the recorded hydrograph was directed towards the hydrograph peak flow rate. Lag time was thus optimised to determine a storm lag time, L_{si} (subscripts refer to a storm lag time determined using incremental hydrograph procedures), providing a synthetic hydrograph of peak flow rate equal to the recorded peak flow rate. To equate synthetic runoff volumes with recorded runoff volumes, the actual storm Curve Numbers determined for each runoff event (Equation 4.13) were used to calculate the volumes of runoff corresponding with each incremental triangular hydrograph. The Coefficinet of Efficiency, E_1, determined by substituting digitised flow rates obtained at intervals along the recorded hydrograph trace and corresponding synthetic hydrograph flow rates into Equation 4.11 was expressed as a percentage and used to determine the accuracy to which the shape of the recorded hydrograph was modelled by the synthetic hydrograph. Since E_1 was required purely as an indication of the accuracy to which the hydrograph shape was modelled and thus had to be calculated when no time lapse occurred between the recorded and synthesised hydrographs, ordinates of peak flow rate for the recorded and synthetic hydrographs of each storm were aligned.

An average of the storm lag times of each catchment was used as an estimate of the catchment lag time, L_{ci}. The ratios of storm lag times divided by the estimated catchment lag time (i.e. L_{si}/L_{ci}) were then regressed against rainfall characteristics in order to evaluate the dependence of L_{si} upon intra-catchment variations in rainfall characteristics. Hydrographs were also synthesised using incremental triangular hydrographs determined following standard SCS procedures, using the actual CN as an input into the SCS lag equation, in order to assess the accuracy of peak flow rate estimates obtained using the

SCS lag equation.

The number of catchments used in this phase of the research was restricted due to the time required to prepare input data and run the computer program written to develop the synthetic hydrograph for each event. Six catchments were selected to provide a suitable data base to enable catchment lag times estimated using incremental hydrograph procedures to be compared with the catchment lag times estimated in Chapter 4. Catchments from the USA were preferred since they offered the widest range in storm size. One catchment from Zululand was, however, included in the study to enable a comparison to be made with the long lag times obtained for this region in Chapter 4.

Incremental triangular hydrographs were convoluted with the rainfall hyetograph to form a synthetic runoff hydrograph. The computer programs, SCSVL and its subroutines, used for this procedure are given in Appendix 2 and discussed in the ensuing sections.

5.1.2 Output options

Digitised rainfall and runoff data having been read, the following output options were possible :

1. The recorded outflow hydrograph could be backrouted to form the inflow hydrograph to the weir, where this was deemed necessary.

2. Synthetic hydrographs could be calculated following standard SCS procedures.

3. Synthetic hydrographs could be calculated by optimising lag time to provide a representative estimate of the recorded runoff hydrograph.

SCS lag equation.

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3. Synthetic hydrographs could be calculated by optimising lag time to provide a representative estimate of the recorded runoff hydrograph.

5.1.3 Backrouting

Backrouting of the outflow hydrograph, when required, was done by means of the level pool flood routing technique (Subroutine ROUTL). Owing to an integer output for breakpoint digitised points on the outflow hydrograph trace, large over- or under-estimations of storage changes with respect to time were calculated for small time steps and stage increments, producing marked fluctuations in the inflow hydrograph. In order to avoid small time steps, stage and time values were interpolated at constant time intervals on the outflow hydrograph trace. Volumes of runoff for each time step (calculated in Subroutine QSTEP) were then combined with the corresponding storage changes determined using stage/storage equations to determine an inflow hydrograph largely free of fluctuations.

5.1.4 Synthetic hydrograph calculation

In the calculation of runoff volumes and hence peak flow rates (Subroutine SYNTL) for incremental rainfall amounts (calculated in Subroutine RSTEP) the ordinates of successive incremental triangular hydrographs were superimposed to produce the synthetic storm hydrograph. The number of incremental hydrographs contributing to each composite hydrograph ordinate is dependent upon the relationship between the incremental duration of effective rainfall and the time to peak. Little variation in peak flow rate estimates were obtained for variations in the relationship between D and t_p, provided a sufficient number of incremental hydrographs were used to cover the peak producing period of the storm's rainfall. The incremental duration of effective rainfall, D, was thus chosen to be

$$D = \frac{t_p}{6}$$

and could thus be related to lag time since

$$t_p = \frac{\Delta D}{2} + L$$

to form the relationship

$$\Delta D = \frac{L}{5.5}$$

Lag time was either determined using the SCS lag equation or optimised to form a composite hydrograph of peak flow rate equal to the recorded hydrograph peak flow rate. Potential maximum retention was determined from recorded rainfall and runoff data (Subroutine SYNTL).

5.1.5 Alignment of recorded and synthetic hydrographs

An option to align synthetic and recorded hydrographs was provided (Subroutine PHASE). Alignment of hydrograph peaks provided a standard method to calculate a Coefficient of Efficiency, thereby providing an index of the accuracy of hydrograph shape simulation.

5.1.6 Efficiency between recorded and synthetic hydrographs

Although synthetic and recorded peak flow rates will be equal when lag time is optimised, a measure of the extent to which total hydrograph shape is represented by the synthetic hydrograph can be determined using the Coefficient of Efficiency, E_1 previously given by Equation 4.11, but where

q_0 = flow rate for each point digitised on the recorded hydrograph trace,

$$t_p = \frac{\Delta D}{2} + L$$

to form the relationship

$$\Delta D = \frac{L}{5,5}$$

Lag time was either determined using the SCS lag equation or optimised to form a composite hydrograph of peak flow rate equal to the recorded hydrograph peak flow rate. Potential maximum retention was determined from recorded rainfall and runoff data (Subroutine SYNTL).

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Although synthetic and recorded peak flow rates will be equal when lag time is optimised, a measure of the extent to which total hydrograph shape is represented by the synthetic hydrograph can be determined using the Coefficient of Efficiency, E_1 previously given by Equation 4.11, but where

q_o = flow rate for each point digitised on the recorded hydrograph trace,

and

q_e = flow rate interpolated on the synthetic hydrograph trace to correspond with each digitised point on the recorded hydrograph trace.

Although the magnitude of E_1 depends on the number and location of points on the recorded hydrograph trace and hence cannot be compared for different storm events, a comparison can be made between E_1 values for different models applied to the same event.

Since full results, which include graphical and listed outputs obtained from each computer run, cannot be presented for all 172 storms used in this phase of the research, results have been summarised in tabular form. Examples of printout and graphs obtained for a few selected events are, however, given in the text.

5.2 Results and discussion

5.2.1 Estimation of catchment lag times

Details pertaining to the hydrographs synthesised for each event using optimised storm lag times and SCS lag times are given in Table 5.1. For each event Table 5.1 indicates the actual storm Curve Number, the optimised storm lag time, the SCS lag time, the Coefficients of Efficiency, expressed as a percentage, for the hydrographs synthesised using each lag time and the ratio of peak flow rate synthesised using the SCS lag equation divided by observed peak flow rate (q_{pes}/q_{po}).

For 34 of the 172 events (for example the event recorded on August 27, 1940 on catchment 26003) the recorded peak flow rates could not be simulated by means of adjustments to the incremental hydrograph

Table 5.1 Details pertaining to hydrograph synthesised using optimised storm lag times and SCS lag times

CATCHMENT 26003

DATE	CN	OPTIMISED STORM LAG (MIN)	ϵ_1 %	SCS LAG (MIN)	E_1 %	q_{pes}/q_{po}
19/6/40	92.0	5.1	98.0	2.0	81.1	1.26
28/6/40	92.5	2.7	93.3	1.4	83.2	1.27
27/8/40	72.6	–	–	2.7	28.7	0.49
4/6/41	93.7	10.8	91.7	1.9	71.6	1.75
29/6/41	70.9	2.1	61.3	2.8	61.3	0.92
7/7/41A	82.1	2.4	95.7	2.0	86.2	1.08
7/7/41B	93.7	4.8	62.3	1.3	19.0	1.40
23/8/44	75.5	4.5	49.4	2.5	13.7	1.45
6/6/47	87.0	2.7	81.7	1.7	70.1	1.04
7/6/47	92.4	10.5	81.6	1.4	62.3	2.44
16/8/47	88.8	4.5	99.0	1.6	87.3	1.24
25/6/56	92.1	4.5	33.2	1.4	-38.5	1.18
27/7/56	85.3	2.4	65.6	1.8	58.6	1.03
28/6/57	77.8	6.3	79.5	2.3	30.1	2.93
31/7/58	86.9	5.1	62.3	1.7	-32.0	1.70
4/8/59	62.9	4.5	57.1	3.5	49.3	1.06
21/8/60	60.4	–	–	3.7	11.5	0.60
29/7/61	68.9	4.8	86.9	3.0	74.0	1.24
2/9/64	70.6	2.1	68.7	3.9	72.6	0.81
7/7/69	87.5	7.8	94.2	1.7	66.0	1.45
27/7/69A	81.4	3.9	95.2	2.1	88.0	1.13
27/7/69B	93.9	12.3	76.3	1.3	-286.3	2.07
29/1/70	90.2	37.5	79.7	1.5	-81.0	2.29
24/4/70	78.9	–	–	2.3	-79.7	0.23
MEAN	91.60	6.73		2.10		1.37
S.E.MEAN	2.01	1.66		0.14		0.14
MINIMUM	60.40	2.10		1.30		0.23
MAXIMUM	93.90	37.50		3.70		2.93
RANGE	33.50	35.40		2.40		2.70

CATCHMENT 37001

DATE	CN	OPTIMISED STORM LAG (MIN)	ϵ_1 %	SCS LAG (MIN)	E_1 %	q_{pes}/q_{po}
18/4/59	88.7	110.1	75.7	9.2	-89.0	1.56
8/5/59	89.8	26.1	89.0	9.3	-55.2	2.02
26/5/59	96.1	–	–	10.3	44.2	0.73
22/7/59	98.1	66.3	33.4	5.9	-190.7	2.97
26/7/59	90.1	19.5	74.6	8.8	61.7	1.16
29/5/60	91.1	32.1	60.4	8.4	-241.3	2.79
27/7/60	77.0	31.7	13.3	13.7	-1834.5	3.13
7/6/61	97.0	58.3	85.7	6.2	-968.4	4.63
15/11/61	90.1	95.2	82.8	5.9	-190.0	3.26
21/11/61	98.7	79.3	58.0	5.6	-1100.7	5.24
4/9/63	70.9	9.3	33.1	16.3	53.7	0.26
1/3/64	87.1	58.3	32.7	9.3	-146.6	1.77
10/5/64	95.3	27.3	91.0	5.9	32.9	1.37
29/8/64	91.1	69.9	80.9	8.2	-1209.4	4.57
20/5/67	87.3	22.5	76.0	9.9	61.7	1.27
24/6/67	79.7	–	–	13.0	2.9	0.56
26/9/67	91.7	14.7	40.7	8.2	-8.5	1.22
7/10/67	93.1	45.9	92.3	7.7	-73.0	2.43
18/3/68	99.4	19.9	-46.1	5.3	-477.7	1.94
6/5/69	85.0	6.9	67.3	19.6	76.7	0.34
7/6/71	84.3	26.7	66.8	9.8	-107.3	1.87
3/6/71	56.9	24.9	36.7	9.9	35.3	1.30
24/9/71	98.4	19.5	87.4	5.3	22.3	1.77
29/12/72	98.6	53.9	46.2	5.7	-1233.8	4.39
6/5/73	95.4	39.9	96.3	6.3	-109.7	1.40
4/9/73	56.9	23.7	73.2	23.4	73.2	1.02
11/10/73	97.8	27.6	33.9	6.3	-129.7	1.37
3/12/73	98.4	25.7	64.5	5.8	-28.5	1.17
20/4/74	94.6	29.4	35.0	7.1	-307.8	2.72
MEAN	89.97	39.39		9.97		2.16
S.E.MEAN	1.76	1.20		0.71		0.24
MINIMUM	56.90	6.90		5.70		0.56
MAXIMUM	98.90	110.10		23.40		5.24
RANGE	42.00	103.20		17.70		[illegible]

Table 5.1 Details pertaining to hydrograph synthesised using optimised storm lag times and SCS lag times

CATCHMENT 26003

DATE	CN	OPTIMISED STORM LAG (MIN)	E_1 %	SCS LAG (MIN)	E_1 %	q_{pos}/q_{po}
18/6/40	92.0	5.1	98.0	2.0	81.1	1.26
28/6/40	92.5	2.7	93.3	1.4	23.2	1.27
27/8/40	72.6	-	-	2.7	28.7	0.49
4/6/41	93.7	10.8	91.7	1.9	71.4	1.75
29/6/41	70.9	2.1	61.3	2.8	61.3	0.92
7/7/41A	82.1	2.4	85.7	2.0	86.2	1.08
7/7/41B	93.7	4.8	62.3	1.3	19.0	1.40
23/8/44	75.5	4.5	69.4	2.5	13.7	1.45
6/6/47	87.0	2.7	81.7	1.7	70.1	1.04
7/6/47	92.4	10.5	81.6	1.4	62.3	2.44
16/8/47	88.8	4.5	99.0	1.6	87.3	1.24
25/6/56	92.1	4.5	33.2	1.4	-38.6	1.19
27/7/56	85.3	2.4	65.6	1.8	58.6	1.03
28/6/57	77.8	6.3	79.5	2.3	30.1	2.93
31/7/58	86.9	5.1	62.3	1.7	-32.0	1.70
4/8/59	63.9	4.5	57.1	3.5	49.3	1.06
21/8/60	60.4	-	-	3.7	11.3	0.60
29/7/61	68.9	4.8	96.9	3.0	74.0	1.24
2/8/64	70.6	2.1	68.7	2.9	72.6	0.81
7/7/69	87.5	7.8	94.2	1.7	66.0	1.45
27/7/69A	81.4	3.9	95.2	2.1	88.0	1.13
27/7/69B	93.9	12.3	76.3	1.3	-226.3	2.97
29/1/70	90.2	37.5	79.7	1.5	-81.0	2.29
24/4/70	78.9	-	-	2.3	-79.7	0.23
MEAN	81.60	6.73		2.10		1.37
S.E.MEAN	2.01	1.66		0.14		0.14
MINIMUM	60.40	2.10		1.30		0.23
MAXIMUM	93.90	37.50		3.70		2.93
RANGE	33.50	35.40		2.40		2.70

CATCHMENT 37001

DATE	CN	OPTIMISED STORM LAG (MIN)	E_1 %	SCS LAG (MIN)	E_1 %	q_{pos}/q_{po}
10/4/59	88.7	110.1	75.7	9.2	-89.0	1.66
8/5/59	68.8	26.1	89.0	9.2	-55.2	2.03
26/5/59	86.1	-	-	10.2	44.2	0.73
23/7/59	98.1	56.3	33.4	5.9	-190.7	2.97
25/7/59	98.1	19.5	74.6	8.0	61.7	1.16
20/5/60	91.1	32.1	60.4	8.4	-241.3	2.79
27/7/60	77.0	31.1	13.3	13.7	-1934.5	[illegible]
7/6/61	67.9	50.3	35.1	6.7	-988.4	4.53
15/11/61	93.1	98.2	32.8	5.9	-199.0	3.26
21/11/61	99.7	79.3	58.0	3.6	-1160.7	5.24
4/9/63	70.9	9.3	32.1	16.3	53.2	[illegible]
1/5/64	97.1	58.2	22.7	9.3	-146.6	1.77
10/5/64	95.3	27.3	71.0	9.7	32.9	1.37
29/8/64	91.1	59.9	30.0	9.2	-1299.4	4.57
20/5/67	87.3	22.5	76.0	9.9	61.7	1.27
24/8/67	79.7	-	-	13.0	2.8	0.56
26/9/67	91.7	14.7	40.7	8.2	-8.5	1.22
7/10/67	93.1	45.0	82.5	7.7	-93.0	2.43
13/3/68	98.4	19.7	-44.1	5.3	-477.7	1.34
6/5/69	85.4	9.9	67.3	19.1	76.7	0.84
7/5/71	87.3	26.7	56.8	7.8	-137.3	1.57
2/6/71	86.7	24.9	36.7	9.9	35.0	1.30
24/9/71	99.4	17.5	87.4	8.8	22.3	1.77
29/12/72	98.5	63.9	16.2	5.7	-1233.2	4.33
6/5/73	95.4	39.9	36.3	5.3	-139.7	1.48
4/9/73	56.9	23.7	73.2	23.4	73.2	1.02
11/10/73	77.0	27.5	33.9	6.3	-123.7	1.37
3/12/73	99.4	26.7	64.5	5.9	-28.5	1.17
20/4/74	94.6	29.4	55.0	7.1	-307.3	2.72
MEAN	89.37	37.37		8.97		2.16
S.E.MEAN	1.75	1.20		0.71		0.24
MINIMUM	56.90	9.30		5.70		0.56
MAXIMUM	98.90	110.10		23.40		5.24
RANGE	42.00	[illegible]		17.70		[illegible]

Table 5.1 continued

CATCHMENT 44005

DATE	CN	OPTIMISED STORM LAG (MIN)	E_1 %	SCS LAG (MIN)	E_1 %	$\frac{q_{pes}}{q_{po}}$
20/5/39	83.3	5.1	88.6	3.4	9.3	1.58
15/6/39	77.4	2.1	88.0	4.1	89.0	0.95
20/6/39	70.9	5.4	81.0	4.9	70.5	1.15
1/8/39	83.0	1.5	77.6	3.4	82.9	0.91
17/5/40	75.4	3.3	41.8	4.3	43.4	0.97
8/6/40	73.1	5.4	92.3	4.6	77.1	1.23
5/6/41	61.7	-	-	6.2	48.1	0.43
7/9/42	72.7	3.3	92.9	4.7	88.6	0.99
10/6/43	64.0	-	-	6.3	75.7	0.75
14/6/43	65.1	6.6	83.3	5.7	98.3	1.21
5/6/45	65.9	-	-	5.6	6.5	0.29
16/7/45A	73.1	-	-	4.6	57.7	0.59
16/7/45B	75.0	5.1	94.3	4.4	83.4	1.31
7/8/46	62.3	-	-	6.2	33.4	0.42
5/9/46	66.8	5.7	31.3	5.5	2.3	1.17
17/6/47	67.5	9.0	79.1	5.4	42.1	1.67
16/6/50	77.4	3.3	80.8	4.1	78.5	0.96
15/9/50	87.4	9.3	39.7	2.9	-155.0	2.73
26/6/52	58.4	-	-	6.8	-57.0	0.09
22/5/54	58.6	3.6	48.0	6.8	51.5	0.79
20/9/55	80.4	6.3	59.9	3.7	-47.3	1.58
15/6/57	73.8	8.7	88.4	4.7	73.9	1.38
16/7/57	75.1	-	-	4.4	63.2	0.73
12/6/58	70.4	-	-	5.0	43.0	0.52
3/7/59	67.4	9.9	78.4	5.4	68.5	1.21
15/5/60	73.8	6.9	97.0	4.5	67.0	1.19
11/8/61	69.0	6.3	47.7	5.2	19.6	1.29
23/8/62	56.9	4.5	89.0	7.1	96.1	0.91
21/6/64	77.6	-	-	4.1	10.4	0.89
26/7/64A	80.2	2.1	5.6	3.7	19.4	0.69
26/7/64B	83.6	3.9	95.3	3.4	94.6	1.11
27/8/64	87.2	2.1	58.0	2.9	64.9	0.94
1/6/65	87.7	-	-	2.9	91.5	0.54
12/6/65	74.7	9.3	93.0	4.4	-17.1	1.77
26/7/66	68.2	-	-	5.3	62.3	0.60
29/7/66	84.7	-	-	3.2	32.7	0.75
8/7/67	77.2	-	-	4.1	41.9	0.61
MEAN	73.13	5.36		4.70		1.01
S.E.MEAN	1.30	0.52		0.19		0.05
MINIMUM	58.40	1.50		2.90		0.09
MAXIMUM	87.40	9.90		7.10		2.73
RANGE	29.00	8.40		4.20		2.64

CATCHMENT 45001

DATE	CN	OPTIMISED STORM LAG (MIN)	E_1 %	SCS LAG (MIN)	E_1 %	$\frac{q_{pes}}{q_{po}}$
22/8/39	97.7	32.1	67.2	31.0	67.0	1.17
29/6/40	86.9	35.4	79.8	50.9	77.0	0.79
1/8/40	91.5	27.3	67.5	42.4	66.3	0.75
6/9/40	88.1	-	-	48.7	-33.7	0.20
26/4/41	77.5	-	-	69.4	-103.3	0.10
16/3/42	93.3	24.9	80.0	57.8	55.7	1.24
11/9/42	89.0	26.7	80.5	47.0	72.9	0.70
28/6/43	87.4	17.1	31.5	50.0	44.1	0.49
23/8/43	81.3	22.5	98.1	60.7	39.2	0.45
17/8/44	96.3	15.3	91.5	51.1	48.7	0.52
5/9/44	96.4	28.3	95.7	51.8	71.9	0.54
3/8/45	90.4	29.7	76.1	44.4	84.6	0.79
11/8/45	91.7	20.1	64.2	42.0	65.1	0.69
6/8/46	97.3	-	-	68.6	24.7	0.57
20/9/47	90.2	25.8	76.8	44.8	59.6	0.71
2/7/47	93.8	15.0	58.1	47.3	24.7	0.41
7/7/50	87.9	9.1	25.8	49.0	55.0	0.38
6/9/50	89.3	24.3	93.2	45.4	65.9	0.53
9/7/53	88.3	4.5	13.7	47.7	21.7	0.27
27/7/53	93.1	19.3	31.7	32.4	49.3	0.43
3/9/54	95.0	27.3	86.1	35.9	51.0	0.41
22/8/54	93.7	23.1	71.3	40.1	59.7	0.67
11/9/54	89.7	15.8	93.9	45.7	38.8	0.44
22/7/55	88.4	7.5	87.3	43.1	22.0	0.29
26/7/57	78.4	10.5	49.9	48.1	-20.0	0.29
5/9/57	89.3	36.9	88.6	45.4	80.6	0.90
5/7/58	82.0	10.8	29.0	50.3	-5.0	0.37
3/8/59	89.2	25.7	53.4	46.6	52.0	0.67
24/7/60	72.0	16.2	83.9	81.9	-4.0	0.31
25/9/62	88.7	18.6	98.5	62.9	25.9	0.49
26/9/62	88.4	24.3	62.2	48.1	59.5	0.55
30/7/63	73.2	23.1	85.1	41.3	15.7	0.24
22/7/65	85.3	11.1	80.4	53.9	26.1	0.53
15/9/66	89.5	6.3	5.6	63.3	-25.0	0.21
23/9/67	82.1	17.5	95.8	60.1	37.3	0.46
MEAN	86.35	21.38		51.79		0.52
S.E.MEAN	0.95	1.49		1.91		0.04
MINIMUM	72.00	4.50		31.00		0.10
MAXIMUM	97.70	36.90		81.20		1.17
RANGE	25.70	32.40		50.20		1.07

Table 5.1 continued

CATCHMENT 45002

DATE	CN	OPTIMISED STORM LAG (MIN)	E, %	SCS LAG (MIN)	E, %	$\frac{q_{pes}}{q_{po}}$
26/7/40	91.8	-	-	47.5	9.8	0.19
23/7/41	92.0	-	-	47.1	-78.7	0.67
7/9/42	93.1	11.1	86.0	44.8	43.1	0.34
9/8/43	96.6	15.9	87.9	37.6	52.4	0.49
9/8/45	97.1	-	-	36.5	17.1	0.46
27/8/45	93.7	12.3	64.3	43.4	-25.0	0.10
3/7/46	87.6	9.3	48.0	56.2	-11.9	0.32
9/7/46	89.9	9.9	81.5	53.4	14.7	0.35
26/6/46	93.6	4.5	38.3	44.0	26.9	0.45
15/8/47	84.3	-	-	63.5	16.2	0.41
12/10/47	84.3	-	-	63.5	-31.0	0.14
7/8/49	89.1	-	-	53.2	-64.0	0.10
15/8/51	96.6	7.8	25.2	37.5	19.4	0.38
27/9/51	90.9	-	-	49.4	-46.0	0.16
28/7/52	94.4	2.7	21.2	42.1	20.6	0.32
16/7/53	92.0	5.7	51.2	47.1	1.6	0.27
22/7/54	84.2	5.1	93.6	63.7	2.1	0.21
[illegible]/7/55	70.8	-	-	75.5	-13.7	0.36
29/7/55	[illegible].7	17.7	76.9	43.6	-19.2	[illegible]
15/8/56	90.0	2.1	-39.0	51.3	-58.4	0.15
30/8/56	90.6	-	-	50.9	-37.2	[illegible]
30/8/57	94.7	8.1	90.6	41.5	29.9	0.29
16/7/59	88.7	-	-	54.0	-50.9	0.24
29/7/59	93.6	11.1	90.6	43.7	-3.1	0.33
15/9/59	85.1	18.3	87.9	59.6	11.2	0.42
22/3/61	83.4	11.7	94.7	65.4	25.4	0.27
30/7/62	82.7	11.1	-9.0	67.0	-27.0	0.20
30/7/65	81.9	-	-	68.8	-53.0	0.15
18/8/65	73.0	3.3	87.6	75.0	-26.8	[illegible]
2/9/65	78.3	2.1	64.5	77.0	[illegible]	[illegible]
27/7/66	79.5	-	-	74.2	[illegible]	[illegible]
29/7/66	82.8	-	-	66.7	-37.1	0.20
20/9/68	84.8	3.4	62.9	63.1	-13.8	[illegible]
13/8/69	82.8	2.1	72.3	66.5	3.2	[illegible]
MEAN	88.67	8.59		52.70		0.27
S.E. MEAN	0.94	1.11		2.50		0.02
MINIMUM	78.30	2.10		36.50		0.09
MAXIMUM	97.10	18.30		77.00		0.48
RANGE	18.80	16.20		[illegible].50		0.39

CATCHMENT 91M17

DATE	CN	OPTIMISED STORM LAG (MIN)	E, %	SCS LAG (MIN)	E, %	$\frac{q_{pes}}{q_{po}}$
24/1/77	73.2	81.7	53.4	10.4	-91.7	4.17
16/11/65	56.5	93.1	65.7	6.5	-446[illegible].0	[illegible]
22/4/78	71.1	107.1	35.4	10.1	-75.2	[illegible]
3/6/78	85.0	131.1	73.0	7.7	-176.3	3.29
11/7/78	84.1	166.5	75.0	7.4	-44.3	[illegible]
8/9/78	76.5	258.3	94.0	10.1	27.[illegible]	[illegible]
12/10/78	87.3	181.3	64.5	6.7	-182.[illegible]	3.73
15/10/79	89.6	72.0	61.4	6.1	-242.[illegible]	4.39
18/11/79	77.3	89.7	93.6	9.2	-127.0	1.75
21/11/79	87.7	253.0	96.0	6.5	-327.[illegible]	3.85
3/3/79	67.0	171.9	91.7	12.4	-237.3	2.66
4/5/79	63.3	224.7	71.3	13.6	[illegible]	[illegible]
12/12/79	79.9	121.5	47.6	9.6	-573.6	5.13
MEAN	78.85	150.48		8.89		5.95
S.E. MEAN	2.36	17.94		0.65		1.30
MINIMUM	63.30	72.05		6.10		2.56
MAXIMUM	89.60	250.30		13.60		18.93
RANGE	26.30	[illegible]		7.50		[illegible]

Table 5.1 continued

CATCHMENT 45002

DATE	CN	OPTIMISED STORM LAG (MIN)	E, %	SCS LAG (MIN)	E, %	$\frac{q_{pcs}}{q_{po}}$
26/7/40	91.8	-	-	47.5	9.8	0.19
23/7/41	92.0	-	-	47.1	-76.7	0.67
7/8/42	93.1	11.[illegible]	86.0	44.8	43.1	0.34
9/8/43	96.6	15.9	87.9	37.6	52.4	0.49
9/8/45	97.1	-	-	36.5	17.1	0.46
27/8/45	93.7	12.3	64.3	43.4	-25.0	0.10
3/7/46	87.6	9.3	48.0	56.2	-11.0	0.22
9/7/46	89.0	9.9	81.5	53.4	14.7	0.35
26/8/46	93.6	4.5	38.3	44.0	26.9	0.45
15/8/47	84.3	-	-	63.5	16.2	0.41
12/10/47	84.3	-	-	63.5	-31.0	0.14
7/8/49	89.1	-	-	53.2	-64.0	0.19
15/8/51	96.6	7.8	25.2	37.5	19.4	0.38
27/9/51	90.9	-	-	49.4	-46.0	0.16
20/7/52	94.4	2.7	21.2	42.1	20.6	0.32
16/7/53	93.0	9.7	51.2	47.1	1.6	0.27
22/7/54	93.2	3.1	93.6	63.7	2.1	0.21
13/7/55	78.8	-	-	75.6	-13.7	0.32
29/7/55	94.7	17.7	76.9	43.6	-19.2	0.47
16/8/56	90.0	2.1	-39.0	51.3	-59.4	0.15
20/[illegible]/56	93.6	-	-	50.0	32.3	[illegible]
30/8/57	94.7	8.1	90.6	41.5	24.9	0.24
16/7/57	88.7	-	-	54.0	-50.9	0.26
29/7/59	93.6	11.1	90.6	43.7	-3.1	0.33
15/8/59	86.1	18.3	87.9	59.6	11.2	0.42
22/[illegible]/61	83.4	11.7	94.7	65.4	[illegible]	0.27
30/7/62	82.7	11.1	-9.0	67.0	-27.0	0.20
30/7/64	81.9	-	-	68.8	-53.0	0.13
18/8/65	93.0	3.3	92.6	45.0	-26.9	0.17
[illegible]/9/65	78.3	2.1	64.5	77.8	[illegible]	[illegible]
27/7/66	79.5	-	-	74.2	-17.1	[illegible]
29/7/66	82.0	-	-	66.7	-37.1	0.26
20/7/69	[illegible]	3.4	62.9	[illegible]	-13.6	[illegible]
13/8/69	82.0	2.1	72.3	64.3	3.2	[illegible]
MEAN	88.67	8.59		52.70		0.27
S.E. MEAN	0.94	1.11		2.50		[illegible]
MINIMUM	78.19	2.10		36.50		0.09
MAXIMUM	97.10	19.30		77.00		0.48
RANGE	13.70	[illegible]		[illegible]		[illegible]

CATCHMENT W1M17

DATE	CN	OPTIMISED STORM LAG (MIN)	E, %	SCS LAG (MIN)	E, %	$\frac{q_{pcs}}{q_{po}}$
24/1/77	73.2	81.7	53.4	10.4	-59.7	4.17
15/11/[illegible]	86.5	92.1	65.7	6.5	[illegible]	[illegible]
22/4/78	71.1	187.1	35.4	10.1	-75.2	10.82
3/6/78	83.4	131.1	73.0	7.7	-176.3	3.29
11/7/78	54.3	156.5	73.9	7.4	-44.3	[illegible]
8/9/78	74.5	258.3	94.0	10.1	27.5	[illegible]
12/10/78	87.3	[illegible]	54.5	6.7	[illegible]	3.93
16/10/78	89.5	72.3	61.4	6.1	-242.7	4.39
18/11/78	77.3	87.7	53.0	9.2	-122.0	1.75
21/11/78	87.5	253.0	76.0	6.5	-307.5	3.45
3/3/79	57.0	175.9	91.7	12.4	-237.3	2.59
4/5/79	63.3	224.7	71.3	13.6	-332.3	5.75
12/12/79	79.9	121.5	47.5	3.2	-373.6	5.13
MEAN	78.85	153.40		8.99		5.85
S.E. MEAN	[illegible]	17.94		0.65		[illegible]
MINIMUM	63.30	72.30		[illegible]		[illegible]
MAXIMUM	[illegible]	258.30		13.60		[illegible]
RANGE	26.30	[illegible]		7.50		[illegible]

lag time, even when lag time was reduced to zero. Storm lag times could thus not be optimised and the events were excluded from further analyses. Such occurrences illustrate the need to adjust both lag time and hydrograph shape to provide accurate estimates of the recorded runoff event. Future research should be directed towards the effects rainfall and catchment characteristics have on hydrograph shape.

An example illustrating the importance of simulating accurately hydrograph shape is given in Figure 5.1, which shows the recorded hydrograph (solid line) and the synthetic hydrograph (broken line) synthesised using the storm lag time optimised for the event recorded on catchment 26003 on June 25, 1956. The storm lag time (4,5 minutes) provides an excellent reproduction of the recorded peak flow rate. The shape of the two hydrographs (when peak flow rate ordinates are aligned) can, however, be seen to differ widely, resulting in a low value of E_1 which is shown in Table 5.1 to equal 33,2%. Generally high values of E_1 are obtained when synthetic peak flow rates are estimated accurately. However, in such cases an incremental hydrograph having a larger portion of runoff under the recession limb is required to simulate the short rise time and long recesion time recorded for the event.

It has been suggested that lag time and unit hydrograph shape are highly variable from burst to burst within storms, especially on small catchments (Reed et al, 1975; Betson et al, 1980). Figure 5.2 shows the recorded hydrograph and the synthetic hydrographs, developed using the SCS lag time (1,9 minutes) and the optimised storm lag time (10,8 minutes) for the storm recorded on catchment 26003 on June 4, 1941, the hyetograph for which is shown in Figure 5.3. Although the high Coefficient of Efficiency, 71,6% (Table 5.1), indicates good association between the hydrograph synthesised using the SCS lag time and the recorded hydrograph, the bursts of rainfall shown in Figure 5.3 produce corresponding bursts of runoff which are not evident in the recorded hydrograph. Incremental hydrographs varying with each increment of rainfall would provide an exact

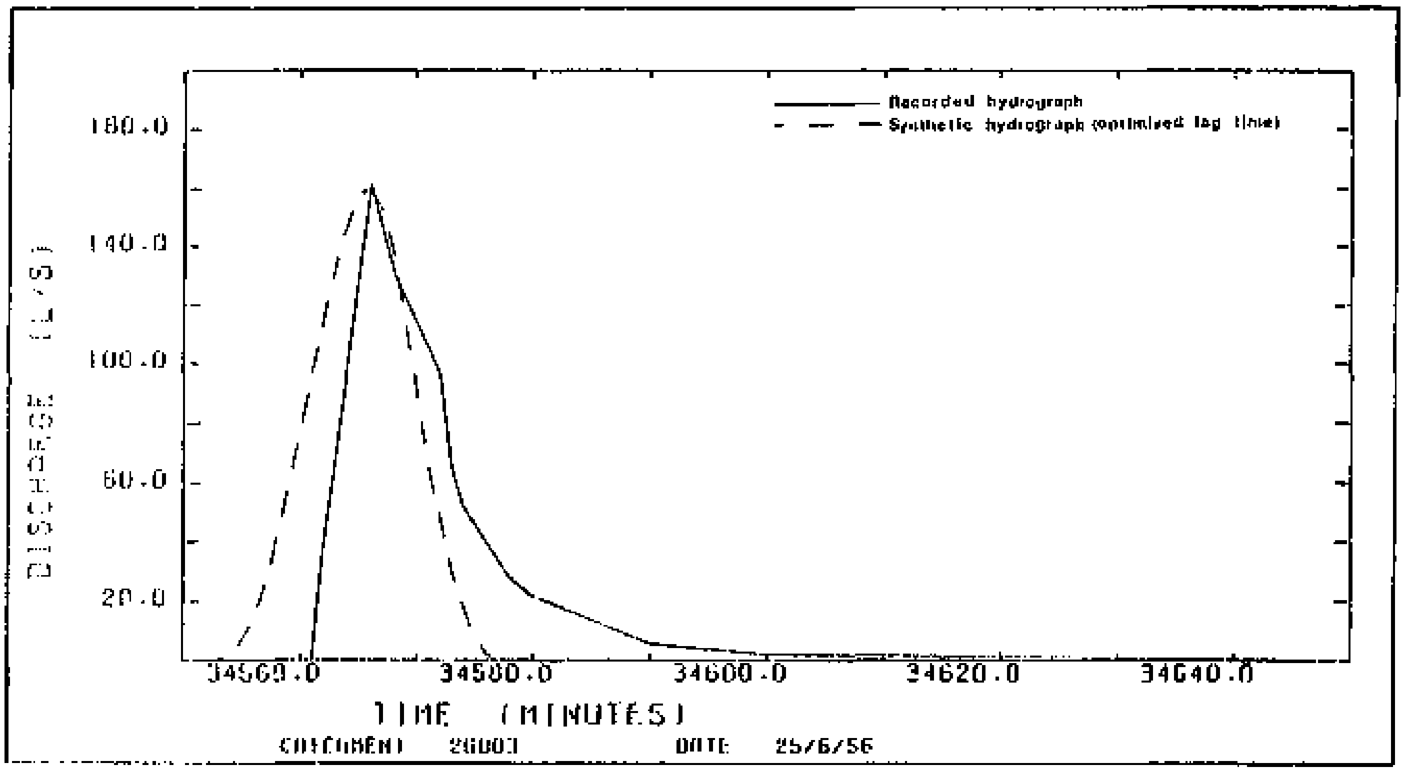

Figure 5.1 Comparison of the hydrograph synthesised using an optimised storm lag time with the hydrograph recorded on catchment 26003 on June 15, 1956

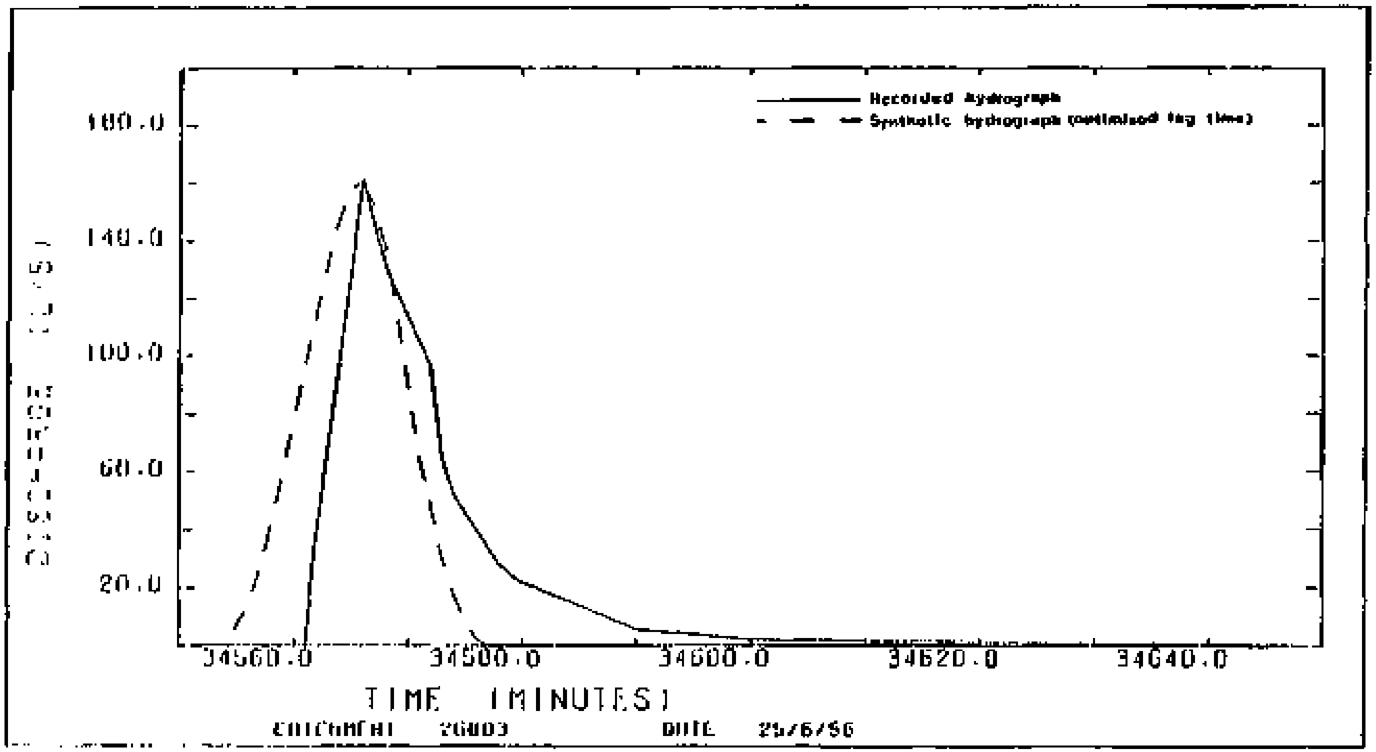

Figure 5.1 Comparison of the hydrograph synthesised using an optimised storm lag time with the hydrograph recorded on catchment 26003 on June 15, 1956

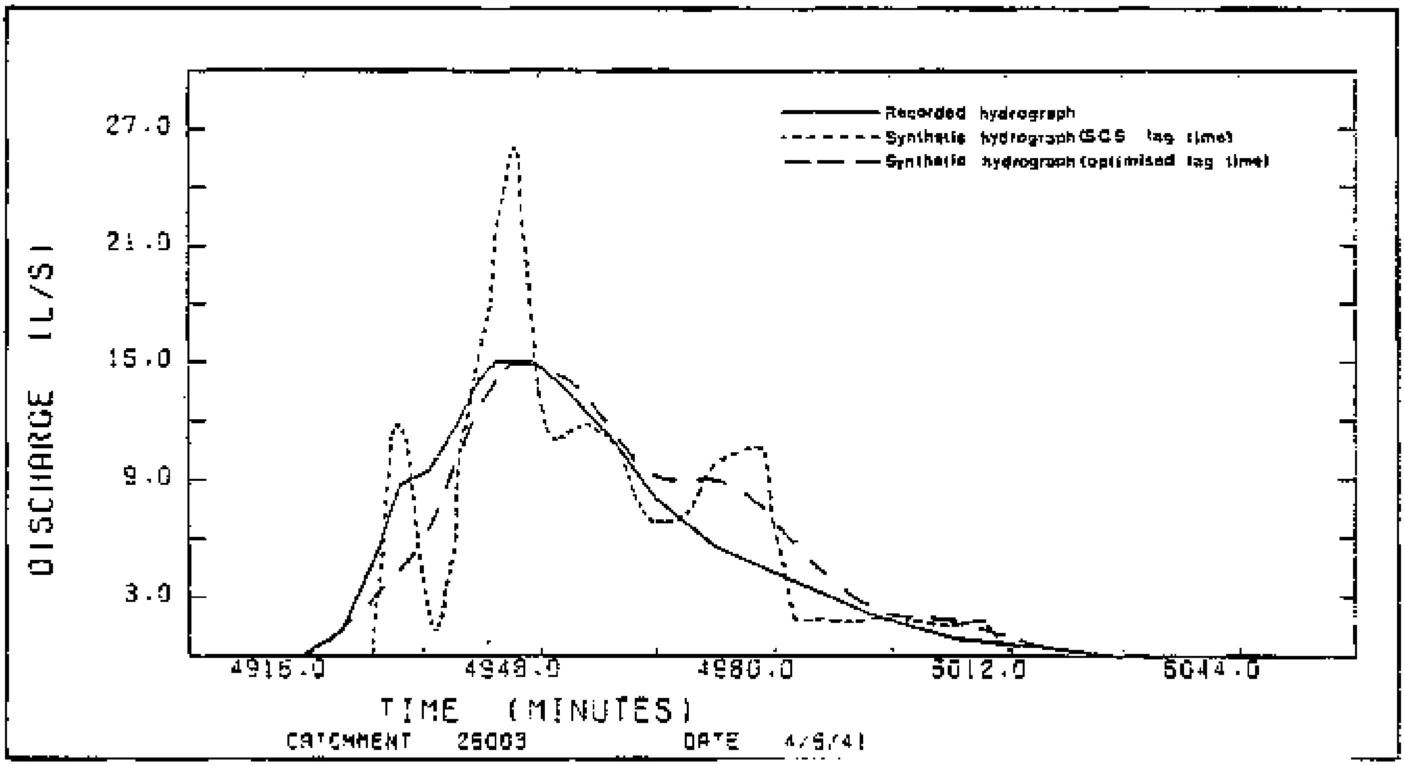

Figure 5.2 Comparison of the hydrographs synthesised using the SCS lag time and the optimised storm lag time with the hydrograph recorded on catchment 26003 on June 4, 1941

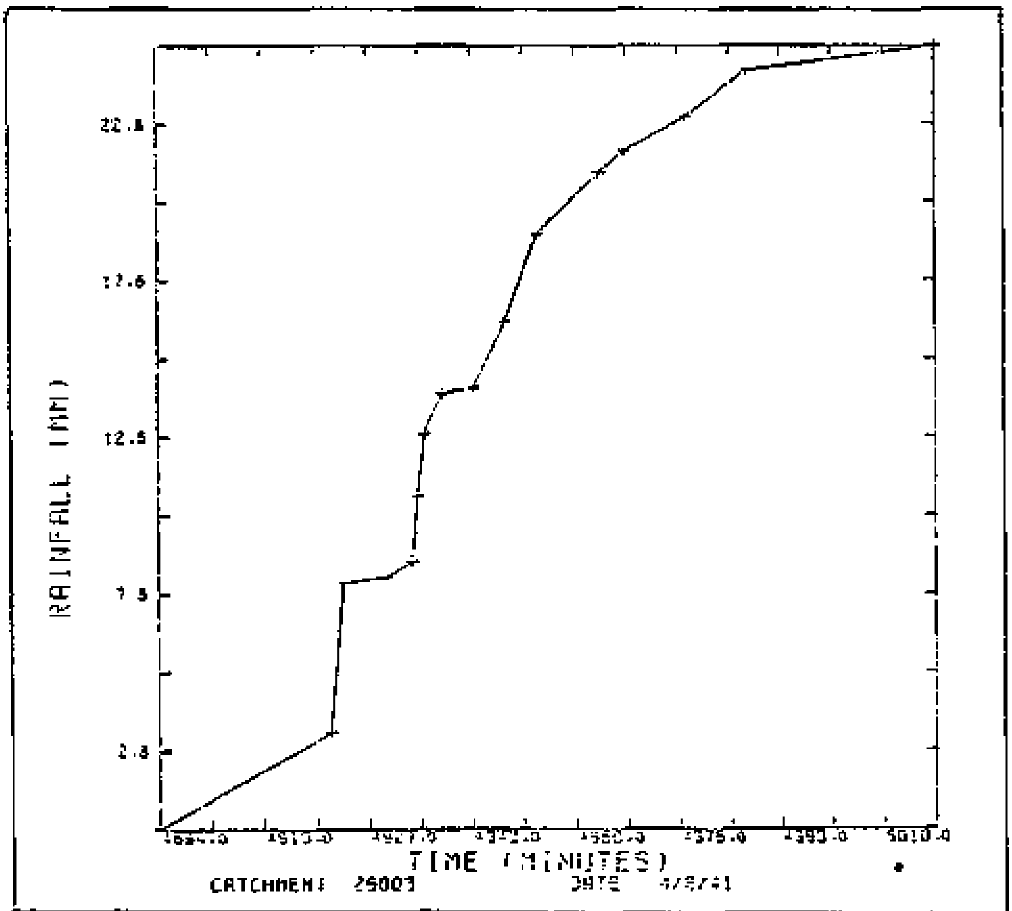

Figure 5.3 Hyetograph for the storm recorded on catchment 26003 on June 4, 1941

representation of the recorded runoff event. However optimising the lag time for the event (10,8 minutes) produces a synthetic hydrograph providing an accurate estimate of the recorded event (E_1 = 91,7%).

Figure 5.4 indicates the typical overestimation of peak flow rates obtained on catchment W1M17 when using the SCS lag equation. The estimate of the population mean of the ratio q_{pes}/q_{po} for catchment W1M17 is shown on Table 5.1 to be 5,85 ± 1,30. Such inaccuracies in hydrograph simulations are further illustrated by the low values of E_1 obtained using SCS lag times when compared with those obtained using optimised storm lag times. The synthetic hydrograph obtained by optimising lag time for the event of March 3, 1979 on catchment W1M17 (Figure 5.4) corresponds with an increase in E_1 from - 237,2% to 81,7% (Table 5.1). The short lag times calculated for catchment W1M17 using the SCS lag equation (estimate of the population mean SCS lag time = 8,80 ± 0,65 minutes) are highly inaccurate when compared with the long lag times optimised for each runoff event (estimate of the population mean optimised storm lag time = 150,48 ± 17,94 minutes).

Figure 5.5 shows the hydrographs synthesised using the SCS lag time (45,0 minutes) and the optimised storm lag time (3,3 minutes) for the storm recorded on August 18, 1965 on catchment 45002. An example of the listing, obtained for the hydrograph synthesised using the 45,0 minute lag time is shown in Table 5.2, indicating the shift required to align ordinates of peak flow rate and the value of the Coefficient of Efficiency for the event. An estimate of the population mean for optimised storm lag times on catchment 45002 is 8,59 ± 1,11 minutes which is much shorter than the estimate of the population mean for SCS lag times which is 52,70 ± 2,50 minutes.

The means of the storm lag times optimised using incremental hydrograph procedures for the sample of storm events of each catchment are compared in Table 5.3, with the catchment lag times estimated using single triangular procedures (Chapter 4) and the catchment lag times calculated using the SCS lag equation (Table representation of the recorded runoff event. However optimising the lag time for the event (10,8 minutes) produces a synthetic hydrograph providing an accurate estimate of the recorded event (E_1 = 91,7%).

Figure 5.4 indicates the typical overestimation of peak flow rates obtained on catchment W1M17 when using the SCS lag equation. The estimate of the population mean of the ratio q_{pes}/q_{po} for catchment W1M17 is shown on Table 5.1 to be 5,85 ± 1,30. Such inaccuracies in hydrograph simulations are further illustrated by the low values of E_1 obtained using SCS lag times when compared with those obtained using optimised storm lag times. The synthetic hydrograph obtained by optimising lag time for the event of March 3, 1979 on catchment W1M17 (Figure 5.4) corresponds with an increase in E_1 from - 237,2% to 81,7% (Table 5.1). The short lag times calculated for catchment W1M17 using the SCS lag equation (estimate of the population mean SCS lag time = 8,80 ± 0,65 minutes) are highly inaccurate when compared with the long lag times optimised for each runoff event (estimate of the population mean optimised storm lag time = 150,48 ± 17,94 minutes).

Figure 5.5 shows the hydrographs synthesised using the SCS lag time (45,0 minutes) and the optimised storm lag time (3,3 minutes) for the storm recorded on August 18, 1965 on catchment 45002. An example of the listing, obtained for the hydrograph synthesised using the 45,0 minute lag time is shown in Table 5.2, indicating the shift required to align ordinates of peak flow rate and the value of the Coefficient of Efficiency for the event. An estimate of the population mean for optimised storm lag times on catchment 45002 is 8,59 ± 1,11 minutes which is much shorter than the estimate of the population mean for SCS lag times which is 52,70 ± 2,50 minutes.

The means of the storm lag times optimised using incremental hydrograph procedures for the sample of storm events of each catchment are compared in Table 5.3, with the catchment lag times estimated using single triangular procedures (Chapter 4) and the catchment lag times calculated using the SCS lag equation (Table

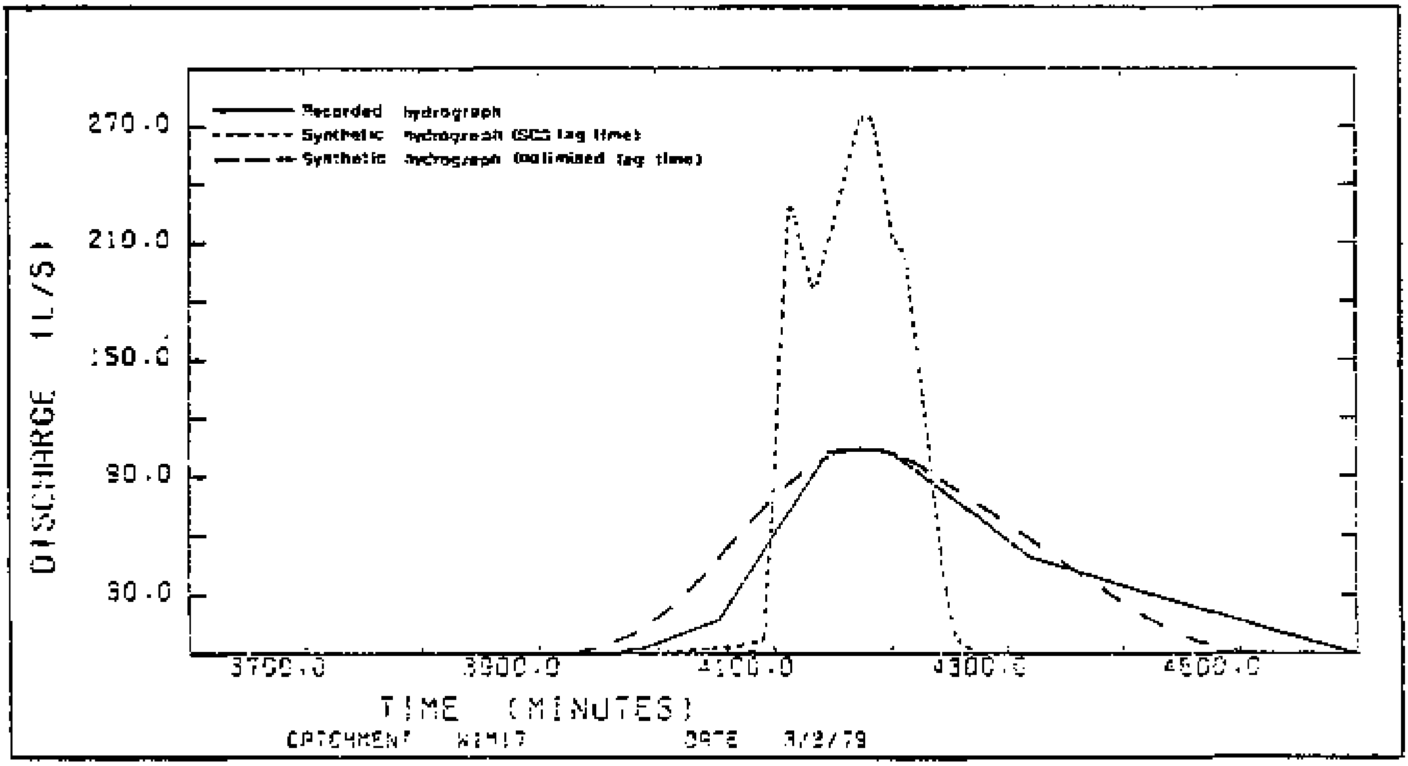

Figure 5.4 Comparison of the hydrographs synthesised using the SCS lag time and the optimised storm lag time with the hydrograph recorded on catchment W1M17 on March 3, 1979

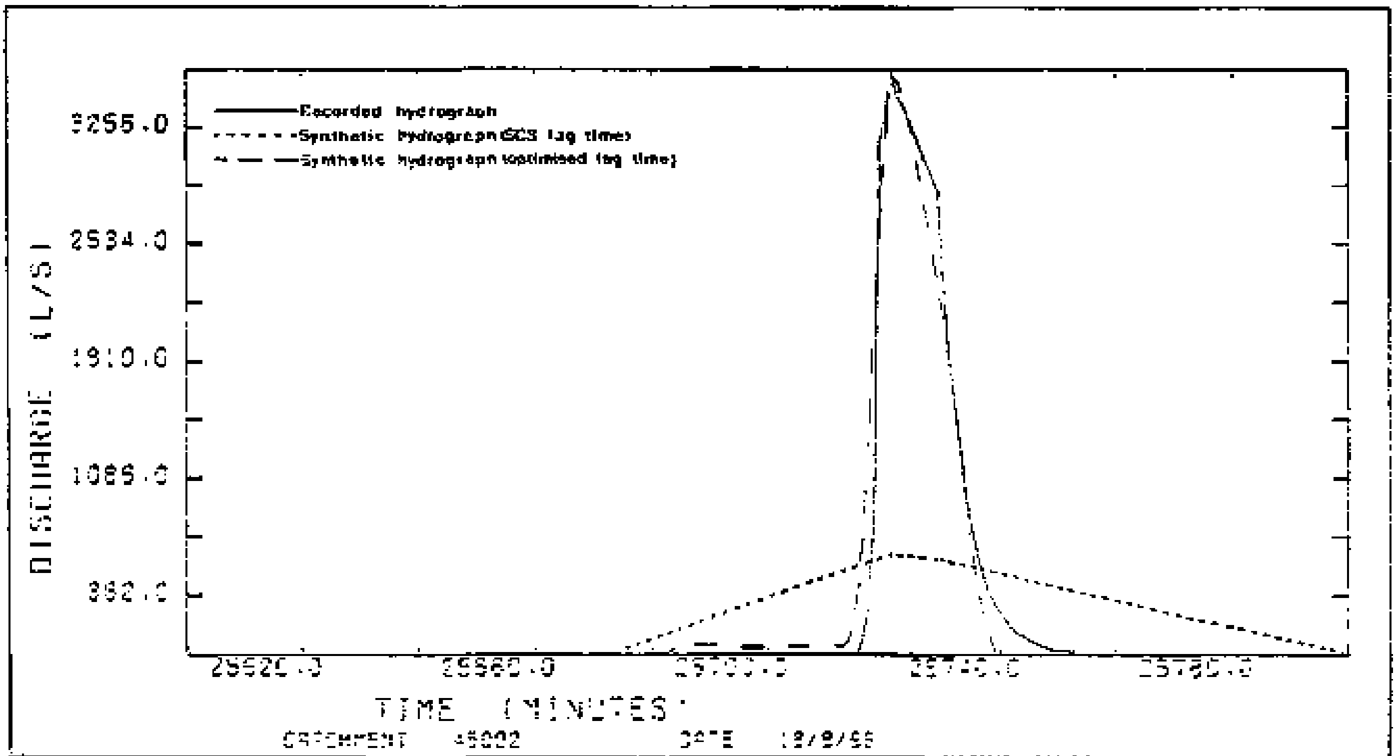

Figure 5.5 Comparison of the hydrographs synthesised using the SCS lag time and the optimised storm lag time with the hydrograph recorded on catchment 45002 on August 18, 1965

Table 5.2 An example of a computer listing for the recorded hydrograph synthesised using the SCS lag time for the event recorded on catchment 45002 on August 18,1965.

HYDROGRAPHS FOR CATCHMENT 45002 (18/8/1965)

Time (MIN)	Recorded Discharge (L/S)	Time (MIN)	SCS synthetic discharge (L/S)
25715,0	0,00	25664,0	5,54
25716,0	68,97	25672,0	19,63
25717,0	291,28	25680,0	104,34
25718,0	758,92	25689,0	215,50
25719,0	3166,23	25697,0	325,79
25720,0	3304,21	25705,0	435,02
25721,0	3618,52	25713,0	542,41
25722,0	3449,82	25721,0	631,71
25723,0	3388,47	25730,0	608,16
25724,0	3304,11	25738,0	541,09
25729,0	2851,65	25746,0	474,02
25730,0	2314,96	25754,0	406,95
25732,0	1471,57	25762,0	339,88
25734,0	942,52	25770,0	272,97
25736,0	605,14	25779,0	206,48
25738,0	375,09	25787,0	140,43
25740,0	252,37	25795,0	74,93
25742,0	160,32	25803,0	16,30
25744,0	106,61	25811,0	0,00
25749,0	29,81	25820,0	0,00
25754,0	6,69	25828,0	0,00

Synthetic hydrograph was shifted by 2,0 minutes

Residual variation = 58077025,0

Initial variation = 45799564,5

Modelling efficiency = -26,8 %

Table 5.2 An example of a computer listing for the recorded hydrograph synthesised using the SCS lag time for the event recorded on catchment 45002 on August 18,1965.

HYDROGRAPHS FOR CATCHMENT 45002 (18/8/1965)

Time (MIN)	Recorded Discharge (L/S)	Time (MIN)	SCS synthetic discharge (L/S)
25715,0	0,00	25664,0	5,54
25716,0	68,97	25672,0	19,63
25717,0	291,28	25680,0	104,34
25718,0	758,92	25689,0	215,50
25719,0	3166,23	25697,0	325,79
25720,0	3304,21	25705,0	435,02
25721,0	3618,52	25713,0	542,41
25722,0	3449,82	25721,0	631,71
25723,0	3388,47	25730,0	608,16
25724,0	3304,11	25738,0	541,09
25729,0	2851,65	25746,0	474,02
25730,0	2314,96	25754,0	406,95
25732,0	1471,57	25762,0	339,88
25734,0	942,52	25770,0	272,97
25736,0	605,14	25779,0	206,48
25738,0	375,09	25787,0	140,43
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25749,0	29,81	25820,0	0,00
25754,0	6,69	25828,0	0,00

Synthetic hydrograph was shifted by 2,0 minutes

Residual variation = 58077025,0

Initial variation = 45799564,5

Modelling efficiency = -26,8 %

4.4). The results shown graphically in Figure 5.6 indicate the close association between catchment lag times estimated from rainfall and runoff records using single and incremental hydrograph procedures.

The underestimation of lag time for the humid and sub-humid catchments when using the SCS lag equation, found in Chapter 4, and the overestimation of catchment lag time on the arid catchments is confirmed by the results of Table 5.3. The SCS lag times shown in Table 5.3 vary from the mean SCS lag times given for each catchment in Table 5.1. Such variations indicate the difference between lag times estimated using a CN obtained from field surveys and those obtained using CN based on recorded storm responses.

From the results of Table 5.3 it may be concluded that the simple technique (described in Chapter 4) to estimate catchment lag times from linear runoff regressions of peak flow rate against runoff volume for single triangular approximations of the runoff hydrograph, provide accurate estimates of the catchment time response between rainfall and runoff. The empirical relationship given in Table 4.9 may thus be considered to be a reliable equation for predicting inter-catchment variations in lag time.

In order to ascertain the dependence of the intra-catchment variations in lag time (shown in Table 5.1) on individual storm characteristics, it remains to examine relationships between the ratios of individual storm lag times divided by the catchment lag time and rainfall characteristics.

5.2.2 Relationships between lag times for individual events and rainfall characteristics

The effect of selected rainfall characteristics on individual storm lag times was determined from a multiple regression analysis, similar to that undertaken in Section 4.3.4. The dependent variable

Table 5.3 Comparison of catchment lag times estimated using single incremental triangular procedures and the SCS lag equation.

Catchment	Catchment lag times (minutes)		
	Single triangular hydrograph	Incremental triangular hydrographs	SCS lag equation
26003	8,0	6,7	2,6
37001	31,4	39,6	8,5
44005	6,6	5,4	5,2
45001	19,6	20,4	66,3
45002	11,8	8,6	60,0
W1M17	117,0	150,3	13,7

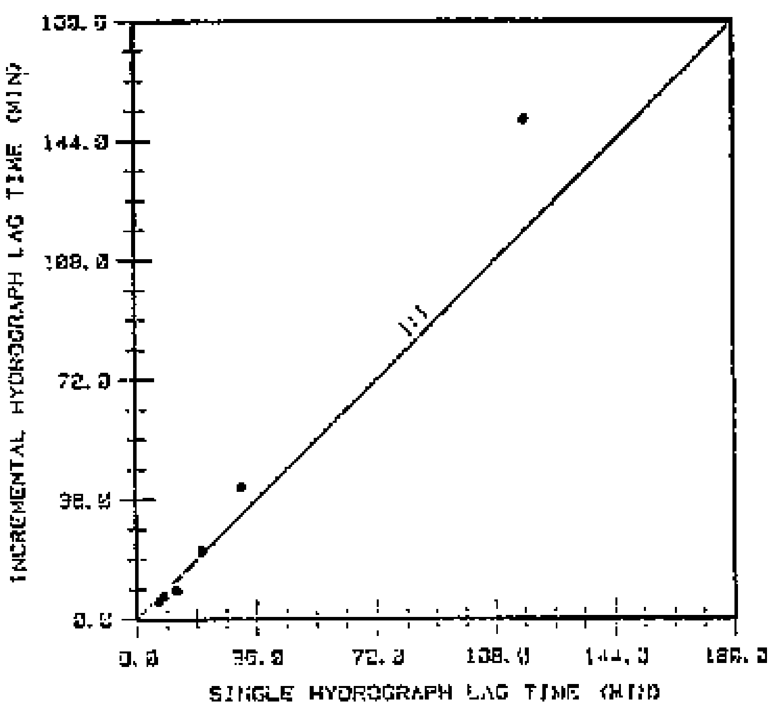

Figure 5.6 Comparison of catchment lag times estimated using and incremental triangular procedures

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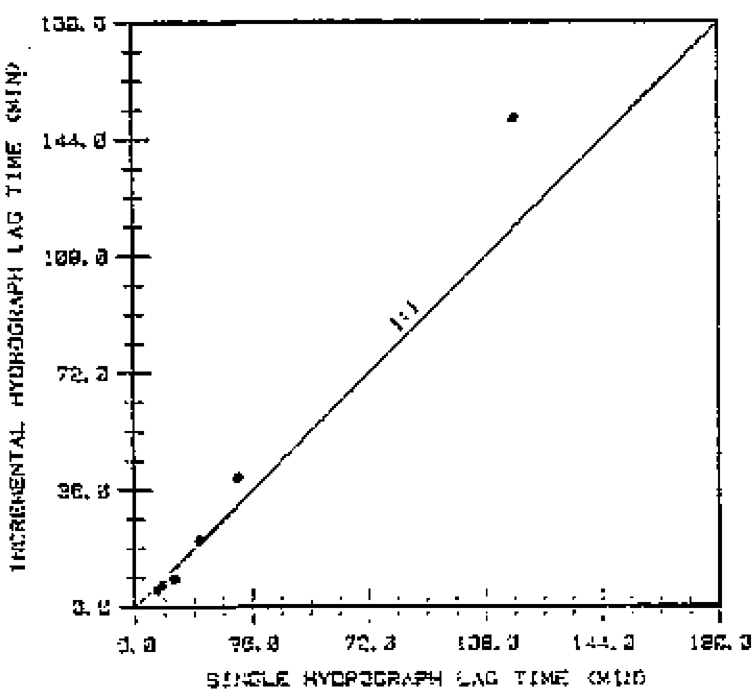

Figure 5.6 Comparison of catchment lag times estimated using and incremental triangular procedures

was the fraction of storm lag time divided by estimated catchment lag time (L_{si}/L_{ci}). The results of the regression analysis are summarised in Table 5.4 which presents the regression equations, Coefficients of Determination and Variance Ratios for each catchment.

The results of Table 5.4 indicate that the storm characteristics considered are only significant in determining individual storm lag times on catchment 37001. Furthermore, Correlation Coefficients between the independent variables and the dependent variate, together with the t-values for testing the partial regression coefficients, which are given in Table 5.5, indicate that no independent variable can be expected to yield consistent and satisfactory regression equations for the estimation of individual storm lag times when using incremental hydrographs.

Incremental hydrographs are generally employed in design applications in conjunction with design storm distributions, such as those shown in Figure 2.3. Such approximations of the temporal distribution of rainfall represent a compromise between the uniform rainfall distribution accepted in Chapter 4 and the recorded hyetograph used in this chapter. Improved estimates of peak discharge accounting for intra-catchment variations in rainfall type and distribution could be made using incremental hydrographs and such design distributions. Either rainfall non-linearity should be accounted for by providing numerous rainfall distributions representing storms of different durations and intensities, which could then be used together with an average catchment lag time, or alternatively a single basic shape of the rainfall distribution could be employed and adjustments, similar to those given in Table 4.15, should be used to introduce non-linearity to the peak flow rate estimates.

5.3 Conclusions

The establishment of incremental hydrographs for incremental time periods of constant rainfall intensity enables the calculation of the

Table 5.4 Regression equations for the five parameter multiple regression analysis of L_{si}/L_{ci} with storm characteristics

Catchment	Regression Equation	Coefficient of Determination (r^2)	Variance Ratio (F)
26003	$\frac{L_{si}}{L_{ci}} = \frac{1{,}77\ D_u^{0,12}\ E^{1,83}}{(API+1)^{0,08}\ P^{1,87}\ I_{30}^{1,79}}$	0,48	2,726
37001	$\frac{L_{si}}{L_{ci}} = \frac{392{,}57(API+1)^{0,05}\ P^{0,29}\ I_{30}^{0,26}}{D_u^{0,28}\ E^{1,22}}$	0,58	5,606(**)
44005	$\frac{L_{si}}{L_{ci}} = 0{,}11\ (API+1)^{0,05} P^{0,03} D_u^{0,05} E^{0,24} I_{30}^{0,08}$	0,17	0,611
45001	$\frac{L_{si}}{L_{ci}} = \frac{6{,}48 \times 10^{-7}\ D_u^{0,25}\ E^{4,79}}{(API+1)^{0,05}\ P^{4,19}\ I_{30}^{0,89}}$	0,30	2,234
45002	$\frac{L_{si}}{L_{ci}} = \frac{53{,}05\ P^{0,60}\ I_{30}^{1,74}}{(API+1)^{0,13}\ D_u^{0,29}\ E^{1,88}}$	0,20	0,738
W1M17	$\frac{L_{si}}{L_{ci}} = \frac{5{,}66\ P^{0,86}}{(API+1)^{0,18}\ D_u^{0,05}\ E^{0,69}\ I_{30}^{0,02}}$	0,66	2,790

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37001	$\frac{L_{si}}{L_{ci}} = \frac{392,57(API+1)^{0,05}\ P^{0,29}\ I_{30}^{0,26}}{D_u^{0,28}\ E^{1,22}}$	0,58	5,606(**)
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45001	$\frac{L_{si}}{L_{ci}} = \frac{6,48 \times 10^{-7}\ D_u^{0,25}\ E^{4,79}}{(API+1)^{0,05}\ P^{4,19}\ I_{30}^{0,89}}$	0,30	2,234
45002	$\frac{L_{si}}{L_{ci}} = \frac{53,05\ P^{0,60}\ I_{30}^{1,74}}{(API+1)^{0,13}\ D_u^{0,29}\ E^{1,88}}$	0,20	0,738
W1M17	$\frac{L_{si}}{L_{ci}} = \frac{5,66\ P^{0,86}}{(API+1)^{0,18}\ D_u^{0,05}\ E^{0,69}\ I_{30}^{0,02}}$	0,66	2,790

Table 5.5 Statistics relating to the five parameter multiple regression analysis of L_{si}/L_{ci} with storm characteristics

Catchment		Independent Variable (API+1)	P	D_u	E	I_{30}
26003	Student's t-value,t	0,460	0,673	0,354	0,707	2,762*
	Correlation Coefficient,r	0,261	-0,380	-0,078	-0,426	-0,659**
37001	t	0,835	0,326	0,846	2,062	0,578
	r	0,303	-0,684**	-0,162	-0,657**	-0,294
44005	t	0,506	0,060	0,163	0,863	0,377
	r	0,289	0,269	0,249	0,339	0,247
45001	t	0,812	2,147*	0,989	2,531*	2,141*
	r	-0,261	0,215	0,007	0,263	0,097
45002	t	0,682	0,461	0,800	1,501	1,375
	r	0,057	-0,066	-0,175	-0,091	0,023
W1M17	t	1,265	1,682	0,275	1,953	0,069
	r	-0,172	0,084	0,555*	-0,503	-0,648*

peak rate of runoff for temporally varying rainfalls without choosing an appropriate storm duration, while adhering to the requirement of constant rainfall intensity within each time period. It is, however, apparent that the lag times for incremental hydrographs should be adjusted according to relevant storm characteristics and incremental bursts of rainfall within the storm.

An indication of the typical catchment response between rainfall and runoff can be determined using the incremental hydrographs and recorded autographic rainfall and runoff data. Such catchment lag times are closely matched with catchment lag times calculated using a linear approximation of the time distribution of rainfall and a single triangular approximation of the runoff hydrograph.

No relationship between individual storm lag times and the corresponding rainfall characteristics for the event can,however, be determined. It is suggested that empirical relationships found to determine storm lag times from rainfall characteristics would only prove practical when incremental hydrographs are applied in conjunction with generalised rainfall depth-duration relationships.

The above findings are based on the supposition that the correct storm lag time is the lag time which provides an accurate estimate of peak flow rate when applied in the SCS Model. In the following chapter lag estimates are not restricted by the application of a particular model and are determined directly from autographic rainfall and runoff records.

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6. DERIVATION OF LAG TIME USING MEASURED TIME DIFFERENCES BETWEEN RAINFALL AND RUNOFF RESPONSE

Lag time has been defined as the time from the centre of mass of effective rainfall to peak flow rate (National Engineering Handbook, 1972). In this chapter time response between effective rainfall and runoff is measured using autographic rainfall and runoff records for the selected storms of catchments 26003, 37001, 44005, 45001, 45002 and W1M17 (c.f. Appendix 1). Lag times are measured for each event and averaged for each catchment to determine an index of catchment lag time.

6.1 Experimental procedures

Following Aron, Miller and Lakatos (1977) and Schulze and Arnold (1979) effective rainfall can be calculated in the SCS Model as

$$P_e = P - I_a \qquad \text{Eq. 6.1}$$

where

P_e = accumulated effective rainfall (mm),

P = accumulated rainfall (mm) and

I_a = initial abstraction (mm).

In accordance with SCS procedures, I_a can be determined from the relationship

$$I_a = 0{,}2S$$

Since S was determined for each storm from recorded rainfall and runoff data using Equation 4.13, the initial abstraction for each event could be estimated by the relationship above. Effective rainfall duration and thus storm lag time was computed using the autographic rainfall and runoff records.

6.2 Results and discussion

Table 6.1 depicts the means of the storm lag times of each catchment, their Standard Errors as well as the minimum and maximum values and hence the range of the storm lag times.

The means of the storm lag times for each catchment were used as an estimate of the catchment lag time and they are compared in Table 6.2 with catchment lag times estimated using single and incremental triangular procedures (Chapters 4 and 5) and the SCS lag equation.

The results of Table 6.2 indicate a close association between corresponding catchment lag times obtained from recorded rainfall and runoff data using the three methods covered in this report. An indication of the association is given graphically in Figures 6.1 and 6.2.

Table 6.1 indicates the high degree of scatter of the measured storm lag times of each catchment. The relatively large Standard Errors of the mean storm lag times indicate that estimates of the population means for catchment lag times obtained from Table 6.1 are far less precise than those obtained from the corresponding Table 5.1 following incremental triangular hydrograph procedures. In addition the presence of negative lag times and large ranges in observed values suggests that measured time differences between rainfall and runoff provide poor indices of runoff response to rainfall.

Owing to negative estimates of storm lag times, logarithmic runoff data using Equation 4.13, the initial abstraction for each event could be estimated by the relationship above. Effective rainfall duration and thus storm lag time was computed using the autographic rainfall and runoff records.

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Owing to negative estimates of storm lag times, logarithmic

Table 6.1 Statistics for the storm lag times (in minutes) measured from autographic rainfall and runoff records

Catchment	Mean	S.E. Mean	Minimum	Maximum	Range
26003	8,61	4,12	-44,0	53,4	97,4
37001	41,93	8,23	-75,5	129,9	205,4
44005	1,97	1,83	-29,0	45,5	74,5
45001	13,80	5,31	-54,2	94,2	148,4
45002	10,65	4,02	-50,2	71,0	121,2
W1M17	92,72	21,51	- 1,0	228,6	229,6

Table 6.2 Comparison of catchment lag times estimated using single and incremental triangular procedures, measured time differences between rainfall and runoff and the SCS lag equation.

Catchment	Catchment lag time (minutes)			
	Single triangular hydrograph	Incremental triangular hydrographs	Measured time difference	SCS lag equation
26003	8,0	6,7	8,6	2,6
37001	31,4	39,6	41,9	8,5
44005	6,6	5,4	2,0	5,2
45001	19,6	20,4	13,8	66,3
45002	11,8	8,6	10,6	60,0
W1M17	117,0	150,3	92,7	13,7

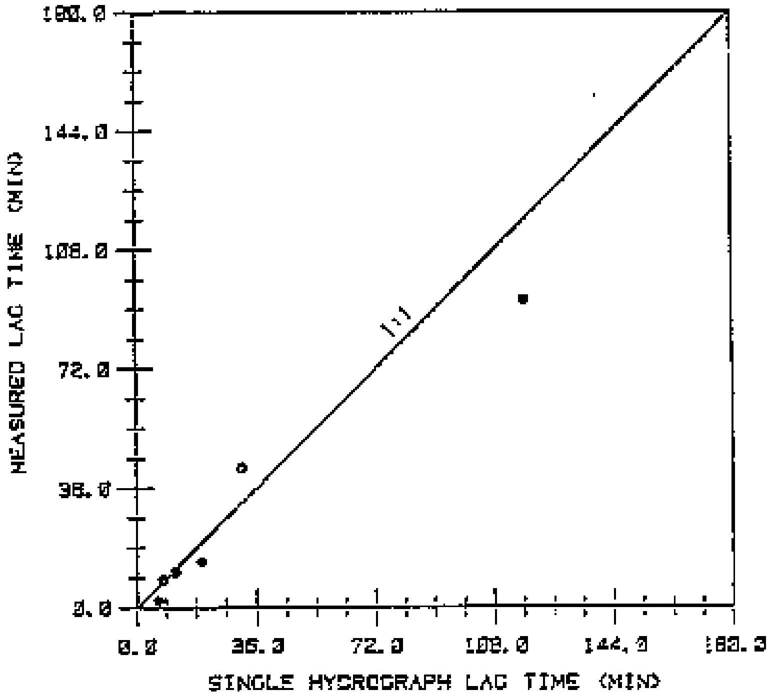


Figure 6.1 Comparison of measured catchment lag time with those estimated using single triangular procedures

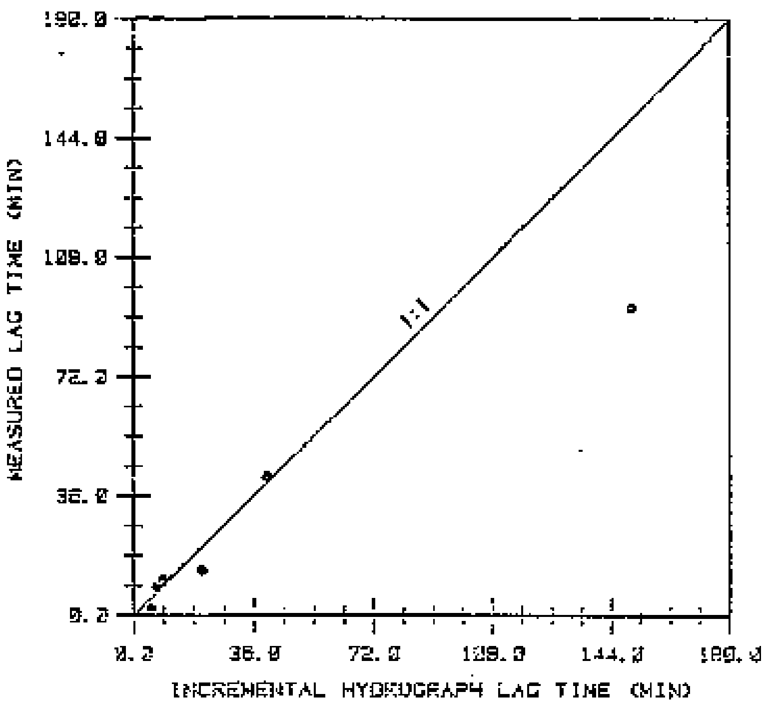
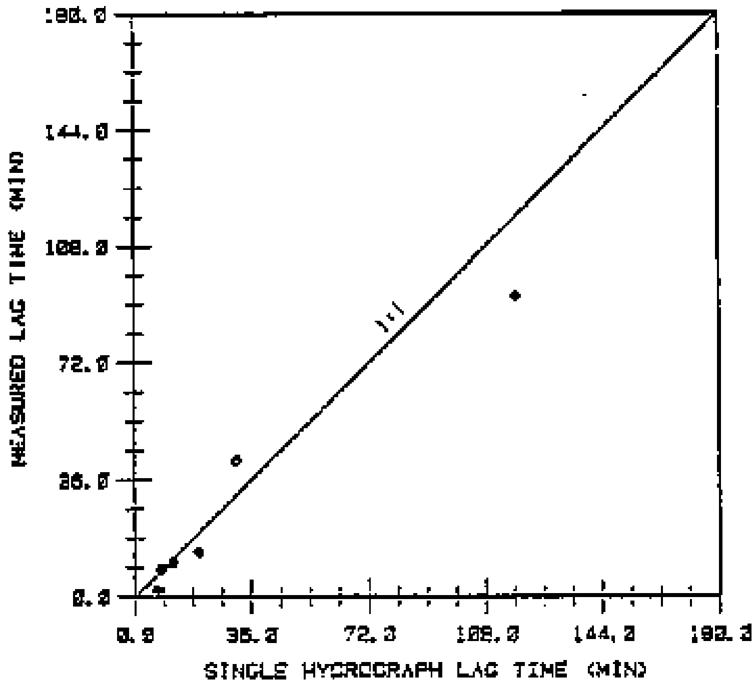


Figure 6.2 Comparison of measured catchment lag time with those estimated using incremental triangular procedures



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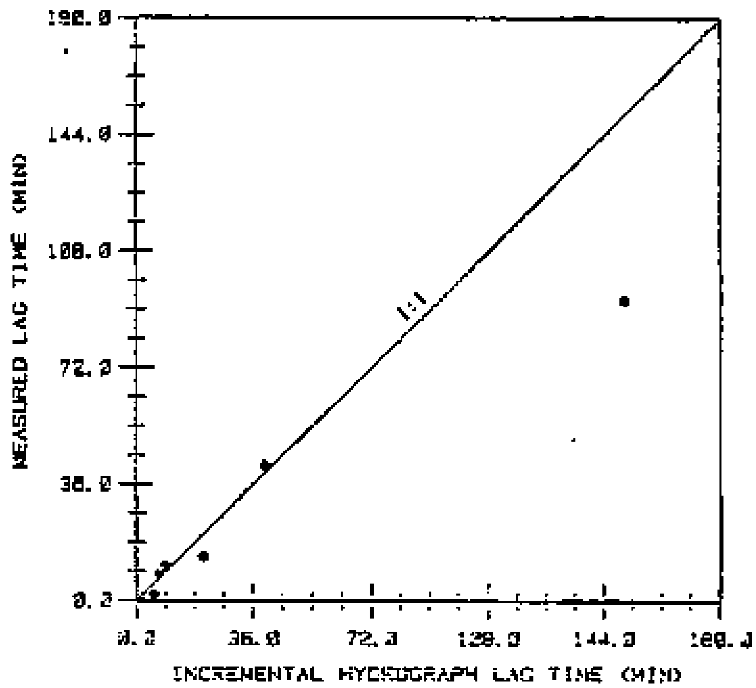

Figure 6.2 Comparison of measured catchment lag time with those estimated using incremental triangular procedures

transformations could not be employed to determine relationships between storm lag times and rainfall characteristics. A linear regression analysis between the ratio of individual storm lag time to the estimate of catchment lag time and the storm characteristics described in Section 4.3.4 was thus investigated. No definite association was found between the measured time response between rainfall and runoff for individual storms and any of the rainfall parameters considered. The poor results may be due to one of three factors:

1. Poorly synchronized rainfall and runoff recorders may contribute to inaccurate estimates of the storm lag time. This problem occurs despite attempts to correct clock errors manually and it seems to give rise to extreme estimates of storm lag time. Although an in-depth examination has not been made, it appears that the lag times measured for individual storms are related closely to the time shifts that were required to align the recorded and synthetic hydrographs in Chapter 5. Clock errors thus substantially reduce the accuracy to which the peak of a synthesised hydrograph will be temporally aligned with the recorded hydrograph peak.

2. The determination of effective rainfall by subtracting an initial abstraction from total storm rainfall is considered inadequate. Effective rainfall comprises all rainfall contributing to direct runoff. In its present form (Equation 6.1) P_e includes all rainfall other than that contributing to detention and depression storages or infiltrating into the soil before runoff occurs. Ideally both an initial abstraction and the portion of infiltrated rainfall which contributes to sub-surface storage should be subtracted from the total rainfall amount to determine the effective component of rainfall. Much recent research has been directed towards the determination of infiltration patterns based on the SCS curve number (for example, Aron <u>et al</u>, 1977; Hawkins, 1980; Hjelmfelt, 1980a; Hjelmfelt, 1980b). The results of such research could be incorporated into methods to

provide more accurate estimates of effective rainfall.

3. A more realistic estimate of initial abstraction should be achieved by means of adjustments to the coefficient of initial abstraction. Reductions to the coefficient of I_a have been suggested by Aron et al, (1977) and Arnold (1980). The season and antecedent moisture status of the catchment may influence the relationship between I_a and S (Arnold, 1980) as may the characteristics of the storm event.

6.3 Conclusions

The SCS (National Engineering Handbook, 1972) has used the definition of lag time as the time from the centre of mass of effective rainfall to the time of peak discharge. It can, however, be concluded from the aforegoing discussion that in practice poorly synchronized rainfall and runoff recorders and inadequacies in determining the amount and temporal distribution of effective rainfall make such measured lag times impractical to use for peak flow rate predictions.

Given sufficient records, a typical estimate of catchment lag time can be determined from measured storm lag times. The large scatter of such storm lag times suggest, however, that the concept of averaging may, in this instance, produce inaccurate estimates of catchment lag time when a limited number of storm records are available.

On the basis of the above findings it may be concluded that estimates of inter- and intra-catchment lag times to be used with the SCS Model should be based on the procedures examined in the previous two chapters. The salient features of those procedures are highlighted again in the following chapter, in which areas where future research is required are also discussed.

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7. CONCLUSIONS

In an attempt to estimate peak flow rates more realistically using the SCS Model, several procedures towards the improvements of estimates of lag time were examined. Conclusions that can be drawn from the research are summarised as follows:

1. Poor estimates of catchment lag time are common on small agricultural catchments when using the standard SCS lag equation.

2. The inadequacies of the SCS lag equation are due in part to its inability to distinguish between dominant mechanisms generating runoff on different catchments.

3. Climate, through its influence on the soil, vegetation and rainfall patterns, all of which affect the extent to which rainfall enters the soil by infiltration, appears to play a major role in determining dominant runoff processes.

4. Physical catchment characteristics, and in particular areal variations in soil properties, modify the effect rainfall characteristics have on the hydrograph shape and lag time. Despite such modifications, improved estimates of peak flow rate are obtained on small agricultural catchments when indices of climate and regional rainfall characteristics are incorporated with physical catchment characteristics in empirical lag equations.

5. Linear regression equations of peak flow rate against runoff volume provide a simple and yet effective means of determining an appropriate catchment lag time for gauged catchments.

6. Marked improvements in the estimations of inter-catchment lag times and hence peak flow rates are obtained when using the empirical lag equation (developed from linear regression equations of peak flow rates regressed against runoff volumes)

which is given as

$$L = \frac{A^{0,35}\ MAP^{1,10}}{41,67\ y^{0,30}\ \bar{I}_{30}^{\ 0,87}}$$

where

L = catchment lag time (h),

A = catchment area (km^2),

y = average catchment slope (%)

MAP = mean annual precipitation (mm) and

$\bar{I}_{30}$ = regional mean of the most intense thirty-minute period of rainfall ($mm.h_{-1}$).

7. A storm's most intense thirty-minute period of rainfall appears to be the best single rainfall variable when simulating intra-catchment variations in lag time. Storm kinetic energy and storm duration also affect individual storm lag times significantly.

8. Empirical equations describing the effects of rainfall characteristics on intra-catchment variations in lag time can be determined for individual catchments or regions. General use of such equations should, however, await further examination, with data from more catchments.

9. Incremental hydrograph procedures for estimating peak flow rates are advantageous since no empirical estimation of the duration of rainfall excess is required and the total time distribution of runoff can be synthesised. Estimates of peak flow rate are, however, sensitive to changes in lag time when incremental hydrographs are convoluted with recorded hyetographs. Empirical

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relationships determining storm lag times from rainfall characteristics are thus only practical when incremental hydrographs are applied in conjunction with generalised rainfall depth-duration relationships.

10. Measured lag times between rainfall and runoff, while defined simply, are impractical to use for peak flow rate prediction, possibly due to poorly synchronised rainfall and runoff records and difficulties in determining the magnitude and temporal distribution of effective rainfall.

In view of the markedly improved estimates of peak flow rates that have been made following the procedures of this report, it can be concluded that similar research into the estimation of peak flow rate, encompassing a wider variety of study regions, is warranted. Three areas where additional research is required have been recognised, the details and objectives of which are now summarised:

1. The proportion of the total volume of runoff under the rising limb of a recorded hydrograph varies with both rainfall and catchment characteristics. The shape of the triangular unit hydrograph used in the SCS Model is, however, constant for all catchments and storms within such catchments. Future research similar to that conducted by Betson et al. (1980) and Ward et al. (1981) should be directed towards the provision of relationships between rainfall and physical catchment characteristics and the shape of the unit hydrograph.

2. For design applications two typical twenty-four hour storm distributions have been derived by the SCS. Future research should be directed towards the development of regional rainfall depth-duration curves, as proposed by Cronshey (1982) for two return periods for the eastern and central USA, together with indices describing such curves for application in empirical equations to estimate lag time according to localised conditions of rainfall duration and intensity.

3. An extensive study of the relationship of peak flow rate regressed against runoff volume should be undertaken. Such distributions provide a simple and yet effective method for predicting peak flow rate when limited records are available. Furthermore, by determining the slopes of linearly regressed runoff relationships a procedure can be adopted to provide accurate estimates of catchment lag time.

4. Finally, since the SCS Curve Number is widely used in hydrological studies, it is suggested that better use should be made of the results of recent research such as that undertaken by Aron et al, (1977), Hawkins (1980), Hjelmfelt (1980a) and Hjelmfelt (1980b) to refine the present method of effective rainfall separation.

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9. APPENDICES

Appendix I : Hydrological storm data

CATCHMENT	STORM NO.	DATE	RAINFALL (MM)	RUNOFF (MM)	PEAK DISCHARGE (MM/H)	I30 (MM/H)	KINETIC ENERGY (J/SQ.M)	D_u (H)	5-DAY API (MM)
26003	1	18/6/40	27.7	3.792	15.05	47.9	714.1	1.0	13.5
	2	29/6/40	19.5	5.546	28.53	35.5	423.9	1.3	59.7
	3	27/8/40	32.8	1.599	5.95	38.5	742.4	2.0	33.3
	4	4/6/41	25.2	3.610	4.91	28.6	601.9	1.4	47.7
	5	29/6/41	39.6	2.852	8.93	61.3	1077.4	1.2	0.5
	6	7/7/41A	30.0	4.826	19.41	56.9	768.1	1.4	15.7
	7	7/7/41B	18.3	6.930	12.55	23.5	406.1	1.8	45.7
	8	23/8/44	30.0	1.920	13.76	58.4	962.2	0.7	8.4
	9	6/6/47	31.5	9.760	49.64	49.9	857.1	0.9	25.9
	10	7/6/47	9.8	1.150	3.44	18.5	233.8	0.3	64.5
	11	16/8/47	31.9	3.050	25.47	42.2	572.9	3.2	23.3
	12	25/6/56	23.9	9.290	52.90	35.6	679.3	0.4	41.9
	13	27/7/56	21.7	3.030	13.76	27.7	541.4	1.2	24.3
	14	29/6/58	60.7	18.031	29.56	29.4	1338.2	6.5	51.7
	15	31/7/58	15.8	1.430	8.83	31.5	430.6	0.3	42.5
	16	4/9/59	44.4	1.257	5.02	35.1	1057.5	3.0	11.4
	17	21/8/60	61.5	4.100	14.13	44.2	1467.0	2.6	19.0
	18	29/7/61	38.9	1.766	7.01	45.3	1017.9	1.5	34.3
	19	3/8/64	36.8	2.014	7.44	44.4	1009.0	1.2	7.6
	20	7/7/69	22.9	4.717	12.18	27.5	441.6	2.6	138.2
	21	27/7/69A	44.4	11.880	48.15	45.3	1219.7	1.4	6.1
	22	27769B	14.0	3.200	12.93	29.4	384.9	0.3	50.5
	23	29/1/70	21.9	3.954	5.26	19.9	313.3	1.6	6.1
	24	24/4/70	40.6	7.670	6.14	12.9	560.6	5.9	23.1
37001	1	13/4/59	27.0	7.950	2.45	32.1	584.1	2.9	3.6
	2	9/5/59	35.5	13.850	10.62	20.2	549.9	5.2	23.4
	3	26/4/59	31.2	8.258	2.84	15.8	380.3	6.7	15.8
	4	22/7/59	30.5	15.502	6.04	20.5	368.5	3.8	35.3
	5	25/7/59	33.5	14.020	5.03	9.4	487.4	7.3	29.5
	6	20/5/60	23.6	8.034	7.59	41.0	604.5	1.4	29.2
	7	27/7/60	31.7	2.962	1.72	37.6	792.4	1.1	11.2
	9	7/6/61	19.8	13.564	6.99	34.4	398.9	2.7	71.1
	9	15/11/61	19.3	4.420	3.91	9.1	124.2	9.1	5.1
	10	21/11/61	14.4	11.280	4.67	14.2	229.3	3.7	2.5
	11	4/9/63	72.6	17.190	10.41	44.8	1420.8	3.7	3.6
	12	1/5/64	32.9	10.112	4.27	19.8	525.7	3.3	1.3
	13	10/5/64	34.0	22.460	10.62	15.1	463.7	7.9	18.3
	14	29/8/64	20.1	6.279	3.58	36.0	493.4	0.7	70.9
	15	20/5/67	29.5	8.288	5.03	15.6	537.9	6.3	0.0
	16	24/6/67	73.6	27.880	27.19	35.6	1460.6	8.2	40.0
	17	26/9/67	47.0	27.450	33.77	44.4	1199.7	2.9	0.0
	19	7/10/67	36.8	21.057	13.03	26.5	748.7	3.3	0.0
	17	19/3/68	35.4	20.940	26.54	32.3	567.8	2.2	0.6
	20	6/5/69	50.3	19.830	20.86	35.7	1152.5	4.6	43.9
	21	7/6/71	36.3	12.720	12.34	53.5	910.2	2.1	18.8
	22	2/6/71	43.7	17.540	16.37	48.3	1018.3	2.3	0.2
	23	24/9/71	33.0	29.506	17.91	21.5	662.2	5.7	0.0
	24	29/12/72	19.8	15.070	8.29	31.0	427.8	6.9	0.0
	25	6/3/73	33.9	13.150	8.43	31.0	549.6	1.5	0.0
	26	4/9/73	57.1	1.633	2.21	106.2	1355.3	1.3	0.0
	27	11/10/73	36.3	28.400	23.61	35.5	785.3	3.5	0.0
	29	3/12/73	29.2	33.820	18.60	20.7	616.3	2.7	0.0
	29	20/4/74	19.9	9.332	11.73	38.7	524.9	0.9	0.0
37002	1	3/5/59	35.5	12.460	5.58	20.2	619.0	5.2	23.4
	2	25/5/59	31.2	6.220	1.94	13.9	380.5	5.7	15.8
	3	25/7/59	33.5	13.070	4.49	9.4	487.4	7.3	39.3
	4	20/5/60	23.6	3.751	5.34	41.5	694.5	1.4	29.2
	5	7/6/71	19.8	19.162	5.34	20.4	328.9	3.7	71.1
	6	21/11/61	14.4	9.167	3.35	14.2	329.3	3.7	5.5
	7	10/5/64	24.0	15.973	7.56	15.1	463.7	7.9	18.3
	8	29/8/64	30.1	2.791	1.73	36.0	495.1	0.7	70.9
	9	30/5/67	29.5	3.380	1.37	15.9	[illegible]	6.3	0.0
	10	25/9/67	47.0	39.270	13.54	41.1	[illegible]	3.3	0.0
	11	7/10/67	36.8	14.540	3.35	25.5	746.7	3.3	0.0
	12	19/3/68	35.4	19.592	9.56	32.3	567.8	2.2	[illegible]
	13	[illegible]	54.3	[illegible]	19.11	53.5	[illegible]	1.5	[illegible]
	14	[illegible]	23.1	17.959	14.29	[illegible]	[illegible]	1.1	50.5
	15	24/4/71	33.4	33.964	9.47	21.5	662.2	5.7	9.2

9. APPENDICES

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CATCHMENT	STORM NO.	DATE	RAINFALL (MM)	RUNOFF (MM)	PEAK DISCHARGE (MM/H)	I30. (MM/H)	KINETIC ENERGY (J/SQ.M)	D_w (H)	5-DAY API (MM)
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	2	28/6/40	19.5	5.546	38.53	39.5	423.9	1.2	57.7
	3	27/8/40	32.8	1.599	5.95	38.5	742.4	2.0	33.3
	4	4/6/41	35.3	3.610	4.91	29.5	601.9	1.4	47.7
	5	29/6/41	39.6	2.852	9.93	61.3	1077.4	1.2	0.5
	6	7/7/41A	30.0	4.826	18.41	52.9	768.1	1.4	15.7
	7	7/7/41B	18.3	6.930	12.55	23.5	406.1	1.8	45.7
	8	23/8/44	30.0	1.930	13.76	58.4	962.2	0.7	9.4
	9	6/6/47	31.5	9.960	49.64	49.9	927.1	0.9	25.9
	10	7/6/47	9.8	1.150	3.44	19.5	233.8	0.3	64.5
	11	16/8/47	21.9	5.050	25.47	42.2	572.9	3.2	23.3
	12	25/6/56	23.9	9.390	52.90	35.6	679.8	0.4	41.9
	13	27/7/56	21.9	3.030	13.76	27.7	541.4	1.2	24.3
	14	29/6/56	60.7	18.031	29.56	39.4	1338.2	4.5	61.7
	15	31/7/58	19.8	1.430	8.83	31.5	430.6	0.3	42.5
	16	4/8/59	44.4	1.257	5.02	35.1	1057.5	3.0	11.4
	17	21/9/60	61.5	4.100	14.13	44.2	1467.0	2.6	19.0
	18	29/7/61	38.9	1.966	7.81	45.3	1017.9	1.5	54.3
	19	3/8/64	36.8	2.014	7.44	44.4	1009.0	1.2	7.6
	20	7/7/69	22.9	4.717	12.18	27.5	441.6	2.6	138.2
	21	27/7/69A	44.4	11.980	48.15	45.3	1219.7	1.4	6.1
	22	27/7/69B	14.0	4.300	12.93	29.0	384.9	0.3	50.5
	23	29/1/70	21.9	5.954	5.26	19.9	513.3	1.6	6.1
	24	24/4/70	40.6	7.670	6.14	12.9	568.6	5.9	23.1
37001	1	18/4/59	27.0	7.950	2.45	32.1	584.1	2.8	9.6
	2	8/5/59	33.3	13.890	10.62	20.2	549.0	5.2	23.4
	3	26/4/59	31.2	8.250	2.84	15.8	380.3	5.7	15.9
	4	22/7/59	20.5	15.592	6.04	20.5	358.6	3.8	35.3
	5	26/7/59	33.5	14.020	5.03	9.4	487.4	7.3	29.5
	6	30/5/60	33.6	8.034	7.59	41.6	604.5	1.4	29.2
	7	27/7/60	31.7	2.962	1.72	37.6	792.4	1.1	11.2
	8	7/6/61	19.8	12.664	6.79	24.4	399.9	2.7	71.1
	9	15/11/61	19.3	4.450	3.91	9.1	124.2	9.1	5.1
	10	21/11/61	14.4	11.290	4.67	14.2	229.3	3.7	2.5
	11	4/9/63	72.6	17.180	10.41	44.8	1420.8	5.7	5.5
	12	1/3/64	33.8	10.112	4.27	19.3	625.7	3.3	1.8
	13	10/3/64	34.0	32.460	10.62	15.1	463.7	7.9	18.3
	14	29/8/64	20.1	6.279	3.58	36.0	493.4	0.7	70.9
	15	20/5/67	29.5	8.208	5.03	15.6	537.5	6.3	0.0
	16	24/5/67	73.6	27.880	27.19	39.5	1460.5	3.2	40.0
	17	26/9/67	47.0	27.450	33.77	44.4	1199.7	2.8	0.0
	18	7/10/67	36.8	21.097	13.03	26.5	748.7	3.3	4.0
	19	13/3/68	25.4	28.940	26.54	32.3	567.8	2.2	0.0
	20	6/5/69	50.3	19.838	20.86	35.7	1152.5	4.5	43.9
	21	7/6/71	36.3	12.720	12.34	53.5	910.2	2.1	18.8
	22	3/6/71	43.7	17.548	16.37	48.3	1019.3	2.3	8.2
	23	24/9/71	33.0	29.506	17.81	21.5	562.2	5.7	0.0
	24	29/12/72	19.9	15.870	3.29	31.0	427.0	0.9	0.0
	25	3/5/73	23.9	13.150	9.43	31.0	549.0	1.5	0.0
	26	4/9/73	57.1	1.633	2.21	195.2	1555.3	1.3	0.0
	27	11/10/73	36.3	28.400	23.61	35.5	765.5	3.5	0.0
	28	3/12/73	29.2	23.328	18.58	29.7	515.5	2.7	0.0
	29	30/4/74	19.9	9.332	11.73	38.7	324.9	0.9	0.0
37102	1	3/5/59	35.5	12.460	[illegible]	21.2	649.1	5.2	23.4
	2	25/5/59	31.2	8.229	1.34	13.9	380.3	5.7	15.9
	3	26/7/59	33.5	13.970	3.49	9.4	487.4	7.3	35.3
	4	30/5/60	33.6	8.761	5.34	41.6	614.5	1.4	29.2
	5	7/6/71	19.3	11.152	6.74	24.4	[illegible]	[illegible]	[illegible]
	6	21/11/61	14.4	8.197	3.15	[illegible]	[illegible]	3.7	[illegible]
	7	[illegible]	[illegible]	16.993	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	8	[illegible]	30.1	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	9	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	10	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	11	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	12	13/3/68	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	13	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	14	[illegible]	[illegible]	[illegible]	11.20	[illegible]	[illegible]	[illegible]	[illegible]
	15	[illegible]	33.0	33.460	[illegible]	[illegible]	662.2	[illegible]	[illegible]

CATCHMENT	STORM NO.	DATE	RAINFALL (MM)	RUNOFF (MM)	PEAK DISCHARGE (MM/H)	I30 (MM/H)	KINETIC ENERGY (J/SQ.M)	D_w (M)	5-DAY APT (MM)
44005	1	20/5/39	12.2	0.074	0.45	24.4	320.8	1.5	4.5
	2	15/6/39	17.8	0.117	0.71	35.5	495.8	0.3	9.5
	3	20/6/39	37.2	0.363	1.79	48.5	741.5	0.3	17.3
	4	11/8/39	19.6	1.380	9.58	37.2	523.0	0.5	16.3
	5	17/5/40	29.1	0.140	0.71	36.1	510.9	0.7	5.9
	6	8/6/40	20.8	0.048	0.30	39.0	541.3	0.5	1.0
	7	5/6/41	36.9	0.173	1.17	35.1	827.3	3.1	59.1
	8	7/9/42	33.6	0.122	1.17	45.2	663.6	0.2	93.2
	9	10/6/43	33.5	0.165	1.26	52.5	835.1	2.0	52.5
	10	14/6/43	33.3	0.257	1.44	35.7	901.3	0.9	55.1
	11	5/6/45	32.5	0.377	2.38	59.9	908.5	0.6	0.9
	12	16/7/45A	20.8	0.046	0.42	40.4	568.5	0.8	17.5
	13	16/7/45B	21.5	0.249	1.34	39.2	545.1	1.3	12.4
	14	7/8/46	40.1	0.544	4.85	79.7	1170.9	0.6	23.3
	15	5/9/46	38.5	8.206	0.86	53.9	823.5	1.1	38.6
	16	17/6/47	37.7	0.086	0.33	48.8	726.3	0.8	47.2
	17	16/6/50	16.3	0.028	0.24	32.6	451.9	0.3	10.6
	18	15/9/50	13.0	0.759	2.79	26.0	386.4	0.2	0.9
	19	26/6/52	45.3	2.532	16.08	81.8	1625.5	0.8	2.8
	20	22/5/54	52.5	3.454	16.76	40.6	1633.5	2.0	9.1
	21	20/9/55	25.1	2.154	11.20	50.2	735.3	0.3	8.4
	22	15/6/57	50.5	7.979	21.56	47.7	1326.2	0.7	41.7
	23	16/6/57	45.0	6.939	34.29	34.6	952.6	1.1	191.5
	24	12/6/58	39.1	3.543	17.20	72.8	1176.1	4.0	0.0
	25	3/7/59	66.5	10.537	22.38	100.5	1967.4	9.6	56.4
	26	15/5/60	55.6	9.591	24.64	70.4	1476.7	1.0	4.3
	27	11/8/61	40.5	3.461	11.20	79.8	1192.9	1.1	0.0
	28	23/8/62	47.3	0.366	1.52	87.2	1355.6	0.6	16.2
	29	21/6/64	25.9	1.501	9.52	28.2	636.3	1.0	0.0
	30	26/7/64A	32.5	4.823	38.10	65.0	997.4	0.9	0.0
	31	26/7/64B	34.8	9.287	32.26	42.3	904.5	0.2	34.9
	32	27/8/64	21.1	3.660	27.18	39.6	589.1	1.2	0.0
	33	1/6/65	29.4	7.778	18.31	43.1	719.4	0.7	1.3
	34	12/6/65	26.9	0.788	3.38	49.8	792.1	1.0	52.8
	35	25/7/66	40.9	2.195	15.39	31.9	1023.5	0.5	3.8
	36	29/7/66	26.3	4.575	19.91	16.9	592.6	1.3	43.4
	37	8/7/67	45.0	8.578	44.70	47.9	1209.7	1.6	3.5
45001	1	22/8/40	15.5	10.119	11.16	31.0	442.1	0.5	0.4
	2	29/6/40	26.2	6.035	6.81	33.7	642.3	0.9	8.0
	3	1/8/40	15.7	3.485	4.17	29.7	429.2	1.1	4.1
	4	6/9/40	13.7	4.510	4.66	31.7	304.9	1.0	12.0
	5	26/4/41	20.9	1.351	2.34	36.4	146.7	2.8	14.8
	6	16/8/42	21.6	2.090	2.56	31.5	567.9	0.6	9.0
	7	11/9/42	29.9	7.582	9.44	35.9	527.8	1.8	2.0
	8	28/6/43	16.0	1.548	2.34	28.4	369.2	1.3	0.0
	9	23/8/43	45.2	12.718	18.24	82.2	1258.7	1.3	0.0
	10	17/8/44	23.6	4.618	6.11	38.6	611.0	1.1	0.0
	11	3/9/44	45.7	18.290	21.19	87.8	1324.7	1.0	0.0
	12	3/9/45	21.1	5.799	6.45	41.6	581.2	0.7	13.5
	13	11/8/45	21.6	7.171	8.45	34.6	521.9	2.3	17.3
	14	6/9/46	19.5	0.923	0.79	19.3	301.4	4.2	0.0
	15	20/8/47	13.5	1.795	2.34	27.0	370.3	0.3	1.3
	16	2/7/49	10.9	0.544	1.18	21.8	291.9	0.4	1.8
	17	1/1/50	15.7	1.732	4.44	34.5	398.8	0.8	14.2
	18	6/9/50	14.9	1.646	3.34	27.6	373.7	0.8	0.8
	19	9/7/53	12.7	0.786	2.24	30.0	302.9	0.9	6.3
	20	27/7/53	20.3	7.686	12.12	40.6	552.6	0.4	11.4
	21	3/8/54	10.4	2.912	3.42	20.8	267.1	0.4	14.5
	22	22/8/54	21.3	8.070	10.18	38.7	317.4	2.4	5.1
	23	11/9/54	19.0	4.067	9.44	38.0	564.7	0.3	0.0
	24	22/7/55	11.4	4.592	1.25	20.9	248.5	0.8	0.0
	25	25/7/57	17.8	5.462	8.10	35.1	463.8	0.5	18.3
	26	5/9/57	16.0	2.146	2.55	29.4	414.7	1.0	0.0
	27	5/7/58	17.5	0.548	1.03	28.9	422.1	1.3	4.5
	28	3/9/59	25.1	7.267	9.31	47.8	[illegible]	0.3	[illegible]
	29	[illegible]/7/60	31.[illegible]	1.257	1.82	24.0	756.5	[illegible]	[illegible]
	30	25/9/62	33.0	5.303	8.30	62.9	925.7	[illegible]	5.3
	31	16/9/62	13.2	1.758	2.03	10.1	[illegible]	[illegible]	28.[illegible]
	32	30/7/63	30.0	0.958	1.40	30.0	[illegible]	[illegible]	[illegible]
	33	21/7/65	[illegible]	3.231	5.58	40.6	603.2	[illegible]	[illegible]
	34	15/9/66	28.7	3.664	8.97	30.[illegible]	[illegible]	[illegible]	[illegible]
	35	23/8/67	28.7	1.252	5.97	33.9	751.7	[illegible]	[illegible]

CATCHMENT	STORM NO.	DATE	RAINFALL (MM)	RUNOFF (MM)	PEAK DISCHARGE (MM/H)	I30. (MM/H)	KINETIC ENERGY (J/SQ.M)	D_u (H)	5-DAY APC (MM)
45002	1	26/7/40	35.6	17.996	41.56	10.7	743.3	3.3	0.0
	2	23/7/41	10.9	1.446	6.39	7.4	142.7	3.0	4.1
	3	7/8/42	35.4	11.565	29.92	45.8	678.4	1.0	0.0
	4	9/8/43	25.7	17.399	38.35	51.4	729.0	0.4	11.4
	5	7/8/45	20.1	13.150	20.05	39.7	526.8	0.6	33.0
	6	27/7/45	9.9	1.773	4.32	16.4	199.5	1.4	0.0
	7	3/7/46	14.5	1.242	2.50	17.8	323.5	2.0	0.0
	8	9/7/46	23.6	6.172	12.25	38.6	592.7	1.1	3.8
	9	26/8/46	35.1	20.353	33.15	40.6	908.1	1.3	2.5
	10	15/8/47	41.7	13.090	16.90	23.6	954.2	2.0	0.0
	11	17/10/47	33.0	7.788	21.89	16.6	519.9	8.5	4.1
	12	7/8/49	25.7	10.320	22.70	31.8	399.8	9.5	0.0
	13	15/8/51	10.2	4.112	10.63	15.4	330.7	0.6	8.4
	14	29/9/51	17.5	4.051	9.30	14.2	279.4	4.1	0.0
	15	28/7/52	13.7	4.329	8.23	12.3	220.1	1.7	18.2
	16	16/7/53	14.7	3.993	9.97	38.6	384.6	0.9	39.4
	17	22/7/54	32.8	7.606	21.22	63.4	982.2	2.4	28.2
	18	13/7/55	13.4	0.320	1.18	17.0	295.8	1.1	11.3
	19	29/7/55	9.1	1.407	2.87	10.5	118.9	0.3	32.1
	20	16/9/56	9.9	0.949	2.77	16.3	154.3	0.9	30.6
	21	20/8/56	16.3	3.282	10.37	28.1	434.7	0.7	14.7
	22	30/9/57	14.7	5.409	14.95	24.4	321.4	0.4	13.2
	23	16/7/57	32.3	11.481	30.63	59.5	917.8	0.9	5.8
	24	29/7/59	9.9	1.300	3.57	17.9	223.6	0.3	11.8
	25	15/8/59	22.6	3.746	5.83	39.4	579.1	1.0	5.3
	26	22/8/61	33.0	7.132	15.91	97.6	897.4	2.0	10.2
	27	30/7/62	14.0	0.198	0.64	24.0	335.3	0.6	15.5
	28	30/7/64	16.3	0.724	2.13	30.4	405.7	1.9	19.6
	29	10/8/65	8.6	1.041	4.72	8.4	179.8	1.1	4.6
	30	3/9/65	53.8	14.308	20.98	70.4	1393.9	2.0	4.8
	31	27/7/66	25.6	3.017	6.95	50.5	699.2	0.5	15.0
	32	29/7/66	17.5	0.820	1.77	32.0	648.6	0.6	50.0
	33	20/9/66	19.8	1.753	5.77	34.1	507.2	0.9	12.7
	34	13/8/69	20.1	1.067	2.69	29.1	460.9	2.3	0.0
47002	1	14/9/39	13.7	6.930	11.93	17.1	288.7	1.3	6.9
	2	13/7/40	13.7	1.483	4.09	24.1	320.1	1.2	0.0
	3	20/7/41	19.6	4.680	12.37	34.6	516.2	0.6	3.8
	4	30/6/42	27.7	3.890	10.49	49.3	715.8	1.5	9.0
	5	4/9/42	11.2	3.629	9.40	22.4	298.6	0.4	10.2
	6	14/9/43	18.9	3.746	3.04	18.9	252.7	0.7	4.0
	7	28/7/44	21.9	5.988	9.29	23.8	420.3	3.7	11.9
	8	17/9/44	14.5	3.106	8.58	24.2	307.7	1.1	1.3
	9	16/10/44	19.8	10.620	31.70	31.1	472.9	1.1	2.3
	10	25/5/47	13.7	1.146	3.55	26.1	331.9	0.9	3.8
	11	4/9/48	15.2	4.470	14.19	23.4	289.1	2.6	2.9
	12	10/9/49	7.1	1.950	5.87	14.2	192.6	0.2	3.3
	13	7/7/52	15.5	4.590	13.94	19.9	351.5	1.1	2.8
	14	21/7/54	21.6	10.820	29.26	31.3	832.2	1.1	5.2
	15	22/7/55	9.9	4.710	14.95	19.8	232.9	0.5	1.5
	16	19/8/55	9.9	7.740	21.10	19.9	245.8	0.5	20.0
	17	19/5/59	17.3	9.690	29.36	29.7	420.0	1.1	8.9
W1H16	1	25/11/76	12.2	0.512	0.05	2.0	132.0	15.0	11.8
	2	13/12/76	18.6	0.367	0.04	17.1	383.5	17.0	7.4
	3	22/12/76	67.7	10.956	1.10	15.8	1244.0	10.0	7.8
	4	1/3/77	12.6	0.563	0.05	4.3	61.2	16.0	24.1
	5	10/3/77	25.3	2.337	0.22	14.0	371.9	23.0	4.1
	6	14/6/77	20.3	0.534	0.05	5.0	292.8	18.0	5.8
	7	2/7/77	17.4	0.448	0.05	6.9	311.8	17.0	5.8
	8	24/9/77	72.9	9.111	0.67	20.4	1413.0	15.0	7.5
	9	7/10/77	22.3	6.180	0.06	10.7	154.4	25.0	1.5
	10	19/10/77	18.9	0.289	0.43	7.7	104.5	8.8	4.4
	11	22/10/77	12.4	1.041	0.15	16.2	189.0	5.0	25.7
	12	29/10/77	13.5	0.338	0.04	5.3	92.2	9.0	5.8
	13	14/12/77	22.9	0.607	0.08	11.7	329.3	18.0	16.4
	14	1/1/78	13.8	0.611	0.04	4.2	36.3	17.0	29.4
	15	10/2/78	11.0	0.546	0.06	8.8	107.8	16.0	29.3
	16	21/2/78	27.5	0.895	0.02	14.6	403.7	7.8	15.5
	17	1/4/78	16.0	0.877	0.12	22.5	360.4	3.0	107.2
	18	23/4/78	75.6	17.053	1.58	14.0	984.4	17.0	18.7
	19	13/10/78	23.0	3.747	0.36	7.4	141.1	12.0	18.1
	20	2/11/78	16.9	0.573	0.09	17.2	284.4	3.0	2.2
	21	14/11/78	11.3	0.306	0.04	4.0	25.2	10.0	10.2
	22	21/11/78	23.1	3.119	0.29	9.4	178.7	16.0	36.1
	23	17/12/78	13.3	0.327	0.03	4.4	85.4	16.0	12.0
	24	2/1/79	28.7	0.693	0.08	19.4	518.6	9.0	5.2
	25	7/1/79	11.8	0.190	0.03	8.1	180.2	5.0	38.9
	26	3/3/79	37.6	1.300	0.24	15.2	502.4	7.0	13.1
	27	4/5/79	38.8	0.951	0.10	9.1	340.7	13.0	12.5
	28	13/6/79	17.0	0.540	0.05	3.7	307.2	14.0	16.1
	29	1/9/79	21.5	0.245	0.02	11.1	297.0	6.0	1.6
	30	7/9/79	17.5	0.406	0.04	6.9	85.2	12.0	12.6
	31	23/9/79	11.9	0.152	0.02	3.9	13.9	7.0	15.5
W1H17	1	24/1/79	44.8	5.123	2.09	61.1	1150.3	2.0	11.6
	2	16/11/76	23.2	3.751	1.61	38.9	510.2	1.0	14.9
	3	22/4/78	75.6	19.030	3.62	13.0	979.3	17.0	18.7
	4	3/6/78	23.7	2.137	0.55	13.3	377.3	4.0	7.5
	5	11/7/78	21.4	2.166	0.39	9.8	164.8	17.0	14.7
	6	8/9/78	56.0	11.558	1.27	13.9	530.3	15.0	1.0
	7	12/10/78	23.0	3.757	0.56	7.0	115.7	12.0	18.1
	8	18/10/78	43.6	13.492	3.43	31.8	732.4	7.0	[illegible]
	9	18/11/78	34.9	3.615	0.58	8.5	420.7	18.0	14.9
	10	21/11/78	23.1	3.507	0.46	9.4	140.2	16.0	36.1
	11	3/3/79	46.9	2.619	0.55	16.2	559.8	16.0	13.1
	12	4/5/79	51.0	1.789	0.28	9.1	640.0	13.0	13.5
	13	12/12/79	32.0	4.149	0.95	20.1	570.5	4.0	22.6

CATCHMENT	STORM NO.	DATE	RAINFALL (MM)	RUNOFF (MM)	PEAK DISCHARGE (MM/H)	I30 (MM/H)	KINETIC ENERGY (J/SQ.M)	D_u (H)	5-DAY API (MM)
45002	1	26/7/40	35.6	17.996	41.56	19.7	743.3	3.3	0.0
	2	23/7/41	11.9	1.446	6.39	7.4	142.7	3.0	4.1
	3	7/8/42	35.4	11.565	29.32	45.9	678.4	1.8	0.0
	4	9/9/43	25.7	17.399	38.35	51.4	729.8	0.4	11.4
	5	7/8/45	29.1	13.150	29.85	39.7	526.8	0.6	33.0
	6	27/7/45	9.9	1.773	4.32	15.4	179.5	1.4	0.0
	7	3/7/46	14.3	1.342	2.58	17.9	323.5	2.0	0.3
	8	9/7/46	23.5	6.172	12.25	38.5	572.7	1.1	3.8
	9	26/8/46	38.1	20.353	33.15	40.6	908.1	1.2	2.5
	10	15/8/47	41.7	13.090	16.90	23.5	754.2	2.0	0.0
	11	12/10/47	33.0	7.788	21.89	16.6	519.9	8.5	4.1
	12	7/8/49	25.7	10.320	22.78	31.8	399.8	9.5	0.0
	13	15/8/51	10.2	4.112	10.63	15.4	230.7	0.6	8.4
	14	29/9/51	17.5	4.051	9.30	15.2	279.4	4.1	0.0
	15	30/7/53	13.5	4.323	8.53	17.3	320.1	1.7	10.2
	16	16/7/53	14.7	3.993	7.97	28.6	384.6	0.9	39.4
	17	22/7/54	32.8	7.600	21.22	63.4	903.2	2.4	28.2
	18	13/7/55	13.4	0.320	1.18	17.0	296.8	1.1	11.3
	19	27/7/55	9.1	1.407	2.37	10.5	110.9	0.3	32.1
	20	16/8/56	9.9	0.909	2.77	16.2	254.2	0.9	30.6
	21	20/8/56	16.3	3.282	10.37	28.1	434.7	0.7	19.7
	22	30/8/57	14.7	5.400	14.95	24.4	321.4	0.4	18.2
	23	16/7/59	32.3	11.481	30.63	59.5	917.0	0.9	3.8
	24	29/7/59	8.9	1.300	3.57	17.9	223.6	0.3	11.8
	25	15/8/59	22.6	3.746	5.83	39.4	579.1	1.0	5.3
	26	23/8/61	33.0	7.132	15.71	57.6	997.4	2.0	10.2
	27	30/7/62	14.0	0.196	0.64	24.0	335.3	0.6	15.5
	28	30/7/64	16.3	0.724	2.13	30.4	405.7	1.9	19.6
	29	13/9/65	8.6	1.041	4.72	8.4	179.8	1.1	4.5
	30	3/9/65	53.8	14.308	28.98	70.4	1393.9	2.0	4.8
	31	27/7/66	35.6	3.017	6.05	50.5	699.2	0.5	15.0
	32	29/7/66	17.5	0.820	1.77	32.0	648.6	0.6	50.0
	33	20/7/66	19.8	1.753	5.77	34.1	507.2	0.9	12.7
	34	13/8/69	20.1	1.067	2.69	29.1	460.9	2.3	0.0
47002	1	14/9/39	13.7	6.930	11.93	17.1	288.7	1.3	6.9
	2	12/7/40	13.7	1.483	4.09	24.1	320.1	1.2	0.0
	3	30/7/41	19.6	4.680	12.37	34.5	516.3	0.6	3.8
	4	20/6/42	27.7	3.890	10.49	49.3	715.8	1.5	0.0
	5	4/9/42	11.2	3.620	9.48	22.4	298.6	0.4	10.2
	6	14/9/43	10.7	3.746	8.04	18.9	252.7	0.7	4.0
	7	20/7/44	31.9	5.900	9.29	23.0	420.3	3.7	11.9
	8	17/8/44	14.5	3.106	8.50	24.2	307.7	1.1	1.3
	9	16/10/44	19.8	10.620	31.70	31.1	472.9	1.1	2.3
	10	25/3/47	13.7	1.146	3.55	26.1	331.9	0.9	3.8
	11	4/9/48	15.2	4.470	14.19	23.4	289.1	2.6	2.8
	12	10/9/49	7.1	1.960	5.87	14.2	192.6	0.2	3.3
	13	7/7/52	15.5	4.599	13.94	19.9	351.5	1.1	2.8
	14	21/7/54	21.6	10.820	29.25	31.3	832.2	1.1	5.2
	15	23/7/55	9.9	4.710	14.95	17.8	232.8	0.5	1.5
	16	19/8/55	9.9	7.740	21.10	19.3	245.8	0.5	20.0
	17	19/5/59	17.3	9.590	29.26	29.7	420.0	1.1	8.9
W1M16	1	25/11/76	12.2	0.512	4.45	2.4	152.8	15.0	11.8
	2	13/12/76	18.6	0.369	0.44	17.3	383.5	17.0	7.4
	3	23/12/76	47.7	10.956	1.10	15.4	1246.3	10.0	7.8
	4	1/3/77	12.6	0.563	0.05	4.3	61.2	16.0	24.1
	5	10/3/77	25.3	2.337	0.22	14.8	371.9	23.0	4.1
	6	14/6/77	20.3	0.534	0.05	5.4	292.0	18.0	5.4
	7	2/7/77	17.4	0.448	0.05	6.9	311.8	17.0	5.8
	8	24/9/77	23.9	9.111	0.57	20.4	1413.8	15.0	7.5
	9	7/10/77	22.3	6.100	0.06	10.7	164.0	35.0	4.5
	10	19/10/77	10.9	0.209	0.03	7.7	104.5	8.0	4.4
	11	22/10/77	12.4	1.041	0.15	14.2	189.0	5.0	25.7
	12	29/10/77	13.5	0.338	0.04	5.3	72.2	9.0	5.4
	13	14/12/77	33.9	0.647	0.08	14.7	329.3	18.0	16.4
	14	1/1/78	13.8	0.611	0.04	4.2	36.3	17.0	20.4
	15	10/2/78	11.8	0.546	0.06	4.4	107.4	16.0	24.3
	16	21/2/78	27.5	0.095	0.02	19.6	413.7	7.0	15.5
	17	1/4/78	16.8	0.877	0.12	22.5	360.4	3.0	107.2
	18	22/4/78	75.6	17.053	1.58	14.0	984.4	17.0	14.7
	19	17/10/78	23.8	1.747	0.36	7.4	101.1	12.0	18.1
	20	2/11/78	16.9	0.573	0.09	17.2	283.4	3.0	2.3
	21	14/11/78	11.3	0.306	0.44	4.0	25.2	10.0	18.2
	22	21/11/78	23.1	3.119	0.29	9.4	178.7	15.0	30.1
	23	17/12/78	13.3	0.327	0.03	4.4	85.4	16.0	12.0
	24	3/1/79	28.7	0.693	0.08	19.4	518.6	9.0	5.2
	25	7/1/79	11.8	0.190	0.03	8.1	180.2	5.0	24.9
	26	3/3/79	27.6	1.509	0.20	16.2	502.4	9.0	11.1
	27	4/5/79	30.8	0.951	0.10	7.1	340.7	13.0	13.5
	28	13/6/79	17.0	0.540	0.05	3.7	307.2	14.0	16.1
	29	1/9/79	21.5	0.245	0.02	14.1	397.0	6.0	1.6
	30	7/9/79	17.5	0.406	0.00	6.9	85.2	12.0	12.6
	31	23/9/79	11.9	0.152	0.02	3.9	13.9	7.0	16.5
W1M17	1	24/1/79	44.8	5.173	2.49	64.1	1150.1	2.0	11.4
	2	13/11/76	23.3	3.751	1.61	28.7	510.2	1.0	14.3
	3	22/4/78	75.6	17.030	1.52	13.0	929.3	17.0	19.7
	4	3/6/78	23.7	2.147	3.55	13.5	377.3	4.0	7.3
	5	11/7/79	21.4	2.156	0.79	9.8	154.0	17.0	14.7
	6	3/9/78	54.0	11.550	1.27	13.9	558.3	16.0	1.8
	7	12/10/78	23.0	3.757	0.50	7.0	115.7	12.0	18.1
	8	18/10/78	43.6	12.492	3.03	31.3	732.0	7.0	17.0
	9	18/11/78	34.9	3.615	0.58	8.5	429.7	18.0	14.9
	10	21/11/78	23.1	3.507	0.16	7.4	140.3	16.0	36.1
	11	3/1/79	46.9	2.914	0.55	16.2	659.9	16.0	13.1
	12	4/5/79	51.0	1.784	0.29	9.1	540.0	17.0	12.5
	13	12/12/79	32.0	4.149	0.95	30.1	570.5	4.0	27.6

CATCHMENT	STORM NO.	DATE	RAINFALL (MM)	RUNOFF (MM)	PEAK DISCHARGE (MM/H)	I30. (MM/H)	KINETIC ENERGY (J/SQ.M)	D_u (H)	5-DAY APC (MM)
V1M12	1	29/1/65	23.4	1.510	0.79	37.4	658.9	0.5	0.0
	2	21/12/55	16.0	0.051	0.03	28.4	422.2	0.5	0.0
	3	3/12/66	30.1	0.209	0.11	33.7	661.9	1.4	2.1
	4	6/1/68	23.8	0.036	0.03	37.9	621.7	1.1	2.0
	5	23/1/68	17.4	0.033	0.02	29.7	463.7	0.5	0.0
	6	15/2/58	51.4	0.491	0.38	51.9	1302.1	3.3	12.2
	7	4/12/68	39.5	0.051	0.03	57.2	1093.2	0.9	4.8
	8	3/12/69	21.9	0.337	0.10	15.8	496.9	1.2	0.0
	9	16/12/69	15.5	0.025	0.01	30.9	548.3	0.3	0.0
	10	7/1/71	36.4	0.076	0.05	56.0	1195.2	0.5	17.1
	11	21/8/71	18.3	0.906	0.45	18.1	488.0	1.1	12.6
	12	19/2/72	24.2	0.012	0.01	19.7	453.1	1.5	0.0
	13	23/2/72	20.2	0.360	0.09	9.6	329.1	5.0	0.0
	14	12/3/72	17.2	0.242	0.07	8.3	174.2	4.0	8.7
	15	11/4/72	20.3	0.514	0.22	40.6	722.9	0.3	0.0
	16	27/11/72	37.3	2.601	1.37	57.6	1195.7	1.1	29.0
	17	5/1/73	33.5	0.088	0.03	27.6	729.7	1.7	24.0
	18	20/1/73	33.3	0.649	0.03	65.2	1200.5	0.2	0.0
	19	23/1/73	47.5	1.667	1.07	46.5	1335.4	2.2	34.8
	20	19/3/73	16.2	0.146	0.05	29.4	502.8	0.6	0.0
V1M28	1	21/12/76	22.0	0.395	0.21	13.2	306.1	2.5	0.0
	2	25/1/77	22.3	0.370	0.14	19.9	384.7	2.4	0.0
	3	5/3/77	13.2	2.044	0.85	12.5	158.1	0.6	33.0
	4	23/4/77	18.3	0.142	0.16	36.5	589.0	0.4	0.0
	5	9/10/77	17.8	0.385	0.23	15.3	292.0	5.0	15.4
	6	22/12/77	24.6	0.399	0.58	24.6	551.8	4.1	5.7
	7	5/3/78	39.4	3.233	1.29	25.9	907.8	1.6	21.5
	8	9/4/78	14.9	0.536	0.51	27.9	411.6	0.9	0.0
	9	26/9/78	21.3	0.474	0.64	39.4	649.2	0.7	9.8
	10	1/12/78	29.8	0.825	0.65	54.4	918.1	2.4	13.8
	11	16/1/79	26.0	5.060	2.76	31.9	533.4	4.0	10.9
	12	6/1/79	16.1	2.320	0.73	28.0	374.8	4.3	1.8
	13	22/2/79	26.4	1.843	0.43	20.9	500.9	5.0	24.9
V7M03	1	2/12/76	25.9	1.378	0.70	37.7	654.0	4.4	9.5
	2	21/12/76	24.0	0.387	0.09	12.3	340.7	2.4	0.0
	3	25/1/77	22.4	0.487	0.16	19.9	384.7	2.4	11.2
	4	7/2/77	20.4	0.909	0.25	19.2	374.2	2.4	7.2
	5	5/3/77	13.0	0.474	0.19	12.5	158.2	0.6	33.0
	6	23/4/77	18.3	0.255	0.11	36.5	589.0	0.4	0.0
	7	7/4/77	12.0	1.529	0.36	8.9	124.1	2.4	0.0
	8	9/10/77	17.9	1.182	0.30	15.3	292.0	5.0	15.4
	9	29/10/77	24.7	3.991	0.96	22.0	539.8	3.1	3.2
	10	22/12/77	24.0	0.922	0.20	24.5	551.8	4.1	5.7
	11	15/1/78	17.5	1.239	0.52	24.1	421.4	1.0	1.3
	12	6/1/79	15.0	6.640	1.16	13.0	237.4	2.3	0.0
	13	2/2/79	21.1	7.090	1.20	15.2	383.8	3.7	3.7
	14	5/3/78	39.3	9.190	1.34	25.0	907.7	1.6	17.0
	15	26/9/79	25.3	2.010	1.73	48.1	305.3	0.3	19.8
	16	1/12/78	29.8	3.070	3.68	54.4	918.1	2.4	13.8
	17	15/12/78	35.4	14.540	5.07	41.1	341.0	1.5	7.3
	18	28/12/79	23.5	3.670	0.98	23.9	[illegible]	[illegible]	[illegible]
	19	6/1/79	16.1	2.765	2.03	28.0	374.8	3.0	1.8
	20	17/1/79	[illegible]	1.780	0.51	27.1	[illegible]	3.2	[illegible]
	21	22/2/79	[illegible]	0.926	0.21	12.7	231.8	5.0	35.0
	22	21/3/79	29.3	1.309	0.75	46.1	[illegible]	[illegible]	[illegible]
	23	3/5/79	27.0	1.018	0.44	27.3	475.9	7.0	0.0

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C PROGRAM TO A)BACKROUTE THE OUTFLOW HYDROGRAPH TO OBTAIN
C              AN INFLOW HYDROGRAPH
C            B)CALCULATE THE SYNTHETIC HYDROGRAPH USING STANDARD SCS
C              PROCEDURES. (INCREMENTAL UNIT HYDROGRAPH SHAPE AND LAG
C              VALUES CAN BE CHANGED AS AN OPTION).
C            C)OPTIMISE LAG TO OBTAIN ASYNTHETIC PEAK SYNTHETIC PEAK
C              MAGNITUDE EQUAL TO EITHER THE INFLOW OR OUTFLOW HYDROGRAPH
C              AND  CALCULATE THE TIME DISTRIBUTION OF RUNOFF FOR THIS LAG.
C
C---------------------------------------------------------------------
C
C DATA IS READ IN AS FOLLOWS : WEIR AND RAINGAUGE DATA
C                              -------------------------
C JSTID  - SITE IDENTIFICATION    )
C STNOJ  - SITE NUMBER            )
C Q(I)   - OUTFLOW RATE (L/S)     )       WEIR
C B(I)   - BASE FLOW RATE (L/S)   )
C ST(I)  - STAGE (M)              )
C QT(I)  - TIME (MINUTES)         )
C JQ(I)  - USA OUTFLOW RATE(MM/H) )
C
C ISTID  - SITE IDENTIFICATION    )
C STNOI  - SITE NUMBER            )
C JD(I)  - DAY                    )      RAINGAUGE
C JH(I)  - HOUR                   )
C JM(I)  - MINUTE                 )
C JR(I)  - DEPTH (MM)             )
C
C
C                         : CONTROL CARD
C                           ------------
C TSTPQ  - INFLOW/OUTFLOW ROUTING TIME INTERVAL (MINS)
C CIA    - COEFFICIENT OF INITIAL ABSTRACTION (PERCENT)
C QTOT   - QUICK FLOW VOLUME (MM)
C AREA   - CATCHMENT AREA (SQ KM)
C CN     - CURVE NUMBER FOR A.M.C CONDITION 2
C CNA    -  "     "       "  ACTUAL A.M C CONDITION.
C CL     - HYDRAULIC LENGTH OF CATCHMENT (M)
C YS     - AVERAGE CATCHMENT SLOPE (M/M)
C C1     - STILLING BASIN DEPTH STORAGE COEFFICIENT    S=C1*H+C2*H**2
C C2     -  "       "     "     "        "
C SHIFT  - TIME NEEDED TO ALLIGN HYDROGRAPHS  (MINUTES)
C          +VE SHIFTS SYNTHETIC HYDROGRAPH TO THE RIGHT
C COEFQ  - 1/(1+TR/TP) X 1000  NORMALLY 208.3 IN STANDARD SCS PROCEDURE
C          THIS FACTOR DESCRIBES THE SHAPE OF THE TRIANGULAR HYDROGRAPH
C COEFL  - CONSTANT IN THE SCS LAG CALCULATION EQUATION. NORMALLY 7069.0
C IRUTE  - OPTION TO BACKROUTE OUTFLOW HYDROGRAPH
C ISYNT  - OPTION TO CALCULATE SYNTHETIC HYDROGRAPH
C IPLTQ  - OPTION TO PLOT HYDROGRAPHS
C IWRQ   - OPTION TO TABULATE HYDROGRAPHS
C IEFFCY - OPTION TO CALCULATE THE EFFICIENCY OF FIT OF THE SYNTHETIC
C          HYDROGRAPH.
C LAGCAL - OPTION TO OPTIMISE LAG TO OBTAIN CORRECT PEAK DISCHARGE.
C IUSAD  - SPECIFICATION AS TO WHETHER DATA IS LOCAL OR U.S.A
C NC     - NUMBER OF TIME STEPS PER UNIT HYDROGRAPH
C ID     - DAY
C NP     - NUMBER OF TIME STEPS IN THE UNIT HYDROGRAPH TIME TO PEAK.
C A(I)   - COEFFICIENTS TO MULTIPLY ORDINATES OF UNIT HYDROGRAPH FOR
C          LINEAR SUPERPOSITION EG. .333 .655 1. .9 .6 .4 .2
C QPACT  - MAXIMUM FLOW RATE OF THE RECORDED HYDROGRAPH.
C DL     - (NP-0.5)   FACTOR RELATING INCREMENTAL TIME STEP TO LAG TIME



      PARAMETER IDIM =1500

      DIMENSION QIN(IDIM),QOUT(IDIM),QSYN(IDIM),STAGE(IDIM),QTIME(IDIM),
     1RAIN(IDIM),PPT(IDIM),RTIME(IDIM),TMIN(IDIM),X(IDIM),Y(IDIM),JD(7),
     2ST(4),QT(4),JD(7),JH(7),JM(7),JR(7),QP(IDIM),XHEAD(10),YHEAD(26),
     3QBASE(IDIM),B(4),A(40),STEPQ(IDIM),STEPB(IDIM),STEPS(IDIM),
     4STEPT(IDIM),Q(4)

      DATA BLANK/'     '/,IBLNK/'   '/,IBLAN/' '/

C      INITIALIZATION

      XMAX=0.
      XMIN=0.
      YMAX=0.
      YMIN=0.
      QPACT=0.
      J=0
      TI=0.
      BSQ=0.
      SLOPE=0.
      TI=0.
      X=0
      RFT=0.
      EFF=0.
      DO    1 I=1,IDIM
          QOUT(I)=0.
          QBASE(I) = 0.0
          STAGE(I)=0.
          QTIME(I)=0.
          RAIN(I)=0.
          PPT(I)=0.
          TMIN(I)=0.
          X(I)=0.
          Y(I)=0.
          RTIME(I)=0.
          QSYN(I)=0.
    1 CONTINUE


C      READ CONTROL CARD

C---------------------------------------------------------------------

      READ(5,1000)TSTPQ,CN,CNA,CL,YS,CIA,QTOT,C1,C2,SHIFT,COEFQ,COEFL,
     1               AREA,NC,NP,ID,IRUTE,ISYNT,IPLTQ,IWRQ,
     2               IEFFCY,LAGCAL,IUSAD,IMIN
      READ(5,1001)DL,(A(I),I=1,40)

C-------------------------------------------
C
C READ DIGITISED RUNOFF RECORDS
C
C-------------------------------------------
C
```

Appendix 2 : Main program SCSVL and subroutines

```
C PROGRAM TO A)BACKROUTE THE OUTFLOW HYDROGRAPH TO OBTAIN
C                 AN INFLOW HYDROGRAPH
C               B)CALCULATE THE SYNTHETIC HYDROGRAPH USING STANDARD SCS
C                 PROCEDURES. (INCREMENTAL UNIT HYDROGRAPH SHAPE AND LAG
C                 VALUES CAN BE CHANGED AS AN OPTION).
C               C)OPTIMISE LAG TO OBTAIN ASYNTHETIC PEAK SYNTHETIC PEAK
C                 MAGNITUDE EQUAL TO EITHER THE INFLOW OR OUTFLOW HYDROGRAPH
C                 AND  CALCULATE THE TIME DISTRIBUTION OF RUNOFF FOR THIS LAG.
C
C-----------------------------------------------------------------------
C
C DATA IS READ IN AS FOLLOWS : WEIR AND RAINGAUGE DATA
C                              -----------------------
C JSTID   - SITE IDENTIFICATION      }
C STNOJ   - SITE NUMBER              }
C Q(I)    - OUTFLOW RATE (L/S)       }        WEIR
C B(I)    - BASE FLOW RATE (L/S)     }
C ST(I)   - STAGE (M)                }
C QT(I)   - TIME (MINUTES)           }
C JQ(I)   - USA OUTFLOW RATE(MM/H)   }
C
C ISTID   - SITE IDENTIFICATION      }
C STNOI   - SITE NUMBER              }
C ID(I)   - DAY                      }        RAINGAUGE
C JH(I)   - HOUR                     }
C JM(I)   - MINUTE                   }
C JR(I)   - DEPTH (MM)               }
C
C
C                                  : CONTROL CARD
C                                    ------------
C TSTPQ   - INFLOW/OUTFLOW ROUTING TIME INTERVAL (MINS)
C CIA     - COEFFICIENT OF INITIAL ABSTRACTION (PERCENT)
C QTOT    - QUICK FLOW VOLUME (MM)
C AREA    - CATCHMENT AREA (SQ KM)
C CN      - CURVE NUMBER FOR A.M.C CONDITION 2
C CNA     -   "       "      "   ACTUAL A.M C CONDITION.
C CL      - HYDRAULIC LENGTH OF CATCHMENT (M)
C YS      - AVERAGE CATCHMENT SLOPE (M/M)
C C1      - STILLING BASIN DEPTH STORAGE COEFFICIENT    S=C1*H+C2*H**2
C C2      -   "        "     "     "        "
C SHIFT   - TIME NEEDED TO ALLIGN HYDROGRAPHS  (MINUTES)
C           +VE SHIFTS SYNTHETIC HYDROGRAPH TO THE RIGHT
C COEFQ   - 1/(1+TR/TP) X 1000  NORMALLY 208.3 IN STANDARD SCS PROCEDURE
C           THIS FACTOR DESCRIBES THE SHAPE OF THE TRIANGULAR HYDROGRAPH
C COEFL   - CONSTANT IN THE SCS LAG CALCULATION EQUATION. NORMALLY 7069.0
C IRUTE   - OPTION TO BACKROUTE OUTFLOW HYDROGRAPH
C ISYNT   - OPTION TO CALCULATE SYNTHETIC HYDROGRAPH
C IPLTQ   - OPTION TO PLOT HYDROGRAPHS
C IWRQ    - OPTION TO TABULATE HYDROGRAPHS
C IEFCY   - OPTION TO CALCULATE THE EFFICIENCY OF FIT OF THE SYNTHETIC
C           HYDROGRAPH.
C LAGCAL  - OPTION TO OPTIMISE LAG TO OBTAIN CORRECT PEAK DISCHARGE.
C IUSAD   - SPECIFICATION AS TO WHETHER DATA IS LOCAL OR U.S.A
C NC      - NUMBER OF TIME STEPS PER UNIT HYDROGRAPH
C ID      - DAY
C NP      - NUMBER OF TIME STEPS IN THE UNIT HYDROGRAPH TIME TO PEAK.
C A(I)    - COEFFICIENTS TO MULTIPLY ORDINATES OF UNIT HYDROGRAPH FOR
C           LINEAR SUPERPOSITION EG. .333 .666 1. .9 .6 .4 .2
C QPACT   - MAXIMUM FLOW RATE OF THE RECORDED HYDROGRAPH.
C DL      - (NP-0.5)    FACTOR RELATING INCREMENTAL TIME STEP TO LAG TIME


      PARAMETER IDIM =1500

      DIMENSION QIN(IDIM),QOUT(IDIM),QSYN(IDIM),STAGE(IDIM),QTIME(IDIM),
     1RAIN(IDIM),PPT(IDIM),RTIME(IDIM),TMIN(IDIM),X(IDIM),Y(IDIM),JD(7),
     2ST(4),QT(4),ID(7),JH(7),JM(7),JR(7),QP(IDIM),XHEAD(10),YHEAD(26),
     3QBASE(IDIM),S(4),A(40),STEPQ(IDIM),STEPB(IDIM),STEPS(IDIM),
     4STEPT(IDIM),Q(4)

      DATA BLANK/'    '/,IBLNK/'  '/,IBLAN/' '/

C       INITIALIZATION

      XMAX=0.
      XMIN=0.
      YMAX=0.
      YMIN=0.
      QPACT=0.
      J=0
      II=0.
      RSQ=0.
      SLOPE=0.
      TI=0.
      K=0
      RFT=0.
      EFF=0.
      DO    1 I=1,IDIM
            QOUT(I)=0.
            QBASE(I) = 0.0
            STAGE(I)=0.
            QTIME(I)=0.
            RAIN(I)=0.
            PPT(I)=0.
            TMIN(I)=0.
            X(I)=0.
            Y(I)=0.
            RTIME(I)=0.
            QSYN(I)=0.
    1 CONTINUE


C       READ CONTROL CARD

C-----------------------------------------------------------------------

      READ(5,1000)TSTPQ,CN,CNA,CL,YS,CIA,QTOT,C1,C2,SHIFT,COEFQ,COEFL,
     1              AREA,NC,NP,ID,IRUTE,ISYNT,IPLTQ,IWRQ,
     2              IEFCY,LAGCAL,IUSAD,IMIN
      READ(5,1001)DL,(A(I),I=1,NC)

C-----------------------------------------
C
C READ DIGITISED RUNOFF RECORDS
C
C-----------------------------------------
C
```

```
C      READ OUTFLOW RATE (GAUGED) , STAGE AND CORRESPONDING TIME ARRAYS
C-------------------------------------------------------------------------

       IF(IUSAD .EQ. 0)THEN
C
C READ OUTFLOW RATE (GAUGED), BASE FLOW RATE AND STAGE FOR SA DATA
C--------------------------------------------------------------------------
    2    READ (5,1002)JSTID,STNOJ,(Q(I),B(I),ST(I),QT(I),I=1,3)
         IF((JSTID .EQ. IBLANK) .AND. (STNOJ .EQ. BLANK))  GO TO    2

         DO    3 I=1,3
            IF(QT(I) .EQ. 0.0)GO TO  10
            J=J+1
            QOUT(J)=Q(I)
            QBASE(I)=B(I)
            STAGE(J)=ST(I)
            QTIME(J)=QT(I)
    3    CONTINUE
         GO TO    2
       ENDIF
C
C   READ OUTFLOW RATE (GAUGED) FOR USA DATA
C ------------------------------------------------------------------------

    4 READ(5,1005)JSTID,STNOJ,IYR,IMTH,(JD(I),JH(I),JM(I),JQ(I),I=1,7)
       IF((JSTID .EQ. IBLANK) .AND. (STNOJ .EQ. BLANK))GO TO    4
       DO    5 I=1,7
            IF(JD(I) .EQ. 0)GO TO    6
            J=J+1
            QOUT(J)=FLOAT(JQ(I))/100.
            QOUT(J)=QOUT(J)*AREA*1000000./3600.

            QTIME(J)=FLOAT(JD(I)-1)*1440.+FLOAT(JH(I)*60+JM(I))
    5 CONTINUE
       GO TO    4

C SEPARATE BASE FLOW FROM TOTAL FLOW FOR USA CATCHMENTS
C ------------------------------------------------------------------
    6 NPTSQ=J
       DO    7 I=1,NPTSQ
         IF(QOUT(I+1) .GT. QOUT(I))THEN
            M=I
            BSQ=QOUT(I)
            QBASE(I)=BSQ
            GO TO    8
         ENDIF
    7 CONTINUE
    8 NPTSQ=NPTSQ-1
       DO    9 I=M,NPTSQ
          SLOPE=1.13*AREA*10.**5/1440./86400.
          J=I+1
          TI=TI+(QTIME(J)-QTIME(I))
          QBASE(J)=BSQ+(TI*SLOPE)
    9 CONTINUE
       NPTSQ=NPTSQ+1
C ----------------------------------------------
C        READ RAINFALL INPUT TO SYNTHETIC HYDROGRAPH
C-------------------------------------------------------------------------

   10 IF(IMIN .EQ. 0)THEN
         NPTSQ=J
         READ(5,1003)ISTID,STNOI,IYR,IMTH,(JD(I),JH(I),JM(I),JR(I),I=1,7)
         IF((ISTID .EQ. IBLANK) .AND. (STNOI .EQ. BLANK))GO TO  10

         DO  11 I=1,7
            IF(JD(I) .EQ. 0)GO TO  14
            K=K+1


C        CONVERTS DAY , HOUR , MINUTE READINGS TO MINUTES FROM THE START
C        OF THE MONTH.
C-----------------------------------------------------------------------
              TMIN(K)=FLOAT(JD(I)-1)*1440.+FLOAT(JH(I)*60+JM(I))
              PPT(K)=FLOAT(JR(I))
   11    CONTINUE
         GO TO  10
       ENDIF
C READ RAINFALL TIMES IN MINUTES FROM START OF MONTH
C ------------------------------------------------------------
       NPTSQ=J
   12 READ(5,1006)ISTID,STNOI,IYR,IMTH,(JM(I),JR(I),I=1,7)
            IF((ISTID .EQ. IBLANK) .AND. (STNOI .EQ. BLANK))GO TO  12
               DO  13 I=1,7
                IF(JM(I) .EQ. 0)GO TO  14
                K=K+1
                TMIN(K)=FLOAT(JM(I))
                PPT(K)=FLOAT(JR(I))
   13          CONTINUE
               GO TO  12
   14 NPTSP=K

C   IN ORDER TO PREVENT DUPLICATE TIME WHEN THE FLOW RATES ARE NOT THE
C   SAME , THE TIME VALUES ARE SEPARATED BY HALF A MINUTE . THE DATA
C   ERROR IS DUE TO THE LIMITATIONS ON ACCURACY OF THE DIGITIZER .
C-------------------------------------------------------------------------

       J=J-1
       DO  15 I=1,J
           M=I+1
           IF(QTIME(M) .EQ. QTIME (I)) THEN
               QTIME(I) = QTIME(I)-.25
               QTIME(M) = QTIME(M)+.25
               ENDIF
   15 CONTINUE

C      BACK-ROUTING OPTION IS CARRIED OUT IF IRUTE IS NONE ZERO
C-------------------------------------------------------------------------


       IF (IRUTE .EQ. 1)  THEN
           CALL ROUIL(TMIN,C1,C2,ISTPQ,QOUT,QBASE,STAGE.QTIME,NPTSQ,
     1     STEPQ,STEPR,STEPS,STEPT,QIN,K,QPACT)


C    IF NO BACKROUTING IS DONE THE DIGITIZED POINTS OF THE OUTFLOW
C    HYDROGRAPH WITH BASE FLOW DEDUCTED ARE USED IN FURTHER ANALYSIS
```

```
C     IF BACKROUTING IS DONE THE OUTFLOW AND INFLOW HYDROGRAPHS ARE
C     SPECIFIED AT AN OPTIONAL INCREMENTAL TIME STEP.

            GO TO  17
            ENDIF

        DO  16 I=1,NPTSQ
            STEPT(I)=QTIME(I)
            STEPQ(I)=QOUT(I)-QBASE(I)
            QIN(I)=0.

C     MAXIMUM FLOW RATE OF THE HYDROGRAPH IS LOCATED.

            IF(STEPQ(I) .GT. QPACT)QPACT=STEPQ(I)
   16 CONTINUE


C     SYNTHESISING PROCESS IS CARRIED OUT IF ISYNT IS NON ZERO
C-----------------------------------------------------------------------

   17 IF(ISYNT .EQ. 1)THEN
            CALL SYNTL(TSTEP,AREA,RAIN,QSYN,OP,LSTEP,
     1      PPT,TMIN,NPTSP,RTIME,RFT,CIA,COEFQ,JSTID,STNOJ,ID,IMTH,
     2      IYR,NC,A,QPACT,QTOT,DL,NP,CN,CNA,CL,YS,LACCAL,COEFL)
            LSTEP=LSTEP+NC
            ENDIF

C  LISTING OPTION OF HYDROGRAPHS
C-------------------------------------------------------------------------


        IF(IWRQ .EQ. 1)THEN
            WRITE(6,1007) JSTID,STNOJ,ID,IMTH,IYR
            DO  18 I=1,2000
                IF((NPTSQ .GE. I) .AND. (LSTEP .GE. I))
     1          WRITE(6,1008)STEPT(I),QIN(I),STEPQ(I),RTIME(I),QSYN(I)
                IF((NPTSQ .GE. I) .AND. (LSTEP .LT. I))
     1          WRITE(6,1009) STEPT(I),QIN(I),STEPQ(I)
                IF((NPTSQ .LT. I) .AND. (LSTEP .GE. I))
     1          WRITE(6,1010)RTIME(I),QSYN(I)
   18       CONTINUE
            ENDIF

C       PHASING OPTION TO LINE UP THE INFLOW & SYNTHETIC HYDROGRAPHS ON
C       THE TIME SCALE
C-----------------------------------------------------------------------

        IF(SHIFT .NE. 0.)CALL PHASE(LSTEP,RTIME,SHIFT)

C       PLOTTING OPTION FOR RUNOFF - (INFLOW,OUTFLOW & SYNTHETIC)

C-----------------------------------------------------------------

        IF(IPLTQ .EQ. 1)THEN
            LSTEP=LSTEP-NC


C     READ LABELS FOR THE PLOT

            READ(5,1004)XHEAD,YHEAD

C      SCAN FOR MAX AND MIN FLOWRATES

            DO  19 I=1,IDIM
                IF(YMAX .LT. STEPQ(I))YMAX=STEPQ(I)
                IF(YMAX .LT. QIN(I))YMAX=QIN(I)
                IF(YMAX .LT. QSYN(I))YMAX=QSYN(I)
                IF(YMIN .GT. STEPQ(I))YMIN=STEPQ(I)
                IF(YMIN .GT. QIN(I))YMIN=QIN(I)
                IF(YMIN .GT. QSYN(I))YMIN=QSYN(I)
   19       CONTINUE
            XMIN=STEPT(1)
            XMAX=STEPT(K)
            IF(ISYNT .EQ. 1)THEN
                DO  20 I=1,IDIM
                    IF(XMIN .GT. RTIME(1))XMIN=RTIME(1)
                    IF(XMAX .LT. (RTIME(I)+(NC-NP)*TSTEP))
     1                 XMAX =(RTIME(I)+(NC-NP)*TSTEP)
                    IF(XMAX .LT. STEPT(I)) XMAX=STEPT(I)
   20           CONTINUE
                ENDIF
C     -------------------------

C      GRAPH AXES ARE PLOTTED

      -------------------------
       READ(5,1011) XMIN,XMAX,YMIN,YMAX
 1011  FORMAT (4F10.3)
            NY=10
            NX=10
            XLN=30.
            YLN=15.
            IENTR=1
            CALL VPLOT(XMAX,XMIN,YMAX,YMIN,NX,NY,XHEAD,YHEAD,
     1      IENTR,IPNT,N,X,Y,ICNCT,ISMTH,ICORR,XLN,YLN,DD)


C      OUTFLOW HYDROGRAPHS ARE PLOTTED.
C      --------------------------------

            IENTR=2
            DO  21 I=1,NPTSQ
                X(I)=STEPT(I)
                Y(I)=STEPQ(I)
   21       CONTINUE

            N=NPTSQ
            IPNT=7
            ICNCT=0
            ISMTH=1
            ICORR=1
            CALL VPLOT(XMAX,XMIN,YMAX,YMIN,NX,NY,XHEAD,YHEAD,
     1      IENTR,IPNT,N,X,Y,ICNCT,ISMTH,ICORR,XLN,YLN,DD)
```

```
C     IF BACKROUTING IS DONE THE OUTFLOW AND INFLOW HYDROGRAPHS ARE
C     SPECIFIED AT AN OPTIONAL INCREMENTAL TIME STEP.

            GO TO  17
            ENDIF

        DO   16 I=1,NPTSQ
             STEPT(I)=RTIME(I)
             STEPQ(I)=QOUT(I)-QBASE(I)
             QIN(I)=0.

C     MAXIMUM FLOW RATE OF THE HYDROGRAPH IS LOCATED.

         IF(STEPQ(I) .GT. QPACT)QPACT=STEPQ(I)
   16 CONTINUE


C_____SYNTHESISING PROCESS IS CARRIED OUT IF ISYNT IS NON ZERO_____
C----------------------------------------------------------------------

   17 IF(ISYNT .EQ. 1)THEN
            CALL SYNTL(TSTEP,AREA,RAIN,QSYN,QP,LSTEP,
     1      PPT,TMIN,NPTSP,RTIME,RFT,CIA,COEFQ,JSTID,STNOJ,ID,IMTH,
     2      IYR,NC,A,QPACT,QTOT,DL,NP,CN,CHA,CL,YS,LAGCAL,COEFL)
            LSTEP=LSTEP+NC
            ENDIF

C  LISTING OPTION OF HYDROGRAPHS
C---------------------------------------------------------------------------------


        IF(IWRQ .EQ. 1)THEN
            WRITE(6,1007) JSTID,STNOJ,ID,IMTH,IYR
            DO   18 I=1,2000
                 IF((NPTSQ .GE. I) .AND. (LSTEP .GE. I))
     1           WRITE(6,1008)STEPT(I),QIN(I),STEPQ(I),RTIME(I),QSYN(I)
                 IF((NPTSQ .GE. I) .AND. (LSTEP .LT. I))
     1           WRITE(6,1009) STEPT(I),QIN(I),STEPQ(I)
                 IF((NPTSQ .LT. I) .AND. (LSTEP .GE. I))
     1           WRITE(6,1010)RTIME(I),QSYN(I)
   18       CONTINUE
            ENDIF

C      PHASING OPTION TO LINE UP THE INFLOW & SYNTHETIC HYDROGRAPHS ON
C      THE TIME SCALE
C-----------------------------------------------------------------------

        IF(SHIFT .NE. 0.)CALL PHASE(LSTEP,RTIME,SHIFT)

C      PLOTTING OPTION FOR RUNOFF - (INFLOW,OUTFLOW & SYNTHETIC)

C-----------------------------------------------------------------

        IF(IPLTQ .EQ. 1)THEN
            LSTEP=LSTEP-NC


C     READ LABELS FOR THE PLOT

            READ(5,1004)XHEAD,YHEAD

C      SCAN FOR MAX AND MIN FLOWRATES

            DO   19 I=1,IDIM
                 IF(YMAX .LT. STEPQ(I))YMAX=STEPQ(I)
                 IF(YMAX .LT. QIN(I))YMAX=QIN(I)
                 IF(YMAX .LT. QSYN(I))YMAX=QSYN(I)
                 IF(YMIN .GT. STEPQ(I))YMIN=STEPQ(I)
                 IF(YMIN .GT.QIN(I))YMIN=QIN(I)
                 IF(YMIN .GT. QSYN(I))YMIN=QSYN(I)
   19       CONTINUE
            XMIN=STEPT(1)
            XMAX=STEPT(K)
            IF(ISYNT .EQ. 1)THEN
                 DO   20 I=1,IDIM
                      IF(XMIN .GT. RTIME(1))XMIN=RTIME(1)
                      IF(XMAX .LT. (RTIME(I)+(NC-NP)*TSTEP))
     1                XMAX =(RTIME(I)+(NC-NP)*TSTEP)
                      IF(XMAX .LT. STEPT(I)) XMAX=STEPT(I)
   20            CONTINUE
                 ENDIF
C      ---------------------------

C      GRAPH AXES ARE PLOTTED

       ---------------------------
        READ(5,1011) XMIN,XMAX,YMIN,YMAX
 1011 FORMAT (4F10.3)
            NY=10
            NX=10
            XLN=30.
            YLN=15.
            IENTR=1
            CALL VPLOT(XMAX,XMIN,YMAX,YMIN,NX,NY,XHEAD,YHEAD,
     1      IENTR,IPNT,N,X,Y,ICNCT,ISMTH,ICORR,XLN,YLN,80)


C      OUTFLOW HYDROGRAPHS ARE PLOTTED.
C      ---------------------------------

            IENTR=2
            DO   21 I=1,NPTSQ
                 X(I)=STEPT(I)
                 Y(I)=STEPQ(I)
   21       CONTINUE

            N=NPTSQ
            IPNT=7
            ICNCT=0
            ISMTH=1
            ICORR=1
            CALL VPLOT(XMAX,XMIN,YMAX,YMIN,NX,NY,XHEAD,YHEAD,
     1      IENTR,IPNT,N,X,Y,ICNCT,ISMTH,ICORR,XLN,YLN,80)
```

```
C     SYNTHETIC HYDROGRAPH IS PLOTTED
C    -------------------------------

          DO  22 I=1,IDIM
   22     Y(I)=0.
          IF(ISYNT .EQ. 1)THEN
              DO  23 I=1,IDIM
                  IF(RTIME(I) .LE. 0.0)GO TO  24
                  X(I)=RTIME(I)
                  Y(I)=QSYN(I)
   23         CONTINUE

   24     N=I-1
          IPNT=7
          DO  25 I=1,N
              IF (X(I) .LE. 0.0)X(I)=XMIN
   25     CONTINUE
          CALL VPLOT(XMAX,XMIN,YMAX,YMIN,NX,NY,XHEAD,YHEAD,
     1    IENTR,IPNT,N,X,Y,ICNCT,ISMTH,ICORR,XLN,YLN,00)
          ENDIF

C     INFLOW HYDROGRAPH IS PLOTTED
C    ----------------------------

          IF(IRUTE .EQ. 1)THEN
              DO  26 I=1,IDIM
                  IF(STEPT(I) .EQ. 0.0)GO TO  27
                  X(I)=STEPT(I)
                  Y(I)=QIN(I)
   26         CONTINUE
   27         N=I-1
              IPNT=7
              ISMTH=1
              CALL VPLOT(XMAX,XMIN,YMAX,YMIN,NX,NY,XHEAD,YHEAD,
     1        IENTR,IPNT,N,X,Y,ICNCT,ISMTH,ICORR,XLN,YLN,00)
              ISMTH=1

C------------------------------------------------------------------------

C  OPTION TO CALL MODEL EFFICIENCY SUBROUTINE.

C------------------------------------------------------------------------

              ENDIF
          ENDIF
      IF(IFFCY .EQ.1)CALL EFFCY(RTIME,STEPT,QSYN,STEPQ,NPISQ,LSTEP)
      STOP



C
 1000 FORMAT(8F10.0,/,5F10.0,3I2,13X,8I1)
 1001 FORMAT(16F5.3)
 1002 FORMAT(A2,A3,3(F8.3,F6.3,F5.3,F6.0))
 1003 FORMAT(1X,A1,A4,2I2,7(3I2,I4))
 1004 FORMAT(10A4,10A4)
 1005 FORMAT(A2,A4,2I2,7(3I2,I4))
 1006 FORMAT(1X,A1,A4,2I2,7(I6,I4))
 1007 FORMAT(1H1,35X,'HYDROGRAPHS FOR CATHMENT',1X,A2,A4,1X,
     1'(',I2,'/',I2,'/19',I2,')',/35X,51('='),//,10X,'TIME',10X,'INFLOW'
     2,9X,'RECORDED',16X,'TIME',10X,'SYNTHETIC',/,40X,'OUTFLOW',30X,
     3'DISCHARGE',/,9X,'(MIN)',10X,'(L/S)',12X,'(L/S)',17X,'(MIN)',13X,
     4'(L/S)',//)
 1008 FORMAT(9X,F6.0,5X,F10.2,9X,F8.2,16X,F6.0,10X,F8.2)
 1009 FORMAT(9X,F6.0,5X,F10.2,9X,F8.2)
 1010 FORMAT(63X,F6.0,10X,F8.2)
      END
```

```
      SUBROUTINE RQUIL (IDIM,C1,C2,TSTPQ,QOUT,QBASE,STAGE,QTIME,NPTSQ,
     1STEPQ,STEPB,STEPS,STEPT,QIN,K,QPACT)
C
C-----------------------------------------------------------------------
C
C
C      THIS SUBROUTINE CALCULATES THE INFLOW HYDROGRAPH BY MEANS OF
C      BACKROUTING THE INCREMENTAL QUICKFLOW VOLUMES CALCULATED IN
C      SUBROUTINE QSTEP THROUGH THE STORAGE OF THE WEIR.
C      CHANGES IN STORAGE WITH RESPECT TO TIME ARE CALCULATED BY
C      MEANS OF THE DEPTH/STORAGE EQUATIONS, FOR THE PARTICULAR
C      WEIR.
C
C
C
C-----------------------------------------------------------------------
C
       DIMENSION QOUT(1),QBASE(1),STAGE(1),QTIME(1),STEPQ(1),STEPS(1),
     3           STEPB(1),STEPT(1),QIN(1)
       QMAX=0.
       BMAX=0.
       TMAX=0.
       DO 5 I=1,NPTSQ
       IF (QOUT(I) .GT. QMAX)THEN
         QMAX=QOUT(I)
         BMAX=QBASE(I)
         TMAX=QTIME(I)
       ENDIF
 5     CONTINUE

       CALL QSTEP ( IDIM,QOUT,QBASE,STAGE,QTIME,TSTPQ,NPTSQ,
     1             STEPQ,STEPS,STEPB,STEPT,K)

       QPACT=0.
       DO 1 I=1,IDIM
 1     QIN(I)=0.0

       S1=C1*STEPS(1)+C2*STEPS(1)**2.
       NPTSQ=NPTSQ-1
       DO 2 I=1,NPTSQ
           J=I+1
           S2=C1*STEPS(J)+C2*STEPS(J)**2.
           DELTS=S2-S1
           IF(STEPQ(I) .LE. STEPB(I))GO TO 4
           QIN(I)=STEPQ(I)+DELTS
           QIN(I)=QIN(I)-STEPB(I)
           STEPQ(I)=STEPQ(I)-STEPB(I)
           S1=S2
 2     CONTINUE
 4     DO 3 I=1,NPTSQ
           STEPQ(I)=STEPQ(I)/TSTPQ/60.*1000.
           IF(STEPQ(I) .GT. QPACT)THEN
              QPACT=STEPQ(I)
              M=I
           ENDIF
           QIN(I)=QIN(I)/TSTPQ/60.*1000.
 3     CONTINUE
       STEPQ(M)=QMAX
       QIN(M)=QMAX
       STEPT(M)=TMAX
       NPTSQ = NPTSQ+1
       RETURN
       END
```

```
      SUBROUTINE RQUTL (IDIM,C1,C2,TSTPQ,QOUT,QBASE,STAGE,QTIME,NPTSQ,
     1STEPQ,STEPB,STEPS,STEPT,QIN,K,QPACT)
C
C-----------------------------------------------------------------------
C
C
C     THIS SUBROUTINE CALCULATES THE INFLOW HYDROGRAPH BY MEANS OF
C     BACKROUTING THE INCREMENTAL QUICKFLOW VOLUMES CALCULATED IN
C     SUBROUTINE QSTEP THROUGH THE STORAGE OF THE WEIR.
C     CHANGES IN STORAGE WITH RESPECT TO TIME ARE CALCULATED BY
C     MEANS OF THE DEPTH/STORAGE EQUATIONS, FOR THE PARTICULAR
C     WEIR.
C
C
C-----------------------------------------------------------------------
C
      DIMENSION QOUT(1),QBASE(1),STAGE(1),QTIME(1),STEPQ(1),STEPS(1),
     2            STEPB(1),STEPT(1),QIN(1)
      QMAX=0.
      BMAX=0.
      TMAX=0.
      DO 5 I=1,NPTSQ
      IF (QOUT(I) .GT. QMAX)THEN
        QMAX=QOUT(I)
        BMAX=QBASE(I)
        TMAX=QTIME(I)
      ENDIF
5     CONTINUE

      CALL QSTEP ( IDIM,QOUT,QBASE,STAGE,QTIME,TSTPQ,NPTSQ,
     1             STEPQ,STEPS,STEPB,STEPT,K)

      QPACT=0.
      DO 1 I=1,IDIM
1     QIN(I)=0.0

      S1=C1*STEPS(1)+C2*STEPS(1)**2.
      NPTSQ=NPTSQ-1
      DO 2 I=1,NPTSQ
           J=I+1
           S2=C1*STEPS(J)+C2*STEPS(J)**3.
           DELTS=S2-S1
           IF(STEPQ(I) .LE. STEPB(I))GO TO 4
           QIN(I)=STEPQ(I)+DELTS
           QIN(I)=QIN(I)-STEPB(I)
           STEPQ(I)=STEPQ(I)-STEPB(I)
           S1=S2
2     CONTINUE
4     DO 3 I=1,NPTSQ
           STEPQ(I)=STEPQ(I)/TSTPQ/60.*1000.
           IF(STEPQ(I) .GT. QPACT)THEN
              QPACT=STEPQ(I)
              M=I
           ENDIF
           QIN(I)=QIN(I)/TSTPQ/60.*1000.
3     CONTINUE
      STEPQ(M)=QMAX
      QIN(M)=QMAX
      STEPT(M)=THAX
      NPTSQ = NPTSQ+1
      RETURN
      END
```

```
      SUBROUTINE QSTEP(IDIM,QOUT,QBASE,STAGE,QTIME,TSTPQ,NPTSQ,
     1STEPQ,STEPS,STEPB,STEPT,X)
C
C---------------------------------------------------------------------
C
C    THIS SUBROUTINE DIVIDES THE OUTFLOW HYDROGRAPH INTO STRIPS OF
C    OPTIONAL DURATION , AND CALCULATES THE VOLUME OF TOTAL FLOW AND
C    BASE FLOW IN EACH STRIP, TOGETHER WITH THE CORRESPONDING TIME
C    VALUE, THESE VOLUMES MAY THEN BE USED IN SUBROUTINE ROUTL.
C
C---------------------------------------------------------------------
C
C    KEY TO ARRAYS AND VARIABLES.
C-------------------------------
C
C   STEPQ   -   TOTAL VOLUME OF RUNOFF IN THE TIME INTERVAL
C   STEPB   -   VOLUME OF BASE FLOW IN THE TIME INTERVAL
C   STEPS   -   STAGE AT THE END OF THE TIME INTERVAL
C   STEPT   -   TIME AT THE END OF THE TIME INTERVAL
C
C    NOTE
C   ======
C   IF A TIME INTERVAL (TSTPQ) STRADDLES A NUMBER OF DIGITISED
C   POINTS THE VOLUME FOR THE TIME INTERVAL IS CALCULATED BY
C   ADDING THE VOLUMES BETWEEN THE DIGITISED POINTS AND ADDING
C   TO THESE THE VOLUME CALCULATED BETWEEN THE FIRST/LAST DIGITISED
C   POINT IN THE TIME INTERVAL AND THE POSITION OF THE BEGINNING/
C   END OF THE TIME STEP. THE BEGINNING AND END POINTS OF A TIME
C   STEP ARE CALCULATED BY LINEAR INTERPOLATION. IF A TIME
C   INTERVAL IS SMALLER THAN THE TIME BETWEEN TWO DIGITISED POINTS
C   THE VOLUME IS CALCULATED FROM THE LINEARLY INTERPOLATED
C   TIME INTERVAL.
C
C---------------------------------------------------------------------
C
C
C
       DIMENSION QOUT(1),QBASE(1),STAGE(1),QTIME(1),STEPQ(1),STEPS(1),
     1              STEPB(1),STEPT(1)

      DO 1 I=1,IDIM
          STEPQ(I) = 0.
          STEPB(I) = 0.
          STEPS(I) = 0.
          STEPT(I) = 0.
1     CONTINUE

      K = 1
      TDIFF = 0.0
      QDIFF = 0.0
      BDIFF = 0.0
      TEND = TSTPQ+QTIME(1)
      NPTSQ = NPTSQ-1
      STEPS(1) = STAGE(1)
      DO 2 I=1,NPTSQ
          J=I+1
          SS=STAGE(I)
          QS=QOUT(I)
          BS=QBASE(I)
          IF(QTIME(J) .GT. QTIME(I))THEN
              DIFFT=QTIME(J)-QTIME(I)
              DIFFQ=(QOUT(J)+QOUT(I))/2.*DIFFT*60./1000.
              DIFFB=(QBASE(J)+QBASE(I))/2.*DIFFT*60./1000.
              IF(QTIME(J) .LE. TEND)THEN
                  TDIFF=TDIFF+DIFFT
                  QDIFF=QDIFF+DIFFQ
                  BDIFF=BDIFF+DIFFB
              ELSE
                  FRAC=(TSTPQ-TDIFF)/DIFFT
                  FRACT=(TSTPQ-TDIFF)/DIFFT
3                 STEPT(K)=TEND-TSTPQ/2.
                  QE=QS+(QOUT(J)-QS)*FRACT
                  BE=BS+(QBASE(J)-BS)*FRACT
                  SE=SS+(STAGE(J)-SS)*FRACT
                  QDIFF=QDIFF+(QE+QS)/2.*DIFFT*FRAC*60./1000.
                  BDIFF=BDIFF+(BE+BS)/2.*DIFFT*FRAC*60./1000.
                  STEPQ(K)=QDIFF
                  STEPB(K)=BDIFF
                  IF(STEPQ(K) .LE. STEPB(K))GO TO 4
                  K=K+1
                  STEPS(K)=SE
                  DIFFT=QTIME(J)-TEND
                  FRACT=TSTPQ/DIFFT
                  TEND=TEND+TSTPQ
                  FRAC=TSTPQ/DIFFT
                  QS=QE
                  BS=BE
                  SS=SE
                  QDIFF=0.0
                  BDIFF=0.0
                  IF(QTIME(J) .GE. TEND)GO TO 3
                  TDIFF=QTIME(J)-TEND+TSTPQ
                  FRAC=TDIFF/DIFFT
                  QE=QOUT(J)
                  BE=QBASE(J)
                  QDIFF=(QS+QE)/2.*DIFFT*FRAC*60./1000.
                  BDIFF=(BS+BE)/2.*DIFFT*FRAC*60./1000.
              ENDIF
          ENDIF
2     CONTINUE
4     IF(QTIME(J) .LE. TEND)THEN
          STEPT(K)=TEND-TSTPQ+TDIFF/2.
          STEPQ(K)=QDIFF
          STEPB(K)=BDIFF
          K=K+1
          STEPS(K)=STAGE(J)
          ENDIF
      NPTSQ=K-1
      RETURN
      END
```

```
      SUBROUTINE SYNTL (TSTEP,AREA,RAIN,QSYN,QP,
     1NSTEP,PPT,TMIN,NPTSP,RTIME,RFT,CIA,COEFU,ISTID,STNOJ,ID,IMTM,
     2IYR,NC,A,QPACT,QTOT,DL,NP,CN,CNA,CL,YS,LAGCAL,COEFL)
C-----------------------------------------------------------------------
C
C THIS SUBROUTINE CALCULATES RUNOFF VOLUMES AND HENCE PEAK FLOW RATES
C FOR THE INCREMENTAL RAINFALL VALUES CALCULATED IN SUBROUTINE RSTEP.
C THESE INCREMENTAL VALUES ARE THEN SUPERIMPOSED TO OBTAIN THE SYNTHETIC
C HYDROGRAPH FOR THE STORM. THE VALUE OF LAG MAY BE ALTERED TO OBTAIN A
C PEAK EQUAL TO THAT OF THE RECORDED HYDROGRAPH PEAK.
C
C KEY TO ARRAYS AND VARIABLES.
C-------------------------------
C SA      - POTENTIAL MAXIMUM RETENTION FOR CATCHMENT (MM)- THIS VALUE
C           MAY EITHER BE CALCULATED FROM THE RECORDED FLOOD
C           VOLUME AND RAINFALL DATA OR MAY BE INPUTED BY MEANS
C           OF A CURVE NUMBER.
C CNA     - CATCHMENT CURVE NUMBER (ADJUSTED FOR A.M.C)
C QSYN(J)- PEAK RESULTING FROM NC ADJACENT HYDROGRAPHS
C QP(J)   - PEAK FLOW RATE FOR EACH INCREMENTAL HYDROGRAPH
C-----------------------------------------------------------------
C
      DIMENSION  QP(1),QSYN(1),RAIN(1),PPT(1),TMIN(1),RTIME(1),A(1)
      P=0.
      QPRES=0.
      QPREV=0.
      QPMAX=0.
      IDIM=1500
      DIR1=0.
      DIR2=0.
      DIR3=0.
      VALUE1=0.
      VALUE2=0.
      FINIS=0.
      ACCNO=1.
      ALTER=0.
      CHANGE=0.
      DIFF=0.
C
C
C     OPTION TO OPTIMISE LAG IS GIVEN . IF LAG IS TO BE OPTIMISED
C     S IS CALCULATED FROM RAINFALL AND RUNOFF DEPTHS.
C
C-----------------------------------------------------------------
C
      IF (LAGCAL)  2,  1,  2
    1 SA=25400./CNA-254.
      S=25400./CN-254.
      WL=(CL**0.8)*((S+25.4)**0.7)/COEFL/(YS**0.5)
      WRITE(3,1000)WL,CN,S
      GO TO   3
C
C
C     LAG IS TO BE OPTIMISED. LAG IS INITIATED AT 0.6 HOURS
C-----------------------------------------------------------------
C
    2 WL=0.6
C
C
C TSTEP - TIME PERIOD OF INCREMENTAL RAINFALL - THIS VALUE IS
C         CALCULATED AS BEING  DL  X  LAG .  DL DEPENDS
C         ON THE NUMBER OF TIME STEPS IN THE UNIT HYDROGRAPH
C
    3 TSTEP=WL*60.*DL
C
C
C RSTEP IS CALLED TO OBTAIN INCREMENTAL RAINFALL VALUES
C ------------------------------------------------------
C
      CALL RSTEP (PPT,TMIN,TSTEP,NPTSP,RAIN,RTIME,RFT,NSTEP,NC)
C
C POTENTIAL MAXIMUM RETENTION IS CALCULATED
      IF(LAGCAL .EQ. 1)THEN
         AB=(QTOT-(QTOT*CIA)+(2.*RFT*CIA))
         B=((RFT**2.)-(QTOT*RFT))
         SA=(AB-((AB**2.)-(4.*B*(CIA**2.)))**.5)/(2.*(CIA**2.))
         CNA=(SA+254.)/25400.
         CNA=1./CNA
      ENDIF
         WRITE(3,1001)CNA,SA
C
C INITIALIZATION
C
      DO   4 I=1,IDIM
      QSYN(I)=0.
      QP(I)=0.
    4 CONTINUE
      P=0.
      QPMAX=0.
      I=0
      J=0
      QPREV=0.
      QPRES=0.
C
C  NUMBER OF INCREMENTAL HYDROGRAPHS USED MUST BE INCREASED TO
C  ALLOW FOR CALCULATIONS OF FLOW RATE DUE TO THE RECEEDING
C  LIMB OF THE LAST INCREMENTAL HYDROGRAPH.
C
      NSTEP=NSTEP+(NC-NP)
C
C INCREMENTAL PEAKS ARE CALCULATED
C---------------------------------
C
      DO   9 I=1,NSTEP
      J=I+NC-NP
      P=RAIN(I)+P
C
C  VOLUME OF RUNOFF FOR EACH INCREMENTAL HYDROGRAPH IS CALCULATED
C
      QPRES=(ABS(P-CIA*SA))**2./(P+(1.-CIA)*SA)
       IF (P-CIA*SA)   5,   5,   7
    5 QP(J)=0.
      Q=0.
      QPRES=0.
    6 GO TO    8
    7 Q=QPRES-QPREV
C
C  PEAK FLOW RATE OF EACH INCREMENTAL HYDROGRAPH IS CALCULATED
C
```

```
      SUBROUTINE SYNTL (TSTEP,AREA,RAIN,QSYN,QP,
     1NSTEP,PPT,TMIN,NPTSP,RTIME,RFT,CIA,COEFQ,JSTID,STNOI,ID,IMTH,
     2ITR,NC,A,QPACT,QTOT,DL,NP,CN,CNA,CL,YS,LAGCAL,COEFL)
C-----------------------------------------------------------------------
C
C THIS SUBROUTINE CALCULATES RUNOFF VOLUMES AND HENCE PEAK FLOW RATES
C FOR THE INCREMENTAL RAINFALL VALUES CALCULATED IN SUBROUTINE RSTEP.
C THESE INCREMENTAL VALUES ARE THEN SUPERIMPOSED TO OBTAIN THE SYNTHETIC
C HYDROGRAPH FOR THE STORM. THE VALUE OF LAG MAY BE ALTERED TO OBTAIN A
C PEAK EQUAL TO THAT OF THE RECORDED HYDROGRAPH PEAK.
C
C KEY TO ARRAYS AND VARIABLES.
C-----------------------------
C SA      - POTENTIAL MAXIMUM RETENTION FOR CATCHMENT (MM)- THIS VALUE
C           MAY EITHER BE CALCULATED FROM THE RECORDED FLOOD
C           VOLUME AND RAINFALL DATA OR MAY BE INPUTED BY MEANS
C           OF A CURVE NUMBER.
C CNA     = CATCHMENT CURVE NUMBER (ADJUSTED FOR A.M.C)
C QSYN(J)- PEAK RESULTING FROM NC ADJACENT HYDROGRAPHS
C QP(J)   - PEAK FLOW RATE FOR EACH INCREMENTAL HYDROGRAPH
C-----------------------------------------------------------------------
C
      DIMENSION  QP(1),QSYN(1),RAIN(1),PPT(1),TMIN(1),RTIME(1),A(1)
      P=0.
      QPRES=0.
      QPREV=0.
      QPMAX=0.
      IDIM=1500
      DIR1=0.
      DIR2=0.
      DIR3=0.
      VALUE1=0.
      VALUE2=0.
      FINIS=0.
      ACCNO=1.
      ALTER=0.
      CHANGE=0.
      DIFF=0.
C
C
C    OPTION TO OPTIMISE LAG IS GIVEN . IF LAG IS TO BE OPTIMISED
C    S IS CALCULATED FROM RAINFALL AND RUNOFF DEPTHS.
C
C-----------------------------------------------------------------
C
      IF (LAGCAL)  2,  1,  2
    1 SA=25400./CNA-254.
      S=25400./CN-254.
      WL=(CL**0.8)*((S+25.4)**0.7)/COEFL/(YS**0.5)
      WRITE(3,1000)WL,CN,S
      GO TO   3
C
C
C    LAG IS TO BE OPTIMISED. LAG IS INITIATED AT 0.6 HOURS
C-----------------------------------------------------------
C
    2 WL=0.6
C
C
C TSTEP - TIME PERIOD OF INCREMENTAL RAINFALL - THIS VALUE IS
C         CALCULATED AS BEING  DL  X  LAG .  DL DEPENDS
C         ON THE NUMBER OF TIME STEPS IN THE UNIT HYDROGRAPH
C
    3 TSTEP=WL*60.*DL
C
C
C RSTEP IS CALLED TO OBTAIN INCREMENTAL RAINFALL VALUES
C -----------------------------------------------------------
C
      CALL RSTEP (PPT,TMIN,TSTEP,NPTSP,RAIN,RTIME,RFT,NSTEP,NC)
C
C POTENTIAL MAXIMUM RETENTION IS CALCULATED
      IF(LAGCAL .EQ. 1)THEN
         AB=(QTOT-(QTOT*CIA)+(2.*RFT*CIA))
         D=((RFT**2.)-(QTOT*RFT))
         SA=(AB-((AB**2.)-(4.*D*(CIA**2.)))**.5)/(2.*(CIA**2.))
         CNA=(SA+254.)/25400.
         CNA=1./CNA
      ENDIF
         WRITE(3,1081)CNA,SA
C
C INITIALIZATION
C
      DO    4 I=1,IDIM
      QSYN(I)=0.
      QP(I)=0.
    4 CONTINUE
      P=0.
      QPMAX=0.
      I=0
      J=0
      QPREV=0.
      QPRES=0.
C
C  NUMBER OF INCREMENTAL HYDROGRAPHS USED MUST BE INCREASED TO
C  ALLOW FOR CALCULATIONS OF FLOW RATE DUE TO THE RECEEDING
C  LIMB OF THE LAST INCREMENTAL HYDROGRAPH.
C
      NSTEP=NSTEP+(NC-NP)
C
C INCREMENTAL PEAKS ARE CALCULATED
C-------------------------------------
C
      DO    9 I=1,NSTEP
      J=I+NC-NP
      P=RAIN(I)+P
C
C  VOLUME OF RUNOFF FOR EACH INCREMENTAL HYDROGRAPH IS CALCULATED
C
      QPRES=(ABS(P-CIA*SA))**2./(P+(1.-CIA)*SA)
      IF (P-CIA*SA)  5,  5,  7
    5 QP(J)=0.
      D=0.
      QPRES=0.
    6 GO TO    8
    7 D=QPRES-QPREV
C
C  PEAK FLOW RATE OF EACH INCREMENTAL HYDROGRAPH IS CALCULATED
C
```

```
      QP(J)=COEFQ*AREA*Q/(WL+TSTEP/60./2.)
    8 QPREV=QPRES
    9 CONTINUE
C
C THE NECESSARY NUMBER OF INCREMENTAL HYDROGRAPHS ARE SUPERIMPOSED
C DEPENDING UPON NC.
C
      DO  12 I=1,NSTEP
      ISTAR=I
      IEND=I+NC-1
      DO  10 J=ISTAR,IEND
      K=NC+ISTAR-J
      QSYN(I)=QSYN(I)+A(K)*QP(J)
   10 CONTINUE
C
C  ---------------------------------------------------------------
C   MAXIMUM FLOW RATE OF SYNTHETIC HYDROGRAPH FOR THIS PARTICULAR
C   LAG VALUE IS CALCULATED.
C
C
C----------------------------------------------------------------
      IF (QSYN(I)-QPMAX) 12, 12, 11
   11 QPMAX=QSYN(I)
   12 CONTINUE
C
C  ---------------------------------------------------------------
C   IF NO OPTIMISATION IS TO BE DONE, THE SYNTHETIC HYDROGRAPH IS
C   RETURNED TO THE MAIN PROGRAMME FOR PLOTTING. IF OPTIMISATION
C   IS TO BE EXECUTED , LAG IS INCREASED OR DECREASED TO FIND THE
C   CORRECT VALUE.
C
C
C----------------------------------------------------------------
      IF (LAGCAL) 13, 34, 13
   13 IF(FINIS .NE. 1.)THEN
        CHANGE=ABS(QPMAX-QPACT)
      ENDIF
      IF(FINIS .EQ. 1.)THEN
        DIFF=ABS(QPMAX-QPACT)
        IF(DIFF .GT. CHANGE)THEN
          WL=WL-ALTER
          CHANGE=DIFF
          GO TO   3
        ENDIF
      ENDIF
      WRITE (6,1002) WL,ACCNO
       WRITE (6,1003) QPMAX,QPACT
      IF (WL-0.01) 33, 33, 14
   14 IF (FINIS-1.) 15, 31, 15
   15 ACCNO=ACCNO+1.
      IF (ACCNO-50.) 16, 16, 32
   16 IF (QPMAX-QPACT) 17, 31, 19
   17 IF (DIR1-1.) 25, 18, 25
   18 DIR2=1.
      WL=WL-0.01
      GO TO   3
   19 IF (VALUE1-1.) 22, 20, 22
   20 IF (DIR3-1.) 21, 22, 21
   21 VALUE2=1.
      WL=WL+0.01
      GO TO   3
   22 IF(DIR3-1.) 23, 30, 23
   23 IF(DIR2-1.) 24, 30, 24
   24 DIR1=1.
      WL=WL+0.1
      GO TO   3
   25 WRITE(6,1004) WL
      IF (WL-0.11) 26, 26, 27
   26 DIR3=1.
      WRITE (6,1005) WL
      WL=WL-0.01
      WRITE (6,1006) WL
      GO TO   3
   27 VALUE1=1.
      WRITE(6,1007) WL
      IF (VALUE2-1.) 28, 29, 28
   28 WL=WL-0.1
      GO TO   3
   29 FINIS=1.
      WL=WL-0.005
      ALTER=-.005
      GO TO   3
   30 FINIS=1.
      WL=WL+0.005
      ALTER=.005
      GO TO   3
   31 WL=WL*60.
      WRITE (6,1008) WL,QPMAX
      WRITE (6,1009) RFT
      GO TO   34
   32 WRITE (6,1010)
      GO TO   34
   33 WRITE (6,1011)
   34 NSTEP=NSTEP-(NC-NP)
      RETURN
C
 1000 FORMAT(1X,'LAG = ',F7.3,//,'CN =  ',F5.1,'S =   ',F5.1,//)
 1001      FORMAT(1X,'CNA = ',F5.1,'SA = ',F5.1,//)
 1002 FORMAT (1X,T4,'LAG = ',F6.3,'HRS   ',T40,'ACCNO = ',F4.0,/,
     1T4,13('-'),T40,13('-'),/)
 1003 FORMAT (1X,T4,'SYNTHETIC DISCHARGE = ',F8.2,T40,
     1'ACTUAL DISCHARGE = ',F8.2,/,T9,'(L/S)',T44,'(L/S)',/,80('-'),/)
 1004 FORMAT(1X,'1',F10.6)
 1005 FORMAT(1X,'2',F10.6)
 1006 FORMAT(1X,'3',F10.6)
 1007 FORMAT(1X,'4',F10.5)
 1008 FORMAT (1X,T3,'LAG TIME = ',F9.3,' MINS',T32,
     1'MAXIMUM FLOW RATE = ',F10.3,' L/S',/,55('-'),/,65('-'))
 1009 FORMAT (1X,T3,'TOTAL RAINFALL = ',F5.1,1X,'MM',/,32('-'))
 1010 FORMAT (1X,'NO OF ITERATIONS EXCEEDS 50 .. STOP')
 1011 FORMAT (1X,'LAG VALUE IS LESS THAN .6 MINUTES. ERROR SUSPECTED')
      END
```

```
      SUBROUTINE RSTEP(PPT,THIN,TSTEP,NPTS,RAIN,RTIME,RFT,LSTEP,NC)
C-----------------------------------------------------------------------
C
C     THIS SUBROUTINE SUMS THE TOTAL RAINFALL IN SUCCESSIVE PERIODS OF
C     DURATION TSTLP AND STORES THEM IN ARRAY RAIN . THE ARRAY RTIME
C     CONTAINS THE TIME AT THE END OF THE PERIOD CORRESPONDING TO THE
C     RAINFALL IN ARRAY RAIN . THE RAINFALL IN ARRAY RAIN IS TO BE USED
C     AS THE INCREMENTAL RAINFALL INPUT TO THE SUBROUTINE SYNTH .
C
C-----------------------------------------------------------------------
C
C     KEY YO ARRAYS AND VARIABLES
C     ---------------------------
C
C     PPT   - ARRAY OF DIGITIZED RAINFALL READINGS
C     THIN  - TIME ARRAY CORRESPONDING TO PPT
C     RAIN  - ARRAY OF INCREMENTAL RAINFALL (RAIN IN SUCCESSIVE PERIODS
C             OF DURATION TSTEP)
C     RTIME - TIME ARRAY CORRESPONDING TO RAIN
C     TSTEP - INCREMENTAL TIME STEP OVER WHICH THE RAINFALL IS TO BE ADDED
C     RFT   - RAINFALL TOTAL FOR COMPLETE STORM
C     NPTS - NNUMBER OF DIGITIZED POINTS IN ARRAY PPT
C     LSTEP - NUMBER OF ENTIES IN ARRAY RAIN . (IE. THE NUMBER OF IN-
C             CREMENTAL UNIT HYDROGRAPHS THAT HAVE TO BE CONSTRUCTED IN
C             SUBROUTINE SYNTH)
C     KSTEP - STEP COUNTER
C     RDIFF - RAINFALL AMOUNT THAT FELL BETWEEN TWO SUCCESSIVE DIGITIZED
C             POINTS
C     TDIFF - TIME DIFFERENCE CORRESPONDING TO RDIFF
C     POSNE - TIME AT END OF PRESENT TIME STEP
C
      DIMENSION PPT(1),THIN(1),RAIN(1),RTIME(1)

      IDIM=1500

      DO 1 I=1,IDIM
           RAIN(I)=0.
           RTIME(1)=0.
1     CONTINUE

      RDIFF=0.
      P=0.
      QPRES=0.
      QPREV=0.
      QPMAX=0.
      RFT=0.
      I=0
      J=0
      TDIFF=0.
      KSTEP=1
      LSTEP=IFIX((THIN(NPTS)-THIN(1))/TSTEP)+1

      IF(LSTEP .GT. IDIM)THEN
           WRITE(3,2)TSTEP,LSTEP,IDIM
           STOP
      ENDIF
      NPTS=NPTS-1

      DO 3 I=1,NPTS
           J=I+1
           IF(PPT(I) .GE. -50.)THEN
4               IF(PPT(J) .LT. -50.)THEN
                     J=J+1
                     GO TO 4
                ENDIF
                RDIFF=(PPT(J)-PPT(I))/10.
                TDIFF=THIN(J)-THIN(I)
                IF(RDIFF .LT. 0.)RDIFF=0.0
                IF(TDIFF .LT. 0.)WRITE(3,5)
                IF(TDIFF .NE. 0.0)THEN
                     POSNE=FLOAT(KSTEP)*TSTEP+THIN(1)
                     POSNJ=THIN(J)-POSNE
                     RFT=RFT+RDIFF
                     IF(POSNJ .GT. 0.)THEN
                          FRAC=(POSNE-THIN(I))/TDIFF
                     ELSE
                        FRAC=1.
                     ENDIF
6                    RAIN(KSTEP)=RAIN(KSTEP)+FRAC*RDIFF
                     IF(POSNJ .GT. 0.)THEN
                    KSTEP=KSTEP+1
                          POSNE=FLOAT(KSTEP)*TSTEP+THIN(1)
                          POSNJ=THIN(J)-POSNE
                          IF(POSNJ .LT. 0.)THEN
                              FRAC=(TSTEP+POSNJ)/TDIFF
                          ELSE
                               FRAC=TSTEP/TDIFF
                          ENDIF
                          GO TO 6
                     ENDIF
                ENDIF
           ENDIF
3     CONTINUE
      RTIME(1)=THIN(1)+RTIME(1)+TSTEP/2.
      LSTEP = LSTEP+NC
      DO 7 I=2,LSTEP
           RTIME(I)=RTIME(I-1)+TSTEP
7     CONTINUE
      LSTEP = LSTEP-NC
      NPTS=NPTS+1
2     FORMAT(1X,' INCREMENT ARRAY SIZE.FOR THE PRESENT TIME INCREMENT OF
     *',F7.3,'MINUTES,',I7,'STEPS ARE REQUIRED.',/,' PROVISION IS MADE F
     *OR ONLY',I5 )
5     FORMAT(1X,'TIME ARRAY NOT IN CHRONOLOGICAL ORDER')
      RETURN
      END
```

```
      SUBROUTINE RSTEP(PPT,THIN,TSTEP,NPTS,RAIN,RTIME,RFT,LSTEP,NC)
C-----------------------------------------------------------------------
C
C     THIS SUBROUTINE SUMS THE TOTAL RAINFALL IN SUCCESSIVE PERIODS OF
C     DURATION TSTEP AND STORES THEM IN ARRAY RAIN . THE ARRAY RTIME
C     CONTAINS THE TIME AT THE END OF THE PERIOD CORRESPONDING TO THE
C     RAINFALL IN ARRAY RAIN . THE RAINFALL IN ARRAY RAIN IS TO BE USED
C     AS THE INCREMENTAL RAINFALL INPUT TO THE SUBROUTINE SYNTH .
C
C-----------------------------------------------------------------------
C
C     KEY TO ARRAYS AND VARIABLES
C     ---------------------------
C
C     PPT   - ARRAY OF DIGITIZED RAINFALL READINGS
C     THIN  - TIME ARRAY CORRESPONDING TO PPT
C     RAIN  - ARRAY OF INCREMENTAL RAINFALL (RAIN IN SUCCESSIVE PERIODS
C             OF DURATION TSTEP)
C     RTIME - TIME ARRAY CORRESPONDING TO RAIN
C     TSTEP - INCREMENTAL TIME STEP OVER WHICH THE RAINFALL IS TO BE ADDED
C     RFT   - RAINFALL TOTAL FOR COMPLETE STORM
C     NPTS - NNUMBER OF DIGITIZED POINTS IN ARRAY PPT
C     LSTEP - NUMBER OF ENTIES IN ARRAY RAIN . (IE. THE NUMBER OF IN-
C             CREMENTAL UNIT HYDROGRAPHS THAT HAVE TO BE CONSTRUCTED IN
C             SUBROUTINE SYNTH)
C     KSTEP - STEP COUNTER
C     RDIFF - RAINFALL AMOUNT THAT FELL BETWEEN TWO SUCCESSIVE DIGITIZED
C             POINTS
C     TDIFF - TIME DIFFERENCE CORRESPONDING TO RDIFF
C     POSNE - TIME AT END OF PRESENT TIME STEP
C
      DIMENSION PPT(1),THIN(1),RAIN(1),RTIME(1)

      IDIM=1500

      DO 1 I=1,IDIM
           RAIN(I)=0.
           RTIME(I)=0.
1     CONTINUE

      RDIFF=0.
      P=1.
      QPRES=0.
      QPREV=0.
      QPMAX=0.
      RFT=0.
      I=0
      J=0
      TDIFF=0.
      KSTEP=1
      LSTEP=IFIX((THIN(NPTS)-THIN(1))/TSTEP)+1

      IF(LSTEP .GT. IDIM)THEN
           WRITE(3,2)TSTEP,LSTEP,IDIM
           STOP
      ENDIF
      NPTS=NPTS-1

      DO 3 I=1,NPTS
           J=I+1
           IF(PPT(I) .GE. -50.)THEN
4               IF(PPT(J) .LT. -50.)THEN
                     J=J+1
                     GO TO 4
                ENDIF
                RDIFF=(PPT(J)-PPT(I))/10.
                TDIFF=THIN(J)-THIN(I)
                IF(RDIFF .LT. 0.)RDIFF=0.0
                IF(TDIFF .LT. 0.)WRITE(3,5)
                IF(TDIFF .NE. 0.0)THEN
                     POSNE=FLOAT(KSTEP)*TSTEP+THIN(1)
                     POSNJ=THIN(J)-POSNE
                     RFT=RFT+RDIFF
                     IF(POSNJ .GT. 0.)THEN
                          FRAC=(POSNE-THIN(I))/TDIFF
                     ELSE
                          FRAC=1.
                     ENDIF
6                    RAIN(KSTEP)=RAIN(KSTEP)+FRAC*RDIFF
                     IF(POSNJ .GT. 0.)THEN
                    KSTEP=KSTEP+1
                          POSNE=FLOAT(KSTEP)*TSTEP+THIN(1)
                          POSNJ=THIN(J)-POSNE
                          IF(POSNJ .LT. 0.)THEN
                               FRAC=(TSTEP+POSNJ)/TDIFF
                          ELSE
                               FRAC=TSTEP/TDIFF
                          ENDIF
                          GO TO 6
                     ENDIF
                ENDIF
           ENDIF
3     CONTINUE
      RTIME(1)=THIN(1)+RTIME(1)+TSTEP/2.
      LSTEP = LSTEP+NC
      DO 7 I=2,LSTEP
           RTIME(I)=RTIME(I-1)+TSTEP
7     CONTINUE
      LSTEP = LSTEP-NC
      NPTS=NPTS+1
2     FORMAT(1X,' INCREMENT ARRAY SIZE FOR THE PRESENT TIME INCREMENT OF
     *',F7.3,'MINUTES,',I7,'STEPS ARE REQUIRED.',/,' PROVISION IS MADE F
     *OR ONLY',I5 )
5     FORMAT(1X,'TIME ARRAY NOT IN CHRONOLOGICAL ORDER')
      RETURN
      END
```

```
      QP(I)=COEFQ*AREA*Q/(WL+TSTEP/60./2.)
    8 QPREV=QPRES
    9 CONTINUE
C
C THE NECESSARY NUMBER OF INCREMENTAL HYDROGRAPHS ARE SUPERIMPOSED
C DEPENDING UPON NC.
C
      DO  12 I=1,NSTEP
      ISTAR=1
      IEND=I+NC-1
      DO  10 J=ISTAR,IEND
      K=NC+ISTAR-J
      QSYN(I)=QSYN(I)+A(K)*QP(J)
   10 CONTINUE
C
C ---------------------------------------------------------------------
C  MAXIMUM FLOW RATE OF SYNTHETIC HYDROGRAPH FOR THIS PARTICULAR
C  LAG VALUE IS CALCULATED.
C
C
C----------------------------------------------------------------------
      IF (QSYN(I)-QPMAX) 12, 12, 11
   11 QPMAX=QSYN(I)
   12 CONTINUE
C
C ---------------------------------------------------------------------
C  IF NO OPTIMISATION IS TO BE DONE, THE SYNTHETIC HYDROGRAPH IS
C  RETURNED TO THE MAIN PROGRAMME FOR PLOTTING. IF OPTIMISATION
C  IS TO BE EXECUTED , LAG IS INCREASED OR DECREASED TO FIND THE
C  CORRECT VALUE.
C
C
C----------------------------------------------------------------------
      IF (LAGCAL) 13, 34, 13
   13 IF(FINIS .NE. 1.)THEN
        CHANGE=ABS(QPMAX-QPACT)
      ENDIF
      IF(FINIS .EQ. 1.)THEN
        DIFF=ABS(QPMAX-QPACT)
        IF(DIFF .GT. CHANGE)THEN
          WL=WL-ALTER
          CHANGE=DIFF
          GO TO   3
        ENDIF
      ENDIF
      WRITE (6,1002) WL,ACCNO
       WRITE (6,1003) QPMAX,QPACT
      IF (WL-0.01) 33, 33, 14
   14 IF (FINIS-1.) 15, 31, 15
   15 ACCNO=ACCNO+1.
      IF (ACCNO-50.) 16, 16, 32
   16 IF (QPMAX-QPACT) 17, 31, 19
   17 IF (DIR1-1.) 25, 18, 25
   18 DIR2=1.
      WL=WL-0.01
      GO TO   3
   19 IF (VALUE1-1.) 22, 20, 22
   20 IF (DIR3-1.) 21, 22, 21
   21 VALUE2=1.
      WL=WL+0.01
      GO TO   3
   22 IF(DIR3-1.) 23, 30, 23
   23 IF(DIR2-1.) 24, 30, 24
   24 DIR1=1.
      WL=WL+0.1
      GO TO   3
   25 WRITE(6,1004) WL
      IF (WL-0.11) 26, 26, 27
   26 DIR3=1.
      WRITE (5,1005) WL
      WL=WL-0.01
      WRITE (6,1006) WL
      GO TO   3
   27 VALUE1=1.
      WRITE(6,1007) WL
      IF (VALUE2-1.) 28, 29, 28
   28 WL=WL-0.1
      GO TO   3
   29 FINIS=1.
      WL=WL-0.005
      ALTER=-.005
      GO TO   3
   30 FINIS=1.
      WL=WL+0.005
      ALTER=.005
      GO TO   3
   31 WL=WL*60.
      WRITE (6,1008) WL,QPMAX
      WRITE (6,1009) RFT
      GO TO  34
   32 WRITE (6,1010)
      GO TO  34
   33 WRITE (6,1011)
   34 NSTEP=NSTEP-(NC-NP)
      RETURN
C
 1000 FORMAT(1X,'LAG = ',F7.3,//,'CN =  ',F5.1,'S =  ',F5.1,//)
 1001      FORMAT(1X,'CNA = ',F5.1,'SA = ',F5.1,//)
 1002 FORMAT (1X,T4,'LAG = ',F6.3,'HRS  ',T40,'ACCNO = ',F4.0,/,
     1T4,12('-'),T40,13('-'),/)
 1003 FORMAT (1X,T4,'SYNTHETIC DISCHARGE = ',F8.2,T40,
     1'ACTUAL DISCHARGE = ',F8.2,/,T9,'(L/S)',T44,'(L/S)',/,80('-'),/)
 1004 FORMAT(1X,'1',F10.6)
 1005 FORMAT(1X,'2',F10.6)
 1006 FORMAT(1X,'3',F10.6)
 1007 FORMAT(1X,'4',F10.5)
 1008 FORMAT (1X,T3,'LAG TIME = ',F9.3,' MINS',T32,
     1'MAXIMUM FLOW RATE = ',F10.3,' L/S',/,65('-'),/,65('-'))
 1009 FORMAT (1X,T3,'TOTAL RAINFALL = ',F5.1,1X,'MM',/,32('='))
 1010 FORMAT (1X,'NO OF ITERATIONS EXCEEDS 50 .. STOP')
 1011 FORMAT (1X,'LAG VALUE IS LESS THAN .6 MINUTES. ERROR SUSPECTED')
      END
```

```
      SUBROUTINE EFFCY (RTIME,STEPT,QSYN,STEPQ,NPTSQ,LSTEP)
C
C-----------------------------------------------------------------------
C
C  SUBROUTINE TO CALCULATE THE MODELLING EFFICIENCY OF THE SYNTHETIC
C  HYDROGRAPH.  THE COEFFICIENT OF EFFICIENCY IS USED AS AN
C  INDICATION OF EFFICIENCY.
C
C-----------------------------------------------------------------------
      DIMENSION  STEPT(1),STEPQ(1),QSYN(1),RTIME(1),CRTIME(1500),
     P            CSTEPT(1500),CSTEPQ(1500),CQSYN(1500)

      PERC =0.
      NNPTEP=0.
      DO 1 K=1,1500
         CRTIME(K)=0.
         CSTEPT(K)=0.
         CQSYN(K)=0.
         CSTEPQ(K)=0.
1     CONTINUE
      K=1
C
C
C-----------------------------------------------------------------------
C
C   VALUES OF TIME AND FLOW RATE ON THE SYNTHETIC HYDROGRAPH ARE
C   INTERPOLATED TO CORRESPOND TO TIMES ON THE RECORDED HYDROGRAPH
C
C-----------------------------------------------------------------------
      DO 2 I=1,NPTSQ
       DO 3 J=1,LSTEP
       IF((STEPT(I) .LT. RTIME(J)) .AND. (J .EQ. 1))THEN
        CRTIME(K)=STEPT(I)
        CSTEPT(K)=STEPT(I)
        CQSYN(K)=0.
        CSTEPQ(K)=STEPQ(I)
        K=K+1
        GO TO 2
       ENDIF
         IF(STEPT(I) .LT. RTIME(J))THEN
              PERC =(RTIME(J)-STEPT(I))/(RTIME(J)-RTIME(J-1))
              CRTIME(K)=RTIME(J)-(PERC*(RTIME(J)-RTIME(J-1)))
              CSTEPT(K)=STEPT(I)
              CSTEPQ(K)=STEPQ(I)
              CQSYN(K)=QSYN(J)-(PERC*(QSYN(J)-QSYN(J-1)))
              K=K+1
              GO TO 2
              ELSE
              IF(STEPT(I) .EQ. RTIME(J))THEN
                CRTIME(K)=RTIME(J)
                CSTEPT(K)=STEPT(I)
                CQSYN(K)=QSYN(J)
                CSTEPQ(K)=STEPQ(I)
                K=K+1
                GO TO 2
              ENDIF
         ENDIF
3       CONTINUE
        CRTIME(K)=STEPT(I)
        CSTEPT(K)=STEPT(I)
        CQSYN(K)=0.
        CSTEPQ(K)=STEPQ(I)
        K=K+1
2     CONTINUE
      NNPTSP=K
      ERROR1=0.
      ERROR2=0.
C
C
C-----------------------------------------------------------------------
C
C  CALCULATING THE RESIDUAL VARIATION.
C
C-----------------------------------------------------------------------
      DO 4 L=1,NNPTSP
      ERROR1=ERROR1+(CSTEPQ(L)-CQSYN(L))**2.0
4     CONTINUE
      WRITE(6,5)ERROR1
C
C
C-----------------------------------------------------------------------
C
C  CALCULATING THE INITIAL VARIATION.
C
C-----------------------------------------------------------------------
C
      SSTEPQ=0.

      DO 6 L=1,NNPTSP
        SSTEPQ=CSTEPQ(L)+SSTEPQ
6     CONTINUE
      DO 7 M=1,NNPTSP
        ERROR2=(CSTEPQ(M)-(SSTEPQ)/NNPTSP)**2.0+ERROR2
7     CONTINUE
      WRITE(6,8)ERROR2
C
C
C-----------------------------------------------------------------------
C
C  CALCULATING THE MODELLING EFFICIENCY.
C
C
C-----------------------------------------------------------------------
C
C
C
      RE = 100. *((ERROR2-ERROR1)/(ERROR2))
      WRITE (6,9) RE
5     FORMAT (1X,'RESIDUAL VARIATION = ',F17.3,/,40('-'),/)
8     FORMAT (1X,'INITIAL VARIATION = ',F17.3,/,40('-'),/)
9     FORMAT (1X, 'MODELLING EFFICIENCY = ',F12.3,' %',/,50('-'),/,
     950('-'),/)
      RETURN
      END
```

```
      SUBROUTINE EFFCY (RTIME,STEPT,QSYN,STEPQ,NPTSQ,LSTEP)
C
C-------------------------------------------------------------------
C
C   SUBROUTINE TO CALCULATE THE MODELLING EFFICIENCY OF THE SYNTHETIC
C   HYDROGRAPH.  THE COEFFICIENT OF EFFICIENCY IS USED AS AN
C   INDICATION OF EFFICIENCY.
C
C-------------------------------------------------------------------
      DIMENSION  STEPT(1),STEPQ(1),QSYN(1),RTIME(1),CRTIME(1500),
     P         CSTEPT(1500),CSTEPQ(1500),CQSYN(1500)

      PERC =0.
      NNPTSP=0.
      DO 1 K=1,1500
         CRTIME(K)=0.
         CSTEPT(K)=0.
         CQSYN(K)=0.
         CSTEPQ(K)=0.
1     CONTINUE
      K=1
C
C
C-------------------------------------------------------------------
C   VALUES OF TIME AND FLOW RATE ON THE SYNTHETIC HYDROGRAPH ARE
C   INTERPOLATED TO CORRESPOND TO TIMES ON THE RECORDED HYDROGRAPH
C
C-------------------------------------------------------------------
      DO 2 I=1,NPTSQ
        DO 3 J=1,LSTEP
       IF((STEPT(I) .LT. RTIME(J)) .AND. (J .EQ. 1))THEN
         CRTIME(K)=STEPT(I)
         CSTEPT(K)=STEPT(I)
         CQSYN(K)=0.
         CSTEPQ(K)=STEPQ(I)
         K=K+1
         GO TO 2
        ENDIF
          IF(STEPT(I) .LT. RTIME(J))THEN
               PERC =(RTIME(J)-STEPT(I))/(RTIME(J)-RTIME(J-1))
               CRTIME(K)=RTIME(J)-(PERC*(RTIME(J)-RTIME(J-1)))
               CSTEPT(K)=STEPT(I)
               CSTEPQ(K)=STEPQ(I)
               CQSYN(K)=QSYN(J)-(PERC*(QSYN(J)-QSYN(J-1)))
               K=K+1
               GO TO 2
               ELSE
               IF(STEPT(I) .EQ. RTIME(J))THEN
                 CRTIME(K)=RTIME(J)
                 CSTEPT(K)=STEPT(I)
                 CQSYN(K)=QSYN(J)
                 CSTEPQ(K)=STEPQ(I)
                 K=K+1
                 GO TO 2
               ENDIF
          ENDIF
3       CONTINUE
        CRTIME(K)=STEPT(I)
        CSTEPT(K)=STEPT(I)
        CQSYN(K)=0.
        CSTEPQ(K)=STEPQ(I)
        K=K+1
2     CONTINUE
      NNPTSP=K
      ERROR1=0.
      ERROR2=0.
C
C
C-------------------------------------------------------------------
C
C   CALCULATING THE RESIDUAL VARIATION.
C
C-------------------------------------------------------------------
      DO 4 L=1,NNPTSP
      ERROR1=ERROR1+(CSTEPQ(L)-CQSYN(L))**2.0
4     CONTINUE
      WRITE(6,5)ERROR1
C
C
C-------------------------------------------------------------------
C
C   CALCULATING THE INITIAL VARIATION.
C
C-------------------------------------------------------------------
C
      SSTEPQ=0.

      DO 6 L=1,NNPTSP
        SSTEPQ=CSTEPQ(L)+SSTEPQ
6     CONTINUE
      DO 7 M=1,NNPTSP
        ERROR2=(CSTEPQ(M)-(SSTEPQ)/NNPTSP)**2.0+ERROR2
7     CONTINUE
      WRITE(6,8)ERROR2
C
C
C-------------------------------------------------------------------
C
C   CALCULATING THE MODELLING EFFICIENCY.
C
C-------------------------------------------------------------------
C
C
C
      RE = 100.*((ERROR2-ERROR1)/(ERROR2))
      WRITE (6,9) RE
5     FORMAT (1X,'RESIDUAL VARIATION = ',F17.3,/,40('-'),/)
8     FORMAT (1X,'INITIAL VARIATION = ',F17.3,/,40('-'),/)
9     FORMAT (1X,'MODELLING EFFICIENCY = ',F12.3,' %',/,50('*'),/,
     &50('*'),/)
      RETURN
      END
```

```
      SUBROUTINE PHASE(NSTEP,RTIME,SHIFT)
      DIMENSION RTIME(1)
      NSTEP = NSTEP+15
      DO 100I=1,NSTEP
      RTIME(I)=RTIME(I)+SHIFT
100   CONTINUE
      NSTEP = NSTEP-15
      WRITE (3,1000) SHIFT
1000  FORMAT(1X,'SYNTHETIC HYDROGRAPH WAS SHIFTED BY',F6.1,'MINUTES')
      RETURN
      END
```

NOTE
****

SUBROUTINE VPLOT IS A STANDARD PLOTTING ROUTINE AVAILABLE AT THE UNIVERSITY OF NATAL COMPUTER CENTRE