HYDROLOGICAL MODELS FOR APPLICATION TO SMALL RURAL CATCHMENTS IN SOUTHERN AFRICA : REFINEMENTS AND DEVELOPMENT

by

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PREFACE

When this Water Research Commission funded project on a "Hydrological Investigation of Rural Catchments in Natal with Specific Reference to Flood Events" commenced in the Department of Agricultural Engineering at the University of Natal in Pietermaritzburg in 1979, neither the project's staff nor its Steering Committee anticipated that the hydrological focus of the early 1980's was, in fact, going to be on drought. By the same token that water resources managers adapted to changed circumstances, so the Steering Committee of this project was also supportive of changes in emphasis and encouraged new directions as the situation or the experience gained in the course of this project demanded it.

While constantly focussing on the major areas of the proposed research, namely the further development of the SCS hydrograph technique for Southern Africa, the hydrological classification of Southern Africa's soils and the development of new hydrological models, the course of time saw, for example, soil/nutrient loss and soil moisture deficit subprojects deferred to subsequent projects and costly annual land use surveys given a reduced priority. On the other hand, the Steering Committee requested a depth-duration-frequency study of medium to long duration rainfall originally undertaken for Natal (in a previous project) to be extended to the entire country, furthermore supported Professor J.K. Mitchell's input into distributed modelling and initial abstraction research while he was in the Department on sabbatical leave from the University of Illinois and, spurred on by the drought, encouraged the development of the ACRU model from a monthly to a more detailed multi-purpose and multi-soil-layer daily hydrological and agricultural model with application far wider than had originally been the intention.

A project of this duration and scope can only be completed

with the collaboration of many institutions and individuals, whose inputs I should hereby like to acknowledge gratefully, namely,

- the Water Research Commission for funding this project,
- the Steering Committee for their support of this project,
- various academic and administrative departments of the University of Natal in Pietermaritzburg, particularly the Computer Centre,
- the staff who over the years collected and processed field data, especially Messrs. J.J. Pretorius, J.S. Mbatha, V. Freestone and Mesdames E. Ortmann, K. Wiercx and R. Richardson,
- the members of the Department of Agricultural Engineering who helped prepare this document, namely Miss W.J.George as editorial assistant and Mesdames K.M. Temple, J. Whyte, J. Moolman and B. Gaydon,
- Mr M.C. Dent, who managed the computing system and who supervised the project for seven months in 1980 while I was undertaking hydrological research on this project in the U.S.A.,
- Mr W. Reynolds and staff of the Agrometeorology Section of the Department of Agriculture, Cedara for meteorological data, and
- the colleagues, named elsewhere, who contributed to various chapters of this report and to the computer programming.

R.E. Schulze

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HYDROLOGICAL MODELS FOR APPLICATION TO SMALL RURAL CATCHMENTS IN SOUTHERN AFRICA : REFINEMENTS AND DEVELOPMENT

R.E. Schulze

EXECUTIVE SUMMARY

BACKGROUND

In June, 1979 a five year research project entitled "Hydrological Investigation of Rural Catchments in Natal with Specific Reference to Flood Events" commenced in the Department of Agricultural Engineering at the University of Natal in Pietermaritzburg, through funding from the Water Research Commission. The findings contained in this report are the culmination of the major research thrusts of this project. From the aims and motivations which were set out in the original research proposal and through the guidance and decisions of this project's Steering Committee, focus was placed on three areas of research. These were

(i) the further development of the SCS curve number method of determining flood hydrographs, particularly for application of this design technique in Southern Africa,

(ii) a classification of Southern Africa's soils into units of similar hydrological response for use in hydrological models developed here or adapted for use locally, and

(iii) the development and testing of other hydrological models for eventual general application to small catchments in Southern Africa.

These three areas of research therefore also form the three sections into which this report has been divided. The three sections consist of 16 chapters and an appendix. The first eight chapters have been written as separate units and the ensuing eight chapters all concern the development of a new multi-purpose model, namely the ACRU model. The major research aims and research findings are highlighted in the chapter summaries which follow.

SECTION A : REFINEMENTS TO THE SCS MODEL FOR IMPROVED PERFORMANCE

Chapter 1

The standard SCS stormflow equation has been derived as

$$Q = \frac{(P-I_a)^2}{(P-I_a) + S} \qquad \text{for } P > I_a$$

in which

Q = stormflow (mm),

P = rainfall (mm),

I_a = initial abstractions before stormflow begins,

= cS (with 'c' a coefficient), and

S = potential maximum retention of the soil, i.e. an index of maximum soil moisture deficit related to soil properties, land use and moisture status.

The SCS equation for peak discharge rate, q_p ($m^3.s^{-1}$) is given by

$$q_p = \frac{0,2083\ AQ}{D/2 + L}$$

where

A = catchment area (km^2),

D = effective storm duration (h), and

L = catchment lag, i.e. response time (h).

Chapter 2

Following the publication by Schulze and Arnold in 1979 of a manual on the SCS method for use in Southern Africa, this now internationally recognised technique has also become a standard method for small catchments' hydrological design in Southern Africa, primarily because the method is simple, uses daily rainfall input and because graphical solutions are possible.

Despite its simplicity the SCS model has been found to yield generally acceptable results. It was, however, hypothesized that the method's predictive performance of stormflow and peak discharge rates would be improved markedly if the estimates of components S, I_a, L and D could be refined. This was a major task of the project and was approached with a research philosophy revolving around:

(i) keeping the basic SCS equations intact (to maintain the user's confidence in the method),

(ii) making use only of simple, readily obtainable climatic, soils, topographic and land use information (for widespread potential application of the model in its refined state),

(iii) application of realistic, proven soil moisture budgeting techniques and

(iv) aiming at improving model performance for a wide range of environmental conditions. Hence hydrological data from humid to arid regions of Southern Africa and the U.S.A. were used for model testing.

Chapter 3

The variable 'S' was conceptualized as a soil moisture deficit. S was estimated by daily moisture budgeting techniques using a two-horizon soil profile, with simple above and below ground vegetation factors incorporated to model evapotranspiration. Results from 20 catchments in seven hydrologically contrasting locations of the U.S.A. showed marked improvements in stormflow simulations when goodness of fit statistics were compared with those using the conventional SCS method of estimating S. It was further established that in more humid areas the antecedent period to be considered in stormflow simulations should be longer (30 days) than in more arid areas (5-10 days). This research was undertaken while on sabbatical leave in the U.S.A.

Chapter 4

Conventionally initial abstractions of rain falling on the catchment before stormflow begins, have been expressed as

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

Initial research on data from W.R.C. catchments in Natal showed that the coefficient 0,2 was too high generally (0,05 was recommended) and that it varied with the catchment's antecedent moisture status. The hypothesis that the coefficient was influenced further by physiographic factors (e.g. the catchment's area, drainage density, slope or stream order) as well as by climatic factors (e.g. antecedent moisture and rainfall amount, intensity or duration) was substantiated and multiple regression equations were developed for estimating the coefficient of I_a, which improved stormflow estimates significantly.

Chapter 5

In the SCS peak discharge rate equation, a catchment's response or lag time, L, remains a constant, estimated only from invariant physiographic factors (hydraulic length, retardance and slope). Marked improvements in lag time and consequently peak discharge estimates were achieved for both single and incremental hydrographs when rainfall and moisture status characteristics were used in predictive equations. A new, generally applicable lag equation for use on unguaged catchments was proposed.

Chapter 6

Since the SCS model uses only daily rainfall input, but the distribution of rainfall intensities is of primary importance for hydrological design on small catchments, regional synthetic rainfall distributions are used in the SCS peak discharge method. To date, the two rainfall distributions developed for the U.S.A. have been used locally. Research on data from a W.R.C. project on digitized rainfall data illustrated that peak flows in Southern Africa could be underestimated by up to 50% when distributions from the U.S.A. were applied. Four new synthetic rainfall distributions have therefore been proposed for use in Southern Africa and these are considered to yield more realistic design peaks in Southern Africa than has hitherto been the case.

SECTION B : HYDROLOGICAL CHARACTERISTICS OF SOILS IN SOUTHERN AFRICA

Chapters 7 and 8

Soil is a prime regulator of a catchment's runoff response, for it is the soil which absorbs, retains, redistributes and releases rain falling on it. Southern Africa's soils have been classified pedologically into 41 soil forms, which in turn have been divided into 501 recognisable soil series. Based primarily on physical properties of the various horizons making up soil profiles, each of the 501 soil series was classified for hydrological modelling purposes into runoff potential groups, into interflow potential classes, soil textural classes and (by assigning profile clay distribution models to each series) into water retention groups for wilting point, field capacity and porosity of the top- and sub-soils.

SECTION C : DEVELOPMENT OF THE ACRU MODEL

Chapter 9

The ACRU model for application to small catchments, using readily available daily climatic data, is being developed specifically for Southern Africa as a conceptual physical and multi-purpose model. The basis of the ACRU model revolves around multi-soil-layer moisture budgeting, which lays the foundation for the model's versatility in being able to simulate

(i) runoff (storm- and baseflow),

(ii) supplementary irrigation requirements, as well as

(iii) seasonal crop yields (for selected crops).

The ACRU model has been structured such that the soil moisture and runoff regimes are highly sensitive to land use changes.

Chapters 10 to 14

The five chapters which follow describe the input information which is used in the ACRU model, explaining why the input is required and what the computational procedures or options are in applying the model. The descriptions pertain to locational input requirements, rainfall data specifications, the estimation of potential evaporation by various methods (all Chapter 10), soils as well as vegetation/land-use information (Chapter 11), runoff simulation (Chapter 12), supplementary irrigation requirements (Chapter 13) and inputs required for the estimation of maize or sugarcane yields (Chapter 14).

Chapter 15

The ACRU model has a number of options by which simulations may be presented or assessed. These output options include summaries at daily or monthly level of data on the status of moisture budget components, statistical packages in regard to design values of simulated runoff and irrigation requirements, summaries and frequency analyses of crop yields, plotting routines to compare observed and estimated runoff and a statistical analysis of the model's performance.

Chapter 16

The performance of the ACRU model was tested on 1977-1983 daily data from W.R.C. catchments U2M18 (Cedara), V1M28 (DeHoek), W1M16 and W1M17 (Zululand). Monthly runoff totals were modelled successfully on initial runs i.e. without calibration, yielding r^2 values ranging from 0,984 to 0,972 and values of the coefficient of efficiency, E, ranging from 0,922 to 0,975 on grassland catchments. On the steep, forested catchment U2M18, monthly simulations were less successful, with r^2 = 0,693 and E = 0,509. The model's performance on the daily level varied, but suggestions are made which are expected to improve daily simulation to an acceptable level.

RECOMMENDATIONS FOR FUTURE RESEARCH

A number of recommendations for future research emanate from the findings of this report. These may be divided into two broad headings.

(a) Design Stormflow and Peak Discharge Rates for Small Catchments in Southern Africa

The SCS has become an accepted method recommended for use in Southern Africa by, for example, the National Transport Commission. In this report refinements to the model for more generalized use in Southern Africa have been proposed in regard to curve number adjustment for antecedent moisture conditions, the estimation of the coefficient of initial abstraction, an improved lag time equation and new storm rainfall distribution curves. These refinements need some further testing on data which have only now become available, before they can be incorporated into a revised SCS manual for Southern Africa, which, it is suggested, should be at two levels, namely, a more detailed version for the professional engineer and a simpler version for field use.

Furthermore, it is recommended that research be undertaken to determine design runoff from small catchments by considering jointly the probabilities of rainfall and antecedent moisture conditions. Conceptually such an approach is sounder than the one assumed at present, namely that a design runoff of a given recurrence interval is produced by a design rainfall of the same recurrence interval, with other variables such as antecedent moisture introduced as "average" values. This proposed approach would have to be tested and verified on W.R.C. as well as other catchment data and if successful, could be applied to data from over 2000 Southern African rainfall stations for the production of a user manual on design runoff from small catchments.

(b) Further Development of the ACRU Model

The ACRU model as presented in this report is only a first version of the model. As a first step to further refinement the model needs to be tested on catchments with diverse environmental conditions (for example, the Ecca, Cathedral Peak or Southern Cape catchments). There is, to date, also no dynamically structured user model for Southern Africa which assesses effects of afforestation on runoff, and this presents a major challenge to further model refinement. Examination of the model's performance on W.R.C. research catchments also indicates that, in some way or other, storm rainfall distribution will have to be incorporated into the model.

By virtue of its structure the ACRU model lends itself to being a 'carrier' for sediment and water quality models - a further field which requires development. Effects of water utilization and the attendant influences on water resources by crops other than maize and sugarcane need to be examined. Such research would have to include refinements to the soil moisture redistribution processes by testing model performance against available lysimeter data.

Furthermore, having been tested on catchments with soils which respond diversely to the runoff process, it has become clearly evident that lumped hydrological models, in which catchment physical and response characteristics are averaged, will not give us all the answers we require when the effects of land use on water resources are to be assessed. It is seen as imperative that hydrological researchers in this country adapt models (such as the ACRU model) into distributed models or alternatively develop new ones, specific to the uniqueness of Southern African soils and land use practices.

It is therefore recommended that the above proposals be researched in a further project in order to render this user-orientated model more versatile than it is at present and for the model to be used with greater confidence for a variety of decisions in the field of water resources management in Southern Africa.

SECTION A

REFINEMENTS TO THE SCS MODEL

FOR IMPROVED PERFORMANCE

CHAPTER 1

THE SCS STORMFLOW AND PEAK DISCHARGE MODELS

INTRODUCTION

In the early 1950s the Soil Conservation Service (SCS) of the United States Department of Agriculture (USDA) developed a procedure for estimating stormflow[1)] volumes from storm rainfall on small agricultural catchments (< 8 km^2). This procedure, namely the SCS Curve Number Method[2)], was designed to use, as input, total daily rainfall (thereby largely ignoring rainfall intensity) in the estimation of peak discharge rates.

The algebraic and hydrologic relationships between storm rainfall, catchment characteristics and the storm hydrograph response are detailed in the so-called NEH-4, i.e. the SCS National Engineering Handbook Section 4 - Hydrology (USDA-SCS, 1972) and in the SCS manual for use in Southern Africa (Schulze

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1) The term "stormflow" is used in Chapters 1 - 6 of this report in preference to "runoff" because runoff carries the connotation of overland flow rather than the combination of flow processes that occur in a catchment, when it responds to a storm event.

2) In this report the expressions "equation", "procedure" and "model" are used to denote the SCS "method" when used in that context.

and Arnold, 1979).

This first chapter introduces the SCS stormflow and peak discharge models by deriving the SCS equations and explaining briefly the concepts upon which this technique was developed. The aim is to provide some background to the standard SCS model and the research which has been conducted in the past five years on four major components of the model in order to improve the model's performance in Southern Africa and elsewhere.

THE SCS STORMFLOW MODEL

Stormflow volume is computed on the basis that the actual amount of stormflow occurring in relation to the potential stormflow depends on the infiltration which can still occur (after stormflow has commenced) relative to the soil's moisture deficit. Thus, according to the model's original developers,

$$\frac{Q}{P_e} = \frac{F}{S} \qquad \text{Eq. 1}$$

where

Q = accumulated stormflow (mm),

P_e = accumulated effective rainfall i.e. potential stormflow (mm),

F = accumulated infiltration from the time at which stormflow commences (mm) and

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

an index of maximum soil moisture deficit.

Since

$$P_e = P - I_a \qquad \text{Eq. 2}$$

and

$$F = P_e - Q \qquad \text{Eq. 3}$$

where

P = accumulated storm rainfall (mm), and

I_a = initial abstractions (mm) before stormflow begins, consisting mainly of interception, infiltration and surface storage,

Equation 1 can.be written

$$Q = \frac{(P - I_a)^2}{(P - I_a) + S} \qquad \text{for } P \;\; I_a \qquad \text{Eq. 4}$$

In order to eliminate the necessity of estimating both I_a and S, the SCS used limited data from small experimental catchments to express I_a in terms of S by the empirical relationship

$$I_a = 0{,}2S \qquad \text{Eq. 5}$$

thus simplifying Equation 4 to the commonly used

$$Q = \frac{(P - 0{,}2S)^2}{P + 0{,}8S} \qquad \text{Eq. 6}$$

Equation 4 has a conceptual basis since, as the soil moisture deficit decreases, so the stormflow approaches the effective rainfall amount. The potential maximum retention, S, is related to soil surface and profile properties, vegetative cover/ management practices and antecedent moisture characteristics, and is transformed into an index of catchment response to rainfall, or curve number, CN, ranging from 0 to 100 by means of the equation (when metric units are used)

$$CN = \frac{25400}{S + 254} \qquad \text{Eq. 7}$$

Values of CN for various hydrological soil-cover complexes are listed in tables (for example, by Schulze and Arnold, 1979).

Curve Numbers for "average" soil moisture status, designated CN_{II}, are assigned to a catchment. These "average" curve numbers are increased if soil moisture status of the catchment is wet (CN_{III}) or reduced if it is dry (CN_{I}), then transformed to a value of S (by applying Equation 7) and used together with a rainfall amount to estimate stormflow (Equation 4 or 6).

THE SCS PEAK DISCHARGE MODEL

The SCS calculation of peak discharge rate is based on a standard unit hydrograph, which is considered to be an average characteristic of small catchments and which is invariable, given a certain pattern of rainfall. The peak discharge of the hydrograph is proportional to the runoff volume. It is therefore possible to calculate the peak discharge from any runoff volume.

The SCS model uses a dimensionless unit hydrograph developed from a large number of natural unit hydrographs. This standard unit hydrograph, which has 37,5% of the total volume under the rising limb, can be approximated by a triangle to give a triangular unit hydrograph, provided the same proportion of the total volume is under the rising limb.

The triangular unit hydrograph is a practical representation of stormflow with only one rise, one peak and one recession. It has been very useful in the design of soil and water conservation measures and discharge rate estimations for spillway and channel capacities. Its geometric shape which can easily be described mathematically, is shown in Figure 1.1.

The proportion of volume under the rising limb to the total volume may be expressed as a ratio of the time to peak (T_p) to the time of the base of the triangular unit hydrograph (T_b) since both triangles have a common height, q_p (Figure 1.1). Therefore,

$$\frac{T_p}{T_b} = 0,375 \qquad \text{Eq. 8}$$

The total volume of the triangular unit hydrograph may be expressed as

$$Q = 1/2\ q_p(T_p+T_r) \qquad \text{Eq. 9}$$

where

Q = stormflow volume (mm),

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

T_p = time to peak (h), and

T_r = time of recession (h).

Solving Equation 9 for q_p yields

$$q_p = \frac{2Q}{T_p + T_r}$$

It may be seen from Figure 1.1 that this becomes

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

$$q_p = \frac{0{,}75Q}{T_p}$$

Introducing catchment area, A, in km^2, allows conversion of q_p from $mm.h^{-1}$ to $m^3.s^{-1}$, as follows (the full derivation is given in Schulze and Arnold, 1979):

$$q_p = \frac{0{,}75\ A\ Q}{T_p} \quad (mm.km^2.h^{-1})$$

ie $$q_p = \frac{0{,}2083\ A\ Q}{T_p} \quad (m^3.s^{-1}) \qquad \text{Eq. 10}$$

It may be seen from Figure 1.1, that the time to peak, T_p, is related to storm duration and lag such that

$$T_p = D/2 + L \qquad \text{Eq. 11}$$

where

D = effective storm duration (h), i.e. the duration of the stormflow-producing part of a day's rainfall, and

L = catchment lag (h).

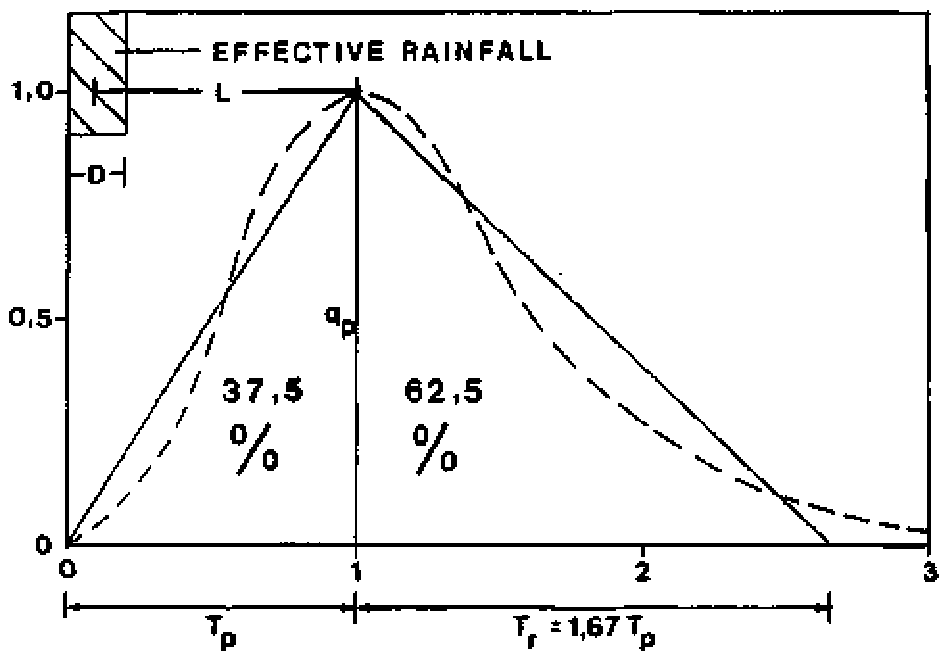

Figure 1.1 Geometrical shape of the triangular unit hydrograph

The equation for the estimation of peak flow therefore becomes

$$q_p = \frac{0,2083\ A\ Q}{D/2 + L} \quad (m^3.s^{-1}) \qquad \text{Eq. 12}$$

Lag is defined as the time from the centre of mass of excess rainfall to the peak rate of runoff (Figure 1.1) and, in SCS literature (USDA-SCS, 1972),is related to the physical properties of a catchment, namely, catchment slope, hydraulic length and flow retardance. The standard SCS equation used for the estimation of lag is

$$L = \frac{l^{0,8}(S' + 25,4)^{0,7}}{7069\ y^{0,5}} \qquad \text{Eq. 13}$$

in which

l = hydraulic length of the catchment (m),

y = average catchment slope (percent), and

$$S' = \frac{25400}{CN'} - 254$$

where

CN' = retardance factor approximated by the runoff curve number unadjusted for antecedent soil moisture i.e. CN_{II}.

Equation 12 assumes storms with a uniform rainfall distribution. Total storm rainfall, however, rarely (if ever) occurs uniformly with respect to time. In order to estimate the peak rate of runoff it is therefore necessary to divide the storm into increments of duration and compute the corresponding increments of runoff.

This requires storm rainfall to be distributed with respect to time because rainfall intensity varies considerably during the storm. Two major typical 24-hour storm distributions, Type I and Type II, were developed from United States data for use in the SCS model and have been adapted provisionally per se for application in South Africa. They are associated with climatic regions. Type I maximum intensities are less than those of Type II. The Type I storm distribution represents maritime climates with winter rainfalls while the Type II storm distribution is typical of the more intense storms usually generated over small areas from summer thunderstorms which then yield higher rates of runoff than storms with a Type I distribution. Time distributions for the two storm types are shown in Figure 1.2.

The duration of the most intense rainfall period contributing to the peak runoff rate is related to the time of concentration for the catchment in question. Time of concentration, T_c, in turn has been related empirically to catchment lag by

$$L = 0,6\ T_c \qquad \text{Eq. 14}$$

By dividing the storm into increments of duration around the most intense rainfall period contributing to the peak runoff rate, the peak discharge equation for an increment of runoff becomes

$$\Delta q_p = \frac{0,2083\ A\ \Delta Q}{\Delta D/2 + L} \qquad \text{Eq. 15}$$

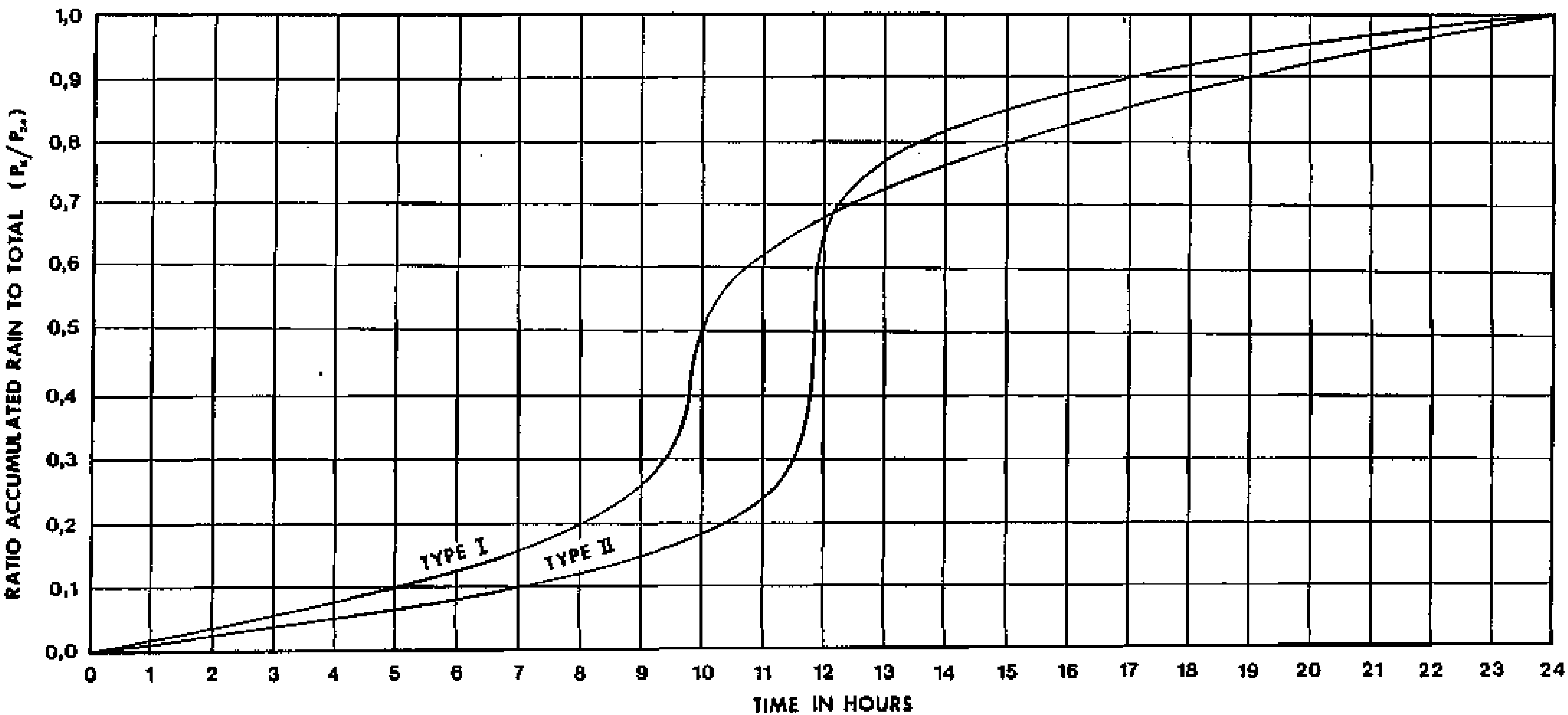

Figure 1.2 The SCS 24-hour storm rainfall distributions (After USDA-SCS, 1972)

where

Δq_p = peak discharge of the incremental triangular hydrograph ($m^3.s^{-1}$)

ΔQ = increment of runoff (mm) produced by the rainfall of that incremental duration, and

ΔD = duration of unit excess rainfall (h).

Figure 1.3 illustrates how the ordinates of the individual incremental triangular hydrographs (with each incremental hydrograph being displaced one incremental duration, D, to the right for each successive time increment) are added to produce a composite hydrograph, using the principle of superpositioning.

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With this background to the so-called "standard" SCS model, the next chapter examines the applications of this model and the research philosophies this author believes should be adhered to when undertaking component research in order to improve the performance of the model.

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Schulze, R.E. and Arnold, H. 1979. Estimation of volume and rate of runoff in small catchments in South Africa based on the SCS technique. University of Natal, Pietermaritzburg, Department of Agricultural Engineering, ACRU Report No. 8 79 pp and appendices.

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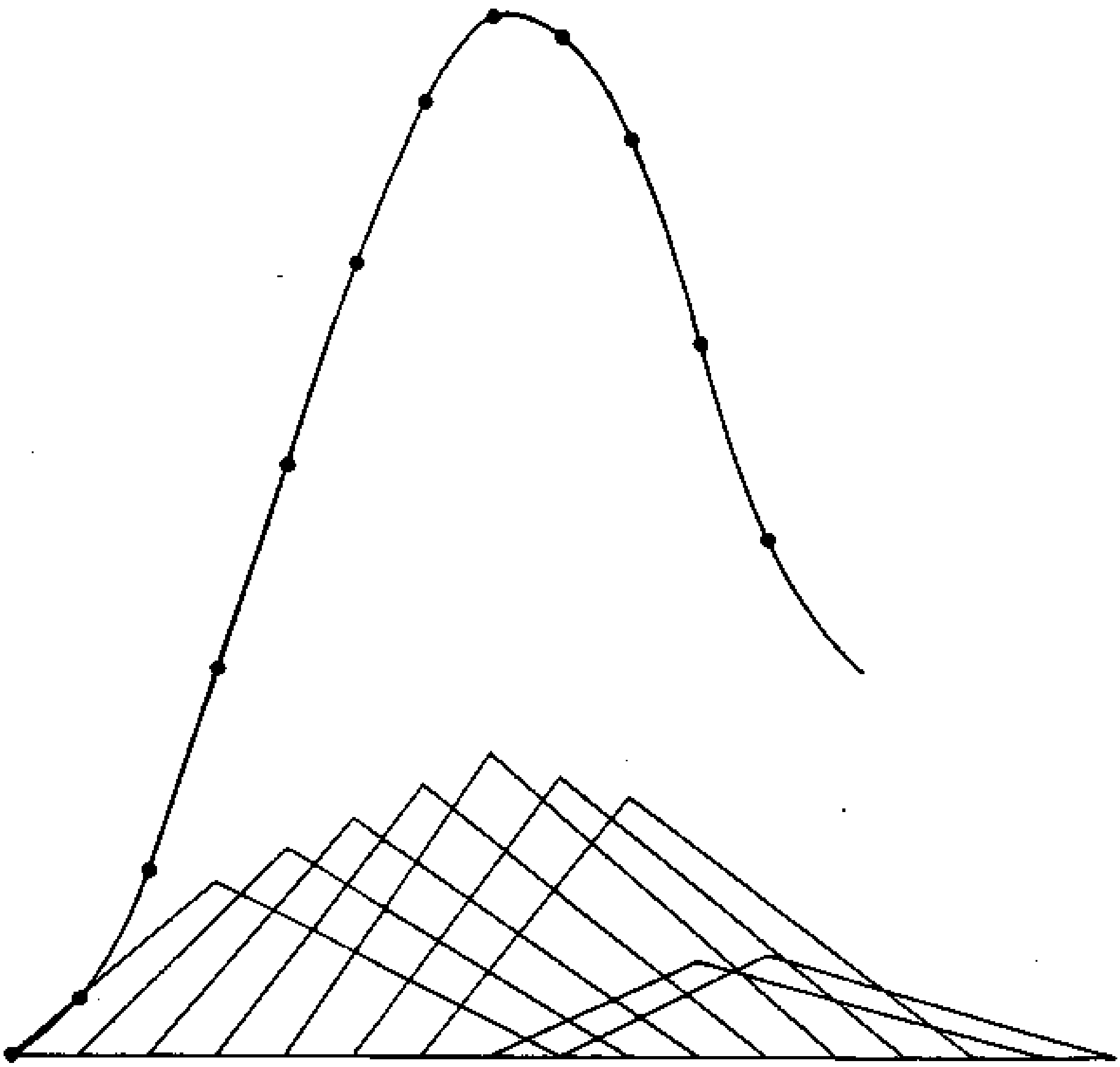

Figure 1.3 Superpositioning of incremental triangular unit hydrographs (Schulze and Arnold, 1979)

This has motivated the need for an alternative method, which should be simple to use computationally or graphically, should have a sound hydrological basis, rely on factors which have classes of relatively fine resolution and may be applied in small catchments on a subcontinental scale. For this reason the SCS hydrograph generating technique for estimation of stormflow volumes and peak discharge rates in catchments of 8 km^2 or less, and slopes not exceeding 30%, was selected.

STATUS OF THE SCS TECHNIQUES

The rationale behind the selection of the SCS technique was strengthened by the facts that in the past 20 years the SCS method had become an accepted and established model for stormflow estimation on small catchments and that the procedure was "used internationally - perhaps several million times annually" (Hawkins, 1980), often as a method recommended by institutions and government agencies (for example, by the states of Maryland and Michigan in the U.S.A.), or as a method the results of which are accepted in court judgements (for example, in the state of Pennsylvania) and as a method being tested and used widely not only in the U.S.A., but also in France, Germany, Middle Eastern and African countries.

USE OF THE SCS TECHNIQUE IN SOUTHERN AFRICA

Developed by Mockus and others over the past three decades, originally for the U.S.A., this method was first proposed for use in Southern Africa as an alternative to the rational formula over 20 years ago by Reich (1962). More recently it has been tested in

Southern Africa at research catchment level by Cousens (1976), while Hiemstra and Frances (1978) have used the SCS method in conjunction with runhydrograph theory and Gibson (1981) has applied the SCS method to large catchments.

A major breakthrough in promoting the use of the SCS technique in Southern Africa was the publication of the first edition of a user manual by Schulze and Arnold in 1979, adapted for local use. Response to the manual resulted in the SCS method's becoming part of the hydrological armoury of engineers and its being recommended as a standard technique by, for example, the National Transport Commission of South Africa and the Natal Provincial Administration.

Simultaneously, weaknesses and overgeneralizations in the model have become exposed. It became, inter alia, the task of this project to research various components of the SCS model with the view to possible improvements and generalizations in order that an eventual further/new edition of the manual could incorporate findings at user level. Subsequent chapters report on these research findings.

REASONS FOR THE WIDESPREAD USAGE OF THE SCS METHODS

The reasons for its widespread usage are numerous :

(a) The equations are simple - if the basic premises of the equations given in Chapter 1 are accepted, it requires only one parameter, S, to be estimated and that parameter (through the CN) integrates catchment characteristics pertaining to soils, land use and moisture status.

(b) The assignment of CN from the many and varied land use and soils categories tabulated and described in NEH-4 (USDA-

CHAPTER 2

THE SCS TECHNIQUE : APPLICATIONS AND RESEARCH PHILOSOPHY

THE NEED FOR A VERSATILE SMALL CATCHMENTS MODEL FOR USE IN SOUTHERN AFRICA

There is frequent need by agricultural and civil engineers, as well as by others, for hydrological data as an information base in planning, design and management of water resources systems. Indeed, in the case of hydraulic structures, many thousands of designs are made annually in Southern Africa for structures costing millions of Rands. Since actual measurements, for example of stormflow and peak discharge rates, are rarely available for small agricultural or periurban catchments, these hydrological data have to be generated or be estimated.

Estimations of peak discharge rates from small catchment areas in Southern Africa are usually still effected by the use of the so-called rational formula, along with other simple, empirical formulae and the unit hydrograph. The popularity of the rational method results largely from its simplicity and from the fact that, on average, the method over-estimates, thus giving an inherent safety factor. Nevertheless, there is much variability in the accuracy of prediction, resulting mainly from the usage of broad classes of the coefficient of catchment imperviousness and the subjective manner in which the quantitative value of this factor is sometimes decided. Furthermore, many of the models used give no estimate of the volume of stormflow generated by an event, which in terms of the total environmental impact of a flood (for example, water quality aspects) may be regarded as equally important to the peak discharge rate.

SCS, 1972) provides a uniform method for estimating stormflow and peak discharge rate for a given catchment. Thus in the U.S.A., for example, some 4000 and in South Africa over 500 soil series have been classified by hydrological response for use with the SCS technique (USDA-SCS, 1972; Schulze and Arnold, 1979), and different hydrologists estimating design volume and peak discharge on an unguaged catchment ought to obtain the same answers.

(c) The method uses daily rainfall input - in fact the peak discharge rate equation was developed from data and for situations where only the total amount of one or more storms occurring in a calendar day was known, but not its distribution (Kent, 1966). This renders the SCS procedure a useful method to apply in areas with sparse autographic rainfall data.

(d) The empirical stormflow and peak discharge equations are related to physical properties of catchments - parameter values can thus be changed in an attempt to simulate changes in catchment conditions. This makes the model well suited to estimating the effects of land use, its treatment, hydrological condition, soil properties and antecedent moisture status on stormflow from small catchments.

(e) The SCS technique is user oriented and various types of nomographic solutions have been presented both by the SCS (for example, USDA-SCS, 1972; Kent, 1973) in imperial units and by Schulze and Arnold (1979) using SI units and with the coefficient of initial abstraction as a variable.

(f) The above factors make the method attractive for use on ungauged catchments because no calibration or parameter optimization is required. Where the method has been tested against other models of a similar level of sophistication it has been found to give not necessarily always the best, but under a variety of conditions consistently usable results (for example, Reich and Jackson, 1971; Dickey, Mitchell and Scarborough, 1979; Mostaghimi and Mitchell, 1982).

(g) Finally, the SCS method uses the generated stormflow volume as an input into its unit hydrograph-based equation for the estimation of peak discharge rates. The accurate estimation of stormflow volumes is thus essential to simulations of peak discharge rates, as over 80% of its variation may be accounted for by stormflow volume alone (Rogers, 1980; Schmidt and Schulze, 1984).

ORIGINAL INTENT AND PRESENT USAGE

The SCS technique was intended originally as a design tool for use on small catchments with agricultural land uses. Thus Kent (1966) states that the "procedures are primarily for establishing safe limits in design and for comparing the effectiveness of alternative systems of measures within a catchment/watershed project. They are not used to recreate specific features of an individual storm".

Because of its simplicity, the SCS curve number method, however, has been used increasingly for purposes other than was the original intention, has been adapted in part or has had procedures for parameter estimation modified.

The following examples of the use of the SCS method by others illustrate these points:

(i) The SCS method has been adapted for use in continuous daily water yield models (for example, Williams and LaSeur, 1976);

(ii) curve numbers have been estimated in conjunction with remotely sensed data (for example, Ragan and Jackson, 1980; Bondelid, Jackson and McCuen, 1980);

(iii) the SCS equation has been used as a tool in environmental impact studies, for example, in assessing effects of strip mining (Fogel, Hekman and Duckstein, 1980) or in the estimation of sediment yield (Williams and Berndt, 1977);

(iv) the SCS itself has adapted the technique for use in urban areas (USDA-SCS, 1975);

(v) curve number adjustment procedures have been changed to improve estimations in semi-arid areas (Simanton, Renard and Sutter, 1973);

(vi) the technique has been used as a basis in the comprehensive CREAMS model on agricultural management systems (Knisel, 1980) and

(vii) it has been applied with modification on large catchments (Gibson, 1981) up to several thousands of km^2 in area.

The original authors did not foresee the widespread application of the SCS method to the "entire spectrum of hydrologic problems on ungaged watersheds" (Rallison, 1980). Although in many cases the SCS procedure has been shown to solve successfully types of problems for which it was not designed, the procedure has, because of the assumptions in the derivation and because of its generalized use, generated substantial criticism (for example, Hawkins, 1978; Hewlett, 1981). While some of the criticism may be misconstrued, it is recognised by the SCS (Rallison and Miller, 1982), but is accepted as a tradeoff against the advantages of simplicity.

RESEARCH PHILOSOPHY REGARDING IMPROVEMENTS TO THE SCS MODEL

In any so-called "improvement" to the performance of a hydrological model the researcher and later the user have to bear in mind the conceptual basis on which any changes to the original model were made and the implications of these changes. The research "philosophy" regarding the improvements to the SCS model proposed in this report consists of four simple considerations:

(a) The basic SCS equations have to be kept intact. This implies that the basic stormflow and peak discharge equations must remain, respectively,

$$Q = \frac{(P - I_a)^2}{(P - I_a) + S}$$

and

$$q_p = \frac{0{,}2083\ A\ Q}{D/2 + L}$$

However, individual components such as S, I_a, D or L may, within the philosophy of model improvement, be derived by means other than those used originally by the Soil Conservation Service. No "new" model, which may take years to become accepted, is therefore developed. By adopting this approach the confidence of the SCS and the users of their technique is, hopefully, maintained.

b) Any modifications suggested therefore may ultimately, at user level, make use only of simple, readily obtainable input data.

(i) These consist first of climatological data in the form of daily (or longer) rainfall and daily temperature values, the climatic statistics available most commonly, especially in developing countries. Temperature is used in the suggested modifications as an index of the energy status of the environment and is used to estimate potential evapotranspiration. Where A-pan data are available they replace temperature-based evapotranspiration estimates. Other climatological information acceptable would be available maps or tables or graphs of, for example, mean annual precipitation or rainfall intensities for given durations/return periods.

(ii) The second type of model input consists of soils information, where use is made either directly or indirectly of the SCS hydrologic soil grouping or of other published information on moisture characteristics of soils.

(iii) A third type of input data comprises topographical information from available maps, for example, on hydraulic length, catchment areas/slopes, stream order, or drainage densities.

(iv) Fourthly, vegetation/land use data should again be available from maps, orthophotos or satellite imagery; alternatively, values such as cropping coefficients should be obtained readily from the literature.

(c) Realistic, proven soil moisture budgeting techniques with procedures and sequences appropriate to daily input data, should be used. The budgeting should consider as variables soil, climate and vegetation characteristics.

(d) Ideally the results obtained from test data should show improvements under a wide range of environmental conditions, be they in humid or arid regions, on catchments with dense or sparse vegetation or with deep or shallow soils.

* * * * * * * * * * *

It is in the light of the above research philosophy that improvements are sought to the SCS stormflow equation by soil moisture budgeting procedures.

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CHAPTER 3

ADAPTING THE SCS STORMFLOW EQUATION FOR APPLICATION TO SPECIFIC EVENTS BY SOIL MOISTURE BUDGETING[1)]

INTRODUCTION

In the SCS equation for the estimation of stormflow, namely

$$Q = \frac{(P - I_a)^2}{(P - I_a) + S} \quad \text{for } I_a > P \text{ and } I_a = cS \qquad \text{Eq. 1}$$

the catchment's curve number, CN, representing the "soil-vegetation-management-antecedent moisture condition", and expressed through S by

$$S = \frac{25400}{CN} - 254 \qquad \text{Eq. 2}$$

is an index of the catchment's stormflow response to rainfall.

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1) This chapter summarizes findings presented under the same heading as an Interim Report to the WRC and accepted in 1982.

Hawkins (1975), as well as more recently Bondelid, McCuen and Jackson (1982), in testing the sensitivity of the SCS procedure to CN variation, conclude that accurate estimates and adjustments of CN are more important than accurate estimates of rainfall, particularly within the range of rainfalls usually used in stormflow estimation from small catchments.

This chapter focusses on a method of improving stormflow estimates for specific events using the SCS method, by the application of moisture budgeting techniques, to obtain more accurate curve number adjustments than those obtained by standard SCS procedures.

The method described fulfills the four basic considerations regarding the research philosophy on improvements to the SCS technique, as outlined in the previous chapter.

CURVE NUMBER ADJUSTMENT : BACKGROUND

The Significance of 'S' in the SCS Stormflow Equation

Rallison and Miller (1981) quote "that in the absence of rainfall intensity in the model, S is limited by the amount of soil water available in the profile". The SCS states that "changes in S from one event to another account for all variation in runoff producing factors except rainfall". Furthermore, in estimating S, "the soil moisture at the beginning of rainfall is usually the most important", and "Of all the variables that go into S, soil moisture was selected as the most important" (USDA-SCS, 1980).

The implications of these statements are that within that part of the soil profile which influences stormflow, S may be conceptualized as a soil moisture deficit, having a high value when the deficit is large and a low value when the deficit is small, and, as a corollary, S must be estimated at the onset of a rainfall event by soil moisture budgeting techniques that have to account for more than merely antecedent rainfall. In the light of the above conclusions on the significance of S, the standard SCS procedure for adjusting "average" CN, hence S, for antecedent moisture conditions are now discussed.

The Standard SCS Procedure for Adjusting CN

In the standard SCS procedure for CN adjustment, lumped 5-day antecedent rainfall amounts for the dormant and growing seasons, respectively, are used to categorize the catchment antecedent moisture condition (AMC) into "dry" (AMC_I), "average" (AMC_{II}) or "wet" (AMC_{III}) and the "average" curve number, CN_{II}, is adjusted if AMC is either "dry" or "wet". The classification and examples of CN adjustment are illustrated in Table 3.1.

Weaknesses in the Standard SCS Procedure for Adjusting CN

(a) Rainfall amounts for AMC grouping are shown as discrete classes (Table 3.1). The implication is that there are discrete CN shifts, when adjustment for AMC takes place, rather than CN being a continuum. As a result there are, what Hawkins (1978) terms "quantum jumps" of estimated stormflow. For example, a rainfall of 50,8 mm on a catchment with a CN_{II} of 80 is estimated to yield stormflow of 2,8 mm, 14,2 mm and 29,5 mm for AMC_I, AMC_{II} and AMC_{III} respectively.

(b) Inter-regional and inter-seasonal variations in evapotranspiration exist, which render the CN adjustment merely by the divisions into "dormant" and "growing" seasons too simplistic.

Table 3.1 SCS antecedent moisture classification and curve number adjustment

AMC Group	Total 5-day Antecedent Rainfall		Examples of corresponding CN and S (bracketed) in mm
	Dormant Season	Growing Season	
I Dry	12 mm	< 36 mm	40(381) 51(244) 62(149)
II Average	12 - 28 mm	36 - 53 mm	60(169) 70(109) 80(64)
III Wet	28 mm	> 53 mm	79(72) 85(49) 91(25)

(c) The use of a five-day period for assessing moisture status may be queried. Five days may be too short, ideal or too long a period, depending *inter alia* on a catchment's area, slope, climate or soil texture. Researchers have found other antecedent periods to give better estimates of stormflow. For example, Hawkins (1961) found one day, Dickey, Mitchell and Scarborough (1979) two days and Hope and Schulze (1982) 15 days as a better antecedent period than five days.

(d) The use of a lumped rainfall amount rather than a weighted index for antecedent moisture status assessment is a further weakness.

(e) By implication in the SCS method the soil profile, in which any changes of S must be taking place, is a uniform, single layer. In order to simulate stormflow more realistically, the hydrologist has to know where and in what amounts in the soil profile soil moisture is "residing" at the onset of an event. A multi-horizon soil profile ought therefore to be considered, taking congnizance of the proportions in which moisture is being extracted from the various horizons according to rooting characteristics of the catchment's vegetation.

Review of CN Adjustment by other Researchers

Attempts at refining CN adjustment are not new. The SCS itself has suggested an adjustment according to stages of vegetative growth and exposure of the soil surface. However, this suggestion has not been pursued. Researchers attempting refinements to CN adjustment have usually developed expressions unique to their locations or hydrologic regimes. Thus Simanton, Renard and Sutter (1973), working in the semi-arid environment of Arizona, subdivided AMC_I into sub-conditions and further combined rainfall intensity with AMC_I. In Texas, where climatic conditions become progressively more arid from east to west, CN for design purposes have been adjusted (USDA-SCS, 1978) by addition of intermediate values such that design CNs decrease towards the west. Dickey et al. (1979) used another approach in Illinois by incorporating the month of the year in their CN correction. A procedure for CN adjustment based on antecedent rainfall, evapotranspiration and drainage/runoff, and therefore of a more universally applicable nature, was derived by Hawkins (1978). This procedure, tested by Hope and Schulze (1982) on catchments in Southern Africa, was found to simulate stormflows consistently more efficiently than does the conventional SCS model.

MOISTURE BUDGETING : CONCEPTS AND ASSUMPTIONS

By the introduction of soil moisture budgeting techniques to CN adjustments, three working concepts and several assumptions are made.

(a) Soil moisture is held in a soil store. Soil moisture is held in a store within that part of the soil profile that is active in regulating the stormflow response of a catchment to rainfall. In the research described in this chapter, this store has been equated to the plant available moisture, PAM, of the profile. A value for PAM has to be obtained either from published data, by estimating PAM from soil texture, or by derivation from concepts implied in the SCS equation.

In the absence of soil information, the last named method has to be used. The derivation of PAM from concepts implied in the SCS equation is outlined below.

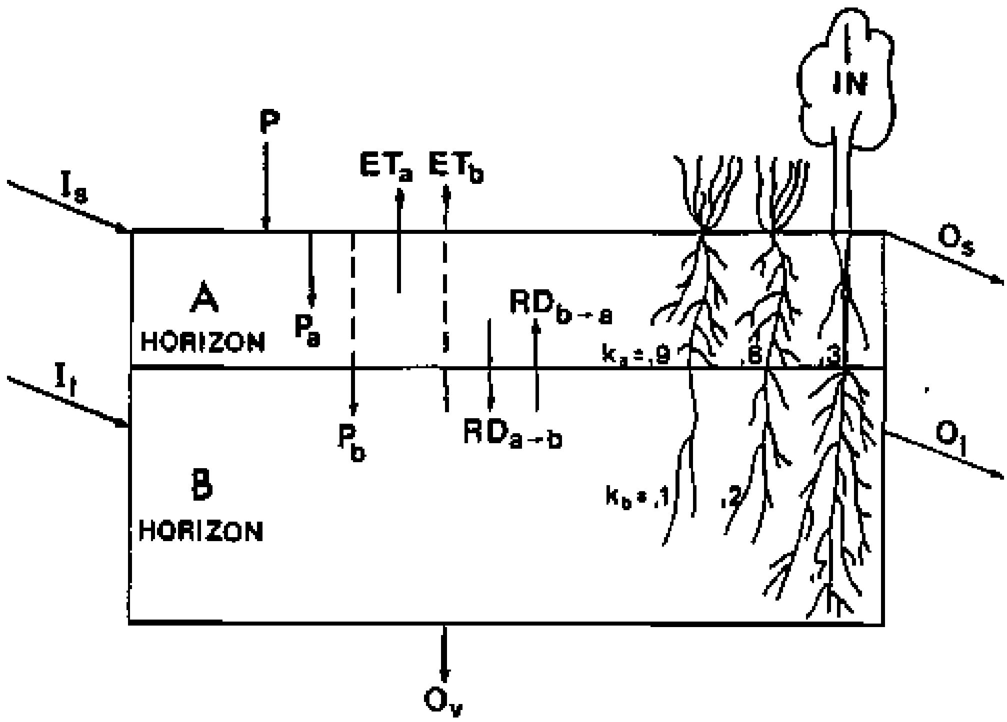
(i) A CN_{II} is obtained for a catchment from fieldwork and tables.

(ii) Using SCS tables (USDA-SCS, 1972), values of CN_I and CN_{III} are derived for the initial CN_{II}.

(iii) From the CN_I and CN_{III}, corresponding values of S_I and S_{III} (both in mm) may be obtained (Equation 2).

(iv) On the assumption that S_I, representing dry antecedent conditions, approximates wilting point and S_{III}, representing wet antecedent conditions, approximates field capacity, the PAM is estimated as being the difference, in mm, between S_I and S_{III}. Within the range of CN_{II} most frequently encountered, namely 60-90, realistic estimates of PAM may be made by this method (Schulze, 1982).

(b) Soil moisture in a profile is partitioned and redistributed. Partitioning and redistribution of soil moisture in a segment of soil within a catchment may be viewed as in Figure 3.1, with vertical as well as lateral flows into and out of the active soil system. In a two-layered soil profile, rainfall (P) first enters the A-horizon (P_a) and when that is "filled" (in the proposed daily model at PAM_a) the remainder (P_b) would percolate into the B-horizon. Evapotranspiration takes place simultaneously from the A-horizon (ET_a) and the B-horizon (ET_b) depending on the vegetation rooting distribution in the respective horizons and on whether the vegetation is stressed, i.e. when soil moisture content is below a given threshold value. Unsaturated redistribution of soil moisture takes place upwards ($RD_{b \to a}$) or downwards ($RD_{a \to b}$), and out of the B-horizon (O_v) dependent on soil moisture gradients. Finally, since the segment of soil considered in Figure 3.1 is an element of the larger catchment, inflows and outflows of water can take place on the surface (I_s, O_s) or laterally within the soil profile (I_l, O_l), but the latter flows are not considered in this research.



P = Precipitation
ET = Evapotranspiration
RD = Redistribution
I = Inflow
O = Outflow
IN = Interception

a = A-horizon
b = B-horizon
l = lateral flow
s = surface flow
v = vertical flow
k = rooting distribution

Figure 3.1 Soil moisture partitioning and redistribution (Schulze, 1982)

Four aspects of the above soil moisture budgeting procedure require further detail.

(i) Estimation of potential evapotranspiration, PE. In the absence of A-pan values PE has to be estimated by a temperature-based equation. One of the simplest equations, requiring only mean temperature data, is that by Blaney and Criddle (1950) in which

$$PE(mm/day) = 10(0,142T + 1,095)(T + 17,8)c\ d/m \qquad \text{Eq. 3}$$

where

T = mean air temperature (^{o}C),

c = empirical crop factor that varies with crop type and stage of growth,

d = daylength correction factor, and

m = number of days in the month.

Guidelines for values of the coefficients 'c' and 'd' may be obtained from the literature.

(ii) Estimation of actual evapotranspiration, AE. The Baier and Robertson (1966) equation was selected to estimate AE for a two-layered soil. In this equation

$$AE_i = \sum_{j=1}^{2} k_j(SM_{j(i-1)}/PAM_j)Z_jPE_i \qquad \text{Eq. 4}$$

where

AE_i = AE for day i (mm),

k_j = the fraction of moisture extraction from that zone by the root system,

$SM_{j(i-1)}$ = available soil moisture (mm) in the j-th zone at the end of the previous day (i-1),

PAM_j = plant available moisture (mm) of the j-th zone,

Z_j = fraction of available soil moisture at which AE PE and plant stress sets in, and

PE_i = PE (mm) for day i.

The k_j values have to be estimated to resemble probable rooting patterns and typical values are shown in Figure 3.1. The proportions of total PAM in the A- and B-horizons may be estimated from soil profile descriptions, but 0,2 - 0,4 PAM is typical for the A-horizon and 0,6 - 0,8 typical for the B-horizon. The function Z_j is set at unity until the bracketed part of Equation 4 becomes less than 0,4, below which fraction AE is assumed to decrease linearly to zero with available soil moisture content.

(iii) <u>Soil moisture redistribution.</u> The amount of redistribution is a function of the moisture gradient between the A- and B-horizons and the amount of soil moisture in the more moist horizon. Details of rates of unsaturated downward movement, unsaturated upward relocation and deep percolation are given by Schulze (1982).

(iv) Time steps in soil moisture budgeting. Consideration has to be given to the duration of the antecedent period selected in a moisture budgeting procedure to be variable. Furthermore, the budgeting time steps have to become shorter as an event date is approached, because of the greater sensitivity of a model to moisture status just prior to an event. Therefore, the moisture budgeting was undertaken in a maximum of five lumped steps starting 30 days prior to an event, namely, for 30-16 days prior to the event (i.e. 15 days), 15-11 days (i.e. 5 days), 10-6 days (i.e. 5 days), 5-3 days (i.e. 3 days) and 2-1 days prior to the event (i.e. 2 days). Depending on local conditions, the moisture budgeting could be preselected to commence at the beginning of any one of the five periods. At commencement of the budgeting it was assumed that both A- and B-horizons had a soil moisture content equal to 0,5 PAM.

(c) Potential Maximum Retention 'S' Represents Soil Moisture Deficit

The concepts that soil moisture is held in a store and that it is partitioned and redistributed apply to any hydrological model; the fact that potential maximum retention, S, is conceived as a moisture deficit (as discussed previously), "marries" the SCS stormflow model to soil moisture budgeting techniques. As a soil moisture deficit, S may therefore be defined as

$$S = PAM - SM \qquad \text{Eq. 5}$$

where SM for the entire soil profile or for the various horizons is calculated by Equation 4.

Procedures

The proposed soil moisture budgeting techniques for a two-layered soil profile model, SMB2, uses the inputs, assumptions and procedures described in preceding sections to calculate a soil moisture deficit, which is equated to S and then used in Equation 1 to estimate stormflow. Conventional moisture budgeting sequences are used for each antecedent period up to the event date. Details of inputs, sequences and outputs have been given by Schulze (1982).

TESTS ON STORMFLOW ESTIMATES USING THE SCS EQUATION MODIFIED BY SOIL MOISTURE BUDGETING

Catchment Data Used

The SMB2 modifications to the SCS equation were tested on 250 events from 20 catchments at seven locations in the U.S.A. The catchment locations are shown in Figure 3.2 and other information is summarized in Table 3.2. Catchment areas varied from 0,51 to 906 ha in widely differing climatic and hydrological regimes in which mean annual rainfall ranged from 175 mm to 975 mm and mean annual runoff from 1 to 300 mm (Table 3.2). All the information on the events was extracted from data published in the annual series by the USDA Water Data Laboratory (Burford, Delaschmutt and Roberts, 1980 and previous years). None of the data were

Figure 3.2 Catchment locations (Schulze, 1982)

Table 3.2 Catchment information

Location	Catchment Identification	Number of Events	Catchment Area (ha)	Mean Annual Rainfall (mm)	Mean Annual Runoff (mm)	Land use/ Vegetation	Curve Number (CN_{II})
Coshocton	26001	11	0,51	975	300	Pasture/meadow	73
(Ohio)	26003	12	1,11			Pasture	73
	26005	12	0,67			Meadow	73
	26007	11	0,90			Hardwood	70
Riesel	42024	11	1,21	825	142	Native grass	81
(Texas)	42028	15	1,22			Pasture	80
Stillwater	37001	17	6,82	725	105	Native grass	80
(Oklahoma)	37002	16	37,55			Native grass	80
	37003	15	84,08			Native grass	77
Hastings	44005	10	1,48	600	70	Native meadow	69
(Nebraska)	44006	9	1,39			Native Meadow	69
	44022	10	1,53			Pasture	69
Tombstone	63003	15	906,12	275	4	Desert shrub/grass	79
(Arizona)	63004	16	228,57			Desert shrub/grass	81
Safford	45001	11	211,84	225	1	Sparse shrub/rangeland	79
(Arizona)	45002	7	278,37			Sparse shrub/rangeland	79
	45004	10	295,10			Sparse shrub/rangeland	81
Albuquerque	47001	16	100,41	175	8	Sparse grasses/shrubs	88
(New Mexico)	47002	14	16,53			Sparse grasses/shrubs	87
	47003	12	71,84			Sparse grasses/shrubs	85

rejected on the grounds that they might give poor results. Information on catchment land use, its hydrologic condition and soils was obtained from the same source and CN_{II} was derived from procedures given in NEH-4 (USDA-SCS, 1972).

Statistical Tests Used

Comparisons of stormflow volume estimation by the standard SCS and the SMB2 modification to the SCS model were made against observed stormflows. In addition to examining regression equations, the accuracy of each procedure was assessed by the Coefficients of Determination (D) and Efficiency (E) of the observed and calculated stormflow in which

$$D = \frac{\Sigma(Q_o - \bar{Q}_o)^2 - \Sigma(Q_o - Q_{est})^2}{\Sigma(Q_o - \bar{Q}_o)^2} \qquad \text{Eq. 6}$$

and

$$E = \frac{\Sigma(Q_o - \bar{Q}_c)^2 - \Sigma(Q_o - Q_e)^2}{\Sigma(Q_o - \bar{Q}_o)^2} \qquad \text{Eq. 7}$$

where

Q_o = observed stormflow,

$\bar{Q}_o$ = mean of the observed stormflows,

Q_e = calculated stormflow, and

Q_{est} = estimated stormflow obtained from the regression line of Q_e on Q_o.

Both D and E describe the degree of association between observed and estimated stormflows. However, these two statistics are not identical (cf. Equations 6 and 7). While D is a good measure of the association between observed and calculated values, it does not reveal systematic error (Aitken, 1973). However, by considering D and E together, it is possible to ascertain whether systematic error is present, the value of E being less than D when this is so. Both D and E will always be less than unity, high values indicating accurate estimates of stormflow amounts. The error function F_1 is the difference between D and E and the closer F_1 is to zero, the less systematic error occurs in simulated stormflow.

INTERPRETATION OF RESULTS

Tests on the SMB2 modifications were undertaken initially to determine whether an antecedent period of 30, 15, 10 or 5 days should be selected in subsequent simulation runs. Results indicated that catchments from humid areas (Coshocton, Riesel, Hastings and Stillwater) responded differently to catchments from the semi-arid areas (Tombstone, Safford and Albuquerque). For events in humid areas the tendency was for simulation statistics (for example D and the slope of the regression equation) to improve with longer antecedent durations and in arid areas the reverse was shown. Examples of these trends are illustrated in Figure 3.3. All subsequent simulations by the SMB2 modification were therefore performed using a 30-day antecedent period for events from humid catchments and a five-day antecedent period from semi-arid catchments.

The error functions D and F_1 are given in Table 3.3. The overall assessment is that SMB2-modified CN adjustments yield markedly better goodness of fit statistics for their simulations than do

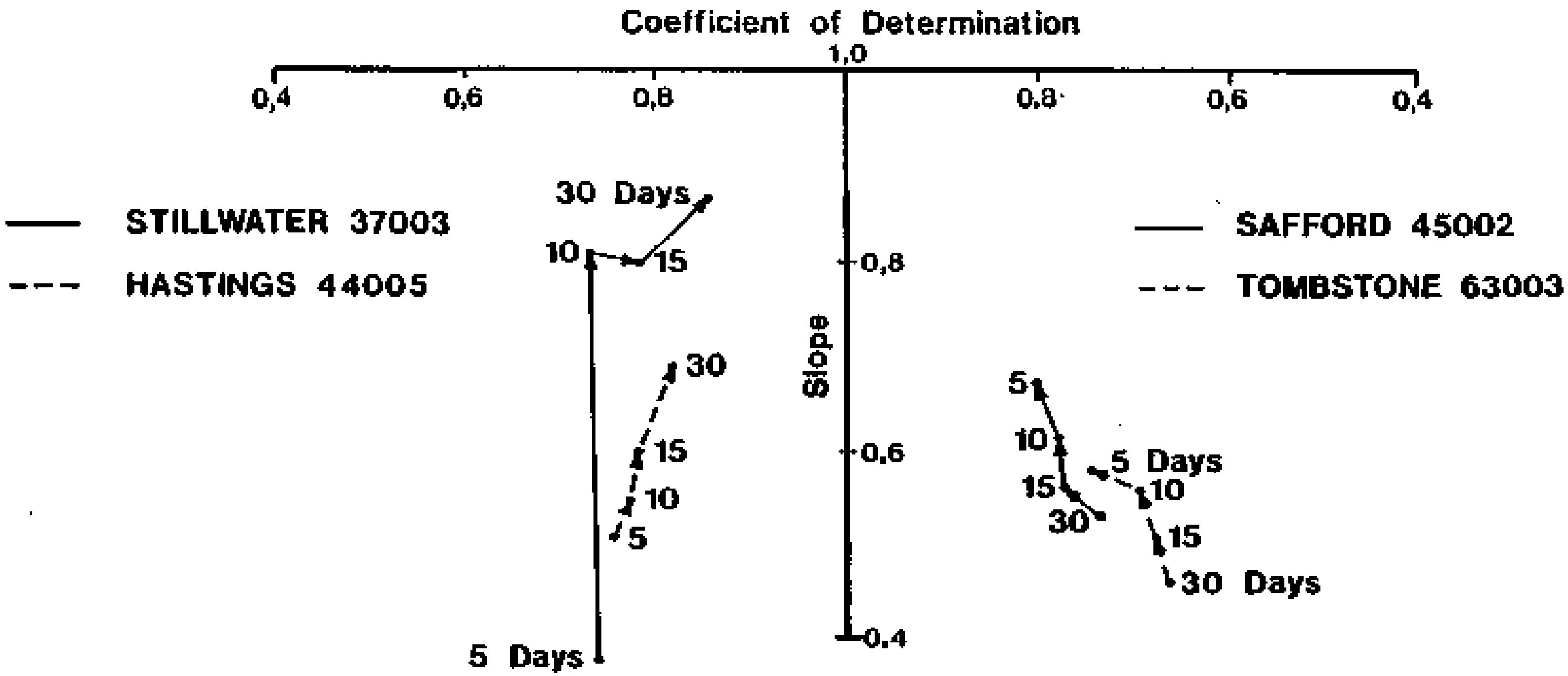


Figure 3.3 Effect of duration of antecedent period on simulation statistics (Schulze, 1982)

Table 3.3 Analysis of results

Catchment		Error Functions				Median CN		
		D		F_1				
		SCS	SMB2	SCS	SMB2	SCS	SMB2	Actual Event
Coshocton	26001	0,457	0,831	0,277	0,029	51,0	78,5	78,8
	26003	0,315	0,836	1,108	0,069	63,0	77,9	80,3
	26005	0,275	0,755	0,654	0,061	63,0	78,6	83,9
	26007	0,166	0,415	9,587	1,273	60,0	64,8	61,5
Hastings	44005	0,331	0,841	0,410	0,058	49,0	77,0	74,1
	44006	0,153	0,919	0,712	0,194	49,0	78,4	78,6
	44022	0,006	0,455	1,666	0,398	49,0	78,0	84,6
Stillwater	37001	0,575	0,816	1,609	0,324	63,0	83,5	92,8
	37002	0,731	0,808	1,303	0,173	63,0	83,8	90,1
	37003	0,518	0,831	0,865	0,093	59,0	81,3	87,5
Riesel	42024	0,090	0,540	0,182	0,007	81,0	86,9	87,5
	42028	0,393	0,789	0,503	0,049	80,0	86,5	95,2
Tombstone	63003	0,248	0,851	0,275	0,244	62,0	81,4	76,9
	63004	0,639	0,873	0,199	0,013	65,0	83,3	80,9
Safford	45001	0,715	0,570	1,903	0,295	62,0	81,6	83,8
	45002	0,665	0,859	1,325	0,311	62,0	81,4	84,5
	45004	0,139	0,382	0,649	3,626	65,0	83,2	74,6
Albuquerque	47001	0,579	0,525	1,265	0,677	76,0	89,2	86,5
	47002	0,313	0,705	2,164	0,548	74,0	88,3	93,4
	47003	0,209	0,459	2,393	1,248	71,0	86,6	88,6

the standard SCS estimates, with improved D in 18 of the 20 and reduced F_1 in 19 of the 20 catchments. The effect of systematic error shows up in the case of Safford 45001, where SMB2 yields a lower D, yet has a better F_1 value than the conventional method, and would therefore be the more efficient model to use there. On the other hand the reverse holds for events simulated from Safford 45004.

Another interpretation of results concerns the accuracy of estimated curve numbers when compared with actual CN for the events. Given observed rainfall : stormflow data, an actual event curve number, CN_a, may be calculated by the equation

$$CN_a = 25400/5\left[P + 2Q + (4Q^2 + 5QP)^{0.5}\right] + 254 \qquad \text{Eq. 8}$$

Table 3.3 summarizes, for each catchment, the median values of CN_a generated by the events tested as well as the median values of CN by the SCS method and its modifications by SMB2. Generally the simulation models used under-estimate actual CN. The SMB2 modifications do, however, approximate the actual CN far more closely than does the standard SCS model. If a tolerance of three CN from the actual is viewed as permissible for accurate simulation of specific events, this is achieved for only nine catchments. For eight catchments the SMB2 estimate of CN was still more than five CN from the actual. This implies that the soil-cover-complex CN_{II} cannot always be estimated accurately; possibly because of overriding local conditions in the stormflow-producing areas of a catchment. Alternatively the moisture budgeting techniques are not sensitive enough to reflect those hydrological processes producing stormflow, and budgeting in the A-horizon on the basis of an upper soil moisture content at effective porosity rather than field capacity may improve the results further.

Finally, the SM82 model may be shown to simulate individual events far more closely to the observed values than the standard SCS method does. This is illustrated in Figure 3.4 in the selected scattergrams of observed vs simulated stormflows by the two methods on a sub-humid and an arid catchment.

CONCLUSIONS

The adjustment of CN for catchment moisture status in the widely applied SCS model was modified by a soil moisture budgeting procedure which accounts, on a daily or longer basis, for the partitioning, extraction and redistribution of moisture in a two-layered soil profile. This procedure, which uses easily obtainable daily rainfall and temperature data, takes account of, and tries to eliminate, many of the weaknesses of the conventional SCS method of adjusting CN.

Applications of the procedure to data from 20 catchments in seven hydrologically constrasting locations in the U.S.A. proved very successful when goodness of fit statistics were compared with those using the conventional SCS method. It was further established that in humid areas the antecedent period to be considered in stormflow simulations should be longer than in more arid areas.

The suggested modifications to CN adjustment imply that the SCS equation may now be used with greater confidence and more generally in a variety of environments when simulating specific events.

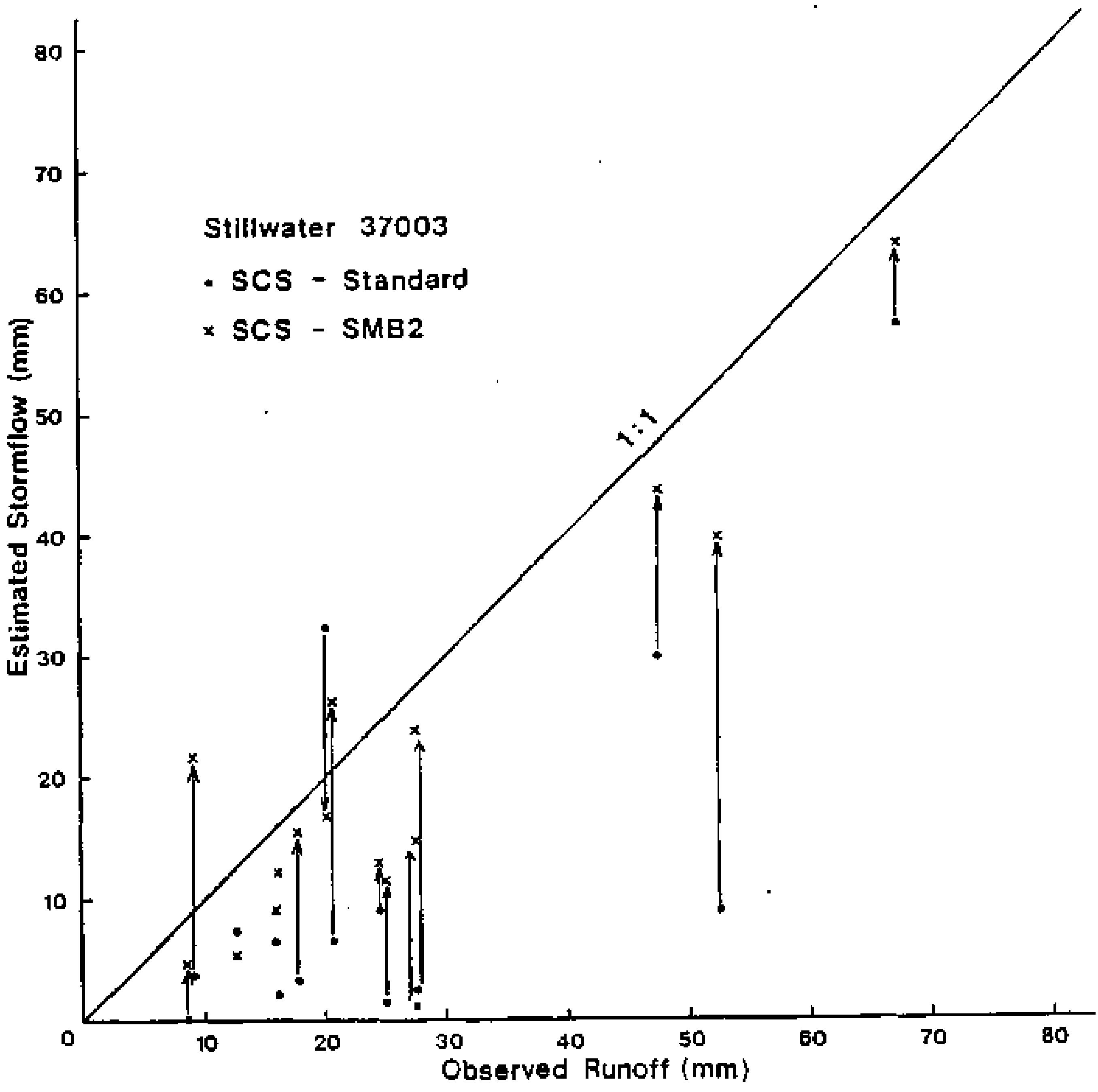


Figure 3.4 Selected scattergrams of simulated vs observed streamflows (Schulze, 1982)

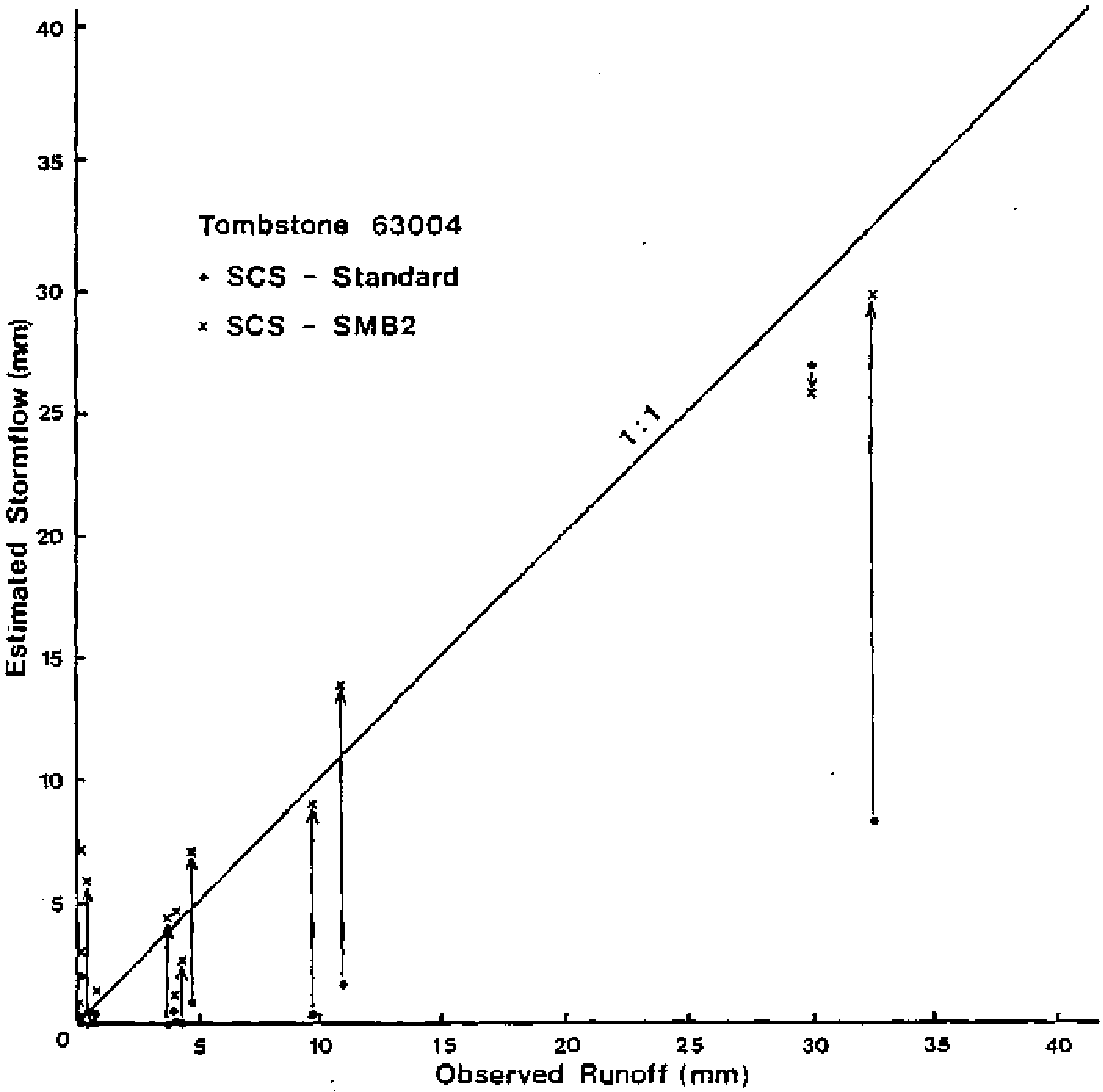


Figure 3.4 (continued)

ACKNOWLEDGEMENTS

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CHAPTER 4

THE COEFFICIENT OF INITIAL ABSTRACTION IN THE SCS MODEL AS A VARIABLE

R.E. Schulze, W.J. George, H. Arnold and J.K. Mitchell[1)]

INTRODUCTION

In the SCS equation for stormflow estimation, namely

$$Q = \frac{(P - I_a)^2}{(P - I_a) + S} \qquad \text{for } P > I_a \qquad \text{Eq. 1}$$

the initial abstractions, I_a, are defined as all that rainfall (mm) occurring before stormflow begins and as consisting "mainly of interception, infiltration and surface storage" (USDA-SCS, 1972).

In order to seek a simple solution to Equation 1 by having only one unknown on the right hand side, namely the potential maximum retention S, an empirical relationship was sought between I_a and

1) Professor J. Kent Mitchell's contribution to this chapter was made while he was on sabbatical leave in the Department of Agricultural Engineering at the University of Natal in 1982 from the University of Illinois, Champaign, Illinois, U.S.A.

S. This empirical relationship between I_a and S was, according to SCS literature (USDA-SCS, 1972), based on research data, some of which is shown in Figure 4.1 - a plot of I_a versus S for individual storms. The data were derived from natural rainfall and runoff records from catchments less than four hectare in size (USDA-SCS, 1972). The large amount of scatter apparent in the diagram was ascribed mainly to errors in the estimation of I_a.

It is, however, from these data that the relationship

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

has become established to the extent that it has become a convention to express Equation 1 as

$$Q = \frac{(P - 0{,}2\ S)^2}{P + 0{,}8\ S} \qquad \text{Eq. 3}$$

REVIEW

A general contention amongst researchers and users of the SCS equation is that the coefficient of I_a in terms of S, namely 0,2, is too high and also that it should be variable. Aaron, Miller and Lakatos (1977) stated that a coefficient of 0,2 might work well for large storms, but usually results in under-estimation of stormflow for small to medium storms. They therefore suggested a reduction of the coefficient from 0,2 to 0,1 or even lower. Based on similar experience, 0,15 was used by Fogel, Hekman and Duckstein (1980). Springer, McGurk, Hawkins and Coltharp (1980), working with data from both humid and semi-arid catchments in the U.S.A. also found that in most cases they examined, the coefficient was less than 0,2 and on several catchments was zero.

In regard to the coefficient of I_a being a variable, Smith (1978) maintains that it varies within a storm and with rainfall intensity and duration. Golding (1979), on the other hand,

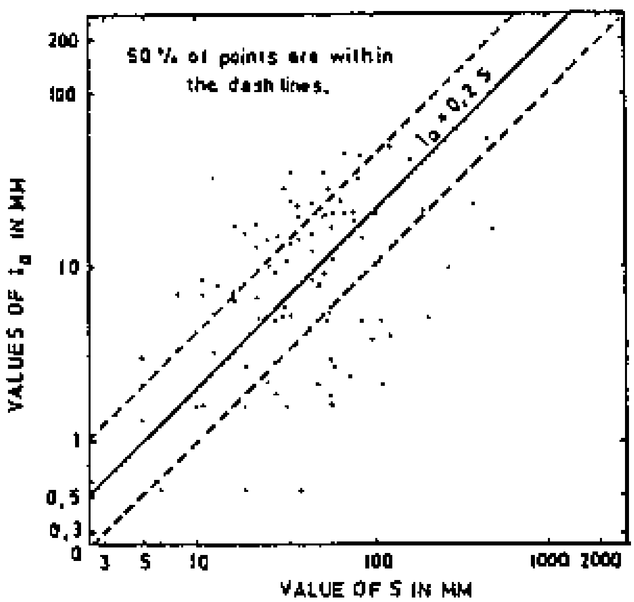

Figure 4.1 The SCS plot of I_a vs S (after USDA,SCS, 1972)

suggests a variation of the coefficient with curve number, CN, when simulating stormflow in urban areas.

Rallison and Miller (1981), commenting on the assumption that I_a = 0,2 S state : "Further refinement of I_a is possible but not recommended, because under typical field conditions very little is known of the magnitudes of interception, infiltration and surface storage".

Schulze (1982) felt that it was "shortsighted that the SCS should not recommend further research in this area". He states : "Great strides have been made in the past decade in our understanding of the stormflow process in terms of contributing or partial areas. Since a catchment does not usually respond uniformly to rainfall, it is hypothesized that, in addition to varying with storm intensity and duration, I_a may vary with rainfall amount (rather than CN varying with rainfall amount as Hawkins (1979) argues), antecedent conditions (i.e. related to the contributing area) or the area, physiography or drainage density (as a measure of the efficiency of discharge) of a catchment. The whole concept of varying I_a in the SCS equation is an area of research that needs to be encouraged. It is in anticipation of positive research results that the metricated graphical solutions to the SCS stormflow equations developed by Schulze and Arnold (1979) contain the coefficient of I_a as a variable".

RESEARCH AIMS

In the light of the above discussion, this project set out to examine the coefficient of initial abstraction from three viewpoints:

(a) First, the point scatter of I_a vs S given by the SCS (c.f. Figure 4.1.) would be analysed in order to establish from those data whether a relationship other than I_a = 0,2S, in fact, gave a better fit to the scatter of points.

(b) The standard SCS procedure of accounting for antecedent moisture status adjusts curve numbers in "quantum" jumps up or down for "wet" or"dry" conditions. Furthermore, these conditions are defined for so-called "growing" and "dormant" seasons. An analysis of the possible influence of antecedent condition and season on optimized values of the coefficient of initial abstraction was therefore a second aim of this project.

(c) In the previous section (Review) possible relationships between physiographic factors as well as climatic factors on initial abstractions were suggested. The third aim of this project was to examine, by multiple regression techniques, whether physiographic and climatic factors could be used to explain variations in the coefficient of I_a.

ANALYSIS OF SCS DATA ON THE I_a : S RELATIONSHIP

As a starting point in this investigation of the initial abstraction component of the SCS model, the SCS data presented in Figure 4.1 are examined with the aim of determining an alternative empirical relationship between I_a and S which would account for a greater proportion of the variability than would I_a = 0,2S. A number of regression models were therefore fitted to the SCS data.

Co-ordinate pairs of I_a and S were obtained by digitizing from the point scatter shown in Figure 4.1. Since a high degree of accuracy was achieved in extracting the co-ordinate pairs, it was assumed that any errors present in the data were random.

Results of the Analyses

The results from these regression analyses are given in Table 4.1. The t-values for Student's t-test are used to establish whether the regression coefficients are significantly different from zero. As illustrated in Table 4.1, the correlation coefficients of all the regression equations are highly significant (at the 0,001 level). Furthermore, the constant term fitted in each of the regression models is not significantly different from zero. This result is compatible with the curve number concept. A CN of 100 results in an S value of zero. Such a value of S would be associated with, for example, a free water surface, saturated marsh or exposed rock, on which land uses the stormflow is approximately equal to the rainfall amount. Therefore I_a should be zero when S is zero and no constant term needs to be fitted in the regression of I_a on S.

For this reason a further set of regression equations was developed, in which the fitting of a constant term was omitted by forcing the regression lines through the origin. The resulting regression equations are given in Table 4.2. The correlation coefficients in Table 4.2 are all much higher than the corresponding correlation coefficients for the regression equations in Table 4.1. It is important to note that the fitting of a regression model without a constant term must inevitably lead to correlation coefficients which are not comparable with those obtained from the usual model in which a constant term is fitted, since the method is tantamount to assuming that the constant term is zero.

The relationships between I_a and S in Table 4.2 are all highly significant. The logarithmic model yielded the highest correlation coefficient. However, the applicability of the logarithmic model is doubtful. An inherent assumption in such a model is that the variance of the dependent variable is a linear function of the independent variable. Since no theoretical

Table 4.1 Results of regression analyses of initial abstraction on potential maximum retention

Regression Model	Regression Equation (for I_a in mm on S in mm)	Correlation Coefficient r	t-value for Students t-test
Linear Regression	$I_a = 0,0705\ S + 7,7264$	0,4724(***)	5,673(***) 0,761(NS)
Log-log Regression	$\log_{10}I_a = 0,6317\ \log_{10}S - 0,1532$	0,5254(***)	6,535(***) 0,343(NS)
Quadratic Regression	$I_a = -0,00026\ S^2 + 0,1651\ S + 4,1803$	0,5340(***)	3,101(***) 5,037(***) 0,595(NS)

N.B. ***, ** and NS denote, respectively, significance at 0,1% and 1% levels and non-significance at the 5% level

Table 4.2 Results of regression analyses of initial abstraction on potential maximum retention when no constant term is fitted

Regression Model	Regression Equation (for I_a in mm on S in mm)	Correlation Coefficient r	t-value for Students t-test
Linear Regression	$I_a = 0,1206\ S$	0,7215(***)	15,665(**)
Log-log Regression	$\log_{10}I_a = 0,5540\ \log_{10}S$	0,9272(***)	37,198(***)
Quadratic Regression	$I_a = -0,00041\ S^2 + 0,2324\ S$	0,82048(***)	9,243(***) 16,888(***)

N.B. ***, ** and NS denote respectively significance at 0,1% and 1% levels and non-significance at the 5% level grounds in support of such an assumption could be found, the logarithmic model is therefore not considered as a feasible alternative prediction model for I_a. From the remaining regression equations the simple linear model was chosen for the purpose of estimating I_a because the more complex quadratic model given in Table 4.2 does not appear to be more efficient. The slope of the regression line of the linear model is 0,1206. As shown below, this value is significantly different from the value of 0,2 suggested by the authors of the SCS model.

$$t = \frac{\mu - \overline{X}}{Q^2} = \frac{0,2000 - 0,1206}{0,0077} = 10,313^{(***)}$$

Remarks

The authors of the SCS model point out that in Figure 4.1, from which the data for these analyses were taken, only enough points were plotted to indicate the variability of the data. There are, however, 114 points in Figure 4.1 - enough to obtain a realistic picture of the I_a : S relationship. It must, nevertheless, be concluded that the data presented in Figure 4.1 are not necessarily representative of the complete data base which was originally available to the authors of the SCS model. It is, however, noteworthy that analyses of the data points given by the SCS were shown to yield significantly lower values of I_a than I_a = 0,2 S would, and that the coefficient of 0,1206 which was determined, is far more in line with values found or suggested by numerous researchers, as quoted in the Review section of this chapter.

EFFECTS OF SEASON AND ANTECEDENT MOISTURE ON THE COEFFICIENT OF INITIAL ABSTRACTION

Introduction

Storm durations and storm types, as well as vegetation and soil properties, vary according to season. For this reason it was thought worthwhile to investigate whether distinct seasonal differences did exist in the magnitudes of the coefficient of initial abstraction, which are not accounted for by the discrete changes in the curve number for different antecedent conditions, which furthermore differ in definition according to season (c.f. Table 3.1.)

Data

For the purpose of this study 131 runoff events were selected from the W.R.C. catchments at Cedara, DeHoek and Zululand. Details of the catchments are summarized in Table 4.3, while details of the individual events (storm rainfall, observed runoff, rainfall duration and intensity) have been given by Arnold (1980).

For the purpose of this study, each of the storms was categorized according to the season in which it occured and the AMC class prevailing at the onset of the storm. Only two seasons were considered, namely the growing season and the dormant season. The growing season was defined as the months of November to February (inclusive), and the SCS rainfall limits required for the classification of the AMC class were taken (c.f. Table 3.1).

Procedure

The initial abstraction for each event was calculated after rewriting the SCS stormflow equation (Equation 1, Introduction) as

$$I_a = P - 0,5 \left[Q + (Q^2 + 4\ Q\ S)^{0,5}\right] \qquad \text{Eq.4}$$

Using Equation 4 the initial abstraction for each event may be calculated by substituting the observed runoff volume for Q. In any one of the categories as defined by season and AMC, the

Table 4.3 Catchment information

Catchment Identification	Catchment Area (km^2)	Main Land Uses	Curve Number	No. of Events
Cedara				52
U2M16	5,25	Forest/Veld	67	14
U2M18	1,31	Forest	74	14
U2M19	0,09	Veld	69	8
U2M20	0,26	Veld	71	16
DeHoek				60
V1M12	0,50	Veld	74	16
V1M15	1,03	Veld	71	18
V1M28	0,41	Veld	68	13
V7M03	0,45	Veld	74	13
Zululand				19
W1M16	3,28	Veld	77	9
W1M17	0,61	Veld	63	10

"best" coefficient of initial abstraction may then be evaluated for a particular category. This is obtained by performing the linear regression of I_a on S within that category. Consistent with the findings in the previous section, the regression line was forced through the origin. Thus in

$$I_a = cS$$

where

c = the "best" coefficient of initial abstraction for a particular category, and

$$c = \frac{\sum_{i=1}^{n} I_{ai} S_i}{\sum_{i=1}^{n} S_i^2} \qquad \text{Eq. 5}$$

where

I_{ai} = the initial abstraction for event i,

S_i = the corresponding potential maximum retention for event i, and

n = the number of events in the category being considered.

For a given season and AMC class the maximum potential retention is constant cn any one individual catchment, since only one CN was used to describe the soil-cover complex irrespective of season (Table 4.3). Thus Equation 5 may be further reduced to give

$$c = \bar{c} = \frac{1}{n} \sum_{i=1}^{n} \frac{I_{ai}}{S_i} \qquad \text{Eq. 6}$$

where

$\bar{c}$ = the mean of the coefficients of initial abstraction in any one category.

When combining the storms on several catchments in order to investigate regional trends in c, or when combining storms in different AMC classes in order to investigate seasonal trends, Equation 6 does not apply. This is due to the fact that S is no longer constant when several categories are grouped together. The value of c must therefore be calculated by Equation 5 and may be viewed as the weighted mean of the best coefficients of each of the combined categories.

Trends in the Magnitude of the Coefficient of Initial Abstraction

The "best" values of the coefficient of initial abstraction for the various category and catchment combinations considered are given in Table 4.4. The coefficients were calculated using Equation 5. By way of comparison the mean coefficient for each category is also given in Table 4.4 whenever it differed from the "best" coefficient.

It is evident from Table 4.4 that a large proportion of the events fall into the AMC-I category, while the AMC-III category is poorly represented. Nevertheless, it is important to note that values of the coefficient of initial abstraction larger than 0,2 occur predominantly under AMC-III. Furthermore, the coefficients generally increase from AMC-I to AMC-III in both the growing and the dormant seasons.

Table 4.4 Best coefficients and mean coefficients (where they differ, lower line) of initial abstraction (after Arnold, 1980)

Catchment	Growing Season				Dormant Season				Irrespective of Season
	AMC-I	AMC-II	AMC-III	Mean	AMC-I	AMC-II	AMC-III	Mean	
U2M16	0,0705 (5)	0,1902 (2)	None (0)	0,0776 0,1004 (8)	0,0638 (3)	0,1184 (2)	0,05008 (1)	0,0742 0,1549 (6)	0,0764 0,1237 (14)
U2M18	0,0906 (7)	0,1837 (3)	None (0)	0,0978 0,1185 (10)	0,0220 (1)	0,2588 (2)	0,5052 (1)	0,0977 0,2612 (4)	0,0978 0,1593 (14)
U2M19	0,0525 (5)	None (0)	None (0)	0,0525 (5)	0,0954 (2)	0,1130 (1)	None (0)	0,0970 0,1013 (3)	0,0661 0,0708 (8)
U2M20	0,0336 (8)	0,1146 (1)	None (0)	0,0355 0,0426 (9)	0,0621 (4)	0,0807 (2)	0,1952 (1)	0,0647 0,0864 (7)	0,0457 0,0617 (16)
Cedara	0,0617 0,0611 (26)	0,1764 0,1744 (6)	None (0)	0,0667 0,0823 (32)	0,0660 0,0652 (10)	0,1429 0,1470 (3)	0,4167 0,4007 (7)	0,0779 0,1442 (20)	0,0701 0,1061 (52)
V1M12	0,0898 (6)	None (0)	0,1975 (3)	0,0911 0,1256 (9)	0,0489 (3)	0,0725 (2)	0,0713 (2)	0,0518 0,0620 (7)	0,0770 0,0978 (16)
V1M25	0,0722 (16)	0,1405 (1)	None (0)	0,0731 0,0762 (17)	None (0)	0,2330 (1)	None (0)	0,2330 (1)	0,0750 0,0850 (18)
V1M28	0,0150 (5)	-0,0731 (1)	None (0)	0,0118 0,0003 (6)	0,0102 0,0179 (5)	0,1502 (1)	0,0421 (1)	0,0161 0,0402 (7)	0,0138 0,0218 (13)
V7M03	0,0155 (5)	None (0)	None (0)	0,0155 (5)	0,0501 0,0464 (5)	0,1117 0,1347 (2)	0,2511 (1)	0,0553 0,0941 (8)	0,0332 0,0639 (13)
DeHoek	0,0568 0,0592 (32)	0,0187 0,0337 (2)	0,1975 (3)	0,0566 0,0690 (37)	0,0286 0,0360 (13)	0,1356 0,1330 (6)	0,0961 0,1089 (4)	0,0373 0,0740 (23)	0,0512 0,0709 (60)
W1M16	0,0563 (2)	0,0402 (1)	None (0)	0,0550 0,0510 (3)	0,0667 (2)	0,1631 (4)	None (0)	0,0927 0,1310 (6)	0,0960 0,1043 (9)
W1M17	-0,0413 (3)	None (0)	None (0)	-0,0413 (3)	-0,0475 (3)	0,0103 (3)	0,0484 (1)	-0,0371 -0,0090 (7)	-0,0390 0,0167 (10)
Zululand	-0,0272 -0,0023 (5)	0,0402 (1)	None (0)	-0,0263 0,0048 (6)	-0,0310 -0,0018 (5)	0,0471 0,0976 (7)	0,0484 (1)	-0,0163 0,0556 (13)	-0,0208 0,0396 (19)
All Catchments Combined	0,0494 0,0551 (63)	0,1314 0,1282 (9)	0,1975 (3)	0,0517 0,0696 (75)	0,0278 0,0397 (28)	0,1022 0,1255 (20)	0,2012 0,2107 (8)	0,0382 0,0948 (56)	0,0472 0,0803 (131)

Number of events shown in brackets

The range of the "best" coefficients within a season appears to be considerable. For example, in Table 4.4 under "ALL CATCHMENTS COMBINED", the coefficients in the growing season range from 0,0494 to 0,1975 while those in the dormant season range from 0,0278 to 0,2012. However, the t-values indicate that neither of the above pairs of coefficients is significantly different from the other at the 0,05 level (Arnold, 1980).

It is concluded therefore that antecedent moisture status does not significantly affect the coefficient of initial abstraction. The general trend of the coefficients to increase from AMC-I to AMC-III within the seasons probably reflects inadequacies in the procedure for adjusting curve numbers according to antecedent moisture conditions.

For all catchments combined, the "best" coefficient for the growing season is 0,0517 while that for the dormant season is 0,0382. Again the t-value demonstrates that the two coefficients for the growing and dormant seasons are not significantly different at the 0,05 level (Arnold, 1980).

Since there is no significant difference between the "best" coefficients for the two seasons, it is suggested that the overall "best" coefficient of 0,0472 should be applied on the catchments tested. The value of 0,0472 is significantly different from 0,2 at the 0,01 level, supporting the suggestion made by several other researchers that the coefficient of 0,2 was generally too high (c.f. Review).

As may be gleaned from Table 4.4 several of the "best" coefficients calculated for W1M17 and Zululand are negative. This indicates that either consistent errors are present in the rainfall or runoff data, or that the curve number assigned to catchment W1M17 is far too low..

Performance of the SCS Model Using Calculated "Best" Coefficients

An indication of the degree of improvement of the estimate of runoff volume that may be achieved by optimizing the initial abstraction component of the SCS model can be obtained by incorporating the calculated "best" coefficients into the model.

Detailed results presented by Arnold (1980), in a comparison of these results with those obtained using the standard SCS model, show that on seven of the ten catchments the systematic error decreases substantially and the higher values of the Coefficient of Efficiency indicate considerable improvements in the estimate of runoff volume when using the "best" coefficients. The same observations apply to the analysis of all storms combined, as well as at DeHoek and Zululand. In the case of the Cedara storms, the degree of association increases marginally with a corresponding increase in the systematic error.

It was concluded in the previous section that the coefficient of initial abstraction is not significantly affected by season or AMC. Furthermore, it is not practical to apply different coefficients on different catchments since the "best" coefficient for a particular catchment is unknown unless the catchment is gauged. Therefore, the overall "best" coefficient of 0,0472 should be used. The performance of the SCS model using a coefficient of 0,0472 in preference to 0,2 has been shown by Arnold (1980) to result in a significant correlation coefficient for the Zululand region and a substantially higher correlation coefficient for all storms combined. Although Arnold (1980) shows the correlation coefficient for DeHoek storms to decrease slightly, systematic errors are no longer present for that region. The SCS model, however, failed to yield satisfactory results for storms at Cedara, irrespective of the coefficient of initial abstraction used (Arnold, 1980) and this must be attributed either to incorrect curve numbers or to inadequate curve number adjustment for antecedent soil moisture status.

EFFECTS OF PHYSIOGRAPHIC AND CLIMATIC FACTORS ON THE COEFFICIENT OF INITIAL ABSTRACTION

Introduction

In addition to having

(i) demonstrated from the published SCS plots of I_a on S that the coefficient of I_a was closer to 0,1 than to the conventionally used 0,2, and having

(ii) illustrated from analysis of 131 storm events from Natal catchments that the "best" coefficient for those data at 0,0472 was significantly lower than the suggested 0,2,

it was furthermore hypothesized that the coefficient was variable, dependent on physiographic features of a catchment as well as on the characteristics related to rainfall of the event and rainfall prior to the event.

The physiographic features which were selected and the effect that the features were considered to have on the coefficient of initial abstraction were :

(i) catchment area (km^2) : the larger the area the higher the coefficient;

(ii) mean catchment slope (percent) : the steeper the slope the lower the coefficient;

(iii) stream order : the higher the stream order (by the Strahler method of ordering) the lower the coefficient; and

(iv) drainage density ($km.km^{-2}$) : the higher the drainage density the more efficient the stream discharge was likely to be, also the greater the area contributing to stormflow was likely to be, hence the lower the initial abstraction and its coefficient.

It was appreciated, when these catchment features were selected, that some inter-correlation may exist between them, but it was not known which of the physiographic features may be dominant.

The selected rainfall-related characteristics thought to affect initial abstraction and hence its coefficient were

(i) rainfall amount (mm) : higher rainfall amounts would be subject to more abstraction than relatively lower rainfall amounts, possibly because rainfall intensities were likely to be lower and total infiltration consequently higher;

(ii) rainfall intensity ($mm.h^{-1}$) : the higher the intensity the more rapid the runoff response and consequently the lower the initial abstraction;

(iii) duration (h) : the longer the duration the higher the initial abstraction, and

(iv) antecedent moisture condition (curve number) : the moister the soil, the larger the contributing area of a catchment to stormflow, consequently the lower the initial abstraction was likely to be, all other factors being equal.

Again it was appreciated that some inter-correlation between the first three rainfall characteristics was likely to exist, but it was not possible to predetermine which characteristic was dominant.

The basic premise of this research was to determine, by stepwise multiple regression, which of these variables would account for the coefficient of initial abstraction more satisfactorily than the "fixed" 0,2 used conventionally.

Choice of Events

In order to cover a wide spectrum of hydrological environments, the data sets selected initially for this exercise consisted of

(i) the 131 events from 10 Southern African catchments used in the previous section and

(ii) the 250 events from the 20 catchments in seven widely ranging hydrological regimes which had been used in the study of curve number adjustment reported in Chapter 3 of this report. The details of these 250 events had previously been extracted from the series "Hydrologic Data for Experimental Agricultural Watersheds in the United States" (Burford et al, 1980 and previous years).

Details of the individual storm events, antecedent conditions and the physiographic features of the catchments have been published in other chapters of this report and by Arnold (1980), Schulze (1982) and Schmidt and Schulze (1984), and are not repeated here.

From the initial data set, an elimination process rejected events as follows:

(i) Forested catchments (three catchments out of 30), were omitted on the basis that their land use constituted a special case warranting separate study in terms of initial abstraction.

(ii) Events of less than 25 mm rainfall generally were eliminated from the data set. A few events with a threshold of 20mm were included where otherwise an entire catchment's data would have to be rejected.

(iii) Events which were not independent were rejected, i.e. at all locations where an event of a certain day was represented in the data of more than one catchment, these events were considered non-independent and only one event of those data was kept at that location. Rejection was done on a random basis.

Following the above elimination processes the data were grouped into three sets, namely from

(i) U.S.A. "humid" regions, with 66 events from catchments 26001, 26003, 26005, 42024, 42028, 37001, 37002, 37003, 44005, 44006 and 44022;

(ii) U.S.A. "arid" regions, with 68 events from catchments 63003, 63004, 45001, 45002, 45004, 47001, 47002 and 47003; and

(iii) Natal catchments with 79 events from W1M16, W1M17, V1M28, V7M03 and U2M20.

Each set's data were further split randomly into two groups in order to obtain so-called "control" data and "test" data sets.

The eight variables tested displayed a wide range of limits, as is shown in Table 4.5, with the result that any improvements made to cI_a would be considered applicable to a similar wide range of conditions.

Table 4.5 Upper and lower values of variables used in the determination of cI_a

Variable	U.S.A. "Humid"		U.S.A. "Arid"		Natal		All Groups	
	Lower Value	Upper Value	Lower Value	Upper Value	Lower Value	Upper Value	Lower Value	Upper Value
Catchment Area (km^2)	0,005	0,84	0,17	9,06	0,259	3,322	0,005	9,06
Slope (percent)	1,8	23,6	5,8	15,8	10,0	19,5	1,8	23,6
Stream Order	1	3	2	4	2	4	1	4
Drainage Density ($km.km^{-2}$)	2,74	54,23	2,38	33,57	3,54	5,50	2,38	54,23
Rainfall Amount (mm)	15,01	119,6	5,8	66,5	20,1	189,0	5,8	189,0
Maximum 30-minute Intensity ($mm.h^{-1}$)	12,70	127,00	7,62	101,60	4,064	88,90	4,06	127,00
Duration (h)	0,5	8,0	0,5	4,0	1,0	33,3	0,5	33,3
CN - SCS	48,81	91,89	61,71	91,89	42,18	89,75	42,18	91,89
CN - SMB2	67,05	96,88	74,42	93,73	75,41	97,49	67,05	97,49

Procedures

(a) Once the data had been prepared, stormflow was simulated using $I_a = 0,2\ S$

(i) by the conventional SCS technique of curve number adjustment, with defined antecedent rainfall classes for the growing and dormant seasons (SCS-STD), and

(ii) by the soil moisture budgeting modification to the SCS method, described in detail as the SCS-SMB2 model in Chapter 3 of this report and in Schulze (1982).

(b) Using observed rainfall (P, in mm), observed stormflow (Q, in mm) and a value of S obtained respectively in the conventional SCS-STD approach and the SCS-SMB2 approach

(i) from the catchment curve number adjusted by antecedent moisture class, which was then converted to S (mm) by

$$S = \frac{25400}{CN} - 254 \qquad \text{and}$$

(ii) by moisture budgeting and considering S to be a moisture deficit (Chapter 3),

the actual values of initial abstraction for each event were determined from the equation

$$I_a = P - 0,5 \left[Q + (Q^2 + 4\ Q\ S)^{0,5} \right]$$

and the coefficient of initial abstraction was then calculated from

$$I_a = cS$$

$$c = I_a/S$$

(c) Stepwise multiple regression analysis was then applied to each of the three groups of "test" data, with the coefficient of initial abstraction of the individual events in each group of data as the dependent variable.

(d) The multiple regression equations for the coefficient were then substituted for the 0,2 used in the "control" data of each group and goodness of fit statistics were applied to determine whether model performance had been enhanced by the multivariate equation for the coefficient of I_a.

Results

(a) Relative Significance of Individual Variables

A ranking of the sequences (and hence importance) of the eight variables used for the determination of a coefficient of I_a by stepwise multiple regression technique is given in Table 4.6. It may be seen that different variables are assigned different rankings, dependent on location and physical environment. For example, catchment slope is an important variant in the cI_a in arid catchments but not in the Natal catchments tested, in which rainfall amount is relatively more significant than elsewhere. Antecedent moisture condition appears a consistently highly ranked variable, irrespective of the method of determining AMC.

(b) Model Performance on Test vs Control Data

Model performances on test vs control data using cI_a = 0,2 and cI_a as a variable are summarized in Table 4.7. The

Table 4.6 Relative significance of individual variables in multiple regression equations of cI_a

Variable	Ranking by Catchment Group and SCS method							
	U.S.A. "Humid"		U.S.A. "Arid"		Natal		All Groups	
	SCS	SMB2	SCS	SMB2	SCS	SMB2	SCS	SMB2
Catchment Area	6	6	4	3	7	5	4	4
Slope	1	1	3	2	8	8	1	1
Stream Order	3	3	6	6	6	6	8	7
Drainage Density	7	7	1	1	5	7	6	6
Rainfall Amount	8	4	5	4	1	1	3	2
Intensity	5	8	7	7	4	3	5	5
Duration	2	5	8	8	3	4	7	8
CN - SCS	4	NA	2	NA	2	NA	2	NA
CN - SMB2	NA	2	NA	5	NA	2	NA	3

Table 4.7 Model performance of cl_a as a variable on test vs control data (catchments selected randomly)

Test	Statistic	U.S.A. DATA																NATAL DATA					
		"Humid" Catchments								"Arid" Catchments													
		4405		3701		3702		4228		6303		4501		4504		4703		W1M16		V7M03		U2M20	
		SCS	SMB	SCS	SMB	SCS	SMB	SCS	SMB	SCS	SMB	SCS	SMB	SCS	SMB	SCS	SMB	SCS	SMB	SCS	SMB	SCS	SMB
a) "Test" data using cl_a = 0,2 (control)	D	,68	,96	,44	,30	,75	,97	,30	,60	(-) ,02	,68	,54	,30	,88	,91	,31	,65	,94	,97	(-) ,22	,22	,17	,53
	F_1	,22	,01	4,18	1,55	1,03	,29	,71	,11	,50	,02	3,36	,66	2,93	,57	2,19	,77	2,03	2,54	2,15	84,36	1,34	42,47
b) Equation with 5 variables developed from "control" data, used with "test" data	D	,71	,95	,60	,31	,88	,97	,33	,58	,46	,55	,35	,15	,89	,91	,81	,67	,89	,92	,19	,07	(-) ,20	(-) ,09
	F_1	,82	,13	,40	,72	,34	,14	,11	,01	,16	,12	,07	,53	2,29	1,57	,34	,48	,07	,01	,33	,67	2,75	5,05
c) Equation with 8 variables developed from "control" data, used with "test" data	D	,74	,96	,45	,30	,90	,96	,40	,58	,31	,55	,23	,15	,90	,91	,76	,67	,89	,92	,41	,07	(-) ,10	(-) ,18
	F_1	1,07	,13	,17	,58	,06	,06	,17	,04	,09	,10	,15	,54	2,30	1,53	,16	,43	,07	,01	,26	,48	2,43	4,55
d) All data, using cl_a = 0,2 (control)	D	,33	,92	,58	,76	,73	,78	,39	,78	,25	,89	,72	,59	,14	,24	,20	,45	,88	,96	,02	,87	,28	,37
	F_1	,41	,003	1,61	,51	1,30	,31	,50	,07	,28	,02	1,90	,28	,65	6,26	2,39	,92	1,91	2,93	,54	3,19	1,52	30,84
e) Equation with 5 variables, developed from all data and used with all data	D	,49	,91	,76	,76	,76	,77	,51	,77	,74	,87	,51	,51	,25	,25	,51	,55	,83	,90	,18	,56	(-) ,01	(-) ,01
	F_1	,46	,09	,23	,20	,19	,10	,02	,0004	,10	,04	,04	,11	,47	3,56	,47	2,63	,16	,03	,11	,10	2,35	6,60
f) Equation with 8 variables, developed from all data and used with all data	D	,54	,89	,79	,76	,78	,78	,57	,78	,75	,87	,48	,50	,26	,26	,50	,54	,83	,90	,12	,56	(-) ,0	(-) ,02
	F_1	,20	,03	,11	,14	,09	,06	,02	,003	,11	,03	,04	,11	,46	3,47	,46	2,54	,15	,03	,10	,05	2,02	5,96

statistic D shown in Table 4.7 is the Coefficient of Determination and the statistic F_1 is the difference between D and E, the Coefficient of Efficiency. The relevance of all three of these statistics is explained in Chapter 3; however, the closer F_1 tends to zero, the less systematic error occurs in simulated stormflows.

From an examination of Table 4.7 the following general observations may be made:

(i) For both SCS-STD and SCS-SMB2 versions of the model, the simulated stormflows generally are improved, for some catchments markedly (in terms of model efficiency and systematic error, i.e. D higher; F_1 lower) when the variable cI_a is compared with the fixed $cI_a = 0,2$.

(ii) In applying the multivariate-derived coefficient of I_a, only the "best" five variables need to be used; there is hardly any further improvement when all eight variables are used to generate a cI_a.

(iii) The improvements by a multivariate-derived cI_a are more evident in the SCS-STD than in the SCS-SMB2 version of the model, probably because the conventional SCS-STD model can have only three values of CN (those for AMC-I, -II and -III) rather than the range of CNs which may be derived in the SCS-SMB2 model.

(c) General Equations for the Coefficient of Initial Abstraction

Following the improvements in the performance of the SCS model by making the coefficient of I_a a variable, the procedures described previously for determining a multivariate coefficient were applied to the combined data sets (i.e. test plus control events) of the three groups of catchments. The resulting equations for improved coefficients of I_a are listed below for the conventional SCS stormflow equation (SCS-STD) and for the moisture budget modified version of the SCS stormflow equation (SCS-SMB2).

(i) U.S.A. "Humid" Regions

$$cI_a \text{ for SCS-STD} = 0{,}0146\ SI + 0{,}0203\ Du - 0{,}0532\ SO + 0{,}0023\ CNSCS + 0{,}0009\ I_{30} - 0{,}3484$$

$$cI_a \text{ for SCS-SMB2} = 0{,}0094\ SI - 0{,}00723\ CNSMB - 0{,}0604\ SO + 0{,}0015\ P + 0{,}0102\ Du + 0{,}5753$$

(ii) U.S.A. "Arid" Regions

$$cI_a \text{ for SCS-STD} = -0{,}0074\ DD + 0{,}0075\ CNSCS + 0{,}0118\ SI + 0{,}0124\ A + 0{,}0005\ P - 0{,}5542$$

$$cI_a \text{ for SCS-SMB2} = 0{,}0055\ DD + 0{,}0229\ SI + 0{,}0099\ A + 0{,}0021\ P - 0{,}0058\ CNSMB + 0{,}3581$$

(iii) Natal

$$cI_a \text{ for SCS-STD} = 0{,}0123\ P + 0{,}0144\ CNSCS - 0{,}0180\ Du - 0{,}0062\ I_{30} + 0{,}1090\ DD - 1{,}3115$$

$$cI_a \text{ for SCS-SMB2} = 0{,}0202\ P + 0{,}0753\ CNSMB - 0{,}0179\ Du - 0{,}0096\ I_{30} + 0{,}0247\ A - 6{,}211$$

In these equations,

- P = rainfall amount (mm),
- Du = duration of rainfall event (h),
- I_{30} = maximum 30-minute intensity ($mm.h^{-1}$),
- A = catchment area (km^2),
- Sl = mean catchment slope (percent),
- SO = stream order, and
- DD = drainage density ($km.km^{-2}$).

CONCLUSIONS

This research on the coefficient of initial abstraction has shown the following:

(a) A coefficient of 0,2 is an overestimate if the published plot by the SCS of I_a vs S is analysed, and a more likely value from the plot would be 0,12 which is in line with values found by other researchers in the U.S.A.

(b) The coefficient is shown to vary, but not significantly, with antecedent moisture status and with season when tested on Natal catchments, tending to increase with high AMC and to be lower in the dormant than in the growing season.

(c) A coefficient of 0,05 was found to be generally more applicable to those Natal catchments tested than the recommended value of 0,2.

(d) By the application of physiographic and rainfall variables, a series of multivariate equations was developed which result in improved estimates of stormflow by conventional and modified SCS equations.

It is in this last-named point that further research is likely to be most promising. The equations which have been presented have been derived from a wide spectrum of hydrological environments, but should be used only within the range of the values of individual variables for which they were developed and within constraints (e.g. 0,3 cI_a 0,03). On ungauged catchments, regional and seasonal estimates of I_{30} and rainfall duration would have to be substituted in the relevant equations. The problem of intercorrelation between variables needs to be examined in detail, possibly by factor analysis. Finally, first tests on data are showing that rather than determining a variable coefficient of initial abstraction, even more improvement in model performance may be achieved by determining a variable amount of initial abstraction.

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CHAPTER 5

MODIFIED SCS LAG EQUATIONS FOR IMPROVED ESTIMATES OF PEAK DISCHARGE RATES[1)]

E.J. Schmidt and R.E. Schulze

INTRODUCTION

The SCS equation for the estimation of peak discharge rates is given by

$$q_p = \frac{0{,}2083\ A\ Q}{D/2 + L} \qquad \text{Eq. 1}$$

where

q_p = peak discharge rate ($m^3.s^{-1}$),

A = catchment area (km^2),

Q = unit volume of stormflow (mm),

D = unit duration of effective rainfall (h), and

L = catchment lag time (h), an index of response time of runoff to rainfall.

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1) This chapter summarizes research findings reported in full in an Interim Report entitled "Improved estimates of peak flow rates using modified SCS lag equations". The Interim Report was recommended to the W.R.C. by the Steering Committee of this project in 1983 and published in 1984.

Lag time is calculated from the physical properties of a catchment and may be expressed in metric units (Schulze and Arnold, 1979) as

$$L = \frac{l^{0,8}(S' + 25,4)^{0,7}}{7069\ y^{0,5}} \qquad \text{Eq. 2}$$

where

l = hydraulic length of the catchment (m),

y = average catchment slope (percent), and

S' = potential maximum retention of the soil (mm) for average antecedent moisture conditions.

When the entire catchment is contributing uniformly to runoff, it is usually sufficient to relate lag time to the catchment's time of concentration (T_c) with the equation given by Kent (1973) as

$$L = 0,6\ T_c \qquad \text{Eq. 3}$$

The estimation of peak flow rate by Equation 1 assumes a storm of uniform areal and temporal distribution. Of the three variables in Equation 1 which might yield improvements to peak discharge estimates, namely the hydrograph shape (expressed by the constant 0,2083), the effective storm duration and catchment lag, this chapter examines background and possible improvements to the estimation of lag, which has frequently been attributed as a major source of error in the q_p equation (Schmidt and Schulze, 1984).

THE NON-LINEARITY OF CATCHMENT RESPONSE

The calculation of peak discharge rate by Equation 1 makes use of a dimensionless triangular unit hydrograph (Chapter 1) in which the catchment's response time, i.e. lag, is related solely to catchment invariant physiographic factors, (namely, hydraulic length, retardance and slope, as in Equation 2), thereby introducing linearity into the response factor.

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. This applies particularly to small catchments, in which peak discharge rates are subject, inter alia, to varying intensities of rainfall.

The need for modifications to the unit hydrograph procedure, to account for variations in rainfall inputs, is apparent to overcome the limitations of the approach.

APPROACHES TO RESEARCH

Various approaches are possible to incorporate non-linearity of the unit hydrograph in the SCS method by defining lag in terms of physiographic as well as rainfall variables. The three approaches adopted in this research are outlined below:

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

(b) Incremental triangular hydrographs are routed through the storm rainfall 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 would then determine the correct storm lag time, and this value would then be explained in terms of catchment and rainfall characteristics.

(c) 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.

CATCHMENT AND DATA DESCRIPTIONS

In total, 291 events were analysed from twelve small catchments located in Southern Africa and the United States of America. Details regarding the varied location, climate, vegetation, physiography and lithology of these catchments are summarized in Table 5.1.

Isolated, clearly defined, single peaked runoff hydrographs were selected from available digitized records and the widely accepted method described by Hewlett and Hibbert (1967) was used to separate quickflow from baseflow. Recorded outflow peaks from the small stilling basins did not differ markedly from backrouted inflow hydrograph peaks (Schmidt and Schulze, 1984) and the

Table 5.1 Catchments and their characteristics

Country	Location	Latitude & Longitude	Elevation (m)	Climate	M.A.P. (mm)	Vegetation	Catchment Identification	Catchment Area (km)	Hydraulic length of catchment (m)	Average Catchment Slope (%)	CN_{II}
USA	Coshocton, OH	40°22'N 82°01'W	373	Sub-humid	975	Pasture	26003	0,011	125	18,4	73
	Stillwater, OK	36°27'N 97°25'W	293	Sub-humid	725	Grassland	37001 37002	0,068 0,372	445 959	4,3 4,7	80 80
	Hastings, NE	40°16'N 98°35'W	597	Sub-humid	600	Grassland	44005	0,015	140	7,2	69
	Safford, AZ	32°51'N 110°00'W	1090	Arid	225	Sparse shrub, 85% bare	45001 45002	2,100 2,760	4530 5898	6,6 7,8	79 79
	Albuquerque, NM	35°05'N 106°50'W	1805	Arid	175	Shrub and short grass, 80% bare	47002	0,164	802	11,0	87
Southern Africa	DeHoek	29°01'S 29°10'E	1450	Sub-humid	850	Grassland	V1M12 V1M28 V7M03	0,500 0,410 0,450	726 808 938	20,0 10,1 15,2	74 74
	Zululand	28°50'S 31°46'E	250	Humid	1450	Grassland	W1M16 W1M17	3,222 0,669	3632 700	19,5 18,9	77 63

Sources : Arnold (1980); Schulze (1982)

recorded digitized trace was used in further analyses.

Indices used in the study to characterize the rainfall event and its antecedent conditions were:

P = storm rainfall amount (mm),

Du = duration of rainfall (h),

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

En = kinetic energy of the storm ($J.m^{-2}$), as calculated from the Wischmeier and Smith (1958) equation, and

API = 5-day rainfall total preceding the event (mm).

The Du and I_{30} indices were characterized regionally using the available data base in order to make comparisons.

DETERMINATION OF LAG TIMES BY SINGLE TRIANGULAR APPROXIMATIONS

Although computer models are used frequently to superimpose incremental hydrographs to obtain a compound hydrograph, it is often preferable and, in the absence of autographic rainfall data, necessary to assume a single triangular approximation of the runoff hydrograph. Such simplifications, which assume a temporally and areally uniform rainfall distribution, were utilized to form a triangular approximation of each runoff hydrograph with the same runoff volume as the recorded hydrograph but with the shape of the SCS unit hydrograph. Complete unit hydrograph techniques require the determination of the duration of effective rainfall for each event for the catchment in question using available rainfall records or, in their absence, a technique based on the runoff hydrograph itself (Pullen, 1969). While a later section deals with a more complete procedure of superimposed hydrographs of incremental duration, this initial analysis is confined by the assumption that the duration of effective rainfall for each storm was equal to the critical storm duration for the catchment, taken as the catchment time of concentration and specified in terms of lag time.

Initially, each catchment was assumed to have linear response characteristics to allow estimates of catchment lag time to be compared with those obtained using the SCS lag equation. For each catchment, linear runoff distributions of peak discharge regressed on runoff volume were derived and combined with Equation 1 to obtain estimates of the catchment lag time. Lag times so derived are tabulated in Table 5.2 and should be compared with the lag estimates derived using the SCS lag equation. The Coefficients of Efficiency, E (Aitken, 1973), for peak discharge estimates using the relevant lag times, are also given.

Deviations between recorded and estimated peak discharges (estimated using single triangular hydrographs) were applied in a regression analysis to identify which rainfall variables possibly accounted for intra-catchment variations of lag time. The variables used in the analysis and which have been defined in the previous section, were API, P, En, Du and I_{30}.

For eight of the 12 catchments, the association between errors in the estimated peak discharges and storm characteristics were significant at the 5 percent level. The most important variables accounting for such errors were the variables I_{30} (significant at the 5 percent level on seven catchments), En and Du (significant at the 5 percent level on five catchments). Since a high degree of intercorrelation existed between En and I_{30}, they were combined as EI_{30}, an index which appears to be a good indicator of rainstorm classification in terms of peak discharge-producing

Table 5.2 Comparisons of Coefficients of Efficiency for peak flow rate prediction for catchment lag times estimated using single triangular procedures and the SCS lag equation

Catchment	Estimated Catchment Lag Time (min)	E_1	SCS Lag Time (min)	E_2
26003	8,0	0,46	2,6	- 7,11
37001	31,4	0,68	8,5	- 4,96
37002	44,0	0,81	21,9	- 1,40
44005	6,6	0,71	5,2	0,59
45001	19,6	0,93	66,3	- 0,31
45002	11,8	0,89	60,0	- 0,54
47002	9,2	0,90	9,8	0,48
V1M12	44,9	0,97	10,2	- 16,06
V1M28	63,7	0,77	18,5	- 5,44
V7M03	78,9	0,69	14,3	- 28,66
W1M16	252,1	0,99	34,3	- 50,25
W1M17	117,0	0,74	13,7	-112,38

capacity and which has already been shown by Wischmeier and Smith (1958) to be a good indicator of rainstorm class in terms of erosion-producing capacity. Improvements to estimates of peak discharge rates based on the relevant catchment lag time (Table 5.2, Column 2), when intra-catchment variations in lag time due to rainfall characteristics are included, are illustrated for two catchments in Figure 5.1. While the improvements which rainfall variables have on estimates of peak discharge can be appreciated by drawing vectors linking corresponding storms, regionalisation did not yield satisfactory equations to link intra-catchment variations in lag time with storm characteristics which would be widely applicable. This was attributed to the complexity of the role played by rainfall and catchment characteristics in determining dominant runoff processes.

From the above, it was concluded that the SCS lag equation did not provide good estimates of catchment lag time when compared with estimates based on simple procedures embodying a single triangular approximation of recorded events with an assumed effective rainfall duration equal to the catchment critical response time. It was further thought that while improved estimates of peak discharge could be obtained when incorporating indices describing the individual rainfall event, a generalized equation could not be developed to describe adequately the factors involved.

DETERMINATION OF LAG TIMES BY INCREMENTAL TRIANGULAR HYDROGRAPHS

Superimposing incremental hydrographs determined from incremental periods of effective rainfall enables the synthesis of peak discharge and the total time distribution of runoff for a recorded storm event. The accuracy to which the synthesized runoff hydrograph approximates the recorded runoff hydrograph depends on the representativeness of the shape and lag time of the incremental hydrograph to be used in the synthesizing process.

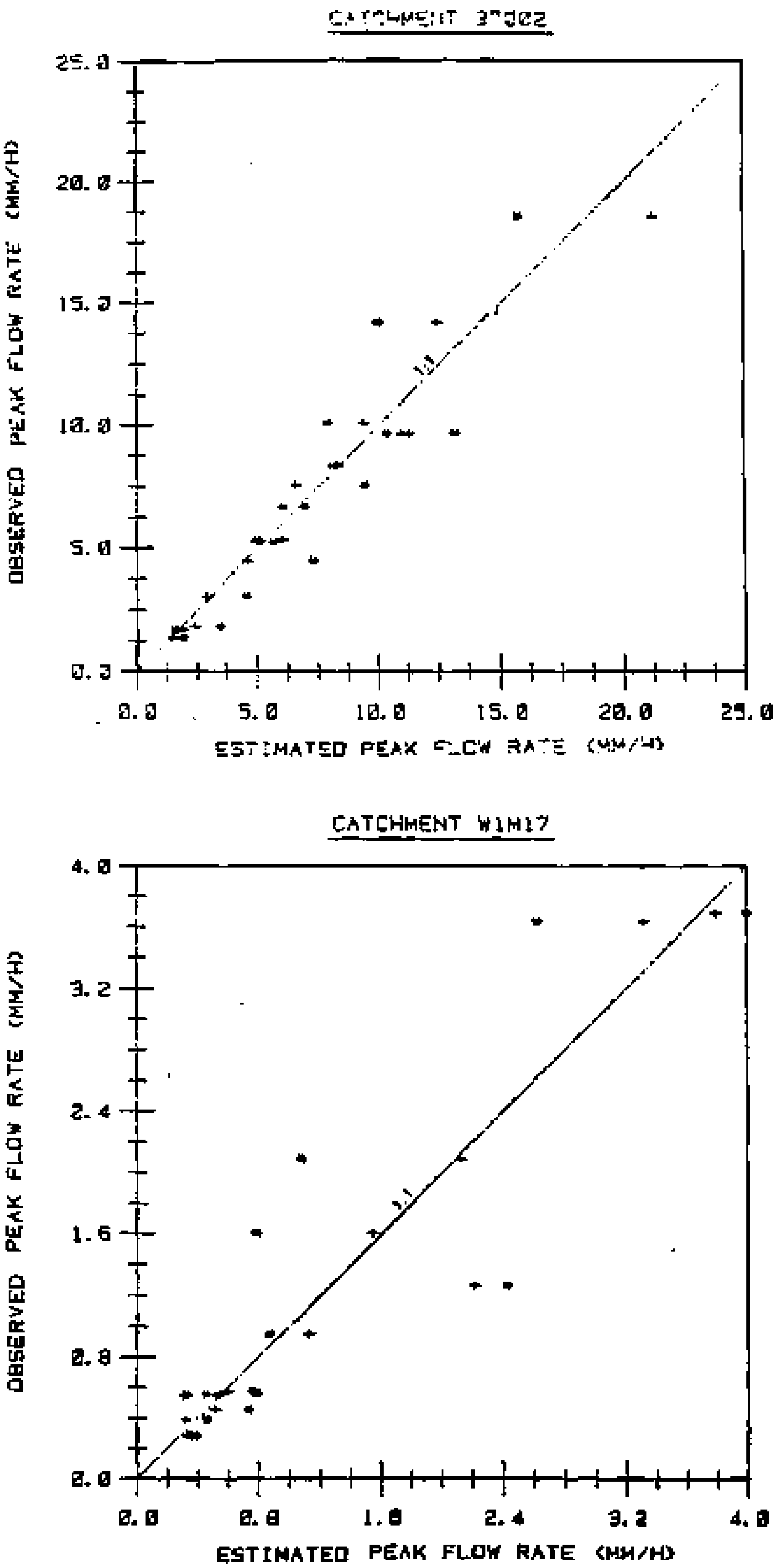

Figure 5.1 Observed peak flow rate vs estimates of peak flow rate for two selected catchments using an estimated catchment lag time (*) and estimated storm lag times (Schmidt and Schulze, 1984)

The lag time required to superimpose incremental triangular hydrographs to form a synthetic hydrograph of peak discharge equal to recorded peak discharge (optimized lag time) was determined for 172 events from catchments 26003, 37001, 44005, 45001 and W1M17, for which prepared data were readily available. Following the procedures employed previously when using single triangular hydrographs, recorded volumes of runoff were utilized in the calculations and the shape of the incremental hydrograph was held to conform to standard SCS procedures. Since the procedures were not restricted by assumptions of a temporally uniform rainfall, distributed over an empirically determined duration, the objective was to ascertain the reliability of the lag estimates derived previously.

Owing to non-linear processes not accounted for by unitgraph theory, lag time exhibited marked differences between the storms on a particular catchment. It was assumed that for a sufficiently large sample the resulting mean lag time represented adequately the catchment lag time. An index of the accuracy to which the shape of the recorded hydrograph was modelled by the synthetic hydrograph was obtained by combining digitized flow rates obtained at intervals along the recorded and synthetic hydrograph traces into the Coefficient of Efficiency, E (Aitken, 1973). Since E was required solely as an indication of the accuracy to which the hydrograph was modelled, ordinates of peak discharge for recorded and synthetic hydrographs of each event were aligned.

For 34 of the 172 events the recorded peak discharge could not be simulated by means of adjustments to the incremental hydrograph lag time. Such occurrences illustrate the need to adjust both lag time and unit hydrograph shape to provide accurate estimates of runoff events.

Figure 5.2 illustrates the recorded and synthetic hydrographs developed using the SCS lag time and optimized storm lag time

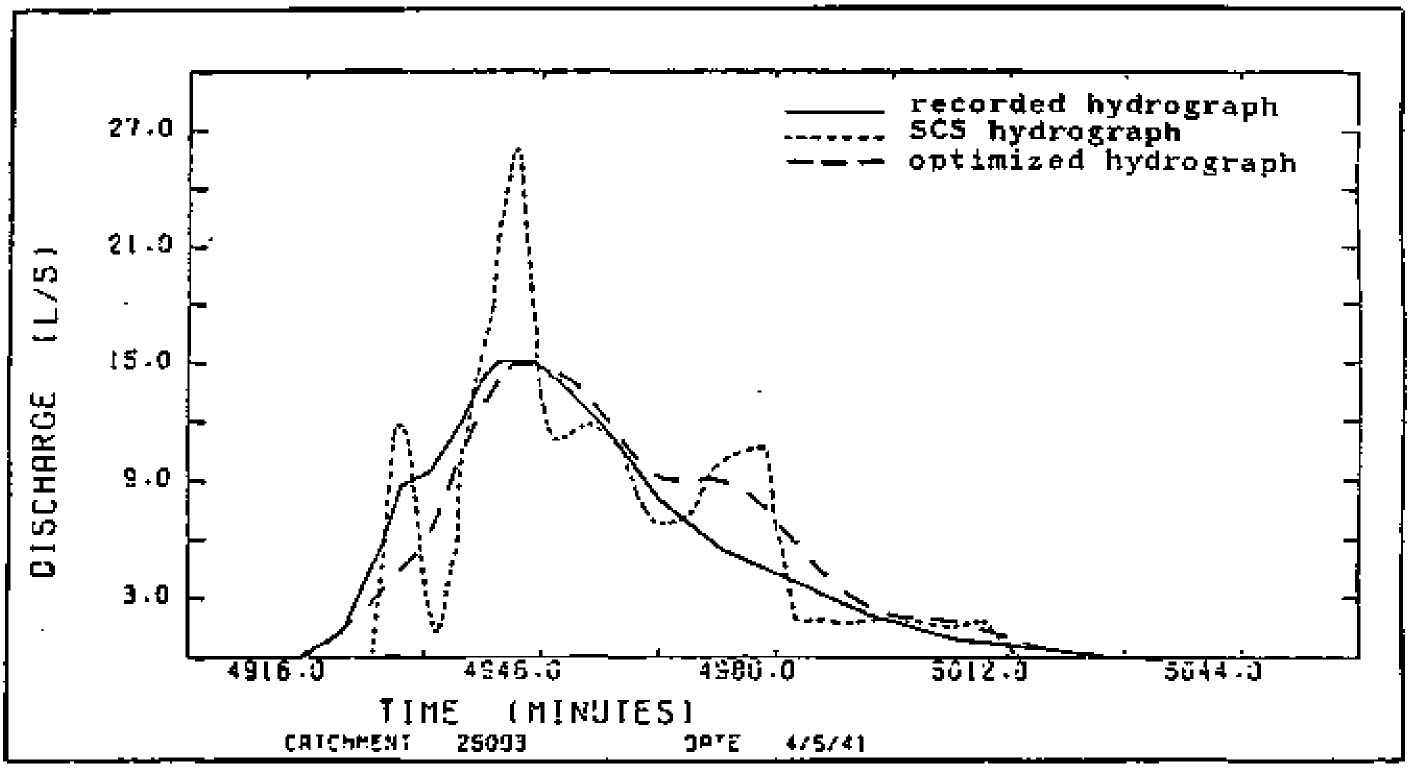

Figure 5.2 Comparison of the hydrographs synthesized using the SCS lag time and the optimized storm lag time with a recorded hydrograph on catchment 26003 on June 4, 1941 (Schmidt and Schulze, 1984)

(10,8 min) for an event recorded on catchment 26003. The SCS lag equation produces a quick response time with a resulting rapid response in generated runoff to the bursts of rainfall indicated in the hyetograph for the event (Figure 5.3). In reality a slower response time was present with a resulting dampening of the runoff processes.

Table 5.3 indicates for each catchment:

(i) the estimated catchment lag time (mean of the optimized storm lag times),

(ii) the standard error of the mean storm of lag time,

(iii) the SCS lag time (c.f. Table 5.2),

(iv) the mean Coefficients of Efficiency for the hydrographs synthesized for each event using the optimized storm lag time (E_1) and the SCS lag equation (E_2), and

(v) the mean ratio of peak discharge, synthesized using the SCS lag equation, divided by the observed peak discharge, namely q_e/q_o.

It may be seen from Table 5.3 that under-estimates of lag time are obtained using the SCS equation for the sub-humid and humid catchments 26003, 37001 and W1M17 (Table 5.1) with resulting excessive over-estimates of peak discharge. For catchments 45001 and 45002, which are located in arid areas (Table 5.1), peak discharge is under-estimated due to excessively long estimates of lag time. Catchment 44005 is the only catchment for which the SCS equation provides acceptable estimates of lag time.

The effect of the previously selected rainfall characteristics on individual storm lag times was determined from a multiple regression analysis, similar to that undertaken in the analysis

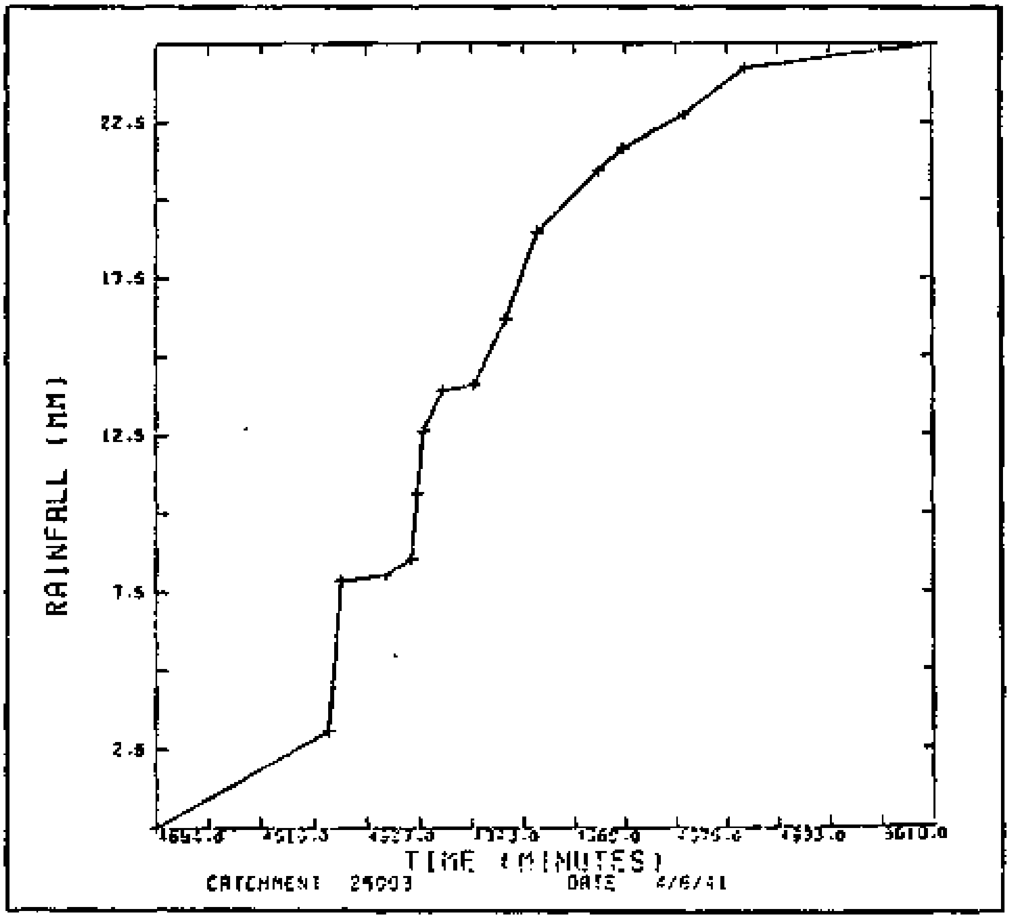

Figure 5.3 Hyetograph for the storm recorded on catchment 26003 on June 4, 1941 (Schmidt and Schulze, 1984)

Table 5.3 Details pertaining to hydrographs synthesized using estimated catchment lag times and SCS lag times

Catchment	Estimated Catchment Lag Time (min)	Standard Error of Mean	E_1	SCS Lag Time (min)	E_2	$\frac{q_e}{q_o}$
26003	6,7	1,7	77,2	2,6	21,5	1,4
37001	39,6	1,2	58,5	8,5	-423,0	2,2
44005	5,4	0,5	72,1	5,2	45,0	1,0
45001	20,4	1,5	71,9	66,3	35,4	0,5
45002	8,6	1,1	63,9	60,0	-9,3	0,3
W1M17	150,5	17,9	70,9	13,7	-520,8	5,8

using single triangular hydrographs. No independent variable was found to yield consistent and satisfactory regression equations. The poor results were attributed to the variable nature of the individual storm lag times which were highly sensitive to the variation in rainfall intensity throughout the storm. It appears that when using incremental procedures, unless the unit hydrograph can be adjusted from burst to burst within storms, rainfall non-linearity can only be acccunted for by providing localised rainfall depth-duration relationships, to be used together with a representative catchment lag time.

The catchment lag times generated using single hydrograph procedures (Table 5.2) are associated closely with those estimated using incremental hydrograph procedures (Table 5.3) which indicates, within the data limitations of this study, that the former approach provides a simple and yet effective means of determining an appropriate catchment lag time for gauged catchments.

DETERMINATION OF LAG TIMES MEASURED BY TIME RESPONSES BETWEEN DIGITIZED RAINFALL AND RUNOFF

Lag time has been defined as the time from the centre of mass of effective rainfall to peak discharge (USDA-SCS, 1972). The time response between effective rainfall and runoff was measured using autographic records for the storms of catchments 26003, 37001, 44005, 45002 and W1M17. Lag times were measured for each event and averaged for each catchment to determine an index of catchment lag time. Table 5.4 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. While the index of catchment lag time compares favourably with catchment lag times estimated using single and incremental triangular procedures, the high degree of scatter among measured storm lag times suggests that estimated sample means for catchment lag times are far less precise than those obtained from

Table 5.4 Statistics for the storm lag times (in minutes) measured from autographic rainfall and runoff records

Catchment	Mean Lag Time (min)	Standard Error of Mean	Minimum Lag Time (mm)	Maximum Lag Time (mm)	Range (min)
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

superimposed incremental hydrograph procedures. The measurement of large negative lag times was common, due to poorly synchronized rainfall and runoff recorders, which suggests that measured time differences between rainfall and runoff provide poor indices of runoff response to rainfall.

DETERMINATION OF LAG TIME FOR UNGAUGED CATCHMENTS

Catchment lag times determined using single and incremental hydrograph procedures have proved to be closely related. The relationship was investigated between catchment lag time, estimated using single hydrographs, and indices of physiography, climate and regional rainfall characteristics (averaged from the data base for each site) to enable the prediction of lag time on non-cultivated rural catchments where hydraulic principles cannot be applied easily to calculate flow times.

The dominant physiographic variables explaining the variance in lag time were catchment area, A, and average catchment slope, y. The mean annual precipitation for the catchment, MAP, an index used widely to characterize overall climate and moisture status of a catchment, and the average of the most intense 30-minute periods of rainfall for the storms of each site, an index of potential runoff from rainfall, provided the best indices accounting for residual variations in lag time.

MAP has a major influence on both soil conditions and their drainage characteristics (Bedient, Huber and Heaney, 1978) and is a dominant factor influencing type and condition of vegetation. Both soils and vegetation affect the retardance and proportions of surface and subsurface flow (the latter contributes up to 70% of direct runoff in the Zululand catchments) suggesting a link between MAP and catchment lag time.

The temporal distribution and intensity of rainfall has a dominating influence on runoff mechanism which is modified by the effect due to soils and vegetation. Short intense storms, such as those recorded typically at station 44005, generally exceed infiltration rates and tend to produce overland flow conditions while long duration storms of low intensity, such as those recorded typically in Zululand, generally tend to initiate subsurface flow. Although storm characteristics vary widely within a region, when typified for a region (as has been done for the available data base or may be done using depth-duration-frequency analyses) they provide improved estimates of lag time when incorporated with physical catchment characteristics in an empirical lag equation.

The regression equation developed is given as

$$L = \frac{A^{0,35} MAP^{1,1}}{41,67\ y^{0,30} I_{30}^{0,87}} \qquad r = 0,93 \qquad \text{Eq. 4}$$

where

L = catchment lag time (h),

A = catchment area (km^2),

y = average catchment slope (percent),

MAP = mean annual precipitation (mm), and

I_{30} = average maximum thirty minute period of rainfall for the location ($mm.h^{-1}$).

The regression equation is significant statistically at the one percent level and is based on meaningful and simply defined variables. A scatter diagram of lag times calculated for each catchment using single triangular procedures and estimates of such lag times based on the SCS equation (Equation 2) and the equation given above (Equation 4), is given in Figure 5.4. The

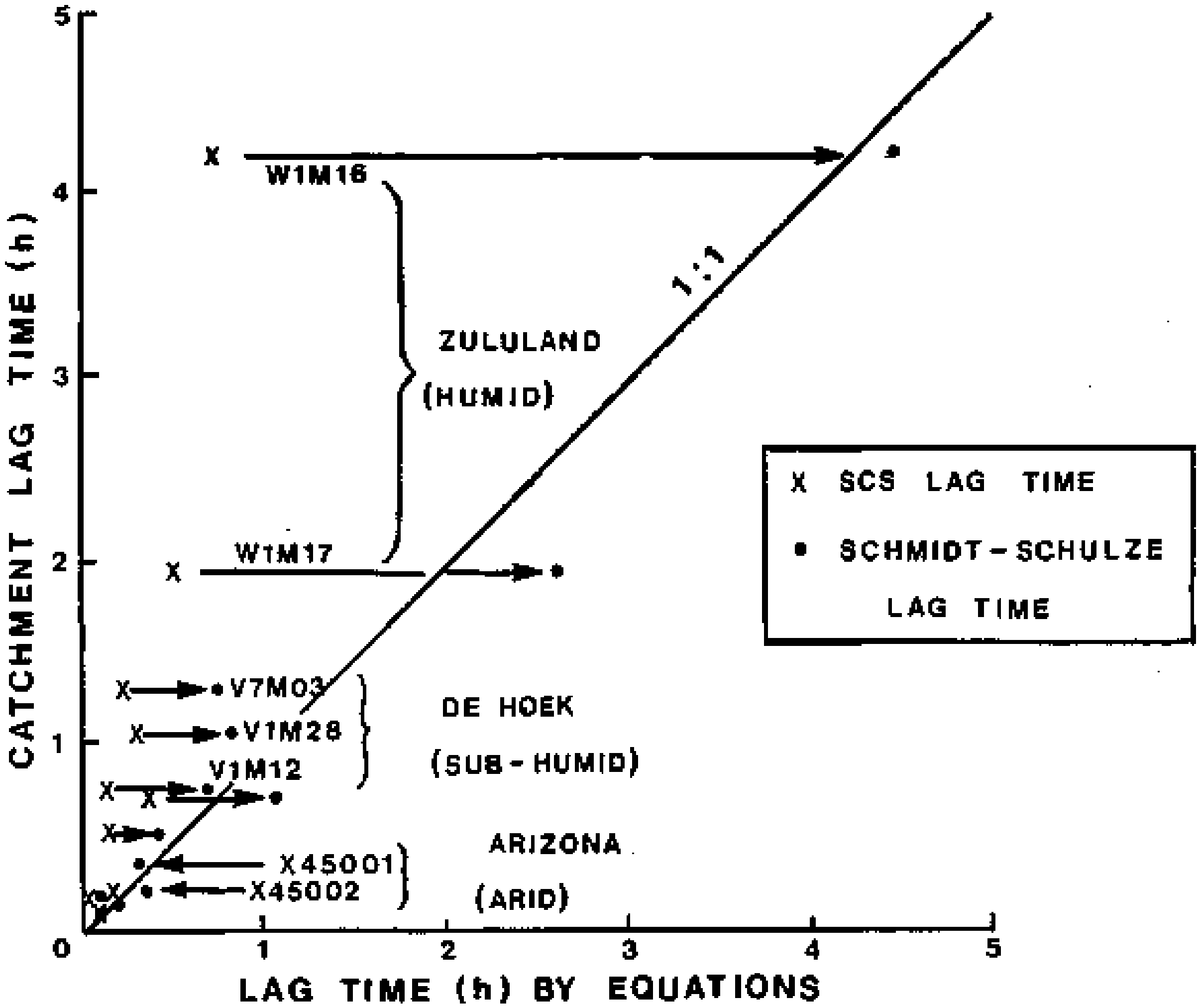

Figure 5.4 Comparison of lag times based on the SCS equations and the Schmidt-Schulze (1984) equation with catchment lag times (after Schmidt and Schulze, 1984)

diagram indicates the close approximation of the point distribution to the 1:1 line when Equation 4 is used to estimate lag time.

Empirically-derived relationships are applicable only in areas adequately represented by the original data base. While a wide range of catchments was examined in this study, it must be concluded that similar research, encompassing the techniques discussed, should be conducted using a bigger sample of Southern African data. Studies such as this emphasize the paucity of readily available digitized data for small catchments offering typical land-use characteristics commonly found in South Africa. Improved modelling efficiencies can only be expected with an accompanying expansion of data for testing purposes, undoubtedly one of the major restrictions in South African hydrological research today.

CONCLUSIONS

In an attempt to estimate peak flow rates more realistically using the SCS model, several procedures towards the improvement of estimates of lag time were examined. It can be concluded that improved catchment estimates of lag time can be obtained for ungauged catchments by incorporating indices of climate and regional rainfall characteristics into an empirical lag equation. Intra-catchment variations in lag time may similarly be determined from storm characteristics, although not as yet on a generalized scale.

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CHAPTER 6

STORM RAINFALL DISTRIBUTION FOR USE IN THE SCS MODEL

INTRODUCTION

The distribution of rainfall intensities is one of the primary inputs into hydrological models used for hydraulic design purposes on small catchments. Since the SCS model uses daily rainfall input, regional synthetic rainfall distributions have to be used. In the SCS manual for Southern Africa the Type I and Type II storm rainfall distributions were adapted provisionally by Schulze and Arnold (1979). Type I "low" intensities were associated with maritime climates and/or winter rainfall regions of the southern and western Cape coast while the Type II distribution, yielding higher peak discharge rates, are more typical of the Southern African interior characterized by high intensity thunderstorms, usually generated over small areas. These two rainfall distributions, in which D-duration rainfall is expressed as a ratio of the 24-hour rainfall, have been illustrated in Chapter 1 (Figure 1.3).

In the 1979 publication on the SCS technique for use in Southern Africa, the authors stated: "Tentative research into time distributions of rainfall in South Africa indicates

(i) that for design storms the Type II distribution can be used throughout the country and

(ii) that even use of the Type II distribution may underestimate peak rates of runoff to a varying extent in parts of the country. The time distribution of rainfall in South Africa is a key area for future research in hydrology" (Schulze and Arnold, 1979).

THE NEED FOR REVISED STORM RAINFALL DISTRIBUTIONS FOR SOUTHERN AFRICA

The need for revised storm rainfall distributions for use in the SCS and other models was highlighted following

(i) the analysis of design rainfall distributions in Natal (Schulze, 1984) based on digitized data generated during a now completed project to the Water Research Commission (Schulze and Dent, 1982) and

(ii) a re-evaluation of the SCS distributions for the eastern U.S.A. by Cronshey (1982), in which more "intense" distributions than the Type II were found.

Some results presented by Schulze (1984) illustrated the need for a revision of synthesized storm distributions in Southern Africa. Table 6.1 and Figure 6.1 show the D-hour to 24-hour ratios generally to be well in excess of those derived from Midgley and Pitman (1978) or Adamson (1981), which in turn are markedly higher than the SCS Type I and Type II distributions. The storm rainfall distributions are, furthermore, apparently not independent of recurrence interval, as stated by Adamson (1981) and by others and as implied by the SCS (and Midgley and Pitman, 1978) distributions. Figure 6.2 illustrates this.

Table 6.1 Ratios of D-hour to 24-hour design rainfalls (Schulze, 1984)
(Log-Normal EV Distribution; 10 Year Return Period; Annual Maximum Series; Methods of Moments)

Location	Selected Durations (hours)										
	0,083 (5 min)	0,167 (10 min)	0,25 (15 min)	0,50	1,00	2,0	4,0	6,0	10,0	16,0	24,0
Inland											
Durban (LB)	0,13	0,18	0,23	0,36	0,45	0,55	0,63	0,69	0,80	0,90	1,00
Makatini	0,14	0,22	0,26	0,36	0,47	0,57	0,66	0,73	0,81	0,88	1,00
Coastal											
Kokstad	0,18	0,30	0,40	0,53	0,59	0,61	0,63	0,66	0,72	0,85	1,00
Pietermaritzburg	0,18	0,31	0,38	0,48	0,59	0,66	0,74	0,78	0,81	0,87	1,00
Ladysmith	0,20	0,31	0,38	0,54	0,67	0,73	0,78	0,81	0,85	0,90	1,00
Estcourt	0,18	0,32	0,41	0,60	0,73	0,81	0,87	0,89	0,93	0,96	1,00
Cedara	0,17	0,26	0,34	0,45	0,57	0,68	0,79	0,85	0,88	0,92	1,00
Waterford	0,20	0,31	0,38	0,52	0,65	0,73	0,80	0,85	0,93	0,96	1,00
Newcastle	0,17	0,26	0,33	0,52	0,65	0,73	0,79	0,84	0,89	0,96	1,00
Generalizations used in S.A.*											
Midgley-Pitman Coastal	0,10	0,15	0,19	0,26	0,36	0,47	0,58	0,66	0,78	0,89	1,00
Midgley-Pitman Inland	0,15	0,24	0,31	0,44	0,55	0,64	0,76	0,81	0,87	0,93	1,00
Adamson Coastal/Winter	0,12	0,19	0,23	0,32	0,41	0,53	0,67	0,75	0,85	0,94	1,00
Adamson Summer Region	0,15	0,25	0,32	0,50	0,60	0,72	0,82	0,87	0,92	0,97	1,00
SCS Type I	0,10	0,13	0,15	0,21	0,28	0,37	0,49	0,57	0,72	0,85	1,00
SCS Type II	0,12	0,22	0,28	0,38	0,45	0,54	0,64	0,70	0,77	0,87	1,00

* From tabulations and re-calculations, including interpolations and extrapolations

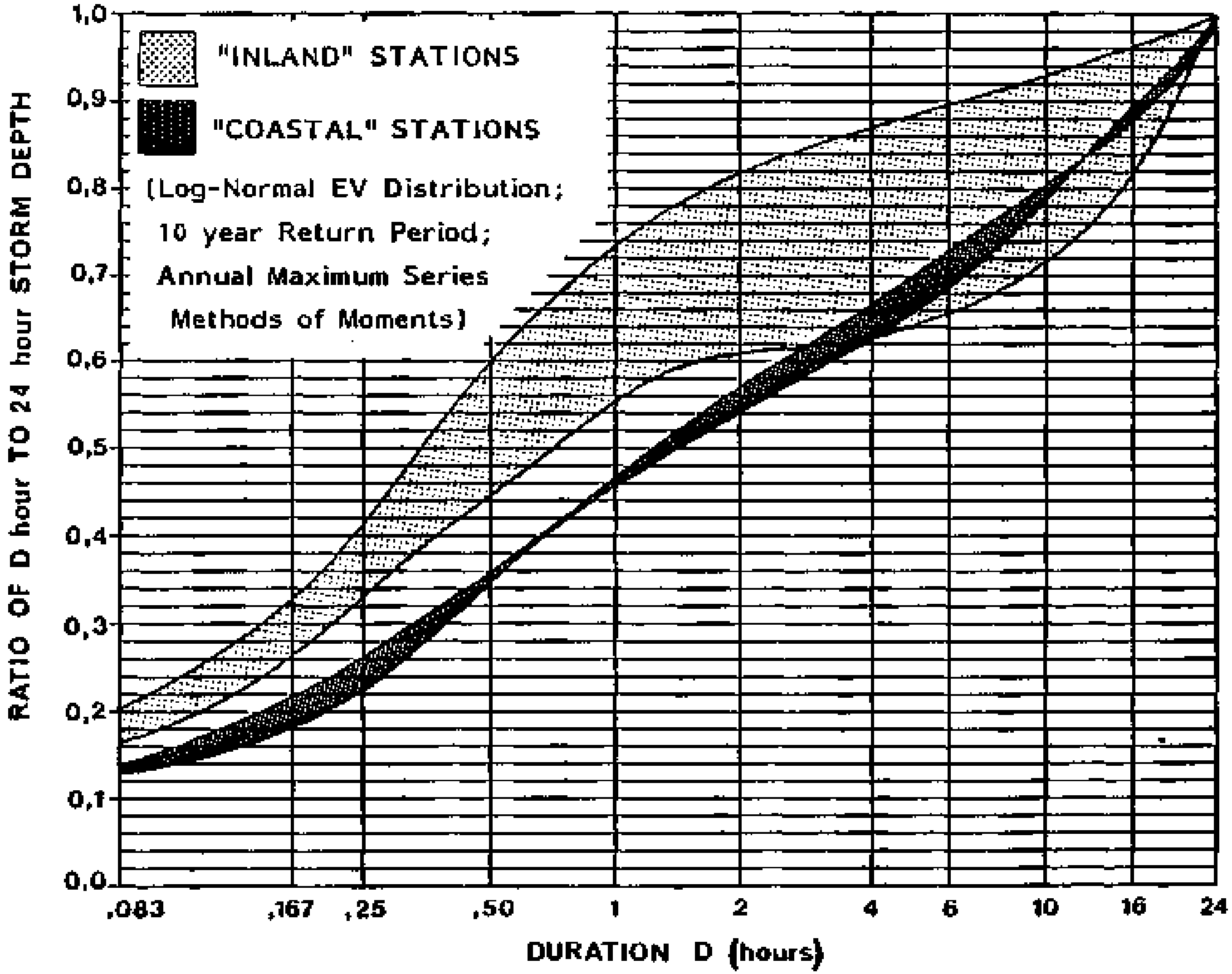
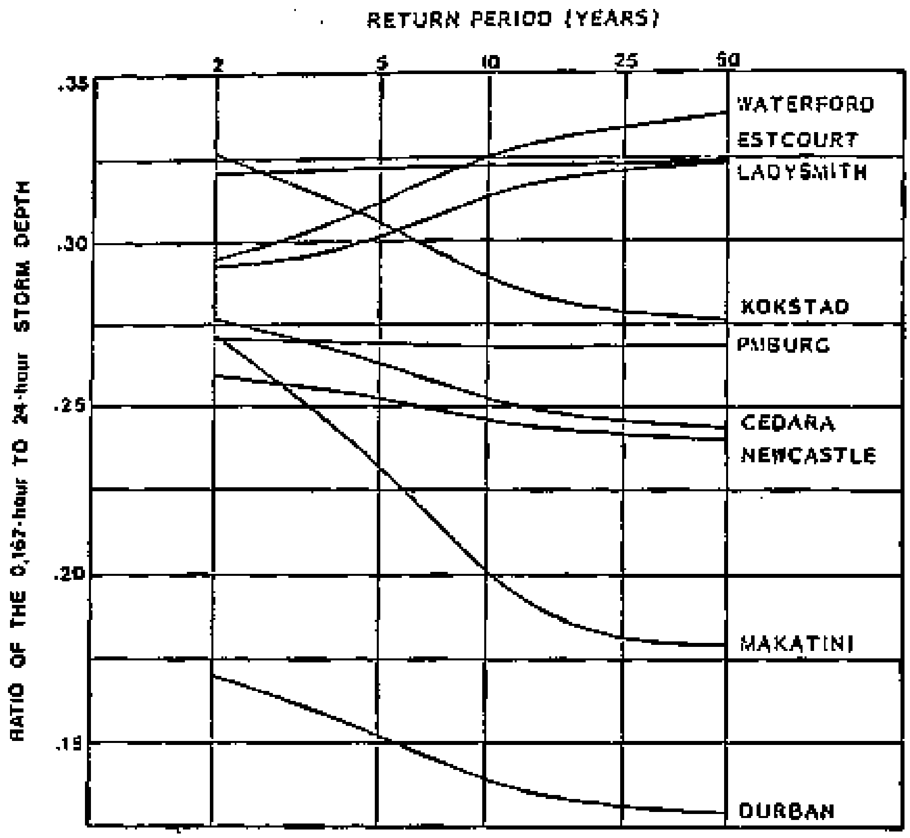


Figure 6.1 Range of D-hour to 24-hour ratios for stations in Natal (Schulze, 1984)



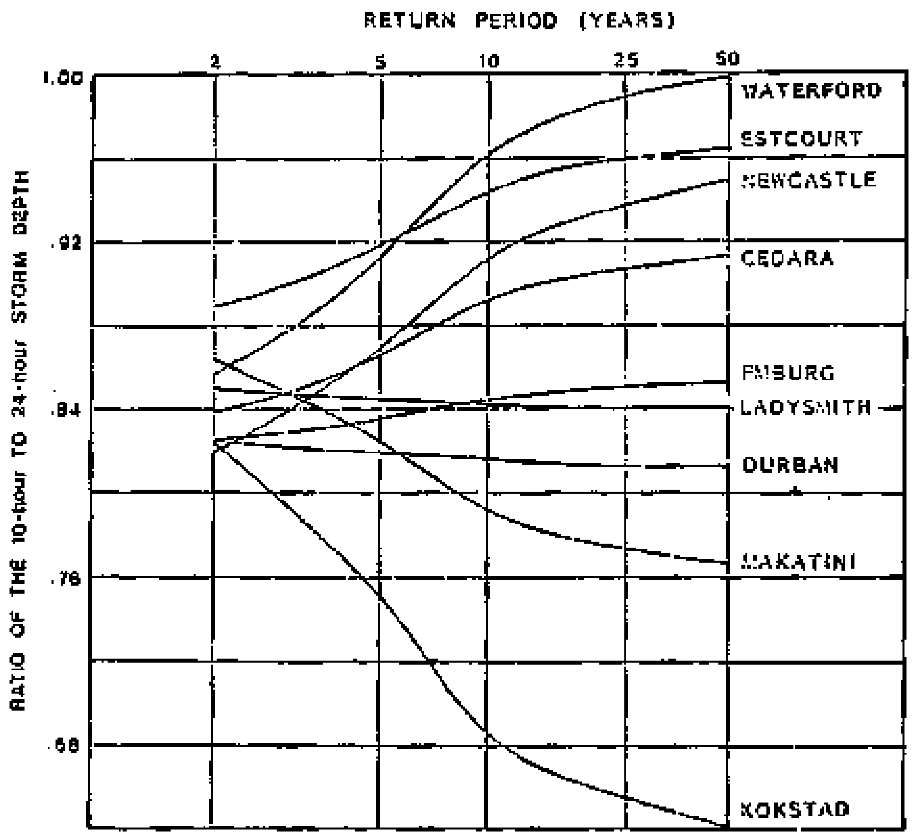


Figure 6.2 Systematic trends of D-hour to 24-hour ratios with return periods in Natal (Schulze, 1984)

PROCEDURES TO DEVELOP REVISED STORM RAINFALL DISTRIBUTIONS FOR SOUTHERN AFRICA

(a) From the digitized rainfall data base for Natal stations ratios of D-hour to 24-hour rainfalls were calculated for selected critical storm durations using a number of extreme value distributions (Schulze, 1984).

(b) These ratios were plotted against duration symmetrically about a central point for durations of 5, 10, 15, 30, 45 and 60 minutes and 2, 4, 6, 8, 10, 12, 16 and 20 hours. On the same graph, the two SCS and the Adamson (1981) distributions were also plotted. The assumption of a symmetrical distribution of rainfall intensity within a design storm may be argued, particularly for short duration thunderstorms in which the highest intensities frequently occur near the beginning and not in the middle of the event, or after runoff has already begun. The event which is distributed symmetrically does, however, produce a higher peak discharge rate than the early peaking event would. Thus an element of safety is inherent in the more convenient symmetrical distribution. The symmetrical distribution has also been used by Cronshey (1982) in his revision of rainfall distributions for the Soil Conservation Service of the U.S.D.A.

(c) From the range of plots, four storm rainfall distributions were drawn for application in Southern Africa. These four distributions approximate the following:

SA Type I : SCS Type I distribution

SA Type II : Durban's 10 year return period and SCS Type II distributions

SA Type III : Adamson's summer region distribution.

SA Type IV : Estcourt's 50 year return period distribution.

RESULTS : TENTATIVE SYNTHETIC STORM RAINFALL DISTRIBUTIONS FOR SOUTHERN AFRICA

(a) The four proposed synthetic storm rainfall distributions for application in Southern Africa are graphed in Figure 6.3. Since, however, critical short duration rainfall distributions of less than three hours are the distributions used most commonly on small catchments, this section of Figure 6.3 has been enlarged in Figure 6.4. These distributions would be applied in the identical manner for the construction of design hydrographs as described in detail and illustrated by worked examples in the SCS manual for Southern Africa (Schulze and Arnold, 1979). These diagrams are simpler to use than the original SCS diagrams on synthetic rainfall distribution because of the assumed symmetry of a design rainfall event and the centering of the highest intensities around 12h00, as Cronshey (1982) has now also proposed for the SCS model in the U.S.A.

(b) The D-hour to 24-hour ratios for the four distributions, as well as the ranges of the ratios, are given for selected durations in Table 6.2.

(c) Using the four synthetic rainfall distributions (Figures 6.3 and 6.4) and the ranges of ratios given in Table 6.2, the digitized rainfall data for nine Natal stations were analysed to determine which distributions would apply at those nine locations. Results are summarized in Table 6.3.

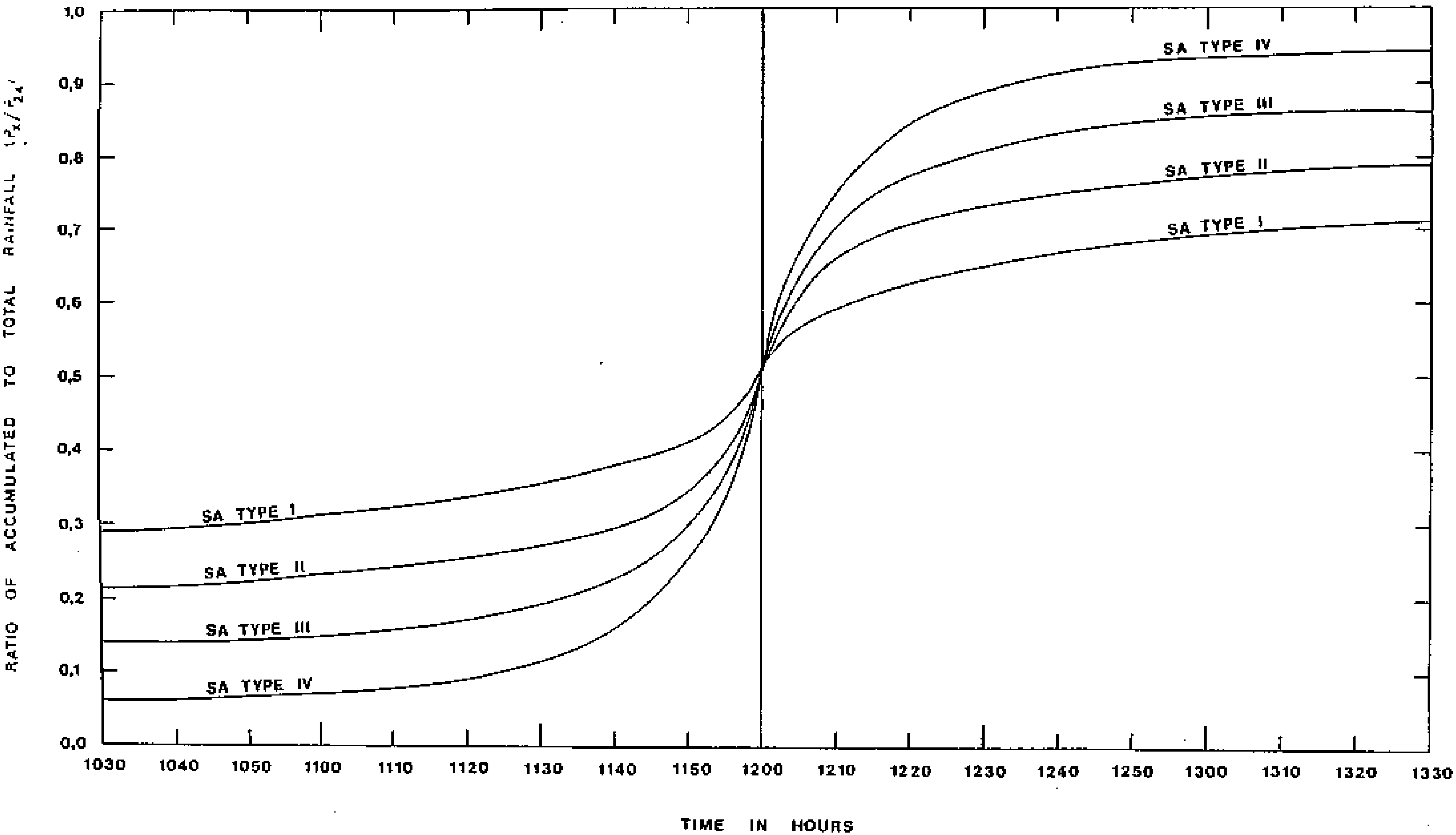


Figure 6.4 Proposed storm rainfall distributions for application in Southern Africa - enlarged critical section

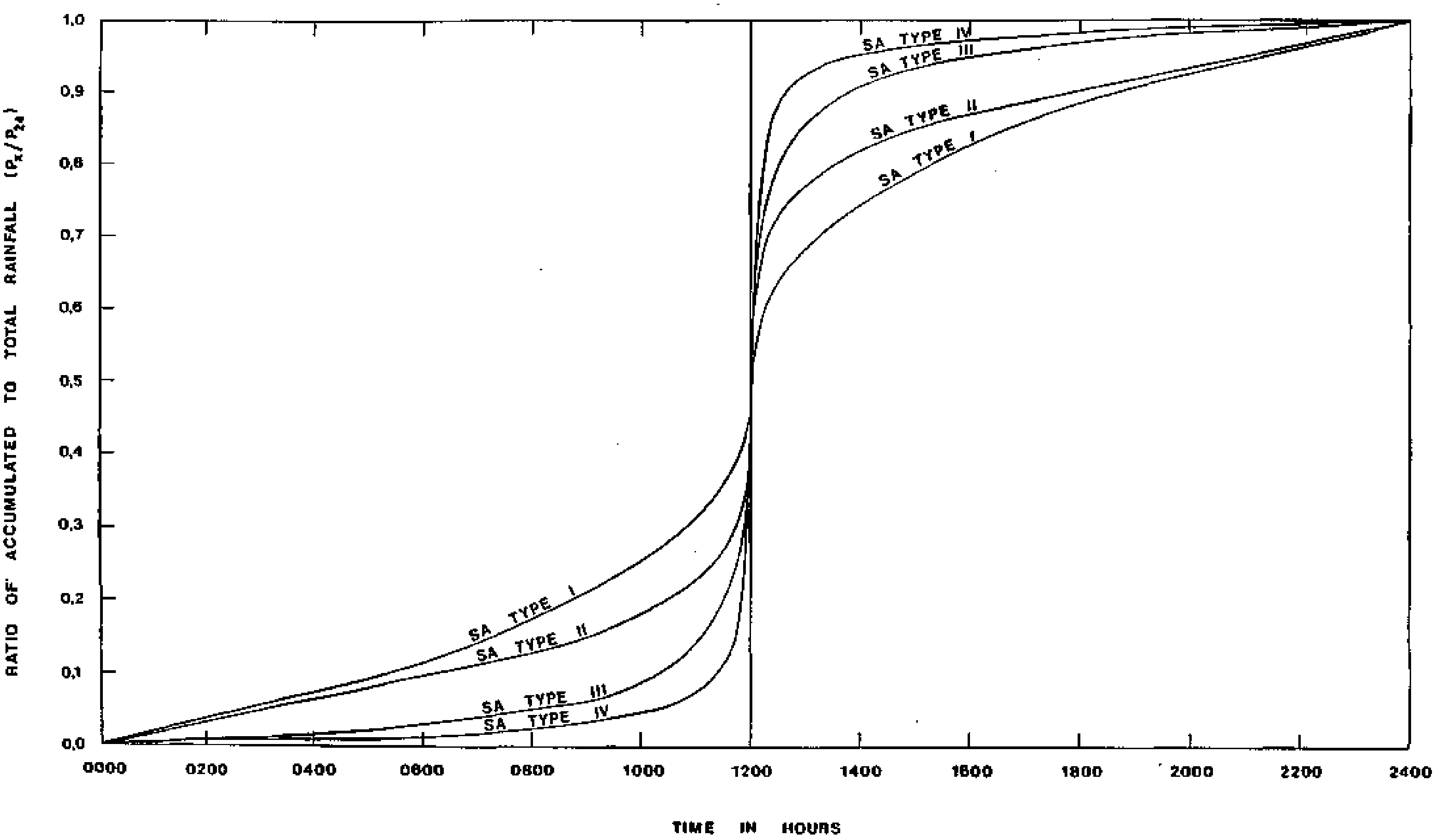


Figure 6.3 Proposed storm rainfall distributions for application in Southern Africa

Table 6.2 D-hour to 24-hour ratios and ranges of ratios (bracketed) for the four proposed storm rainfall distributions for Southern Africa

Duration	Ratios and Ranges of Ratios() for Storm Rainfall Distributions			
	S.A. Type I	S.A. Type II	S.A. Type III	S.A. Type IV
5 minutes 0,083h	0,085(? - 0,100)	0,125(0,100 - 0,140)	0,165(0,140 - 0,188)	0,210(0,188 - ?)
10 minutes 0,167h	0,130(? - 0,165)	0,210(0,165 - 0,235)	0,260(0,235 - 0,295)	0,330(0,295 - ?)
15 minutes 0,250h	0,160(? - 0,215)	0,270(0,215 - 0,305)	0,340(0,305 - 0,380)	0,420(0,380 - ?)
20 minutes 0,333h	0,180(? - 0,245)	0,310(0,245 - 0,355)	0,400(0,355 - 0,445)	0,490(0,445 - ?)
30 minutes 0,500h	0,215(? - 0,292)	0,370(0,292 - 0,430)	0,490(0,430 - 0,547)	0,605(0,547 - ?)
45 minutes 0,667h	0,260(? - 0,342)	0,425(0,342 - 0,495)	0,565(0,495 - 0,637)	0,710(0,637 - ?)
60 minutes 1,0 h	0,295(? - 0,375)	0,455(0,375 - 0,535)	0,615(0,535 - 0,695)	0,775(0,695 - ?)
90 minutes 1,5 h	0,345(? - 0,425)	0,505(0,425 - 0,590)	0,675(0,590 - 0,757)	0,840(0,757 - ?)
120 minutes 2,0 h	0,380(? - 0,460)	0,540(0,460 - 0,622)	0,705(0,622 - 0,782)	0,860(0,782 - ?)
180 minutes 3,0 h	0,382(? - 0,478)	0,575(0,478 - 0,647)	0,720(0,647 - 0,800)	0,880(0,800 - ?)

Table 6.3 Storm rainfall distribution types applicable to Natal stations

Location	Return Period	Storm Rainfall Distribution Type for Selected Durations						
		5 min	10 min	15 min	30 min	45 min	60 min	120 min
Kokstad	2	IV	IV	IV	IV	III	III	III
	10	III	IV	IV	III	III	III	II
	50	III	III	IV	III	III	III	II
Pieter-maritzburg	2	III	III	III	III	III	III	III
	10	III	IV	IV	III	III	III	III
	50	III	IV	IV	III	III	III	III
Makatini	2	III	III	III	III	III	III	III
	10	II	II	II	II	II	II	II
	50	II	II	II	II	II	II	II
Durban	2	II	II	II	II	II	II	II
	10	II	II	II	II	II	II	II
	50	III	II	II	II	II	II	II
Ladysmith	2	III	III	III	III	III	III	III
	10	IV	IV	III	III	III	III	III
	50	IV	IV	IV	IV	IV	IV	III
Estcourt	2	IV	IV	IV	IV	III	III	III
	10	III	IV	IV	IV	IV	IV	IV
	50	III	IV	IV	IV	IV	IV	IV
Cedara	2	IV	III	III	III	III	III	III
	10	III	III	III	III	III	III	III
	50	III	III	III	II	III	III	III
Waterford	2	IV	IV	III	III	III	III	III
	10	IV	IV	IV	III	III	III	III
	50	IV	IV	IV	III	IV	III	III
Newcastle	2	III	III	III	III	III	III	III
	10	III	III	III	III	III	III	III
	50	III	III	III	IV	IV	IV	IV

Clearly, if 30 years' digitized data per station are assumed to be the most accurate data available for those locations in Southern Africa, then the newly proposed synthetic distributions III and IV are warranted, and it appears that the U.S.A. Type I and II distributions, hitherto accepted for Southern African conditions, would have underestimated peak discharge rates on small catchments by the SCS method. It is also of significance to note that synthetic storm rainfall distributions are not necessarily independent either on return period or on critical storm duration at any one location (Table 6.3).

(d) On a Southern African scale, the regionalization of the four distributions can only be attempted very tentatively, because for most of the subcontinent digitized data for long periods (i.e. exceeding 25 years) are not yet available outside Natal. The tentative regionalization shown for the 50 year recurrence interval in Figure 6.5 was compiled using the digitized data for Natal stations supplemented by information published by the South African Weather Bureau (1974) and by Midgley and Pitman (1978). It should be noted that frequent discrepancies were evident between data values and therefore between the synthetic rainfall distributions calculated from the three sources of data. The dependence of the distributions on duration and recurrence interval were also noted again. The following very general observations may nevertheless be made from Figure 6.5:

(i) The S.A. Type I distribution occurs only in a very narrow band along the south coast and in a bulge along the west coast of the Cape Province.

(ii) Most of Southern Africa has a S.A. Type III storm rainfall distribution, and not a Type II distribution.

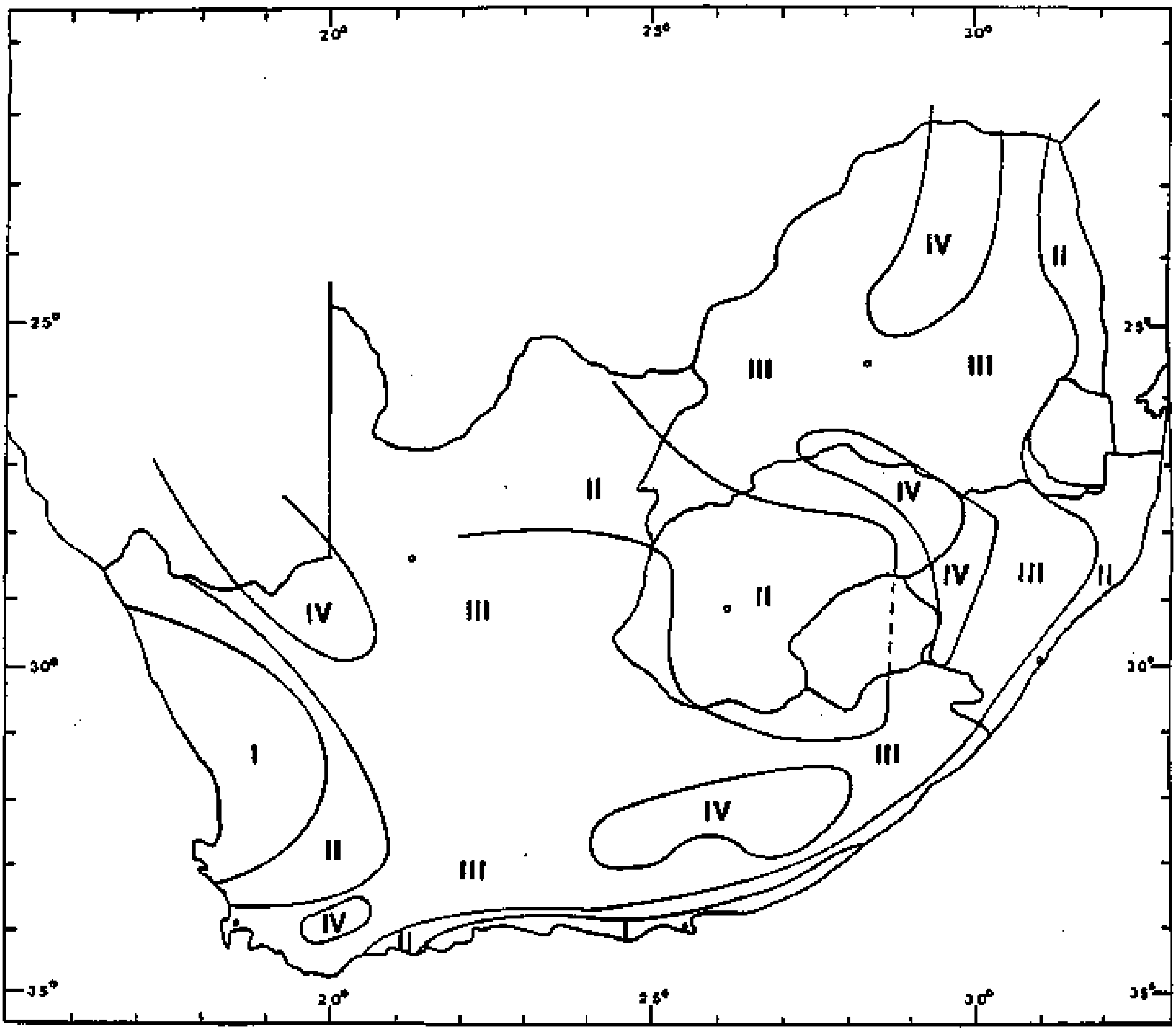


Figure 6.5 A tentative regionalization of storm rainfall distributions in Southern Africa

(iii) S.A. Type IV distributions appear to occur in isolated rather than in broad regions throughout Southern Africa.

(iv) There is evidence that the relatively less intense S.A. Type II distribution occurs in the central Orange Free State.

EFFECT OF STORM RAINFALL DISTRIBUTION ON PEAK DISCHARGE ESTIMATES

If, as has been shown clearly in this chapter, the SCS Types I and II storm rainfall distributions under-estimate short duration design rainfalls contributing to the peak flows over most regions of Southern Africa, then the effects of differences in synthetic storm distributions need to be examined. This was done by calculating peak discharge rates for the four rainfall distributions using seven incremental hydrographs, by the method outlined step by step in the Worked Example 3 of the SCS manual for Southern Africa (Schulze and Arnold, 1979). The following input variables were used in the calculations of the example below:

Catchment area	= 1,5 km^2
Coefficient of Initial Abstraction	= 0,05
Curve Number II	= 63
Curve Number adjusted for antecedent moisture conditions	= 51,3
Storm rainfall	= 93 mm

Stormflow = 20,04 mm

Lag = variable, between 0,5 and 1,0 hours.

Results were plotted in Figure 6.6. The marked differences in peak discharge rate estimates are clearly evident. In fact, this particular example illustrates that the application of the S.A. Type II distribution in an area where the Type III distribution should be used, would under-estimate peaks by 26-28%, while if the Type IV distribution had applied, the under-estimation would have been over 50%, all other variables having remained unchanged.

CONCLUSION

Synthetic storm rainfall distributions have to be used for peak discharge estimations by the SCS model, which uses daily rainfall input. Evidence from digitized rainfall data for Natal stations confirmed an earlier suggestion by Schulze and Arnold (1979) that the SCS Types I and II rainfall distributions under-estimated peak discharge rate estimations over large parts of Southern Africa. From available data four new synthetic storm rainfall distributions are proposed for Southern Africa and a tentative division of the subcontinent into storm rainfall distribution type regions is proposed. It was furthermore illustrated that estimates of peak discharge rates are highly sensitive to the rainfall distribution curves used.

These findings underline the plea made previously (for example, by Schulze, 1984) for support of operational programmes to speed up the digitization of rainfall records from throughout Southern Africa. These data are vital to thousands of design decisions involving many millions of Rands each year.

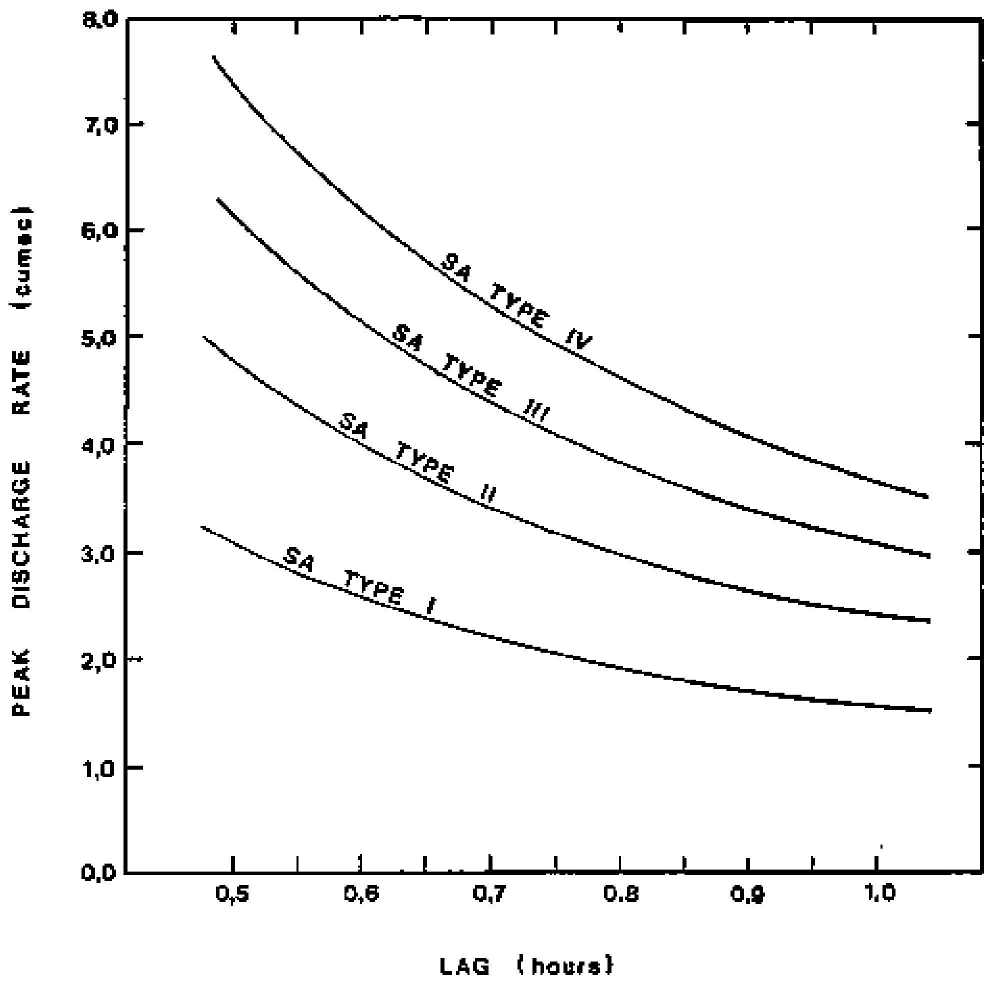


Figure 6.6 Effects of storm rainfall distribution types on peak discharge rates : an example

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SECTION B

HYDROLOGICAL CHARACTERISTICS OF SOILS IN SOUTHERN AFRICA

CHAPTER 7

HYDROLOGICAL CHARACTERISTICS AND PROPERTIES OF SOILS IN SOUTHERN AFRICA : RUNOFF RESPONSE

INTRODUCTION

In hydrological assessment, be it in terms of flood peaks, flood volumes or water yield, a vital role is played by the processes occurring in or on the soil. Indeed, it is the capacity of soil to

(i) absorb,

(ii) retain and

(iii) release/redistribute

water that is a prime regulator of the response of a catchment, and the soil is the medium in/through which the other hydrological processes can operate.

Soils data are often used in hydrological computations by "lumping" the characteristics of many soils found within a catchment to derive an average areal parameter. A catchment is not, however, a "lumped" system in regard to soils, and pronounced differences in magnitude and sequence of hydrological processes may be observed within a catchment. Spatially homogeneous soil units with respect to hydrological response are thus critical in determining overall magnitudes of a variety of hydrological processes taking place at any given time.

In the light of this background the three aims of this first of two chapters on hydrological characteristics of Southern African soils are now described.

AIMS

(a) Any meaningful hydrological categorization of the over 500 soil series now recognized in Southern Africa has to be undertaken within the framework of the existing and now established and accepted "binomial system of soil classification" as presented by MacVicar et al, (1977). The concepts embodied in this classification are therefore outlined at the outset. It is imperative, however, that hydrological modellers and engineering consultants designing structures on small rural catchments in Southern Africa acquaint themselves and become conversant with the detailed classification by MacVicar et al, (1977) and with envisaged changes to the classification.

(b) Secondly, with the recognition of the SCS model as an accepted design tool by many public institutions and engineering consultants, the Southern African classification of over 500 soil series in terms of hydrological response by the SCS method is described and tabulated.

(c) Hydrologically the lateral movement of soil water (interflow) is being recognized as an important mechanism in runoff production. A simple categorization of the interflow potential of Southern African soils is therefore also given.

HYDROLOGICAL CLASSIFICATIONS OF SOILS - NOTES OF CAUTION

A few notes of caution regarding hydrological classifications of soils need to be sounded before technical details of Chapters 7 and 8 are presented.

(a) This is a first attempt at classifying soils in Southern Africa on a hydrological basis. While care has been taken to set out clearly the premises and assumptions on which the various classifications have been undertaken, field experience may prove the need for re-classification in future.

(b) Categories, groups and values are given in these two chapters at the level of the soil series. However, values of the tabulated soil moisture constants, for example, have been derived; the SCS soil grouping and the interflow potential categories, on the other hand, have been deduced. It must be stressed that all groupings should be viewed as generalizations and that all values derived are ball-park figures, to be treated as first approximations when used in hydrological decision-making.

(c) Following on (b), it must be emphasised that the generalized information given in Chapters 7 and 8 does not replace the need for fieldwork, particularly since it is well known that much variation in terms of hydrological response exists within any given soil series in Southern Africa.

(d) Soils classifications, like many others, are dynamic in nature, changing as more experience is gained or as laboratory analyses become available. The "binomial system of soil classification" for Southern Africa is known to be under revision at the present time (MacVicar, 1984) and it will, in all probability, be superseded in the next five years. However, being the classification that users of pedological information in Southern Africa regard as the "official" one at present (and it will remain such for the ensuing few years) this "binomial system" has been retained as the one for which all soil series groupings are presented in this report.

THE BINOMIAL SYSTEM OF SOIL CLASSIFICATION FOR SOUTHERN AFRICA

Soil, as the medium in which hydrological processes occur, has a heterogeneous character by virtue of its horizonation, which controls rates of moisture movement both vertically and laterally. Horizons formed under given genetic conditions tend to be reproduced over and over again, with their organization and re-organization resulting in generalized master horizons (MacVicar et al, 1977). This concept is illustrated in Figure 7.1.

The specific properties of master horizons led to the recognition in the Southern African binomial system of soil classification (MacVicar et al, 1977) of diagnostic horizons (Figure 7.2). In the diagnostic horizon concept a grouping of pedological features is recognized. For example, organic carbon content, colour, structure, thickness or expansive properties distinguish the five diagnostic topsoil horizons. On the other hand, eluviation, gleying, colour variegations, concretions, redistribution of clay materials, differential weathering, podzolization or lack of development are used to categorize the 15 subsoil diagnostic horizons recognized in Southern Africa (MacVicar et al, 1977).

The grouping of specific kinds and sequences of diagnostic horizons has resulted in the concept of the soil form of which 41 have been described to date. These soil forms have been further subdivided into 501 soil series (MacVicar et al, 1977). Criteria used to distinguish series within forms include

(i) soil texture (clay content, sand grading),

(ii) base status in terms of leaching,

(iii) calcareousness,

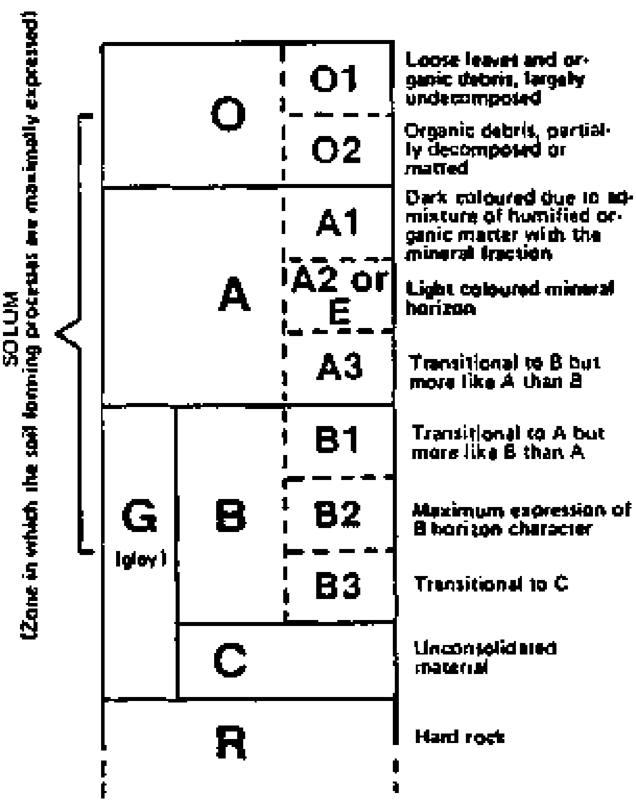

Figure 7.1 Arrangement of master horizons (MacVicar et al, 1977)

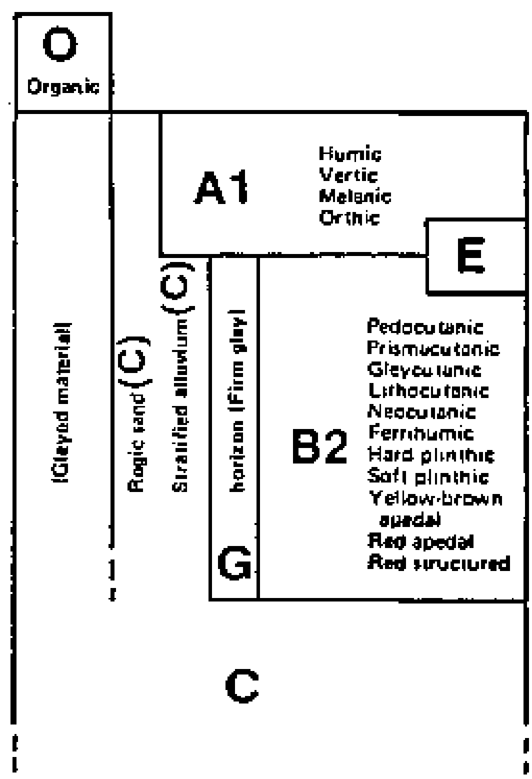

Figure 7.2 Diagnostic horizons (MacVicar et al 1977)

(iv) soil reaction (pH),

(v) surface physical properties,

(vi) colour of the B horizon,

(vii) consistence of the B horizon,

(viii) surface wetness, and

(ix) topography.

At series level no depth limits of the various horizons are set. Depth of horizons, or the slope or topographic position of the series and other local properties, which are most important to hydrological response, cannot be generalized but must be determined in situ and added as a further descriptor of the soil series, namely, the soil phase. Figure 7.3 illustrates the above concepts.

Hydrologically, the division of soils into diagnostic horizons, with their attendant properties and subdivisions, is important. This is so because they constitute the vital heterogeneous soil stores within, between and along which important hydrological processes can take place (arrows in Figure 7.3).

HYDROLOGICAL RESPONSE GROUPING OF SOUTHERN AFRICAN SOILS FOR THE SCS MODEL

Background

A hydrological response grouping of Southern African soils was first undertaken in 1979. The guidelines and criteria for the classification were formulated together with colleagues who had wide pedological, engineering or agronomic experience and who were drawn from the University of Natal, the Department of

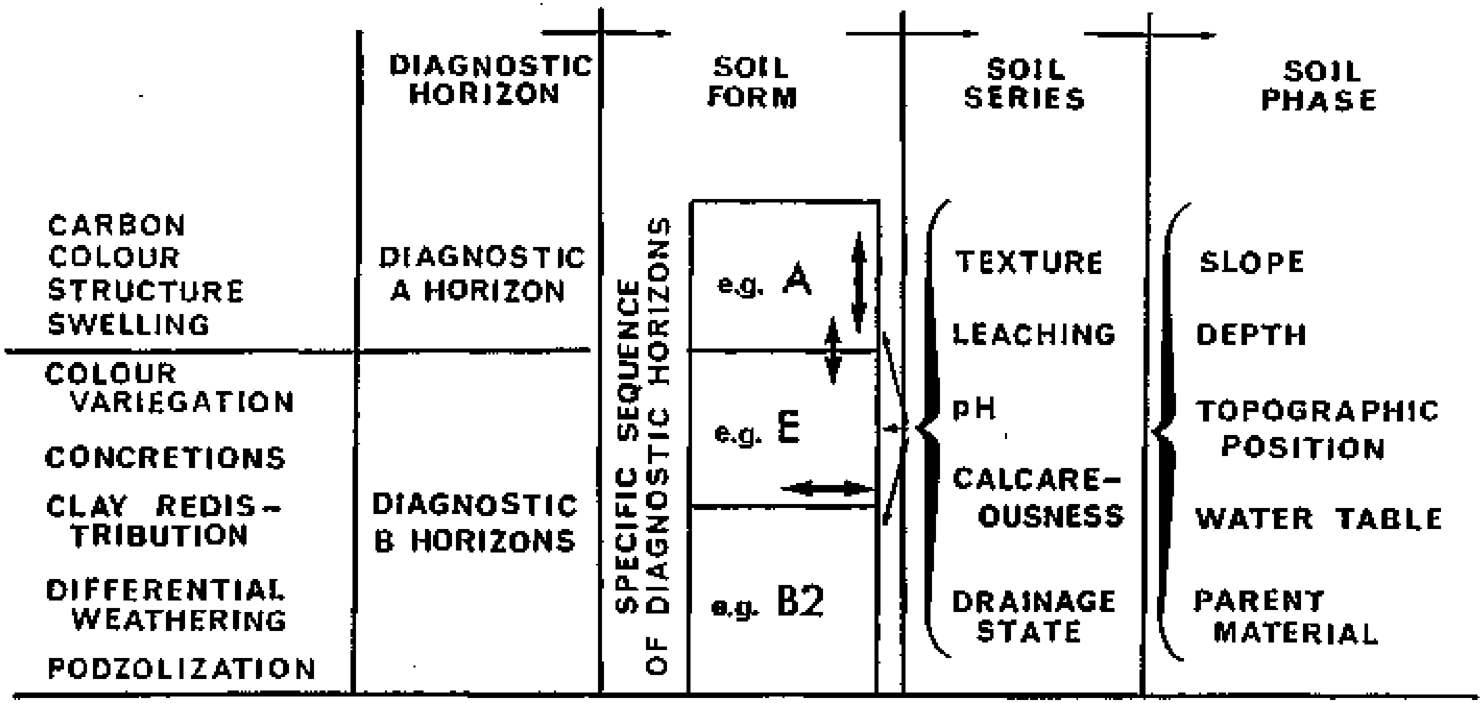

Figure 7.3 Hierarchical classification of soils in Southern Africa (Schulze, 1984)

Agriculture at Cedara, the Soil and Irrigation Research Institute and the Hydrological Research Institute, both in Pretoria.

The parameter which provides the basis for a hydrological response classification of soils in Southern Africa was formulated as a "typical amount of infiltration for the soil at likely moisture content to the point of maximum runoff rate". This premise is somewhat different in concept to the one described by the SCS in the National Engineering Handbook (USDA-SCS, 1972) in which the "minimum rate of infiltration for a thoroughly wetted bare soil assuming maximum swelling" forms the basis of soils grouping. The reason for altering the concept of classification is that a comparison of the actual physical properties of soil series in the U.S.A. and their hydrological grouping showed that many series have been classed intuitively according to "typical" or "likely" moisture characteristics in the field.

Basic Hydrological Grouping

As in the SCS literature (USDA-SCS, 1972), four basic hydrological soil groups have been recognized. Hydrologically, the limiting properties in a soil profile may be

(i) its infiltration rate at the surface (i.e. the rate at which water enters the soil at the surface, which is controlled by surface conditions),

(ii) its permeability (i.e. the rate at which water moves in the soil, which is controlled by the soil horizons), and

(iii) its water storage capacity, which is dependent primarily on the soil texture and its depth.

The four basic hydrological soil groups are :

Soil Group A. Low runoff potential. Infiltration rate is high and permeability is rapid in this group. Overall drainage is excessive to well-drained.

Soil Group B. Moderately low runoff potential. The soils of this group are characterized by moderate infiltration rates, effective depth and drainage. Permeability is slightly restricted.

Soil Group C. Moderately high runoff potential. Infiltration rate is slow or deteriorates rapidly in this group. Permeability is restricted. Soil depth tends to be shallow.

Soil Group D. High runoff potential. Soils in this group are characterized by very slow infiltration rates and severely restricted permeability. Very shallow soils and expansive soils (those of high shrink-swell potential) are included in this group.

With the wide spectrum of properties found in Southern African soils, it was felt that a four-fold grouping of soils was too coarse for the SCS model, and three intermediate soil groups have therefore been used in the classification of soil forms and series. These groups are A/B, B/C and C/D, thus giving seven soil groups in all.

Classification Procedure

Each soil form, according to its overall diagnostic properties (MacVicar et al, 1977) was initially placed in one of the seven groups. The series within each soil form were then graded up or down from the general soil group assigned to the form, according to their specific physical or chemical properties.

The following properties were considered to be relevant:

(a) Texture (t): Soils with A-horizon clay content exceeding 35% were downgraded one group; where clay content was less than 6% and coarse sand made up at least 6% of the soil fraction, soil series were upgraded one group.

(b) Leaching (l): Dystrophic (highly leached) soils were upgraded one group while eutrophic soils were downgraded one group.

(c) Water Table (w): Series with a high water table typically present were downgraded one group.

(d) Crusting (c): Soil forms which typically displayed a crusted surface, but where crusting was absent at series level, were upgraded one group, and vice-versa. Soils exhibiting a hardening of the B-horizon (e.g. a ferrihumic B-horizon) were downgraded one group. There may be exceptions to these general rules, for example, Cass (1984) considers crusting in the Arcadia soil series not to be a hydrological barrier.

At the present stage a degree of uncertainty still exists as to the overall effects of soil coloration and calcareousness on infiltration and permeability rates. Doubts have also been expressed as to whether an up- and downgrading due to degree of leaching is warranted (Cass, 1984). The regrading procedure has nevertheless been kept, pending detailed investigation. Future research and experience will also determine whether/to what degree expansive soils should be downgraded (Cass, 1984).

Because of the variable nature of soil properties within a specific series, some further guidelines for adjustment in the field are given.

(a) Soil depth: Where typically deep soils are in the shallow phase (generally less than 0,5 m), they should be downgraded one group.

(b) Surface sealing: Where surface sealing is evident in loco, soils should be downgraded one group.

(c) Topographic position: Generally series in bottomlands may be downgraded and series formed on uplands upgraded one group.

(d) Parent material: Identical series derived from different parent materials may require re-grouping (e.g. series derived from Table Mountain sandstones would be upgraded relative to the same series derived from Dwyka tillites).

The hydrological soil groupings for the 501 soil series given in MacVicar et al. (1977) are listed in Table 7.1 (at the end of this chapter). In assessing the hydrological response of a catchment the information on soil groups is used in conjunction with different agricultural and non-agricultural land use and treatment classes, which are detailed in the SCS manual for Southern Africa (Schulze and Arnold, 1979).

POTENTIAL FOR INTERFLOW

With the advent of research into distributed hydrological models in Southern Africa, a grouping of soil forms and series into their potential for interflow becomes necessary. The potential for interflow is not just a simple matter of association with soil form and series, however, because the process is dependent largely on slope, on topographic position inducing a convergence of soil water, as well as on soil depth, and in addition also on the degree of transmissivity which can take place through an impeding layer and which can be highly variable.

A threefold grouping into the potential for interflow, namely

(i) interflow unlikely,

(ii) some/low interflow potential, and

(iii) high interflow potential

has nevertheless been attempted.

The following criteria were used as initial 'rules of thumb' to demarcate soils with a 'low interflow potential', namely the presence of

(i) a soft plinthic horizon (for example, with Avalon, Bainsvlei, Tambankulu and Westleigh forms) particularly in shallow phases of series, which then become prone to waterlogging;

(ii) a pedocutanic horizon (for example, with the Bonheim, Swartland and Valsrivier forms);

(iii) a lithocutanic horizon (Cartref, Glenrosa, Mayo and Nomanci forms under certain field conditions);

(iv) a ferrihumic horizon (Houwhoek and Lamotte forms), although many variants of the ferrihumic horizon with little or much sesquioxide hardening may exist and testing in situ becomes imperative;

(v) gleycutanic (Pinedene) and neocutanic (Inhoek, Oakleaf, Vilafontes) horizons, although some doubt exists as to whether interflow would actually be enhanced by the presence of these horizons in the forms named; and

(vi) moderately abrupt textural changes typical of certain series of, for example, the Constantia form.

Soils with a 'high interflow potential' are characterized by

(i) hard plinthic B-horizons (for example, Glencoe and Wasbank forms);

(ii) A-horizons overlying hard/unconsolidated rock directly (Milkwood and Mispah forms);

(iii) highly abrupt textural changes down a soil profile (for example, Estcourt and Sterkspruit forms with prismacutanic B horizons, Kroonstad with a gleycutanic and certain series of the Constantia and Vilafontes forms).

Using the above 'rules of thumb' as an initial guide, the 501 soil series were classed into their interflow potential in Table 7.1. Based on a field knowledge of individual forms and series, appropriate changes were then made, for example, all Estcourt and Vilafontes series were classified as having a 'high' interflow potential, the first seven Glencoe series were changed from the 'unlikely' to the 'some' interflow group, all Longlands series were reassigned a 'high', all Milkwood and Sterkspruit a 'some' and all Bonheim, Cartref, Inhoek, Oakleaf and Shepstone series an 'unlikely' interflow potential.

It should be noted in regard to interflow potential, that <u>in situ</u> examination of soil conditions is crucial. Furthermore, it may be seen in Table 7.1 that not all series of a given soil form respond identically in terms of interflow potential, as series may differ according to the degree of abruptness of clay content changes down a soil profile (for example, Constantia, Fernwood, Houwhoek, Lamotte and Valsrivier forms).

Aspects of the runoff responses of Southern African soils having been discussed in terms of the soil grouping used for the SCS model as well as in regard to the interflow potential of soils, the second chapter on hydrological characteristics of soils focusses on water retention properties of soils.

ACKNOWLEDGEMENTS

The classification of the 501 soil series was first undertaken by the author in 1979 with assistance from Drs. D.M. Scotney, F. Fitzpatrick, J.L. Hutson and Messrs. J.F. Eloff and D.A. Dekker, all of the Department of Agriculture, and Mr. H. Maaren of the Department of Environment Affairs. Their respective contributions are appreciated. Dr. A. Cass of the Department of Soil Science and Agrometeorology of the University of Natal, Pietermaritzburg, is thanked for his thorough review of Chapter 7 and for the many valuable suggestions he made.

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Table 7.1 Hydrological classifications of soil forms and series found in Southern Africa

Legend

A - low runoff potential
B - moderately low potential
C - moderately high potential
D - high runoff potential
c - crusting
l - leaching
t - texture
w - water table

Cl - clay
S - sand
Lm - loam
0 - interflow unlikely
X - some/low interflow potential
XX - high interflow potential

Soil Form	Code	Soil Series	SCS Group-ing	SCS Adjust-ment Factor	Clay Distri-bution Model	Typical Text-ural Class	Inter-flow Poten-tial
ARCADIA	Ar 40	Arcadia	C/D		2e	Cl	0
	Ar 11	Bloukrans	C/D		2e	Cl	0
	Ar 21	Clerkness	C/D		2e	Cl	0
	Ar 41	Eenzaam	C/D		2e	Cl	0
	Ar 20	Gelykvlakte	C/D		2e	Cl	0
	Ar 10	Mngazi	C/D		2e	Cl	0
	Ar 32	Nagana	C/D		2e	Cl	0
	Ar 12	Noukloof	C/D		2e	Cl	0
	Ar 31	Rooidraai	C/D		2e	Cl	0
	Ar 30	Rydalvale	C/D		2e	Cl	0
	Ar 42	Wanstead	C/D		2e	Cl	0
	Ar 22	Zwaarkrygen	C/D		2e	Cl	0
AVALON	Av 13	Ashton	A/B	+l	1b	SLm	X
	Av 26	Avalon	B		1c	SClLm	X
	Av 12	Banchory	A	+l/+t	1a	S	X
	Av 27	Bergville	B/C	-t	1d	SCl	X
	Av 37	Bezuidenhout	C	-t/-l	1d	SCl	X
	Av 33	Bleeksand	B/C	-l	1b	SLm	X
	Av 34	Heidelberg	B/C	-l	1b	SLm	X
	Av 20	Hobeni	A/B	+t	1a	LmS	X
	Av 14	Kanhym	A/B	+l	1b	SLm	X
	Av 24	Leksand	B		1b	SLm	X
	Av 10	Mastaba	A	+l/+t	1a	LmS	X
	Av 32	Middelpos	B	+t/-l	1a	S	X
	Av 31	Mooiveld	B	+t/-l	1a	LmS	X
	Av 25	Newcastle	A/B	+t	1b	SLm	X
	Av 17	Normandien	B	+l/-t	1d	SCl	X
	Av 22	Rossdale	A/B	+t	1a	S	X
	Av 16	Ruston	B	+l	1c	SClLm	X
	Av 36	Soetmelk	B/C	-l	1c	SClLm	X

Table 7.1 (continued)

Soil Form	Code	Soil Series	SCS Group -ing	SCS Adjust -ment Factor	Clay Distri-bution Model	Typical Text-ural Class	Inter-flow Poten-tial
AVALON (contd)	Av 21	Uithoek	A/B	+t	1a	LmS	X
	Av 30	Viljoenskroon	B	+t/-l	1a	LmS	X
	Av 23	Villiers	B		1b	SLm	X
	Av 11	Welverdiend	A	+l/+t	1a	LmS	X
	Av 35	Windmeul	B	+t/-l	1b	SLm	X
	Av 15	Wolweberg	A	+l/+t	1b	SLm	X
BAINSVLEI	Bv 23	Ashkelon	A/B		1b	CLm	X
	Bv 36	Bainsvlei	B	-l	1c	SClLm	X
	Bv 12	Camelot	A	+t	1a	S	X
	Bv 20	Chelsea	A	+t	1a	LmS	X
	Bv 30	Delwery	A/B	+t/-l	1a	LmS	X
	Bv 13	Dunkeld	A/B		1b	SLm	X
	Bv 16	Elysium	A/B		1c	SClLm	X
	Bv 10	Hlatini	A	+t	1a	LmS	X
	Bv 34	Kareekuil	B	-l	1b	SLm	X
	Bv 31	Kingston	A/B	+t/-l	1a	LmS	X
	Bv 26	Lonetree	A/B		1c	SClLm	X
	Bv 25	Maanhaar	A	+t	1b	SLm	X
	Bv 11	Makong	A	+t	1a	LmS	X
	Bv 27	Metz	B	-t	1d	SCl	X
	Bv 22	Oosterbeek	A	+t	1a	S	X
	Bv 37	Ottosdal	B/C	-t/-l	1d	SCl	X
	Bv 24	Redhill	A/B		1b	SLm	X
	Bv 32	Trekboer	A/B	+t/-l	1a	S	X
	Bv 15	Tygerkloof	A	+t	1b	SLm	X
	Bv 33	Vermaas	B	-l	1b	SLm	X
	Bv 21	Vungama	A	+t	1a	LmS	X
	Bv 35	Wedgewood	A/B	+t/-l	1b	SLm	X
	Bv 17	Wilgenhof	B	-t	1d	SCl	X
	Bv 14	Wykeham	A/B		1b	SLm	X
BONHEIM	Bo 41	Bonheim	C/D	-t	1a	LmS	0
	Bo 20	Bushman	C		2c	SClLm	0
	Bo 30	Dumasi	C		2c	SClLm	0
	Bo 31	Glengazi	C/D	-t	2d	SCl	0
	Bo 10	Kiora	C		2c	SClLm	0
	Bo 21	Rasheni	C/D	-t	2d	SCl	0
	Bo 11	Stanger	C/D	-t	2d	SCl	0
	Bo 40	Weenen	C		2c	SClLm	0

Table 7.1 (continued)

Soil Form	Code	Soil Series	SCS Group -ing	SCS Adjust -ment Factor	Clay Distri- bution Model	Typical Text- ural Class	Inter- flow Poten- tial
CARTREF	Cf 10	Amabele	B/C	+t	5a	LmS	0
	Cf 12	Arrochar	C		5c	SClLm	0
	Cf 13	Byrne	C/D	-t	5d	SCl	0
	Cf 21	Cartref	C		5b	SLm	0
	Cf 22	Cranbrook	C		5c	SClLm	0
	Cf 30	Grovedale	B/C	+t	5a	S	0
	Cf 31	Kusasa	B/C	+t	5b	SLm	0
	Cf 32	Noodhulp	C		5c	SClLm	0
	Cf 11	Rutherglen	C		5b	SLm	0
	Cf 20	Waterridge	B/C	+t	5a	LmS	0
CHAMPAGNE	Ch 11	Champagne	D		2c	SLm	0
	Ch 21	Ivanhoe	D		2e	SClLm	0
	Ch 10	Mposa	D		2c	SLm	0
	Ch 20	Stratford	D		2e	SClLm	0
CLOVELLY	Cv 33	Annandale	B	-l	1b	SLm	0
	Cv 18	Balgowan	B	-t	1e	Cl	0
	Cv 40	Bleskop	A	+t	1a	LmS	0
	Cv 36	Blinkklip	B	-l	1c	SClLm	0
	Cv 17	Clovelly	B	-t	1d	SCl	0
	Cv 28	Clydebank	B	-t	1e	Cl	0
	Cv 35	Denhere	A/B	+t/-l	1b	SLm	0
	Cv 46	Dudfield	A/B		1c	SClLm	0
	Cv 11	Geelhout	A	+t	1a	LmS	0
	Cv 25	Gutu	A	+t	1b	SLm	0
	Cv 47	Klippan	B	-t	1d	SCl	0
	Cv 38	Klipputs	B/C	-t/-l	1e	Cl	0
	Cv 10	Lismore	A	+t	1a	LmS	0
	Cv 12	Lundini	A	+t	1a	S	0
	Cv 34	Makuya	B	-l	1b	SLm	0
	Cv 14	Mossdale	A/B		1b	SLm	0
	Cv 48	Nelspan	B	-t	1e	Cl	0
	Cv 27	Newport	B	-t	1d	SCl	0
	Cv 16	Oatsdale	A/B		1c	SClLm	0
	Cv 23	Ofazi	A/B		1b	SLm	0
	Cv 41	Oranje	A	-t	1a	LmS	0
	Cv 32	Paleisheuwel	A/B	+t/-l	1a	S	0
	Cv 31	Sandspruit	A/B	+t/-l	1a	LmS	0
	Cv 22	Sebakwe	A	+t/-l	1a	S	0
	Cv 45	Skipskop	A	+t	1b	SLm	0
	Cv 21	Sonnenblom	A	+t	1a	LmS	0

Table 7.1 (continued)

Soil Form	Code	Soil Series	SCS Group -ing	SCS Adjust -ment Factor	Clay Distri- bution Model	Typical Text- ural Class	Inter- flow Poten- tial
CLOVELLY (contd)	Cv 26	Southwold	A/B		1c	SClLm	0
	Cv 15	Soweto	A	+t	1b	SLm	0
	Cv 24	Springfield	A/B		1b	SLm	0
	Cv 30	Sunbury	A/B	+t/-l	1a	LmS	0
	Cv 37	Summerhill	B/C	-t/-l	1d	SCl	0
	Cv 42	Thornhill	A	+t	1a	S	0
	Cv 44	Torquay	A/B		1b	SLm	0
	Cv 20	Tweefontein	A	+t	1a	LmS	0
	Cv 43	Vaalbank	A/B		1b	SLm	0
	Cv 13	Vidal	A/B		1b	ClLm	0
CONSTAN -TIA	Ct 25	Cintsa	B		3e	SLm/SClLm	XX
	Ct 12	Constantia	B		3a	LmS	X
	Ct 23	Dwesa	B		3e	SLm/SClLm	XX
	Ct 22	Fencote	B		3b	S/SClLm	XX
	Ct 13	Harkerville	B		2b	SLm	0
	Ct 24	Kromhoek	B		3e	SCl/SClLm	XX
	Ct 14	Noetzie	B		2b	SLm	0
	Ct 20	Palmyra	B		3b	LmS/SClLm	XX
	Ct 10	Strombolis	B		3a	Lms	X
	Ct 11	Tokai	B		3a	S	X
	Ct 21	Vlakfontein	B		3b	Lms/SClLm	XX
	Ct 15	Wynberg	B		2b	SLm	0
ESTCOURT	Es 20	Assegaai	D		3c	LmS/SClLm	XX
	Es 11	Auckland	D		3b	LmS/SLm	XX
	Es 22	Avontuur	D		3c	S/SClLm	XX
	Es 35	Balfour	D		3e	LmS/SClLm	XX
	Es 40	Beerlaagte	D		3c	LmS/SClLm	XX
	Es 37	Buffelsdrif	D		3k	SCl/Cl	XX
	Es 42	Darling	D		3c	S/SClLm	XX
	Es 13	Dohne	D		3e	SLm/SClLm	XX
	Es 31	Elim	D		3b	LmS/SLm	XX
	Es 33	Enkeldoorn	D		3e	SLm/SClLm	XX
	Es 36	Estcourt	D		3h	SClLm/SCl	XX
	Es 14	Grasslands	D		3e	SLm/SClLm	XX
	Es 41	Heights	D		3c	LmS/SClLm	XX
	Es 10	Houdenbeck	D		3b	LmS/SLm	XX
	Es 21	Langkloof	D		3c	LmS/SClLm	XX
	Es 30	Mozi	D		3b	LmS/SLm	XX
	Es 12	Potela	D		3b	S/SLm	XX
	Es 16	Rosemead	D		3h	SClLm/SCl	XX
	Es 32	Soldaatskraal	D		3b	S/SLm	XX

Table 7.1 (continued)

Soil Form	Code	Soil Series	SCS Group -ing	SCS Adjust -ment Factor	Clay Distri- bution Model	Typical Text- ural Class	Inter- flow Poten- tial
ESTCOURT (contd)	Es 34	Uitvlugt	D		3e	SLm/SClLm	XX
	Es 15	Vredenhoek	D		3e	LmS/SClLm	XX
	Es 17	Zintwala	D		3k	SCl/Cl	XX
FERNWOOD	Fw 40	Brinley	C	-w	1b	SLm	XX
	Fw 11	Fernwood	A		1b	SLm	0
	Fw 21	Langebaan	A		1b	SLm	0
	Fw 42	Mambone	C	-w	1b	SLm	XX
	Fw 10	Maputa	A		1b	SLm	0
	Fw 20	Motopi	A		1b	SLm	0
	Fw 22	Saldanha	A		1b	SLm	0
	Fw 12	Sandveld	A		1b	SLm	0
	Fw 30	Shasha	B	-w	1b	SLm	XX
	Fw 41	Soetvlei	C	-w	1b	SLm	XX
	Fw 32	Trafalgar	B	-w	1b	SLm	XX
	Fw 31	Warrington	B	-w	1b	SLm	XX
GLENCOE	Gc 16	Appam	B		1c	SClLm	X
	Gc 33	Beatrix	B/C	-l	1b	SLm	X
	Gc 20	Boskuil	A/B	+t	1a	LmS	X
	Gc 15	Delmas	A/B	+t	1b	SLm	X
	Gc 10	Driepan	A/B	+t	1a	LmS	X
	Gc 24	Dunbar	B		1b	SLm	X
	Gc 26	Glencoe	B		1c	SClLm	X
	Gc 37	Graspan	C	-t/-l	1d	SCl	XX
	Gc 11	Hartog	A/B	+t	1a	LmS	XX
	Gc 13	Klipstapel	B		1b	SLm	XX
	Gc 32	Kwezana	B	+t/-l	1a	S	XX
	Gc 34	Leeudoorn	B/C	-l	1b	SLm	XX
	Gc 36	Leslie	B/C	-l	1c	SClLm	XX
	Gc 27	Ontevrede	B/C	-t	1d	SCl	XX
	Gc 21	Penhoek	A/B	+t	1a	LmS	XX
	Gc 31	Ribblesdale	B	+t/-l	1a	LmS	XX
	Gc 17	Shotton	B/C	-t	1d	SCl	XX
	Gc 23	Strathrae	B		1b	SLm	XX
	Gc 22	Talana	A/B	+t	1a	S	XX
	Gc 12	Tranendal	A/B	+t	1a	S	XX
	Gc 35	Uitskot	B	+t/-l	1b	SLm	XX
	Gc 30	Vlakpan	B	+t/-l	1a	LmS	XX
	Gc 14	Weltevrede	B		1b	SLm	XX
	Gc 25	Wesselsnek	A/B	+t	1b	SLm	XX

Table 7.1 (continued)

Soil Form	Code	Soil Series	SCS Group-ing	SCS Adjust-ment Factor	Clay Distri-bution Model	Typical Text-ural Class	Inter-flow Poten-tial
GLENROSA	Gr 28	Achterdam	B/C		5c	SClLm	X
	Gr 27	Dothole	B/C		5c	SClLm	X
	Gr 24	Dunvegan	B/C		5b	SLm	X
	Gr 15	Glenrosa	B	+t	5b	SLm	X
	Gr 13	Kanonkop	B/C		5b	SLm	X
	Gr 22	Knapdaar	B	+t	5a	S	X
	Gr 26	Lekfontein	B/C		5c	SClLm	X
	Gr 25	Lomondo	B	+t	5b	SLm	X
	Gr 21	Majeng	B	+t	5a	LmS	X
	Gr 20	Malgas	B	+t	5a	LmS	X
	Gr 10	Martindale	B	+t	5a	LmS	X
	Gr 11	Oribi	B	+t	5a	LmS	X
	Gr 12	Paardeberg	B	+t	5a	S	X
	Gr 14	Platt	B/C		5b	SLm	X
	Gr 29	Ponda	C	-t	5d	SCl	X
	Gr 18	Robmore	B/C		5c	SClLm	X
	Gr 19	Saintfaiths	C	-t	5d	SCl	X
	Gr 23	Southfield	B/C		5b	SLm	X
	Gr 17	Trevanian	B/C		5c	SClLm	X
	Gr 16	Williamson	B/C		5c	SClLm	X
GRIFFIN	Gf 10	Burnside	A		1b	SLm	0
	Gf 11	Cleveland	A		1c	SClLm	0
	Gf 32	Cradock	B	-t/-l	1d	SCl	0
	Gf 20	Erfdeel	A		1b	SLm	0
	Gf 13	Farmhill	A/B	-t	1e	Cl	0
	Gf 12	Griffin	A/B	-t	1d	SCl	0
	Gf 22	Ixopo	A/B	-t	1d	SCl	0
	Gf 30	Runnymeade	A/B	-l	1b	SLm	0
	Gf 33	Slagkraal	B	-t/-l	1e	Cl	0
	Gf 21	Umzimkulu	A		1c	SClLm	0
	Gf 31	Welgemoed	A/B	-l	1c	SClLm	0
	Gf 23	Zwagershoek	A/B	-t	1e	Cl	0
HOUWHOEK	Hh 20	Albertinia	C		2a	LmS	X
	Hh 10	Elgin	C		2a	LmS	X
	Hh 21	Garcia	C		2b	SLm	XX
	Hh 31	Gouna	B/C	+t	2b	SLm	XX
	Hh 30	Houwhoek	B/C	+t	2a	S	X
	Hh 11	Stormsrivier	C		2b	SLm	XX

Table 7.1 (continued)

Soil Form	Code	Soil Series	SCS Group -ing	SCS Adjust -ment Factor	Clay Distri- bution Model	Typical Text- ural Class	Inter- flow Poten- tial
HUTTON	Hu 10	Alloway	A		1a	LmS	0
	Hu 11	Arnot	A		1a	LmS	0
	Hu 18	Balmoral	A/B	-t	1e	Cl	0
	Hu 25	Bontberg	A		1b	SLm	0
	Hu 22	Chester	A		1a	S	0
	Hu 24	Clansthal	B		1b	SLm	0
	Hu 27	Doveton	A/B	-t	1d	SCl	0
	Hu 17	Farningham	A/B	-t	1d	SCl	0
	Hu 31	Gaudam	A	-l/+t	1a	LmS	0
	Hu 47	Hardap	A/B	-t	1d	SCl	0
	Hu 16	Hutton	A		1c	SClLm	0
	Hu 21	Joubertina	A		1a	LmS	0
	Hu 15	Kyalami	A		1b	SLm	0
	Hu 23	Lichtenburg	A		1b	SLm	0
	Hu 40	Lowlands	A		1a	LmS	0
	Hu 43	Maitengwe	A		1b	SLm	0
	Hu 37	Makatini	B	-t/-l	1d	SCl	0
	Hu 44	Malonga	A		1b	SLm	0
	Hu 33	Mangano	A/B	-l	1b	SLm	0
	Hu 38	Marikana	B	-t/-l	1e	Cl	0
	Hu 14	Middelburg	A		1b	SLm	0
	Hu 48	Minhoop	A/B	-t	1e	Cl	0
	Hu 32	Moriah	A	-l/+t	1a	S	0
	Hu 26	Msinga	A		1c	SClLm	0
	Hu 41	Nyala	A		1a	LmS	0
	Hu 35	Portsmouth	A	-l/+t	1b	SLm	0
	Hu 42	Quaggafontein	A		1a	S	0
	Hu 30	Roodepoort	A	-l/+t	1a	LmS	0
	Hu 46	Shigalo	A		1c	SClLm	0
	Hu 36	Shorrocks	A/B	-l	1c	SClLm	0
	Hu 12	Stonelaw	A		1a	S	0
	Hu 45	Vergenoeg	A		1b	SLm	0
	Hu 28	Vimy	A/B	-t	1e	Cl	0
	Hu 13	Wakefield	A		1b	SLm	0
	Hu 20	Whithorn	A		1a	LmS	0
	Hu 34	Zwartfontein	A/B	-l	1b	ClLm	0
INANDA	Ia 10	Fountainhill	A		1c	SClLm	0
	Ia 11	Inanda	A		1d	SCl	0
	Ia 12	Sprinz	A		1e	Cl	0

Table 7.1 (continued)

Soil	Code	Soil	SCS Group-ing	SCS Adjust-ment Factor	Clay Distri-bution Model	Typical Text-ural Class	Inter-flow Poten-tial
INHOEK	Ik 11	Coniston	C/D	-t	2d	SCl	0
	Ik 10	Cromley	C		2c	SClLm	0
	Ik 21	Drydale	C/D	-t	2d	SCl	0
	Ik 20	Inhoek	C		2c	SClLm	0
KATSPRUIT	Ka 10	Katspruit	C/D		1d	SCl	0
	Ka 20	Killarney	C/D		1d	SCl	0
KRANSKOP	Kp 10	Kipipiri	A		1c	SClLm	0
	Kp 11	Kranskop	A		1d	SCl	0
	Kp 12	Umbumbulu	A		1e	Cl	0
KROONSTAD	Kd 17	Avoca	C/D		3h	SClLm/SCl	XX
	Kd 16	Bluebank	C/D		3h	SClLm/SCl	XX
	Kd 22	Katarra	C/D		3c	S/SClLm	XX
	Kd 20	Koppies	C/D		3c	LmS/SClLm	XX
	Kd 13	Kroonstad	C/D		3e	SLm/SClLm	XX
	Kd 14	Mkambati	C/D		3b	SLm/SClLm	XX
	Kd 10	Rocklands	C/D		3b	LmS/SLm	XX
	Kd 15	Slangkop	C/D		3e	LmS/SClLm	XX
	Kd 12	Swellengift	C	+t	3b	S/SLm	XX
	Kd 18	Uitspan	C/D		3h	SClLm/SCl	XX
	Kd 21	Umtentweni	C/D		3c	LmS/SClLm	XX
	Kd 11	Velddrif	C/D		3b	LmS/SLm	XX
	Kd 19	Volksrust	D	-t	3k	SCl/Cl	XX
LAMOTTE	Lt 10	Alsace	A/B		2a	LmS	X
	Lt 21	Burgundy	B	+c	2a	LmS	XX
	Lt 14	Chamond	A/B		2b	SLm	X
	Lt 22	Franschhoek	B	+c	2a	LmS	XX
	Lt 25	Hooghalen	B	+c	2b	SLm	XX
	Lt 12	Lamotte	A/B		2a	LmS	X
	Lt 11	Laparis	A/B		2a	LmS	X
	Lt 15	Lillesand	A/B		2b	SLm	X
	Lt 20	Lorraine	B	+c	2a	LmS	XX
	Lt 24	Ringwood	B	+c	2b	SLm	XX
	Lt 23	Tillberga	B	+c	2b	SLm	XX
	Lt 13	Vevey	A/B		2b	SLm	X
LONGLANDS	Lo 22	Albany	C/D	-t	1c	SClLm	XX
	Lo 32	Chitsa	C/D	-t	1c	SClLm	XX

Table 7.1 (continued)

Soil Form	Code	Soil Series	SCS Group -ing	SCS Adjust -ment Factor	SCS Distri- bution Model	Typical Text- ural Class	Inter flow Poten- tial
LONGLANDS (contd)	Lo 21	Longlands	C		1b	SLm	XX
	Lo 10	Orkney	C		1a	LmS	XX
	Lo 30	Tayside	C		1a	S	XX
	Lo 31	Vaalsand	C		1b	SLm	XX
	Lo 20	Vasi	C		1a	LmS	XX
	Lo 11	Waaisand	C		1b	SLm	XX
	Lo 12	Waldene	C/D	-t	1c	SClLm	XX
	Lo 13	Winterton	C	-t	1d	SCl	XX
MAGWA	Ma 12	Frazer	A/B		1e	Cl	0
	Ma 11	Magwa	A/B		1d	SCl	0
	Ma 10	Milford	A	+t	1c	SClLm	0
MAYO	My 10	Mayo	C		5c	SClLm	X
	My 11	Msinsini	C/D	-t	5d	SCl	X
	My 21	Pafuri	C/D	-t	5d	SCl	X
	My 20	Tshipise	C		5c	SCl	X
MILKWOOD	Mw 10	Dansland	C		2c	SClLm	X
	Mw 21	Graythorne	C/D	-t	2d	SCl	X
	Mw 11	Milkwood	C/D	-t	2d	SCl	X
	Mw 20	Sunday	C		2c	SClLm	X
MISPAH	Ms 21	Hillside	C		2c	SClLm	XX
	Ms 22	Kalkbank	C		2c	SClLm	XX
	Ms 11	Klipfontein	C		2c	SClLm	XX
	Ms 12	Loskop	C		2c	SClLm	XX
	Ms 23	Misgund	C		2c	SClLm	XX
	Ms 10	Mispah	C		2c	SClLm	XX
	Ms 20	Muden	C		2c	SClLm	XX
	Ms 13	Plettenberg	C		2c	SClLm	XX
	Ms 14	Winchester	C		2c	SClLm	XX
	Ms 24	Vredendal	C		2c	SClLm	XX
NOMANCI	No 11	Lusiki	B		5d	SCl	0
	No 10	Nomanci	B		5c	SClLm	0
OAKLEAF	Oa 43	Allanridge	B		1b	SLm	0
	Oa 45	Calueque	A/B	+t	1b	SLm	0
	Oa 21	Doornlaagte	A/B	+t	1a	LmS	0

Table 7.1 (continued)

Soil Form	Code	Soil Series	SCS Group -ing	SCS Adjust -ment Factor	Clay Distri- bution Model	Typical Text- ural Class	Inter- flow Poten- tial
OAKLEAF (contd)	Oa 25	Hazelwood	A/B	+t	1b	SLm	0
	Oa 17	Highflats	B/C	-t	1d	SCl	0
	Oa 22	Holpan	A/B	+t	1a	S	0
	Oa 36	Jozini	B		1c	SClLm	0
	Oa 23	Kirkton	B		1b	SLm	0
	Oa 13	Klipplaat	B		1b	SLm	0
	Oa 37	Koedoesvlei	B/C	-t	1d	SCl	0
	Oa 16	Leeufontein	B		1c	SClLm	0
	Oa 26	Letaba	B		1c	SClLm	0
	Oa 34	Levubu	B		1b	SLm	0
	Oa 46	Limpopo	B		1c	SClLm	0
	Oa 41	Lovedale	A/B	+t	1a	LmS	0
	Oa 11	Madwaleni	A/B	+t	1a	LmS	0
	Oa 24	Magersfontein	B		1b	SLm	0
	Oa 27	Makulek	B/C	-t	1d	SCl	0
	Oa 12	Mbanyana	A/B	+t	1d	S	0
	Oa 47	Mutale	B/C	-t	1d	SCl	0
	Oa 42	Naulila	A/B	+t	1a	S	0
	Oa 30	Oakleaf	A/B	+t	1a	LmS	0
	Oa 44	Okavango	B		1b	SLm	0
	Oa 31	Oshikango	A/B	+t	1a	LmS	0
	Oa 15	Pollock	A/B	+t	1b	SLm	0
	Oa 14	Rockford	B		1b	SLm	0
	Oa 32	Sezela	A/B	+t	1a	S	0
	Oa 10	Smaldeel	A/B	+t	1a	LmS	0
	Oa 33	Vaalriver	B		1b	SLm	0
	Oa 35	Venda	A/B	+t	1b	SLm	0
	Oa 40	Voorspoed	A/B	+t	1a	LmS	0
	Oa 20	Warrenton	A/B	+t	1a	LmS	0
PINEDENE	Pn 27	Airlie	B/C	-t	1d	SCl	X
	Pn 12	Bethlehem	A	+t/+l	1a	S	X
	Pn 25	Chatsworth	A/B	+t	1b	SLm	X
	Pn 15	Eykendal	A	+t/+l	1b	SLm	X
	Pn 10	Fortuin	A	+t/+l	1a	LmS	X
	Pn 13	Graymead	A/B	+l	1b	SLm	X
	Pn 22	Hermanus	A/B	+t	1a	S	X
	Pn 17	Kilburn	B	-t/+l	1d	SCl	X
	Pn 32	Kleinrivier	B	+t/+l	1a	S	X
	Pn 36	Klerksdorp	B/C	-l	1c	SClLm	X
	Pn 34	Nagtwagt	B/C	-l	1b	SLm	X
	Pn 33	Oewer	B/C	-l	1b	SLm	X
	Pn 16	Ouwerf	A/B	+l	1c	SClLm	X
	Pn 30	Papiesvlei	B	+t/-l	1a	LmS	X
	Pn 14	Pinedene	A/B	+l	1b	SLm	X

Table 7.1 (continued)

Soil Form	Code	Soil Series	SCS Group -ing	SCS Adjust -ment Factor	Clay Distri- bution Model	Typical Text- ural Class	Inter- flow Poten- tial
PINEDENE (contd)	Pn 11	Radyn	A	+t/+l	1a	LmS	X
	Pn 20	Rotterdam	A/B	+t	1a	LmS	X
	Pn 31	Stormsvlei	B	+t/-l	1a	LmS	X
	Pn 26	Suurbraak	B		1c	SClLm	X
	Pn 24	Tulbagh	B		1b	SLm	X
	Pn 23	Vyeboom	B		1b	SLm	X
	Pn 21	Wemmershoek	A/B	+t	1a	LmS	X
	Pn 37	Witpoort	C	-t/-l	1d	SCl	X
	Pn 35	Yzerspruit	B	+t/-l	1b	SLm	X
SHEPSTONE	Sp 12	Addington	A		3a	LmS	0
	Sp 11	Bitou	A		3a	LmS	0
	Sp 13	Gouritz	A		2b	SLm	0
	Sp 15	Inhaminga	A		2b	SLm	0
	Sp 22	Kunjane	A		3c	LmS/SClLm	0
	Sp 23	Pencarrow	A		3e	SLm/SClLm	0
	Sp 24	Portobello	A		3e	SLm/SClLm	0
	Sp 25	Pumula	A		3e	SLm/SClLm	0
	Sp 14	Robberg	A		2b	SLm	0
	Sp 21	Shepstone	A		3c	LmS/SClLm	0
	Sp 20	Southbroom	A		3c	LmS/SClLm	0
	Sp 10	Tergniet	A		3a	LmS	0
SHORT- LANDS	Sd 11	Argent	B		1d	SCl	0
	Sd 10	Bokuil	A/B	+t	1c	SClLm	0
	Sd 30	Ferry	B		1c	SClLm	0
	Sd 21	Glendale	B/C	-l	1d	SCl	0
	Sd 20	Kinross	B	-l/+t	1c	SClLm	0
	Sd 12	Richmond	B/C	-t	1e	Cl	0
	Sd 22	Shortlands	C	-l/-t	1e	Cl	0
	Sd 31	Sunvalley	B/C	-l	1d	SCl	0
	Sd 32	Tugela	C	-l/-t	1e	Cl	0
STERK- SPRUIT	Ss 27	Antioch	D		3k	SCl	X
	Ss 13	Bakklysdrift	D		3c	SLm	X
	Ss 15	Dehoek	D		3e	LmS	X
	Ss 10	Diepkloof	D		3b	LmS	X
	Ss 17	Driebaden	D		3k	SCl	X
	Ss 21	Graafwater	D		3b	LmS	X
	Ss 25	Grootfontein	D		3e	LmS	X
	Ss 20	Halseton	D		3b	LmS	X

Table 7.1 (continued)

Soil Form	Code	Soil Series	SCS Grouping	SCS Adjustment Factor	Clay Distribution Model	Typical Textural Class	Interflow Potential
STERK SPRUIT (contd)	Ss 24	Hartbees	D		3e	SLm	X
	Ss 12	Ruacana	D		3b	S	X
	Ss 22	Silwana	D		3b	S	X
	Ss 23	Stanford	D		3e	SLm	X
	Ss 26	Sterkspruit	D		3h	SClLm	X
	Ss 16	Swaerskloof	D		3h	SClLm	X
	Ss 11	Tina	D		3b	LmS	X
	Ss 14	Toleni	D		3e	SLm	X
SWARTLAND	Sw 12	Breidbach	D	-t	1e	Cl	X
	Sw 21	Broekspruit	C/D		1d	SCl	X
	Sw 32	Hogsback	D	-t	1e	Cl	X
	Sw 40	Malakata	C/D		1c	SCl	X
	Sw 41	Nyoka	C/D		1d	SCl	X
	Sw 42	Omdraai	D	-t	1e	Cl	X
	Sw 22	Prospect	D	-t	1e	Cl	X
	Sw 10	Reveillie	C/D		1c	SClLm	X
	Sw 30	Rosehill	C/D		1c	SClLm	X
	Sw 11	Skilderkrans	C/D		1d	SCl	X
	Sw 31	Swartland	C/D		1d	SCl	X
	Sw 20	Uitsicht	C/D		1c	SClLm	X
TAMBANKULU	Tk 10	Fenfield	C		2c	SClLm	X
	Tk 20	Loshoek	C		2c	SClLm	X
	Tk 21	Masala	C/D	-t	2d	SCl	X
	Tk 11	Tabankulu	C/D	-t	2d	SCl	X
VALSRIVIER	Va 31	Arniston	C/D		1d	SCl	X
	Va 32	Chalumna	C	-t	1e	Cl	X
	Va 21	Craven	C/D		1d	SCl	0
	Va 30	Herschel	C/D		1c	SClLm	X
	Va 12	Lilydale	D	-t	1e	Cl	0
	Va 41	Lindley	C/D		1d	SCl	X
	Va 22	Marienthal	C	-t	1e	Cl	0
	Va 42	Sheppardvale	D	-t	1e	Cl	X
	Va 10	Sunnyside	C/D		1c	SClLm	0
	Va 40	Valsrivier	C/D		1c	SClLm	X
	Va 11	Waterval	C/D		1d	SCl	0
	Va 20	Zuiderzee	C/D		1c	SClLm	0

Table 7.1 (continued)

Soil Form	Code	Soil Series	SCS Group -ing	SCS Adjust -ment Factor	Clay Distri- bution Model	Typical Text- ural Class	Inter- flow Poten- tial
VILA- FONTES	Vf 45	Blombosch	B/A		3e	SLm/SClLm	XX
	Vf 23	Blythdale	B/A		3e	SLm/SClLm	XX
	Vf 31	Brenton	B/A		3a	LmS	XX
	Vf 24	Chantilly	B/A		3e	CLm/SClLm	XX
	Vf 44	Dassenhoek	B/A		3e	SLm/SClLm	XX
	Vf 21	Fairbreeze	B/A		3c	LmS/SCLm	XX
	Vf 43	Geelbek	B/A		3e	SLm/SClLm	XX
	Vf 11	Hudley	B/A		3a	LmS	XX
	Vf 22	Klaarwater	B/A		3c	LmS/SClLm	XX
	Vf 34	Knysna	B/A		2b	SLm	XX
	Vf 40	Kransduinen	B/A		3c	LmS/SClLm	XX
	Vf 20	Matigulu	B/A		3c	LmS/SClLm	XX
	Vf 41	Mazeppa	B/A		3c	LmS/SClLm	XX
	Vf 35	Meulvlei	B/A		2b	SLm	XX
	Vf 10	Moreland	B/A		3a	LmS	XX
	Vf 14	Moyeni	B/A		2b	SLm	XX
	Vf 25	Nhamacala	B/A		3e	SLm/SClLm	XX
	Vf 33	Rheebok	B/A		2b	SLm	XX
	Vf 30	Sedgefield	B/A		3a	LmS	XX
	Vf 32	Swinton	B/A		3a	LmS	XX
	Vf 13	Tinley	B/A		2b	SLm	XX
	Vf 42	Vallance	B/A		3c	LmS/SClLm	XX
	Vf 15	Vilafontes	B/A		2b	SLm	XX
	Vf 12	Zeekoe	B/A		3a	LmS	XX
WASBANK	Wa 12	Burford	C		2c	SClLm	XX
	Wa 13	Endicott	C/D	-t	2d	SCl	XX
	Wa 30	Hamman	B/C	+t	2a	S	XX
	Wa 10	Hoopstad	B/C	+t	2a	LmS	XX
	Wa 11	Kromvlei	C		2b	SLm	XX
	Wa 20	Rondevlei	B/C	+t	2a	LmS	XX
	Wa 31	Sandvlei	B/C	+t	2c	SClLm	XX
	Wa 22	Warrick	C		2c	SClLm	XX
	Wa 21	Wasbank	C		2b	SLm	XX
	Wa 32	Winterveld	C		2c	SClLm	XX
WESTLEIGH	We 10	Chinde	B/C	+t	1a	LmS	X
	We 32	Davel	C		1c	SClLm	X
	We 22	Devon	C		1c	SClLm	X
	We 20	Kosi	B/C	+t	1a	LmS	X
	We 30	Langkuil	B/C	+t	1a	S	X
	We 31	Paddock	B/C	+t	1b	SLm	X

Table 7.1 (continued)

Soil Form	Code	Soil Series	SCS Group -ing	SCS Adjust -ment Factor	Clay Distri- bution Model	Typical Text- ural Class	Inter- flow Poten- tial
WESTLEIGH (contd)	We 12	Rietvlei	C		1c	SClLm	X
	We 13	Sibasa	C/D	-t	1d	SCl	X
	We 11	Westleigh	C		1b	SLm	X
	We 21	Witsand	C		1b	SLm	X
WILLOW- BROOK	Wo 21	Chinyika	D		2d	SCl	0
	Wo 10	Emfuleni	D		2c	SClLm	0
	Wo 20	Sarasdale	D		2c	SClLm	0
	Wo 11	Willowbrook	D		2d	SCl	0

CHAPTER 8

SOIL WATER RETENTION MODELS FOR SOUTHERN AFRICAN SOILS

R.E. Schulze, J.L. Hutson[1] and A. Cass[2]

INTRODUCTION

The amount of water retained in a soil has upper and lower bounds determined respectively by inherent properties of the soil and by plant extraction. It is this retained soil water which may be redistributed under saturated conditions by drainage (with a primarily vertical downward component) or under unsaturated conditions by movement up or down (depending on the relative wetness of respective soil horizons) and by plant root extraction.

In this chapter soil water retention constants used commonly in hydrological models are first discussed and defined. Methods of estimating fractions of water held in the soil at field capacity and wilting point are described next. Water retention equations developed from Southern African data are then given. Since soil water retention is largely a function of clay content and its distribution within the soil profile, clay distribution models applicable to Southern African soils are outlined and typical water holding fractions for the various models and submodels are

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then calculated from equations presented. Finally, Southern African soil series are classified by textural class and this enables a comparison to be made between estimated water retention constants derived by models from Southern Africa and the U.S.A.

DEFINITIONS OF SOIL WATER RETENTION CONSTANTS

Soil water analysis amounts to the arbitrary division of water in soils into a number of categories which are useful in assessing the amount of water available for plants, the storage capacity of soil and many other characteristics of hydrological and engineering importance (Rawls et al, 1982).

Definitions of three soil water retention constants are necessary.

(a) Porosity. Porosity is the percentage of soil volume occupied by voids, i.e. the maximum soil moisture storage or saturation. The matric potential at porosity is 0 kPa.

(b) Field Capacity. Field capacity is the soil water condition reached when water has been allowed to drain naturally from the soil until drainage ceases and the water remaining is held by capillary and osmotic forces that are great enough to resist gravity. Field capacity, FC, is therefore often described as being the wet limit of the moisture available to plants. This theoretical definition has drawbacks when applied to soils in nature and FC can be described as the soil moisture content below which the hydraulic conductivity is sufficiently small that redistribution of moisture due to hydraulic head gradient can be ignored. A definition in terms of matric potential is difficult owing to the fact that FC may vary with texture, but it is traditionally taken to fall somewhere between -5 and -33 kPa, with a present-day value tending away from the -33 kPa towards the -10kPa matric potential value.

(c) Wilting Point. This is taken as the dry limit for water available to plants. At the stage of wilting point, WP, the hydraulic conductivity is so low that water cannot move over even short distances to the roots fast enough to satisfy the transpirational demand. The matric potential at this point is usually accepted to be -1500 kPa.

Using these definitions one can define plant available water, PAM, as PAM = FC - WP.

ESTIMATING SOIL WATER CONTENTS FOR DIFFERENT RETENTION CONSTANTS

The hydrological processes occuring within the upper and lower bounds of the soil water store necessitate the estimation of values, for use in models, of porosity, field capacity and wilting point.

Traditionally, available moisture has been estimated only after time-consuming and expensive laboratory analyses of the soil. The association of the three retention constants with soil physical properties has long attracted the attention of soil scientist and hydrologist alike, and many relationships have been published. These have been reviewed recently by Hutson (1983), who states that these efforts have met with partial success only, and considering the complex and variable nature of soil, little improvement in such relationships can now be expected. It is not possible, he maintains, to characterize retentivity solely in terms of soil type and composition as so many factors influence retentivity, for example, particle shape, bulk density, clay mineralogy, organic matter content, structure, degree of aggregation, and other factors. Some of these factors defy precise quantitative description; consequently their effect on retentivity may be assessed in qualitative terms only.

Detailed and precise retentivity measurements provide insight into the manner in which various soil properties influence retentivity and add to the data base from which useful generalizations may be drawn. The gradual accumulation of a store of accurate data has reduced our dependence on measured data for immediate application and on <u>ad hoc</u> problem solving. This enables soil water research facilities to be used more effectively and directed into areas where it is most needed (Hutson and Joubert, 1983).

In Southern Africa, Hutson (1983) has undertaken a range of analyses from a large data base to determine the extent to which retentivity of local soils can be predicted from a knowledge of soil type, composition and bulk density and secondly, to develop and determine the range of parameters of a retentivity function to facilitate the mathematical description of retentivity for modelling purposes.

Using data from a wide spectrum of physical environments, Hutson (1983) developed a general model, in equation form, based on percentages of clay and silt together with bulk density, which may be applied in Southern African soils.

The model, applicable to "stable" soils, takes the general form

$$\theta_{\psi} = \beta_1 + \beta_2 Cl + \beta_3 Si + \beta_4 \rho_b$$

in which

$\theta\theta$ = water retention in mm/mm for a given matric potential

with

$\psi\psi$ = -5 to -30 kPa at field capacity and -1500kPa at wilting point, Cl = percent clay,

Si = percent silt,

ρ_b = bulk density in $Mg.m^{-3}$, and

β_{1-4} = regression coefficients.

Regression coefficients with goodness of fit statistics for Hutson's (1983) general model for stable soils are given in Table 8.1. The example below illustrates the use of the model, if results of a mechanical analysis of the soil are available:

Soil : Loam with 15% clay
25% silt
Bulk density 1,6 $Mg.m^{-3}$

Water content (volume/volume) at FC :

θ_{-30} = -0,015 + 0,0576 + 0,143 + 0,074 = 0,260 mm/mm

Water content (volume/volume) at WP :

θ_{-1500} = -0,0602 + 0,0483 + 0,077 - 0,0416 = 0,144 mm/mm

PAM = FC - WP = 0,116 mm/mm

= 116 mm water/m soil depth

Since water retention for unstable soils at WP differs from that of stable soils, Hutson (1983) has given similar regression equations for unstable soils at -1500 kPa. Thus, for

(i) vertic soils (with r^2 = 0,472)

Table 8.1 Regression coefficients of the Hutson (1983) model for the estimation of soil water retention constants for stable soils

kPa	Constant	% Clay	% Silt	Bulk Density	r^2	s
- 10	0,0558	0,00365	0,00554	0,0303	0,681	0,066
- 30	-0,0150	0,00384	0,00572	0,0463	0,764	0,055
- 100	0,0290	0,00361	0,00441	0,0049	0,769	0,059
- 500	0,1588	0,00347	0,00170	-0,0838	0,823	0,047
-1500	0,0602	0,00322	0,00308	-0,0260	0,785	0,051

$$\theta_{-1500} = 0,0293 + 0,00606\ Cl + 0,00285\ Si + 0,0384\ C$$

in which

C = percent organic carbon

and

(ii) for prismacutanic,

pedocutanic and

gleycutanic soils ($r^2 = 0,711$)

$$\theta_{-1500} = 0,01616 + 0,0052\ Cl + 0,00222\ Si$$

PROBLEMS ASSOCIATED WITH RETENTION EQUATIONS AND SIMPLIFYING ASSUMPTIONS

The retention equations presented in the previous section for stable and unstable soils found in Southern Africa include clay content, silt content, organic carbon content and bulk density as variables. Of these variables only classes of clay content are used by the binomial system of soil classification for Southern Africa (MacVicar et al, 1977) to distinguish between soil series. Simplifying assumptions therefore have to be made in regard to silt content, organic carbon content and bulk density.

(a) Silt Content. Hutson (1983), in an analysis of over 3000 Southern African soil samples, found that 90,1% of the samples comprised sandy loams, sandy clay loams, clays, sandy clays, sands and loamy sands. If these classes are examined on the Southern African texture triangle it may be seen that the 10% silt content value passes through all the above soil textural classes. Analyses also show that a 20% silt content is very seldom exceeded. A general silt content of 10% may therefore be used with confidence in water retention equations applicable to Southern African soils.

(b) Bulk Density. From data presented by Hutson (1983, p 75), a bulk density of 1,3 $Mg.m^{-3}$ may be assumed for the topsoil horizon (this value also being used in agriculture for fertilizer recommendations) and of 1,5 $Mg.m^{-3}$ for subsoil horizons.

(c) Organic Carbon Content. For vertic A-horizons, organic carbon content is required in its water retention equation and numerous analyses have shown 1,3% to be a representative value. (For the other diagnostic topsoil horizons the following C values are representative : humic 6%, orthic 0,6%, melanic 1,3%, organic 10%).

SIMPLIFIED, GENERALLY APPLICABLE WATER RETENTION EQUATIONS FOR SOUTHERN AFRICA

With the simplifying assumptions made above, Hutson's (1983) equations for stable soils may be rewritten as :

$$\theta_{FC} = \theta_{-10} = 0,1506 + 0,00365\ Cl \text{ for the topsoil horizon}$$

and

$$\theta_{-10} = 0,1567 + 0,00365\ Cl \text{ for subsoil horizons}$$

and

$$\theta_{WP} = \theta_{1500} = 0,0572 + 0,00322\ Cl \text{ for the topsoil horizon}$$

and

$$\theta_{-1500} = 0,0520 + 0,00322 \text{ for the subsoil horizons.}$$

For vertic (unstable) soils

$$\theta_{FC} = \theta_{-10} = \text{identical to the equations for stable soils}$$

and

$$\theta_{WP} = \theta_{-1500} = 0,1077 + 0,00606\ Cl \text{ for all horizons}$$

For prisma-, pedo- and gleycutanic (unstable) soils

$$\theta_{FC} = \theta_{-10} = \text{identical to the equations for stable soils}$$

and

$$\theta_{WP} = \theta_{-1500} = 0,0384 + 0,00522\ Cl \text{ for all horizons.}$$

CLAY DISTRIBUTION MODELS FOR USE WITH RETENTION EQUATIONS

With soil water retention equations for field capacity and wilting point expressed in terms of clay content only, and with the binomial system of soil classification for Southern Africa containing clay content classes, water retention constants may be estimated for various horizons if the clay distribution down the profile is known. From an examination of the 41 soil forms and 501 soil series defined by MacVicar et al. (1977), five clay distribution models are proposed for Southern Africa. These are illustrated in Figure 8.1.

(a) Model 1. In Model 1 clay distribution increases down the soil profile - a phenomenon common in well drained soils in which the process of illuviation has translocated the finer

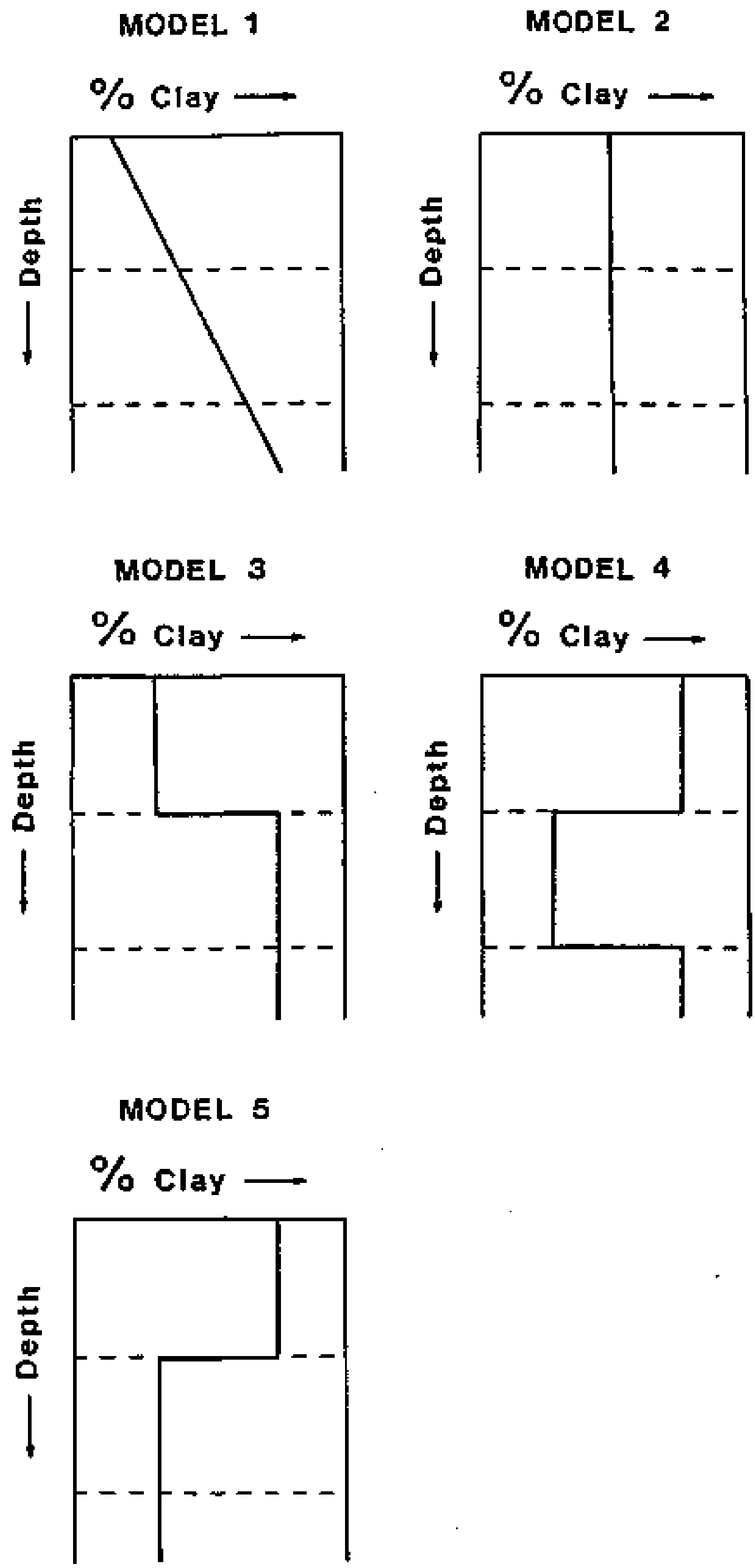

Figure 8.1 Clay distribution models for Southern Africa

clay particles downwards. Since the Southern African binomial system classifies series by clay content of the B21 horizon (Figure 7.2), clay values for a two-horizon profile are reduced from the middle value of a clay class for the topsoil horizon and increased for the subsoil horizon. In assigning topsoil and subsoil values of clay contents for the five classes of clay content used by MacVicar et al, (1977), cognizance was taken of Hutson's (1983) findings, namely that clay contents differed by 25-30% between orthic A-horizons and red apedal B-horizons for the clay class 15-35%, but that the differences were reduced with increasing clay content. Five submodels of Model 1 are proposed, and respective clay contents are given in Table 8.2.

The following soil forms are classed, for water retention purposes, as belonging to Model 1 : Avalon, Bainsvlei, Clovelly, Fernwood, Glencoe, Griffin, Hutton, Inanda, Katspruit, Kranskop, Longlands, Magwa, Oakleaf, Pinedene, Shortlands, Swartland, Valsrivier and Westleigh.

(b) Model 2. In Model 2 the clay distribution remains constant throughout the soil profile. Five submodels of Model 2 are proposed, in accordance with the five clay classes recognized in MacVicar et al, (1977), and the clay percentages assigned to the respective submodels are those shown in column 3 of Table 8.2.

The soil forms conforming to Model 2 are Arcadia, Bonheim, Champagne, Constantia (certain series), Dundee, Houwhoek, Inhoek, Lamotte, Milkwood, Mispah, Rensburg, Shepstone (certain series), Tambankulu, Vilafontes (certain series), Wasbank and Willowbrook.

(c) Model 3. Model 3 soils display an abrupt textural (i.e. clay content) transition from the topsoil to the subsoil.

Table 8.2 Topsoil and subsoil clay percentages assigned to the submodels of the water retention Model 1

Submodel	Clay Class %	Typical Clay % Value	Assigned Topsoil Horizon Clay %	Assigned Subsoil Horizon Clay %
1a	0 - 6	3	2	4
1b	6 - 15	10	8	12
1c	15 - 35	25	17	33
1d	35 - 55	45	36	54
1e	> 55	60	54	66

Three "degrees" of abruptness were recognized, the least abrupt change increasing clay content by 7%, the middle class by 15% and the most abrupt change increasing clay content by 25%. The result is that 12 submodels of Model 3 can be distinguished theoretically. However, only six were found to exist in the 501 series in Southern Africa. Details of the submodels of Model 3 are given in Table 8.3.

Soil forms classified by clay distribution as belonging to Model 3 for water retention calculations are Constantia (certain series), Estcourt, Kroonstad, Shepstone (certain series), Sterkspruit and Vilafontes (certain series).

(d) <u>Model 4</u>. The clay distribution down a profile "bulges" in the E-horizon in Model 4 - a result of chemical reduction following periodic waterlogging and lateral flow of water causing a loss of clay particles.

Soil forms conforming to Model 4 are yet to be determined.

(e) <u>Model 5</u>. Model 5 represents a mirror-image of water retention Model 3, with an abrupt decrease in clay content in the subsoil. Unlike Model 4, however, the reduced clay content persists down the profile. In this Model, clay content of the subsoil horizon is reduced to half the topsoil horizon value, resulting in five submodels according to clay content classes. Suggested submodel clay percentages are listed in Table 8.4.

Water retention constants for the following soil forms should be estimated with values from Model 5 : Cartref, Glenrosa, Mayo and Nomanci.

Each of the 41 soil forms described to date in Southern Africa was assigned to one (and in the case of certain forms, two) of the five clay distribution models and within each form individual

Table 8.3 Topsoil and subsoil clay percentages assigned to the submodels of the water retention Model 3

Submodel	Clay Class %	Clay % Added	Assigned Topsoil Horizon Clay %	Assigned Subsoil Horizon Clay %	Existence in S.A.
3a	0 - 6	7	3	10	
b		15	3	18	
c		25	3	28	
3d	6 - 15	7	10	17	x
e		15	10	25	
f		25	10	35	x
3g	15 - 35	7	25	32	x
h		15	25	40	
i		25	25	50	x
3j	35 - 55	7	45	52	x
k		15	45	60	
l		25	45	70	x

Table 8.4 Topsoil and subsoil clay percentages assigned to the submodels of the water retention Model 5

Submodel	Clay Class %	Assigned Topsoil Horizon Clay %	Assigned Subsoil Horizon Clay %
5a	0 - 6	3	1,5
5b	6 - 15	10	5,0
5c	15 - 35	25	12,5
5d	35 - 55	45	22,5
5e	> 55	60	30,0

soil series were allocated to a submodel. In this way the 501 soil series were classified by their diagnostic and clay distribution characteristics. Table 7.1 lists this classification of each form and series by clay distribution submodel.

The generalized Hutson (1983) equations were applied to the assigned clay contents of all clay distribution submodels discussed above. By this procedure estimates of soil water content at field capacity and wilting point have been made for Southern African soil conditions and are presented in Table 8.5 for topsoil and subsoil horizons for both stable and unstable soil forms.

TEXTURAL CLASSES OF SOUTHERN AFRICAN SOIL SERIES

Generalized values of retention constants have frequently been given for texture classes. Since a silt content around 10% may be assumed for most of Southern African soils, and since the binomial system of soil classification groups soil series by classes of clay content, each soil series may be grouped, in general terms, into a textural class, if the middle value of the clay class is assumed to be representative. By this approach the 501 soil series identified in Southern Africa were placed in textural classes, using the Southern African textural triangle given in MacVicar, et al, (1977). The textural classes are listed in Table 7.1. Series in the 0-6% clay class were grouped as loamy sands, except when distinguished by the coarse sand fractions, in which case they were classed as sands; those in the 6-15% clay class were assigned as sandy loams; 15-35% clay as sandy clay loams; series containing 35-55% clay as sandy clays and series with >55% clay content were classified as clays.

Table 8.5 Estimates of soil water content at field capacity and wilting point from clay distribution models. (Bracketed values refer to unstable soils)

Clay Distribution Model	FC in mm/m		WP in mm/m	
	Topsoil	Subsoil	Topsoil	Subsoil
1a	158	171	64(49)	65(59)
b	180	201	83(80)	91(101)
c	213	277	112(127)	158(211)
d	282	354	173(226)	226(320)
e	348	398	231(320)	265(383)
2a	162	168	67	62
b	187	193	89	84
c	242	248	138(169)	133(169)
d	315	321	202(273)	197(273)
e	370	376	250(352)	245(352)
3a	162	193	67	84
b	162	222	67(54)	110(132)
c	162	259	67(54)	142(185)
e	187	248	89(91)	133(169)
h	242	303	138(169)	181(247)
k	315	376	202(273)	245(352)
4	-	-	-	-
5a	162	162	67	57
b	187	175	89	68
c	242	202	138	92
d	315	239	202	124

A COMPARISON BETWEEN ESTIMATED WATER RETENTION CONSTANTS DERIVED BY MODELS FROM SOUTHERN AFRICA AND THE U.S.A.

Probably the most comprehensive set of retention values classified by textural classes, and based on several thousands of laboratory analyses, was published recently by Rawls, Brakensiek and Saxton (1982). A summary of some of their findings is given in Table 8.6.

The textural classification of Southern African soil series and the information contained in Tables 8.5 and 8.6 facilitate a comparison between estimates of water retention values by models developed in Southern Africa and the U.S.A. Comparative values are given in Table 8.7. For the Southern African values, averages of water retention between the topsoil and subsoil were assumed for the typical clay contents of the five clay classes used in clay distribution Model 2 (Table 8.5). Table 8.7 shows that values compare very well, with those derived by the highly generalized Southern African approximations generally being slightly lower than approximations from the U.S.A. If, however, values of plant available water are examined, then the comparison shows minimal differences (with the exception of an apparent anomaly in sandy clays).

The implications of the above findings are important, since Hutson (1983) and others in Southern Africa have not published equations for the estimation of soil water content at saturation. Porosity values for soil textural classes from the U.S.A. (for example those listed in Table 8.6) may therefore be used with confidence in hydrological models in Southern Africa until local data become available.

CONCLUSIONS

For many years hydrologists in Southern Africa have experienced a genuine need for Southern African soils data to be used in their

Table 8.6 Typical values for retention constants, based on soil textural classes (After Rawls *et al*, 1982)

Textural class	Effective porosity (mm/m)	Water retained at -33 kPa tension (mm/m)	Water retained at -1500 kPa tension (mm/m)
Sand	417	91	33
Loamy Sand	401	125	55
Sandy loam	412	207	95
Loam	434	270	177
Silt loam	486	330	133
Sandy clay loam	330	255	148
Clay loam	390	318	197
Silty clay loam	432	366	208
Sandy clay	321 (?)	339 (?)	239
Silty clay	423	387	250
Clay	385 (?)	396 (?)	272

(?) Denotes apparent anomalies due to different sample sizes

Table 8.7 Comparison of water retention values by soil textural classes

Soil Textural Class	Water Retention (mm/m) at					
	Field Capacity		Wilting Point		Plant Available Water	
	S.A.	U.S.A.	S.A.	U.S.A.	S.A.	U.S.A.
Loamy Sand	165	125	65	55	100	70
Sandy Loam	190	207	86	95	104	103
Sandy Clay Loam	245	255	135	148	110	107
Sandy Clay	318	339	200	239	118	100
Clay	373	396	247	272	126	124

modelling exercises or hydrological designs. Two events have played a major role in the attempts in this report at classifying Southern African soils for various practical purposes. The first was the publication in 1977 of the binomial system of soil classification for Southern Africa by MacVicar and his co-workers, by which soil forms and series can be diagnosed largely by visual, sequential characteristics with a high degree of accuracy in the field. The system is under revision at present. The second was the seminal analytical work on hydrological properties of Southern African soils completed by Hutson in 1983, which has enabled certain key hydrological variables (water retention values) to be estimated with confidence.

The results which have been presented, mainly in tabular form, in this report represent initial working values for the hydrologist. These values will be altered in time and refined as field experience is gained and further laboratory analyses of soils are undertaken. Certainly for detailed hydrological modelling the values and classifications given cannot replace detailed *in situ* examination of the soil or the attendant laboratory analyses necessary for in-depth understanding of the spatial and temporal variations of hydrological processes on a catchment.

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SECTION C

DEVELOPMENT OF THE ACRU MODEL

CHAPTER 9

AIMS AND GENERAL STRUCTURE OF THE ACRU MODEL

HYDROLOGICAL MODELLING : BACKGROUND

A hydrological model provides a way of transferring knowledge from a measured or a study situation to an unmeasured situation where management decisions are needed in regard to water resources systems (Branson et al, 1981). A hydrological model is therefore a quantitative expression of

(i) observation,

(ii) analysis/simulation, and

(iii) prediction/assessment

for planning, design and management.

Literature and practice abound with a multitude of types of models developed for different applications related to water resources, for example, for data management, design, operation, river basin management or research and teaching (Fleming, 1975). All sound conceptual hydrological models, however, have been developed in a sequence of decision and computational steps. An adaptation of these steps as given by Riley and Hawkins (1976) is illustrated in Figure 9.1. The conceptual framework, according to Riley and Hawkins (1976), comprises

(i) a problem situation, for which

(ii) objectives have to be identified,

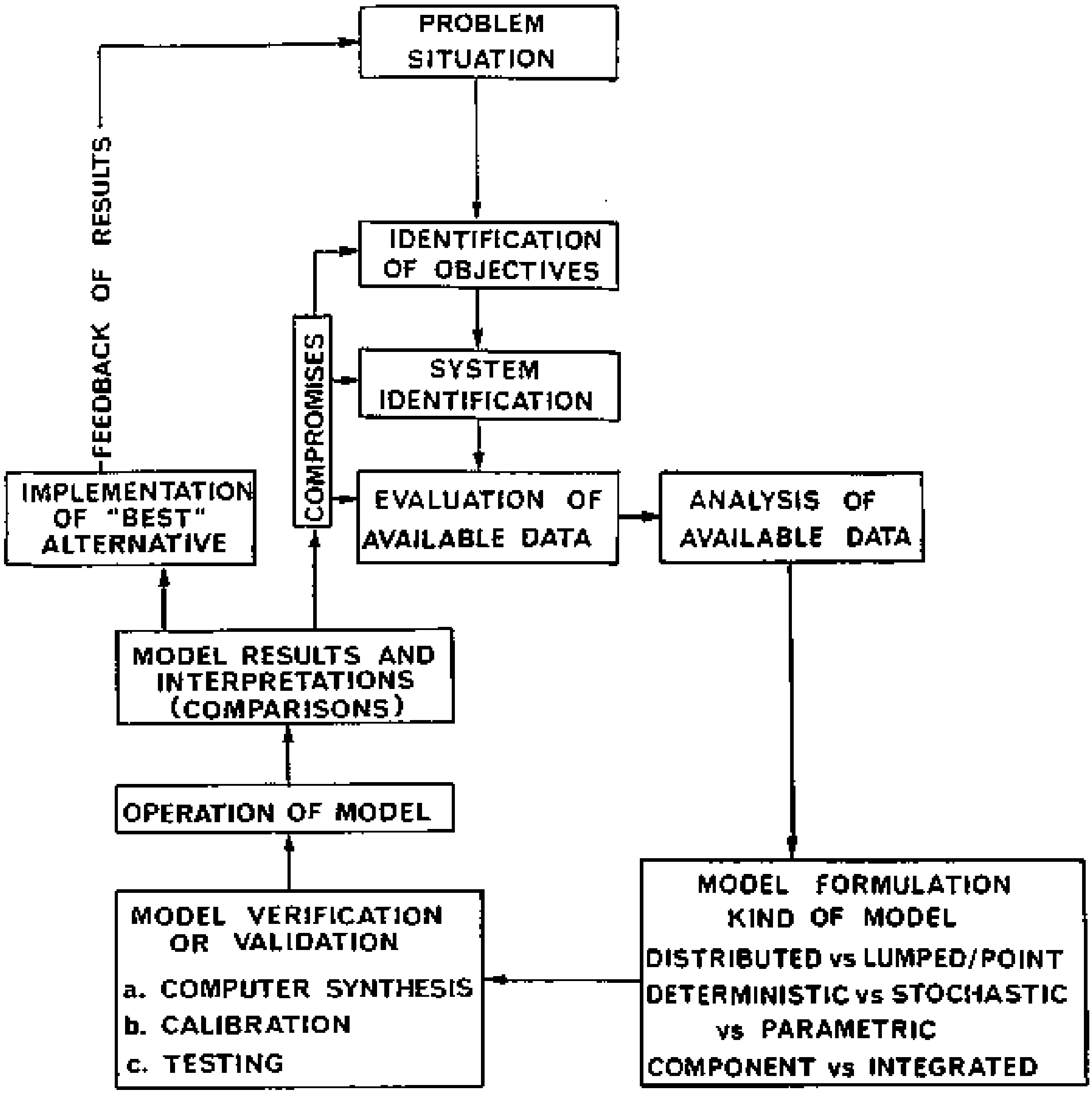

Figure 9.1 Conceptual framework of a hydrological model (After Riley and Hawkins, 1976)

(iii) available data have to be evaluated, then analysed,

(iv) a conceptual model has to be created to represent the various systems of the real world, and this in terms of a desired model complexity,

(v) a working computer model has to be developed to quantify the various processes identified in the conceptual model,

(vi) the model (and/or component parts thereof) has to be verified or validated or calibrated against observed data,

(vii) thereafter the model has to be operated, either as a predictive tool or for detection or identification of certain effects (for example, water yield),

(viii) the results have to be interpreted and, finally and ideally,

(ix) alternatives to the model should be considered in relation to the original problem situation.

THE ACRU MODEL : AIMS AND GENERAL STRUCTURE

Aims

The model name ACRU is derived from the Agricultural Catchments Research Unit of the Department of Agricultural Engineering of the University of Natal, Pietermaritzburg, where the model has been under development since 1981.

In terms of the framework of hydrological model development outlined in the previous section, the ACRU model is being developed for general use, but with specific applicability in

Southern Africa. The model is being developed[1] around the following basic aims:

a) It is a "conceptual physical" model (Eagleson, 1983). It is "conceptual" in the sense that it conceives of a one-dimensional system in which the important processes and couplings are idealized and included in discrete time units. The ACRU model is "physical" to the degree that the ability of the soil to store and transmit water is represented explicitly and that vegetation water use is simulated, using variables which would be observable if the hydrological system "met the idealizations" made (Eagleson, 1983).

(b) The ACRU model is an integrated model i.e. it is a multi-purpose and multi-component model, outputting at present i.e. in the ACRU1 version, either

(i) runoff elements (stormflow, baseflow), and/or

(ii) supplementary irrigation requirements, and/or

(iii) seasonal crop yields (maize, sugarcane).

In the few months of 1984 between the distribution of the draft of this report for review purposes and the final printing, numerous additions/modifications to ACRU1 have been made, some of which are mentioned in the relevant chapters.

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1) This model development is an ongoing process - what is being described in Chapters 9 to 16 is a first version of the model, namely ACRU1. The term ACRU1 is used where reference is made specifically to this first version of the model, while the general term ACRU refers to the model in its broader, longer-term context.

(c) The model, by virtue of its structure, is a small catchments lumped model for use on catchment areas under 10 km^2.

(d) The model has daily time steps and as such uses daily input of climatic data (rainfall and potential evaporation). Certain variables regarding land-use/vegetation characteristics are input at monthly level and are then reduced to daily values by interpolative techniques. The daily time steps for rainfall enables simulations at thousands of locations in Southern Africa to be made by interrogating S.A. Weather Bureau and other data files.

(e) The basis of the ACRU model revolves around daily multi-soil-layer moisture budgeting and developing the model essentially into a versatile actual evapotranspiration model. This distinguishes it from other hydrological models which have been developed to date for general use in Southern Africa, for the ACRU model has been structured to be highly sensitive to land-use changes on the soil moisture and runoff regimes. Thus the model may be used as a basis for crop yield modelling, for calculations of supplementary irrigation requirements, as well as being used as the foundation on which quick and slow responses of runoff may be simulated.

(f) In its final form the ACRU model is visualised as a versatile, user-oriented and user-friendly model which will, in time, be made available at various levels of sophistication, depending on the computing facilities available to the potential user.

General Structure of the ACRU Model

The concepts of the ACRU1 model in terms of input and objectives

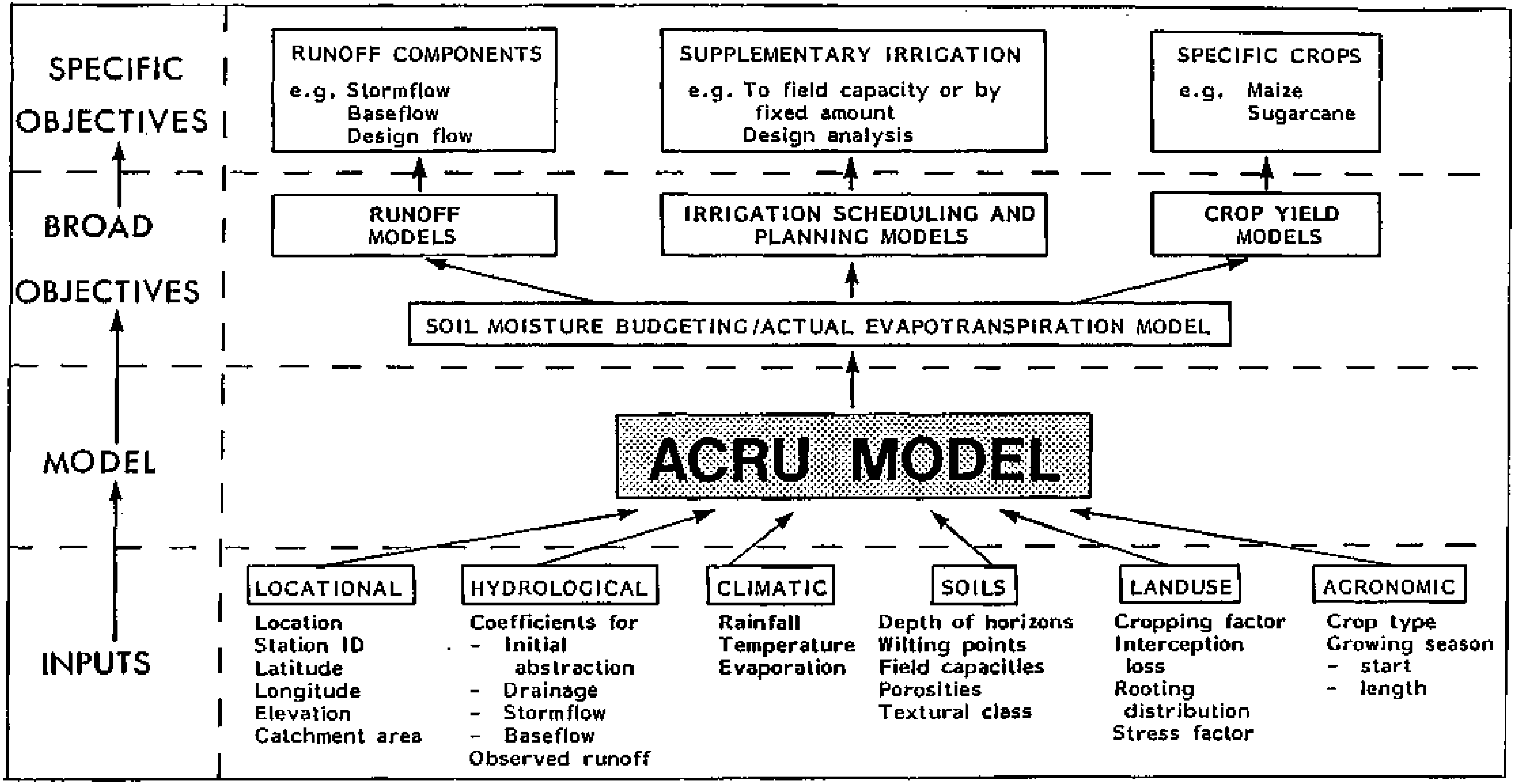

Figure 9.2 The ACRU1 model : concepts

are summarized in Figure 9.2. From the point of view of moisture budgeting at daily level, the partitioning and redistribution of moisture in the ACRU1 version of the model is depicted diagrammatically in Figure 9.3. In a two-layered soil profile, that rainfall which is not abstracted as interception or as direct runoff, first enters into the A-horizon. When that is "filled" (in relation to the field capacity of that horizon) the remaining precipitation would drain into the B-horizon. Should the B-horizon attain a degree of saturation, vertical drainage out of the system takes place. Evapotranspiration, dependent on atmospheric demand and on land use cropping characteristics, takes place from previously intercepted rainfall as well as simultaneously from the A-horizon and the B-horizon as functions of

(i) the vegetation rooting distributions in the respective horizons, and

(ii) whether the vegetation is under moisture stress.

Downward redistribution of soil moisture may be either saturated or unsaturated, while unsaturated upward moisture redistributions may also take place, both redistributions being dependent on relative moisture gradients.

REMARKS

Before embarking on the chapters describing detailed input, techniques and output of this first version of the ACRU model, the following points need to be stressed.

(a) This, and subsequent chapters in this report on the ACRU model do not constitute a manual on the model.

(b) While performance tests of the ACRU1 model are given in later chapters and the runoff simulations are highly

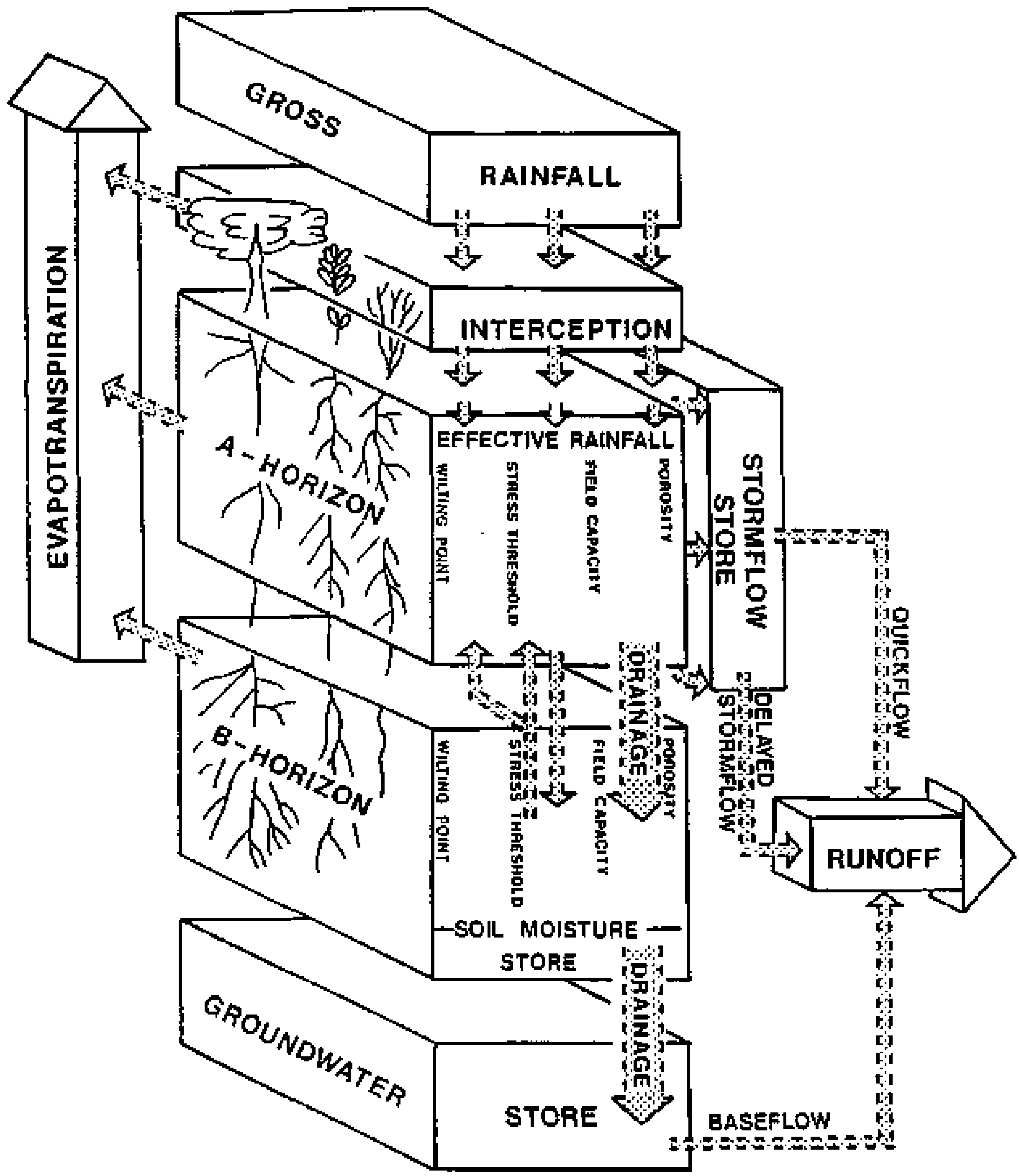

Figure 9.3 The ACRU1 model : general structure

satisfactory and highly significant statistically, potential users should apply the model with the caution deserving of a "new" model, and at this stage communication with the author is requested on additional applications of the model, on results and on obtaining the latest version of the model.

(c) The ACRU model is not conceived as being a "parameter optimizing" model in which combinations of variables are adjusted until an acceptable fit is achieved; neither does the model contain any self-optimizing routines. The ACRU1 version of the model as is shown in a subsequent chapter, can simulate very satisfactorily in its initial run. If the model performs unsatisfactorily under given circumstances, however, it is preferable that further research be undertaken to determine why and where model structure or input may have to be changed.

(d) A number of the statistical "packages" which are called in the model (as listed) may not be available at other centres, thus possibly limiting some of the statistical and graphical output when used at other centres.

* * * * * * * * * * * *

Following the introduction to the ACRU model by reviewing its aims and general structure, the ensuing chapters provide detail of the input requirements into the model and its computational procedures.

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CHAPTER 10

LOCATIONAL AND CLIMATIC INPUT REQUIREMENTS AND COMPUTATIONAL PROCEDURES

INTRODUCTION

This chapter aims at describing the locational and climatic input information which is required in the ACRU1 model, explaining why the input is required in the model and what the computational procedures or options are in applying the input information. All the above will be examined in the light of the respective examples of computer comment-statements for the various input requirements.

LOCATIONAL INPUT REQUIREMENTS

The locational input requirements of the ACRU1 model are outlined in Table 10.1[1].

The following variables require comment.

(a) AREA. The variable AREA is used as a catchment descriptor, as well as in conversions of observed catchment runoff, given in various units, to runoff in millimetres. When catchment area is irrelevant, for example, in crop yield ($t.ha^{-1}$) or supplementary irrigation

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1) Tables 10.1, 10.2, 10.3, 11.1, 11.2, 12.1, 13.1, 14.1 and 15.1, all of which show how control variables in ACRU1 are set out, are of an illustrative and informative nature. In the computer program (Appendix 1), which is the latest version of the ACRU model just prior to going to press, there may be alterations to the actual formatting given in these tables.

Table 10.1 Locational input : control variables

```
C                                     LOCATIONAL INPUT
C                                     ----------------
C
C     VARIABLES
C     ---------
C                   ALAT      = LATITUDE OF LOCATION IN DEGREES AND FRACTION OF
C                               DEGREES
C                   ALONG     = LONGITUDE OF LOCATION IN DEGREES AND FRACTIONS
C                               OF DEGREES
C                   AREA      = AREA OF CATCHMENT IN KM**2 AND FRACTIONS
C                               (IF AREA IS UNKNOWN OR NOT NECESSARY,  = 0.01
C                   ELEV      = ELEVATION IN METRES ABOVE SEA LEVEL
C                   HEAD      = GENERAL HEADING, STATION/LOCATION IDENTIFICATION
C
C     CONTROL VARIABLES FOR LOCATIONAL INPUT
C     --------------------------------------
C
C     COL  1-16   PRINT 'LOCATIONAL INPUT'
C     COL 20-59   WHAT IS YOUR HEADING (LOCATION, STATION ID) ?
C                      USE UP TO 40 COLUMNS FOR 'HEAD'
C     COL 60-64   WHAT IS THE LATITUDE OF THE LOCATION ?              LAT =
C     COL 65-69   WHAT IS THE LONGITUDE OF THE LOCATION ?            LONG =
C     COL 70-74   WHAT IS THE MEAN ELEVATION OF THE LOCATION ?       ELEV =
C     COL 75-79   WHAT IS THE CATCHMENT AREA ?                       AREA =
C
```

(mm) options, AREA may be given as zero or left blank.

(b) ALAT. Latitude, in addition to identifying location, is used in potential evaporation (PE) estimations if the Linacre PE option is selected (Linacre, 1977).

(c) ELEV. Elevation is similarly used in the Linacre option for PE estimations.

RAINFALL DATA SPECIFICATIONS

Rainfall data specifications are given in Table 10.2. Both variables in this section require comment.

(a) PPTINF. For specific applications, users of the ACRU model would prepare their own rainfall data on files (PPTINF=0), according to a specified format. The format details and other information are given in the program listing (Appendix 1). Preparation of daily data for, say, a 30-50 year record is, however, a time-consuming operation prone to errors. Since the South African Weather Bureau has processed daily rainfall data for over 6000 stations and these data are available on magnetic tape, an option (PPTINF=1) in the ACRU1 model facilitates reading these SAWB data from a specified file at the University of Natal. This file is prepared by a program DISKRD which unpacks the daily rainfall data for a specified location, eliminates years in which data are missing or in which critical rainfall totals given on the tape for a given year are accumulated over a period of time. DISKRD rewrites the data in the format required for the ACRU1 model.

(b) PPTCOR. On certain catchments where information from raingauges to be used under- or over-estimate typical catchment daily rainfall systematically, or where it is known that for some or other reason there is a systematic

Table 10.2 Rainfall data : control variables

```
C                                  RAINFALL DATA SPECIFICATIONS
C                                  ----------------------------
C
C     VARIABLES
C     ---------
C                PPTCOR   = CORRECTION FACTOR FOR SYSTEMATIC ERRORS IN
C                           RAINFALL VALUES
C                PPTINP   = OPTION TO READ IN RAINFALL DATA FROM CARDS (=0)
C                           OR FROM A FILE (=1)
C
C     CONTROL VARIABLES FOR RAINFALL DATA
C     -----------------------------------
C
C     COL  1-14  PRINT 'RAINFALL INPUT'
C     COL    20  DO YOU WANT TO READ THE DAILY RAINFALL DATA FROM CARDS
C                    OR FROM A SPECIAL FILE (IN WHICH CASE THE DATA HAS
C                    BEEN EXTRACTED FROM S.A. WEATHER BUREAU MAGNETIC
C                    TAPES FOR USE IN THIS MODEL) ?
C                    FROM CARDS    :  PPTINP = 0
C                    FROM FILE 16  :  PPTINP = 1
C     COL 21-25  DO THE RAINFALL VALUES REQUIRE A CORRECTION COEFFICIENT
C                    FOR SYSTEMATIC ERROR ?
C                    IF NO            PPTCOR = 0
C                    IF YES           PPTCOR = CORRECTION FACTOR - FRACTION
```

error in the rainfall data, this can be corrected by specifying the fraction by which values have to be multiplied (e.g. PPTCOR = 1,05 for a known 5% under-estimation which has to be corrected).

(c) General comments

(i) Daily rainfall in mm and 1/10 mm is used in the ACRU model. An option for conversion from Imperial to metric units is incorporated in the model. Units of rainfall are specified in the data format.

(ii) A number of error checks have been built into the program, for example, if rainfall data are out of sequence, or if a day's rainfall had been omitted inadvertently when the data were being prepared. In such cases, error mesages are printed.

(iii) Daily rainfall is read in and used one month at a time.

THE ESTIMATION OF POTENTIAL EVAPORATION

Being essentially a soil moisture budgeting and actual evapotranspiration model, the accurate estimation of potential evaporation is vital in the ACRU model. Since the model aims at being user-orientated, routines for the estimation of PE by energy balance or combination methods have not been incorporated at the present stage, for lack of readily available data in Southern Africa. At best the PE input in ACRU1 is daily A-pan information, at worst it is estimated from equations using monthly means of maximum and minimum temperatures.

The ACRU model incorporates numerous options for the estimation of PE. These are outlined in Table 10.3. The reasons for the incorporation of a number of options are as follows :

Table 10.3 Estimation of potential evaporation : control variables

```
C                      ESTIMATION OF POTENTIAL EVAPORATION
C                      -----------------------------------
C
C     VARIABLES
C     ---------
C                  CORPAN  = 12 CORRECTION FACTORS (JANUARY - DECEMBER) OF
C                            PAN DATA TO A-PAN EQUIVALENTS
C                  EOPET   = OPTIONS FOR SELECTION OF PE ESTIMATES - EITHER
C                            PAN OR TEMPERATURE BASED METHODS (LINACRE, BLANEY
C                            & CRIDDLE OR THORNTHWAITE)
C                  LINWIN  = WIND FACTOR IN THE LINACRE EQUATION
C                  PANCOR  = CORRECTION FACTOR FOR PAN DATA (E.G. S-PAN TO A-PAN)
C                  PANDAY  = DAILY PAN EVAPORATION
C                  PANMON  = MONTHLY PAN EVAPORATION
C                  TEMP    = MEAN MONTHTLY MAX. AND MIN. TEMPERATURES
C
C     CONTROL VARIABLES FOR ESTIMATION OF POTENTIAL EVAPORATION
C     ---------------------------------------------------------
C
C     LINE 1
C     ------
C     COL   1-23  PRINT 'POTENTIAL EVAPORATION-1'
C     COL     25  DO YOU HAVE MEAN MONTHLY MAXIMUM AND MINIMUM TEMPERATURE
C                     DATA (C) ?
C                     IF YES TEMP = 1, IF NO TEMP = 0
C                     IF TEMPERATURE DATA ARE AVAILABLE OR WILL BE REQUIRED FOR
C                     PE ESTIMATION, THEY ARE READ IN ON LINE 2
C     COL     26  DO YOU HAVE DAILY EVAPORATION PAN DATA ?
C                     IF YES PANDAY = 1, IF NO PANDAY = 0
C     COL     27  DO YOU HAVE ACCUMULATED MONTHLY EVAPORATION PAN DATA ?
C                     IF YES PANMON = 1, IF NO PANMON = 0
C     COL     28  BY WHICH METHOD DO YOU WISH TO ESTIMATE POTENTIAL EVAPORATION ?
C                     LINACRE (1977) METHOD ?                     EOPET = 1
C                     BLANEY & CRIDDLE (1950) METHOD ?            EOPET = 2
C                     THORNTHWAITE (1945) METHOD                  EOPET = 3
C                     DAILY PAN DATA ?                            EOPET = 4
C                     MONTHLY PAN DATA ?                          EOPET = 5
C     COL     29  ARE YOUR EVAPORATION PAN DATA IN MM OR INCHES ?
C                     IF MM UNITPE = 0, IF INCHES UNITPE = 1
C     COL     30  DO THE POTENTIAL EVAPORATION ESTIMATES REQUIRE A CORRECTION
C                     COEFFICIENT ?
C                     IF YES PANCOR = 1, IF NO PANCOR = 0
C     COL 31-78   IF PANCOR = YES, SPECIFY 12 VALUES OF 'CORPAN' FOR JANUARY
C                     TO DECEMBER IN 12 FIELDS OF 4.2
C     COL     79  HAVE YOU CHOSEN THE LINACRE METHOD ?
C                     IF NO                                     LINWIN = 0
C                     IF YES, IF LOCATION IS ON COAST           LINWIN = 1
C                             IF LOCATION IS INLAND             LINWIN = 2
C                             IF LOCATION IS TRANSITIONAL       LINWIN = 3
C     LINE 2
C     ------
C     COL   1-8   PRINT 'PE2-TEMP'
C     COL   9-80  READ IN 12 VALUES OF MONTHLY MINIMUM TEMPERATURES (C)
C                     FOLLOWED BY 12 VALUES OF MONTHLY MAXIMUM TEMPERATURE (C)
C                     IN EACH CASE JANUARY TO DECEMBER VALUES (24F3.1)
```

In many instances not even any evaporation pans are close to a study area, or if they are, they are frequently in another evaporation "regime" due to some or other physiographic discontinuity. In such circumstances, temperature-based equations are employed to estimate evaporation. Their advantage is the close relationship of temperature with elevation and other physiographic factors, which allows temperature estimates from techniques such as trend surface analysis (Schulze, 1981) to be used as a basis for PE estimates. A problem which then remains is selecting the best or most appropriate temperature-based PE equation. It is therefore necessary to present a summary of the three options available in the ACRU model.

(a) <u>The estimation of PE from temperature-based equations</u> (EQPET = 3, 4 or 5). If only long term monthly means of maximum and minimum temperatures are available, mean monthly PE may be estimated by any one of three methods.

(i) <u>Thornthwaite (1948) Method</u>. This universally applied procedure, which has been found generally to under-estimate PE in Southern Africa (Clemence and Schulze, 1982), equates

$$PE(mm.mo^{-1}) = 16(10T_a/I)^a D_{Ti}$$

in which

T_a = mean monthly air temperature (C),

I = annual heat index,

$$= \sum_{i=1}^{12} (T_{ai}/5)^{1,514}$$

a $= 0{,}49 + 0{,}0179\ I - 0{,}000077\ I^2 + 0{,}000000675\ I^3$

D_{Ti} = daylength correction factor to adjust for latitude and month (i).

The 12 values of D_T are calculated for the respective latitude from a data statement in the model.

(ii) Blaney and Criddle (1950) Method. Another standard method, particularly useful for use with irrigation scheduling, this method yields fair to good estimates of PE in Southern Africa (Clemence and Schulze, 1982). In this simple equation

$$PE(mm.mo^{-1}) = (0{,}142\ T_a + 1{,}095)(T_a + 17{,}8)D_{Bi}$$

where

D_{Bi} = daylength correction factor to adjust for latitude and month (i).

Again, monthly values of D_B are derived for the latitude of the location from a data statement in the model.

(iii) Linacre (1977) Method. Linacre (1977) attempted an approximation of the Penman (1948) equation by "disaggregating" it and relating its components to temperature variables or replacing them with equivalent expressions/approximations involving temperature values alone. The outcome is an empirical formula, simple to use, but with a basis which is physical enough to be of general use, i.e. "with sufficient accuracy for many practical problems and unusually modest demands as regards input data" (Linacre, 1977, p. 410).

For cropped surfaces Linacre's equation gives the potential evaporation rate as

$$PE(mm.mo^{-1}) = \frac{500T_m/(100 - ALAT) + LINWIN(T_a - T_d)D_{mi}}{(80 - T_a)}$$

where

LINWIN = wind factor,

T_m = T_a + 0,006 ELEV, with

ELEV = elevation above sea level (m),

D_{mi} = number of days in the month (i),

ALAT = latitude in degrees, and

$(T_a - T_d)$ = 0,0023ELEV + 0,37T_a + 0,53R + 0,35R_{an} - 10,9 in ^{o}C

in which

R = the mean daily range of temperature, and

R_{an} = the difference between the mean temperature of the hottest and coldest months of the year.

Other than the elevation and latitude of a location, all other variables in the equation are obtained from maximum and minimum temperatures. The equation has been tested with temperature and pan evaporation data from 24 widely scattered stations in Natal and was found to yield markedly more reliable simulations of A-pan values in all months of the year when compared with other temperature-based equations commonly in use (Schulze, 1983).

The variable LINWIN used in the Linacre equation and described briefly in Table 10.3, requires some amplification. The original equation contains a constant '15' in its place. During an agrohydrological survey of Natal (Schulze, 1983), estimates by the Linacre equation improved markedly when this constant was replaced by monthly values accounting for the regional influence of wind on PE. The data statement in the ACRU1 program, by which values of LINWIN are delimited on a monthly level for locations on the coast vs inland vs a transitional coastal-hinterland zone, are therefore applicable only to Natal at this stage. Elsewhere LINWIN = 0 and a value of 15 is used in computations.

Clemence and Schulze (1982) compared six commonly used temperature-based equations for the estimation of PE, including the Thornthwaite and Blaney-Criddle equations and found from lysimeter studies undertaken under diverse climatic conditions that for maize, wheat, sugarcane and soyabeans, the equation proposed by Linacre (1977) proved to be superior to the others, most likely since it is derived by incorporating the physical factors which affect evaporation.

(b) Correction of pan data, PANCOR and CORPAN (12). If pan data are used, the assumption is that data are from unscreened A-pans. Correction factors are required to obtain A-pan equivalent values, either if pans were screened or (more likely) if values were available from Symons-pans only. For the conversion of S- to A-pan values, the 12 CORPAN values, which vary by month and by region, may be obtained for Southern Africa from factors given by Louw (1966).

(c) General comments. If temperature-based equations for the estimation of PE are used, or if monthly accumulations of pan data are given, these are converted to daily values. This procedure is undertaken in two steps at present [1]. A weighted interpolative technique, which also considers PE values of the previous and the following months, calculates "pentad" values of PE. Equal values of PE are then assumed for each day in a "pentad" (N.B. the last "pentad" of a month with number of days other than 30 is weighted appropriately). Standard data checks include conversion of data to mm and 1/10 mm when necessary, and ensuring that data are in their correct sequence. Future development envisages a weighting of daily estimates of derived PE according to the occurrence of rainfall.

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CHAPTER 11

SOILS AND VEGETATION INPUT AND COMPUTATIONAL PROCEDURES

SOILS INFORMATION

In regard to soils input requirements, the user is reminded that the ACRU model is a "tank" model comprising two "active" horizons (at present) in which rooting development and hence soil water extraction through evapotranspiration can take place (Chapter 9). A third soil store, in the form of the groundwater store, remains undefined in terms of pedological properties and is active only in the sense that water which has drained to below the active root horizon into this groundwater zone, has magnitude and is released slowly as baseflow.

As a "tank" model, amounts of soil water at the three critical water retention constants, namely at porosity (PO), field capacity (FC), and wilting point (WP), have to be known or inferred for each of the two active soil horizons. These amounts of soil water are, for modelling purposes, functions of soil texture and respective horizon depths. Soil water amounts in excess of WP value are available to plants, for evapotranspiration and hence growth processes; soil water amounts in excess of FC are available for saturated drainage; soil water between FC and WP may be redistributed upwards or downwards, inter alia, according to soil water gradients.

Hydrologically the concept of a multi-layered soil system is sound, as quickflow responses are supposedly highly dependent on properties and moisture status of the topsoil horizon, while the bulk of the active soil water store and also the release of water for baseflow are dependent on properties and moisture status of the active subsoil horizon(s).

Table 11.1 Soils information : control variables

```
C                                   SOILS INFORMATION
C                                   -----------------
C
C     VARIABLES
C     ---------
C                  DEPAHO  = DEPTH OF UPPER SOIL ZONE (M)
C                  DEPBHO  = DEPTH OF LOWER SOIL ZONE (M)
C                  FC1,FC2 = FRACTION OF WATER HELD IN SOIL (VOL/VOL) AT
C                            FIELD CAPACITY (-10 TO -33 KPA)
C                  ITEXT   = SOIL TEXTURE (E.G. CLAY : TEXT = 1 ETC.)
C                  PEDDEP  = STATUS OF SOIL DEPTH (DEEP, SHALLOW OR BETWEEN)
C                  PEDINF  = STATUS OF SOIL INFORMATION I.E. ADEQUATE OR
C                            INADEQUATE
C                  PC1,PC2 = FRACTION OF WATER HELD IN SOIL (VOL/VOL) AT
C                            EFFECTIVE POROSITY (0KPA)
C                  WP1,WP2 = FRACTION OF WATER HELD IN SOIL (VOL/VOL) AT
C                            WILTING POINT (-1500KPA)
C
C     CONTROL VARIABLES FOR SOILS INFORMATION
C     ---------------------------------------
C
C     COL  1-17    PRINT 'SOILS INFORMATION'
C     COL    20    DO YOU HAVE ADEQUATE SOILS INFORMATION ?
C                      IF YES PEDINF = 1, IF NO PEDINF = 0
C                  IF 'PEDINF = 0' THE FOLLOWING MINIMUM SOILS INFORMATION HAS
C                      TO BE GIVEN IN COLS 25 AND 30 (WITH OTHER COLUMNS BLANK)
C     COL    25    SOIL DEPTH : ARE SOILS  DEEP (>1M)                  PEDDEP = 1
C                                  OR      SHALLOW (<0.5M)             PEDDEP = 2
C                                  OR INTERMEDIATE                     PEDDEP = 3
C     COL    30    SOIL TEXTURE : IF TEXTURE IS   CLAY                 ITEXT = 1
C                                                 LOAM                 ITEXT = 2
C                                                 SANDY                ITEXT = 3
C                                                 LOAMY SAND           ITEXT = 4
C                                                 SANDY LOAM           ITEXT = 5
C                                                 SILTY LOAM           ITEXT = 6
C                                                 SANDY CLAY LOAM      ITEXT = 7
C                                                 CLAY LOAM            ITEXT = 8
C                                                 SILTY CLAY LOAM      ITEXT = 9
C                                                 SANDY CLAY           ITEXT = 10
C                                                 SILTY CLAY           ITEXT = 11
C
C                  IF PEDINF = 1 THE FOLLOWING SOIL INFORMATION HAS TO BE GIVEN
C                      FOR UPPER (A) AND LOWER (B) SOIL HORIZONS (6F5.3)
C                  FRACTION OF SOIL WATER AT WILTING POINT
C     COL 35-39                                   UPPER HORIZON          WP1 =
C     COL 40-44                                   LOWER HORIZON          WP2 =
C                  FRACTION OF SOIL WATER AT FIELD CAPACITY
C     COL 45-49                                   UPPER HORIZON          FC1 =
C     COL 50-54                                   LOWER HORIZON          FC2 =
C                  FRACTION OF SOIL WATER AT POROSITY
C     COL 55-59                                   UPPER HORIZON          PC1 =
C     COL 60-64                                   LOWER HORIZON          PC2 =
C     COL 65-69    DEPTH OF 'A' HORIZON IN METRES                     DEPAHO =
C     COL 70-74    DEPTH OF 'A' HORIZON IN METRES                     DEPAHO =
```

For typical operational use of the model, the adequacy of information on soils is often a key issue. The questions in Table 11.1 on soil information therefore revolve around the adequacy and estimation of soil storages at critical water retention constants.

(a) Estimations of Soil Storages with Inadequate Soils Data. Only two items of information need to be known when soils data are inadequate. The first is an estimation of the total active, rooting depth of the soil. Three categories, namely, deep soils (> 1,0m), shallow soils (< 0,5m) and soils with intermediate depths (0,5-1,0m) are catered for. For these three categories, A- and B-horizon depths of 0,3 : 0,8m, 0,2 : 0,2m and 0,3 : 0,5m are used in computations.

Secondly, when inadequate soils information is available, a soil texture class has to be assigned i.e. clay, loam, etc. Generally in Southern Africa, heavy textured soils are clays (ITEXT=1), the very light textured soils may be classed as loamy sands (ITEXT=4) and soils with intermediate textures have a high probability of being sandy clay loams (ITEXT=7). More details on Southern African soils and their textural classification are given in Chapters 7 and 8 of this report. With inadequate soils information, a uniform clay distribution with depth is assumed down the soil profile (Clay Distribution Model 2, Chapter 8). In a data statement fractions of water content (mm/m) at PO, FC and WP are given for each of the 11 soil textures named in Table 11.1. When used in conjunction with soil depths, critical soil water storages for the two horizons are calculated.

(b) Estimations of Soil Storages with Adequate Soils Data. The term "adequate" is a relative one. In the context of the structure of the ACRU model it implies that both A- and B-horizon values of water retention constants and soil depths are known. Effects of different clay distribution models (Chapter 8) on runoff can therefore be accounted for by the ACRU model.

(c) Soil Moisture Redistribution.

(i) Saturated soil moisture redistribution (recharge) takes place from the A- to B-horizon and from the B-horizon to the groundwater store if the soil water storages of the respective upper horizons are above FC. The rate of drainage is exponential, at this stage having been set at 50% of "excess" water drained per day, following Ritchie (1983).

(ii) Unsaturated soil moisture redistribution downwards can take place from the A- to the B-horizon below FC on the condition that the A-horizon is the moister of the two. Redistribution is dependent on the moisture gradient between the A- and B-horizon and the "head" of water (i.e. amount of water in the A-horizon). The rate of movement is set at the product of 2% of A-horizon moisture content and the gradient, the latter being expressed as the fractional difference between the percentages of moisture content in the A- and B-horizons. Upward unsaturated redistribution from the B- to A-horizon takes place when the B-horizon contains the higher soil moisture percentage. The driving forces for upward redistribution are the same as for downward redistribution, but the rate of movement is restricted to 1% of the B-horizon moisture content in calculations. The values used have been derived from the literature (for example, Kniesel et al, 1969; Stone et al, 1973).

VEGETATION AND LAND USE INFORMATION

Above-ground and below-ground vegetation information in terms of interception losses on raindays, cropping coefficients, rooting distribution and the fraction of available water at which plant stress sets in are required in the ACRU model. Information and options are given in Table 11.2. The following background to the variables used is relevant.

(a) Interception loss, VEGINT. Typical values of interception loss in mm per rainday have to be given for each month of the year in order to account for differences in interception losses with stage of growth or dormancy. Detailed values of VEGINT for different crops and their development stages as well as for natural vegetation types found in Southern Africa, and which may be used in the ACRU model, are given by de Villiers (1975) and are summarized by Schulze (1984).

Computational procedures involving VEGINT are as follows:

(i) Interception routines are skipped on rainless days.

(ii) On those raindays when stormflow occurs (Chapter 12), interception losses of the day are incorporated as part of initial abstraction before stormflow commences.

(iii) On raindays which do not yield stormflow, vegetation interception loss is subtracted from gross rainfall and only the net rainfall enters the soil.

(b) Cropping factor, CAY. Twelve values of typical monthly cropping factors are required in the ACRU1 version of the model. The cropping factor is the coefficient by which the daily A-pan (or equivalent) value is multiplied in order to

Table 11.2 Vegetation information : control variables

```
C                                      VEGETATION INFORMATION
C                                      ----------------------
C
C    VARIABLES
C    ---------
C
C                   CAY     = 12 MONTHLY VALUES (FOR JANUARY TO DECEMBER) OF
C                             THE CROPPING COEFFICIENT
C                   CCNST   = FRACTION OF PLANT AVAILABLE WATER (+ OR -0.4) AT
C                             WHICH PLANT STRESS SETS IN
C                   CRLEPO  = CRITICAL LEAF WATER POTENTIAL OF A CROP
C                   ROOTA   = 12 MONTHLY VALUES (FOR JANUARY TO DECEMBER) OF
C                             THE FRACTION OF ROOTS FOUND IN THE A-HORIZON
C                   VEGINT  = 12 MONTHLY VALUES (JANUARY TO DECEMBER) OF
C                             INTERCEPTION LOSS (MM) PER RAINDAY
C
C    CONTROL VARIABLES FOR VEGETATION INFORMATION
C    --------------------------------------------
C
C
C    LINE 1
C    ------
C    COL  1-25   PRINT 'VEGETATION INFORMATION (1)'
C    COL 26-73   PRINT 12 MONTHLY VALUES OF THE CROPPING FACTOR 'CAY' IN
C                    12F4.2 FOR JANUARY TO DECEMBER
C    COL 74-76   DO YOU WANT TO DEFINE THE FRACTION OF PLANT AVAILABLE WATER
C                    AT WHICH PLANT STRESS SETS IN AS A CONSTANT VALUE 'CONST'
C                    OR AS A VARIABLE (DEPENDENT ON PE AND CRITICAL LEAF
C                    WATER POTENTIAL) ?
C                    IF CONSTANT,  CONST = FRACTION, USUALLY + OR -0.4 (F3.1)
C                                          AND COL 77-80 ARE LEFT BLANK
C                    IF VARIABLE,  CONST = BLANK (I.E. COL 73-75)
C    COL 77-80   IF 'CONST' = 0.0, STRESS IS CALCULATED USING CRITICAL LEAF
C                    WATER POTENTIAL 'CRLEPO'
C                    IF CONST = BLANK,         CRLEPO = NEGATIVE VALUE WHICH IS
C                                                       CROP SPECIFIC E.G. -10.
C                                                       I.E. F4.0
C                    IF CONST > 0.0,           CRLEPO = BLANK
C                    N.B. EITHER CONST OR CRLEPO HAVE TO BE SPECIFIED
C    LINE 2
C    ------
C    COL  1-28   PRINT 'VEGETATION INFORMATION-ROOTA'
C    COL 30-77   PRINT 12 MONTHLY VALUES OF FRACTION OF ROOTS FOUND IN
C                    A-HORIZON 'ROOTA' IN 12F4.2 FOR JANUARY TO DECEMBER
C    LINE 3
C    ------
C    COL  1-35   PRINT 'VEGETATION INFORMATION-INTERCEPTION'
C    COL 36-71   PRINT 12 MONTHLY VALUES OF INTERCEPTION LOSS PER RAINDAY
C                'VEGINT' IN 12F3.1 FOR JANUARY TO DECEMBER
```

account for the plant's potential evaporative demand, and its values reflect, inter alia, growth stage, phenological characteristics, canopy cover and aerodynamic resistance.

For cropped surfaces, representative CAY values may be obtained from many sources of literature (for example, Doorenbos and Pruitt, 1977; Dunne and Leopold, 1978) or, in Southern Africa, from the Department of Agriculture (for example, Soil and Irrigation Research Institute). For forested surfaces, values of 0,85 to 1,10 may be used (Roberts, 1984), while for various grassland vegetations in Southern Africa, values have been derived by Snyman et al, (1980). For bare (fallow or ploughed) surfaces a value of 0,3 may be assumed.

(c) Proportion of roots in the A-horizon, ROOTA. In the ACRU model, soil moisture extraction takes place simultaneously from both soil horizons and in proportion to the rooting densities within the respective horizons. No extraction from the groundwater zone takes place because it is assumed in this model to be at greater depth than the active root zone. The fraction ROOTA varies seasonally; hence 12 typical monthly values are required. The corresponding proportion of roots in the B-horizon is (1 - ROOTA). The proportion of roots in any one horizon has to account for the effect of genetic and environment factors on transpiration such as winter dormancy, senescence, spring growth, etc. Typical values of ROOTA are cited in reviews by Saxton (1982) and Schulze (1984). When plants are not under stress, it is the fraction ROOTA which determines to a large extent at what rates differential drying of the soil takes place in the respective horizons.

(d) Plant Stress. The water status of a plant i.e. its turgor pressure, is dependent largely on the soil water content of the root zone and on the atmospheric demand. The atmosphere places an evaporative demand upon the plant and the roots absorb the water from the soil water reservoir. When the reservoir becomes depleted, the roots cannot absorb water at a rate sufficient to meet demand, plant stress sets in and the plant loses turgor. Subsequently, physiological and metabolic processes are affected and plant growth is reduced, with attendant reductions in plant yield.

A problem faced in hydrological modelling is to determine at what point in the depletion of the plant available moisture reservoir the plant stress actually begins. In modelling terms, the problem may be expressed conceptually as the soil moisture content at which the actual evapotranspiration rate, AET, is reduced to below potential evapotranspiration rate, PET.

Experimental evidence shows that AET equals PET until a certain fraction of maximum (profile) available soil water to the plant, PAW, is exhausted. This fraction is expressed by the variable CONST. Beyond this fraction the reduction of AET depends, inter alia, on the remaining water and the PE demand. The classical literature of the past two decades has frequently attributed differences in CONST to soil textural properties, while others, notably irrigation modellers, maintain that stress sets in at a fixed soil moisture content, for example, 0,5 PAM. Meyer and Green (1980) found in Southern Africa that a value of 0,3 was applicable to wheat. However, recent research by Slabbers (1980) shows that CONST may vary according to atmospheric demand (PE) and the critical leaf water potential, ψ^{cr}_{l} of different crops, the latter being an index of the hardiness of crops in drought situations. Slabbers (1980) derived a variable value of the fraction of soil moisture at which stress sets in, and by his equation

$$\text{CONST} = 0{,}94 + 0{,}26 \quad \psi^{cr}_{l}/\text{PE}$$

where

ψ_l^{cr} is referred to as CRLEPO in Table 11.2.

Using the above equation with critical leaf water potentials for different crops, the wide variation of CONST for different daily PE rates has been shown by Schulze (1984). The implications of stress setting in at such different levels of moisture content are highly significant in terms of actual evapotranspiration.

SOIL MOISTURE BUDGETING PROCEDURES AND SEQUENCES

The rainfall, potential evaporation, soil and land-use variables having been explained in previous chapters or sections, this section describes the moisture budgeting procedures and sequences used in the ACRU1 model for a typical day with rainfall.

(a) The plant-intercepted water stored from the previous day, if it had rained, is first evaporated at potential rate (according to atmospheric demand), and the remaining potential evaporation, PE, becomes available for soil moisture extraction.

(b) The PE is then apportioned to the A- and B-horizons in direct proportion to the rooting densities of the two soil layers (ROOTA, ROOTB).

(c) Actual evapotranspiration, AET, is calculated next, initially for the A-horizon.

 (i) First check whether available soil moisture content, SMC, carried forward from the final SMC of the previous day, is above or below the plant stress fraction, CONST.

 (ii) If above, AET = PET for that horizon.

(iii) If below, AET is a fraction of PET for that horizon, depending on the degree of stress.

(d) SMC is now reset, AET having been abstracted.

(e) The above procedures are repeated for the B-horizon.

(f) On a day with rainfall, the effective rainfall is calculated either

(i) as the difference between net rainfall (i.e. rainfall - interception loss) and stormflow, if stormflow occurs, or

(ii) as the difference between gross rainfall and interception loss, if no stormflow occurs.

(g) The SMC for the A-horizon is reset, by the addition of effective rainfall (if any).

(h) SMC for the A-horizon is then reassessed.

(i) If the SMC_A is above FC, a proportion of the excess water drains to the B-horizon, and SMC is reset.

(ii) If the SMC_A is below FC, no resetting of its value is necessary.

(i) The SMC for the B-horizon is considered next.

(i) The previous day's SMC_B is reset by the addition of water drained from the A-horizon under saturated conditions if present.

(ii) If SMC_B is now above its FC, a fraction of the excess water (BFRESP, Chapter 12) percolates into the groundwater zone and the SMC_B has to be reset accordingly.

(iii) If SMC_B is below FC, the storage does not require resetting.

(j) SMC of the A- and B-horizons are expressed as fractions of SMC at FC.

(k) For unsaturated conditions, a check is undertaken to determine whether downward unsaturated moisture redistribution will take place from the A- to B-horizons. If so, the redistribution procedure and rate described previously is applied, and the SMC_A and SMC_B values are reset.

(l) Similarly, a check for unsaturated upward redistribution is undertaken and the procedures described above are applied.

(m) Final values of storages and deficits for the two horizons are calculated, either to be carried forward to the following day, or to be stored for daily/monthly/other statistical output, or to be used in estimations of crop yields.

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CHAPTER 12

RUNOFF SIMULATION

INTRODUCTION

In the ACRU1 model the generated runoff comprises baseflow and stormflow, with the stormflow component consisting of a quickflow response (i.e. released on the day of the rainfall event) and a delayed stormflow response. Baseflow is derived from a groundwater store which is recharged by drainage out of the lower active soil horizon when its water content exceeds field capacity. In a purely diagrammatical depiction, these components are illustrated in Figure 9.3, to which reference should again be made while reading this chapter.

PRINCIPLES AND VARIABLES

The concept of the stormflow routine is based on the principle that the runoff potential is an inverse function of the soil's moisture status, a principle also implicit in the SCS model. Notable conceptual deviations from the "standard" SCS stormflow equations as set out in the National Engineering Handbook (USDA-SCS, 1972) are examined in (a) to (f) below.

(a) Interception as a store is abstracted separately at the commencement of runoff-producing rainfall, and not as part of the initial abstractions in the SCS model (Figure 9.3).

(b) The potential maximum retention of the soil, S, is conceived as a moisture deficit, calculated by multi-horizon moisture budgeting techniques as described in Chapter 11. However, unlike the improvements to the SCS model which were illustrated in Chapter 3, the soil store in the ACRU model ranges from wilting point to porosity, i.e. including the saturated state above field capacity. Furthermore, the moisture store's critical water retention constants are determined as actual moisture contents of the soil, not merely as a plant available water content suspended in an undefined location somewhere within a soil profile.

(c) The depth of the soil profile for which the moisture deficit is calculated may be varied in the ACRU1 model in an attempt to account for different dominant runoff-producing mechanisms prevailing in catchments. In Table 12.1 this variable is designated SMDDEP. Thus a catchment with predominantly short vegetation which is shallow rooted would use the moisture deficit of the A-horizon in estimations of stormflow. On the other hand, on land use with dense canopy cover which can dissipate the rainfall's energy and/or with deep litter/organic layers facilitating steadier infiltration at relatively slow rates, soil moisture deficit of both A- and B-horizons would be considered important, because stormflow on such catchments may be perceived as being produced more by a "push through" (translatory) mechanism involving the entire soil profile. It is for the above reasons that in Figure 9.3 the arrows feeding the stormflow store are shown to include

(i) surface runoff,

(ii) stormflow generated by the A-horizon,

(iii) water which may be derived from a soil interface between the two soil horizons, as well as

(iv) stormflow which may be generated in the B-horizon.

(d) The generated total stormflow may respond rapidly or slowly

Table 12.1 Runoff simulation : control variables

```
C
C                              RUNOFF SIMULATION
C                              -----------------
C
C     VARIABLES
C     ---------
C                 BFRESP   = FRACTION OF SATURATED WATER IN LOWER SOIL HORIZON TO
C                            BE RELEASED INTO THE GROUNDWATER STORE PER DAY
C                            (E.G. 50% = 0.50)
C                 COFRU    = COEFFICIENT OF RUNOFF I.E. FRACTION OF GROUNDWATER
C                            STORE WHICH RUNS OFF PER DAY (E.G. 2% = 0.02)
C                 COIA     = COEFFICIENT OF INITIAL ABSTRACTION, I.E. FRACTION
C                            OF SOIL MOISTURE DEFICIT WHICH NEEDS TO BE FILLED
C                            BEFORE STORMFLOW COMMENCES (E.G. 20% = 0.20)
C                 IOBSQ    = AVAILABILITY OF OBSERVED RUNOFF
C                 IOBSUN   = UNITS OF OBSERVED RUNOFF
C                 RESPCF   = STORMFLOW RESPONSE OF CATCHMENT, I.E. FRACTION OF
C                            TOTAL STORMFLOW RUNNING OFF ON DAY OF EVENT
C                 SMDDEP   = DEPTH TO WHICH SOIL MOISTURE DEFICIT HAS TO BE
C                            CONSIDERED FOR STORMFLOW RESPONSE
C
C     CONTROL VARIABLES FOR RUNOFF SIMULATION
C     ---------------------------------------
C
C     COL   1-17  PRINT 'RUNOFF SIMULATION'
C     COL     20  DO YOU HAVE DAILY OBSERVED RUNOFF DATA AVAILABLE FOR YOUR
C                     CATCHMENT ?
C                     IF NO,                                  IOBSQ = 0
C                     IF YES,                                 IOBSQ = 1
C     COL     25  IF DAILY OBSERVED RRUNOFF DATA ARE AVAILABLE, IN WHICH UNITS
C                     ARE THEY GIVEN ?
C                     IF IN M**3/DAY,                         IOBSUN = 1
C                     IF IN CUMEC,                            IOBSUN = 2
C     COL     30  TO WHICH 'DEPTH' OF SOIL DOES THE SOIL MOISTURE DEFICIT HAVE
C                     TO BE CONSIDERRED FOR STORMFLOW RESPONSE ?
C                     IF A-HORIZON ONLY,                      SMDDEP = 1
C                     IF A- AND B-HORIZONS,                   SMDDEP = 2
C     COL  32-35  SPECIFY THE COEFFICIENT OF INITIAL ABSTRACTION TO BE USED
C                     (F4.2), E.G. 0.20                       COIA =
C     COL  37-40  WHAT IS THE CATCHMENT'S RESPONSE TO TOTAL STORMFLOW ?
C                     IF SLOW,                                RESPCF = 0.40
C                     IF MEDIUM,                              RESPCF = 0.50
C                     IF FAST,                                RESPCF = 0.70
C     COL  42-45  WHAT FRACTION OF SATURATED WATER IN THE LOWER SOIL HORIZON IS
C                     TO BE CLEARED PER DAY INTO THE GROUNDWATER STORE ?
C                     (TYPICALLY 50% I.E. 0.50) F4.2     BFRESP =
C     COL  47-50  WHAT FRACTION OF THE GROUNDWATER STORE IS RELEASED PER DAY AS
C                     BASE FLOW ? (TYPICALLY 2% I.E. 0.02) F4.2
C                                                             COFRU =
```

as runoff at a catchment's outlet. Soils with a high interflow potential (Chapter 7) would respond rapidly, as would "small" catchments when compared with larger ones. Similarly, catchments with dense vegetation are likely to respond slower than those with sparser vegetation, all else being equal. For this reason another deviation from standard SCS procedures is incorporated in the ACRU1 model, by the inclusion of a stormflow response coefficient (fraction), expressed by the variable RESPQF in Table 12.1.

(e) In regard to baseflow generation, two response coefficients are applied in the ACRU1 model. The first relates to the rate of water draining out of a saturated B-horizon store into the groundwater store. While this response is intuitively slower for heavy textured than for light textured soil, no readily available data are at hand as yet in Southern Africa to propose different response rates for different soils. Hence the 0,50 as used by Ritchie (1983) is suggested for the present (variable name in Table 12.1 : BFRESP).

(f) The second baseflow response coefficient concerns the release of water from the groundwater store into the stream. This coefficient is likely to depend on factors such as geology, topography and catchment size. No research has been undertaken with the model to date to determine the magnitude of this variable, COFRU, but 2% per day (i.e. COFRU = 0,02) is suggested as a starting value for small catchments.

COMPUTATIONAL PROCEDURES AT DAILY LEVEL

(a) The magnitudes of the groundwater and stormflow stores, as defined from the previous day's values, are initialized.

(b) If no rainfall occurs, the stormflow store releases an amount of delayed stormflow (according to the coefficient RESPQF) and resets the value of the store after release.

(c) If rainfall occurs, the stormflow-generating routine becomes operational.

(i) Soil moisture deficit is determined either for the A-horizon or for the entire active soil profile, as specified by SMDDEF.

(ii) If the net rainfall (observed rainfall minus interception) is less than the estimated initial abstraction, no stormflow is generated, the net rainfall is infiltrated into the soil and delayed stormflow is calculated, as in (a) above.

(iii) If net rainfall exceeds initial abstraction, stormflow is generated by an SCS-related equation. This stormflow is added to the stormflow store, quickflow is computed by applying the response coefficient RESPQF to the stormflow store, and the stormflow store is reset.

(d) Soil moisture budgeting routines (Chapter 11) are then continued.

(e) Baseflow routines become operative next.

(i) If no contribution is made to the baseflow store by drainage, baseflow is calculated from the previous day's groundwater store and the coefficient of baseflow response and the store's magnitude is then reset.

(ii) If a contribution is made to the baseflow store, in accordance with the amount of water available from the B-horizon and its drainage coefficient (BFRESP), then this contribution is first added to the baseflow store before baseflow is released and the store is reset.

(f) Finally, the baseflow and stormflow components are summed for use in runoff simulations.

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CHAPTER 13

SUPPLEMENTARY IRRIGATION REQUIREMENTS[1)]

INTRODUCTION

The irrigation requirements of plants can be determined for a period of time

(i) if the water consumption of the plant, i.e. its PE, can be estimated for the period,

(ii) if the amounts of water from rainfall, which replenish soil moisture, are known,

(iii) if it is known how much water the soil can hold in the active rooting zone, and

(iv) if it is known how much water can be withdrawn from the soil before plant stress sets in.

The ACRU model incorporates the above factors and an option for supplementary irrigation has therefore been incorporated to run in tandem with the soil moisture budgeting routines. In irrigation practice different types of supplementary irrigation may be applied in accordance with climatic/crop conditions and available equipment. Furthermore, certain irrigation systems are more efficient than others. Types of supplementary irrigation and

---

1) At the time of going to print, the irrigation routines included a further option on the assessment of irrigation application, a more refined recharge analysis and an option to size irrigation schemes in relation to dam capacities.

its efficiency have been included, therefore, as variables in the irrigation routine, the options of which are given in Table 13.1.

SUPPLEMENTARY IRRIGATION ROUTINES

The following variables require comment:

(a) SCHED. In the ACRU model one of three types of supplementary irrigation may be selected. These are

(i) irrigating to field capacity, or

(ii) irrigating to a planned deficit, or

(iii) irrigating by a fixed amount.

Irrigating to field capacity, FC, is the most common type of supplementary irrigation applied. However, in areas or seasons with a high probability of rains occurring, and where irrigation water is expensive, it may be more economical to irrigate to a planned deficit of, say, 0,8 of FC. If irrigation by planned deficit is selected, the "magnitude" of the planned deficit may be specified by varying the fraction in PLADEF.

Irrigation pumping capacity or logistics involving irrigation practice (labour or amount of piping available) sometimes enables only a fixed amount of irrigation to be applied. In such cases the amount (mm) which can be irrigated in one application, AMTIR, has to be specified.

(b) EFFIRR. The field efficiency of various irrigation systems varies considerably, dependent on field equipment as well as on local climatic factors such as spray drift. Jensen (1980) for example, cites centre pivot systems as having a 0,8 efficiency while travelling big guns are only

Table 13.1 Supplementary irrigation requirements : control variables

```
C                                IRRIGATION REQUIREMENTS
C                                -----------------------
C
C     VARIABLES
C     ---------
C                   APTIR     = AMOUNT OF SUPPLEMENTARY IRRIGATION TO BE APPLIED IF
C                               'SCHED' OPTION FOR FIXED AMOUNT IS SELECTED
C                   CONSTI    = FRACTION OF PLANT AVAILABLE WATER (+ OR - 0.5) AT
C                               WHICH IRRIGATION SHOULD BE APPLIED
C                   EFFIRR    = IRRIGATION EFFICIENCY ACCOUNTING FOR WATER LOST BY
C                               SPRAY DRIFT ETC. (USUALLY + OR - 0.8)
C                   NOIRAP    = NUMBER OF IRRIGATION APPLICATIONS PER MONTH
C                   PLADEF    = IF TE 'SCHED' FOR PLANNED DEFICIT IS SELECTED, THIS
C                               HAS TO BE QUALIFIED (USUALLY 'PLADEF' IS TO + OR -
C                               0.6 OF FIELD CAPACITY)
C                   SCHED     = OPTIONS FOR TYPES OF SUPPLEMENTARY IRRIGATION (E.G.
C                               FIELD CAPACITY OR PLANNED DEFICIT ETC.)
C                   WRIRR     = OPTION TO PERFORM SUPPLEMENTARY IRRIGATION ROUTINE
C
C     CONTROL VARIABLES FOR SUPPLEMENTARY IRRIGATION
C     ----------------------------------------------
C
C     COL  1-24   PRINT 'SUPPLEMENTARY IRRIGATION'
C     COL    25   DO YOU REQUIRE INFORMATION ON SUPPLEMENTARY IRRIGATION ?
C                      IF YES,                                         WRIRR = 1
C                      IF NO.                                          WRIRR = 0
C
C     IF NO, THE FOLLOWING OPTIONS CAN BE LEFT BLANK
C
C     COL    26   IRRIGATION SCHEDULING PROCEDURE.  IF YOU WANT TO :
C                      IRRIGATE TO FIELD CAPACITY,                     SCHED = 2
C                      IRRIGATE TO PLANNED DEFICIT,                    SCHED = 1
C                      IRRIGATE BY A FIXED AMOUNT,                     SCHED = 3
C     COL 30-34   IF EACH IRRIGATION APPLICATION IS BY A FIXED AMOUNT (MM),
C                      SPECIFY THE FIXED AMOUNT (F5.0)                 APTIR =
C                      OTHERWISE LEAVE BLANK
C     COL 35-39   IF IRRIGATION IS TO A PLANNED DEFICIT, I.E. TO A FRACTION OF
C                      THE FIELD CAPACITY SPECIFY THE PLANNED DEFICIT FRACTION
C                      (F5.2)                                          PLADEF =
C                      OTHERWISE LEAVE BLANK
C     COL 40-44   WHAT IS THE FIELD EFFICIENCY OF THE IRRIGATION SYSTEM
C                      EXPRESSED AS A FRACTION ?  (F5.2)               EFFIRR =
C     COL 45-49   AT WHAT FRACTION OF PLANT AVAILABLE WATER (USUALLY C.5)
C                      SHOULD IRRIGATION BE APPLIED (F5.2)             CONSTI =
```

0,7 efficient in the field. Field efficiency may thus be varied by changing EFFIRR.

(c) CONSTI. In an irrigation scheme, supplementary water should be applied before stress sets in. The variable CONSTI, which in this routine signifies at what fraction of plant available water consumptive use of the plant drops to below its potential, is therefore used in place of CONST (which applies to dryland conditions). CONSTI would normally be slightly higher than CONST, and 0,5 is a recommended value (Hensley and de Jager, 1982).

(d) In the irrigation option, the same moisture budgeting sequences as used for dryland conditions (Chapter 11) are applied, running in parallel with the dryland routine.

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CHAPTER 14

CROP YIELD ESTIMATIONS BY THE ACRU MODEL

PRINCIPLES OF CROP YIELD MODELLING

Crop yield is influenced by the degree of stress the crop is subjected to and the timing of the stress in relation to the phenological development of the plant. In Southern Africa, which is characterized generally by water scarcity, crop production is frequently limited by insufficient water at some stage during the growing season and crop yield-modelling becomes important not only in terms of the yield potential but also of crop effects on regional water resources.

Many very simple crop models use rainfall (plus irrigation) as a direct indicator of yield, resulting in broad generalizations such as "for deep soils each inch of annual precipitation accounts for a bag of maize per morgen" (cited in Crafford and Nott, 1981). Such simplistic models seldom yield satisfactory results. In the case of maize, for example, results from one location cannot be transferred to other locations and different planting dates are not accounted for. Water used by a crop in the growth process comes from the soil moisture store, from which rainwater may be lost through stormflow or deep percolation, and in which rainwater may be distributed unequally. Crop production is usually limited by insufficient water at some stage during the growing season. A sound crop yield model should account for plant water stress and ideally even for the sensitivity of yield to the occurrence of moisture deficits at critical development stages.

The structure of the multi-layer moisture budgeting ACRU model, which also accounts for rooting and development and stage of crop growth, facilitates the "attachment" of crop yield models of various complexities, developed by various researchers, to run in tandem with the model. To date, maize and sugarcane submodels have been incorporated into the model. The level of model complexity is that of so-called "evapotranspiration models" in which the premise is made that crop production is related to evapotranspiration or alternatively to soil moisture deficit. This premise has been shown to hold true, in general terms, for many crops, as is testified by the abundance of papers on this subject in say, the Journal of Agronomy, over the past five years.

MAIZE YIELD MODELS[1)]

At the present stage, four empirical maize yield models are attached to the ACRU model, the first three being based on actual evapotranspiration and the fourth focussing on reductions of yield due to stress in the critical flowering period in maize.

(a) The De Jager (1982) Model. The model suggested by de Jager (1982) is a robust evapotranspiration-based model in which maize yield is expressed as

$$Y_m = \frac{30(AET_{gs} - 100)0,45}{1000} \qquad \text{Eq. 1}$$

in which

Y_m = maize (grain) yield ($t.ha^{-1}$), and

---

1) At the time of going to print, new maize yield prediction equations were being developed for Southern Africa, in the Department of Agricultural Engineering at the University of Natal, Pietermaritzburg, based on a comprehensive data set of "control" yields from research stations.

AET_{gs} = total actual evapotranspiration (mm) from both the A- and B-horizons for the duration of the active growing season.

From Equation 1 it may be seen that a threshold of 100 mm AET is required for maize yield.

(b) The Du Pisani (1977) Model. This very simple model relates

$$Y_m = 0,0092\ AET_{gs} \qquad \text{Eq. 2}$$

There is no AET threshold in Equation 2; consequently it computes higher yields in dry years, but relatively lower yields in moist years when results are compared with those from the de Jager model.

(c) The Stewart (1977) Model. This model, developed in the U.S.A. by Stewart et al, (1977) estimates maize yield as

$$Y_m = 0,01845\ AET_{gs} - 3,0825 \qquad \text{Eq. 3}$$

This model has a threshold of maize yield at 168 mm AET. However, Equation 3 has a steep slope; consequently it predicts higher yields than models (a) and (b) in "good" years but lower yields in "poor" years and results in higher coefficients of variation of maize yield than the other two AET models.

(d) The Du Pisani (1978) Model. The du Pisani (1978) model was developed using data from several divergent locations in South Africa and estimates maize yield by

$$Y_m = P_{ym} 0,88^{MSD} \qquad \text{Eq. 4}$$

where

P_{ym} = potential maize yield ($t.ha^{-1}$)

$$= \frac{4575\ PET_{gs}}{1000\ .\ 424,4}$$

in which

PET_{gs} = total potential evapotranspiration (mm) from the A- and B-horizons for the duration of the active growing season, and

MSD = number of moisture stress days for the critical flowering period, 70-100 days after planting.

When used in the ACRU1 model a moisture stress day has been defined as occurring when the AET of both the A- and B-horizons was less than 0,5 PET. Because the exponent MSD can be high in "dry" seasons, this model predicts very low yields when the flowering period of maize experiences stressed conditions.

(e) At the present stage, maize yields estimated by the ACRU model are approximations based on work by others. No cognizance is taken of genetic factors or other technological development which may enhance yields. The yield estimate furthermore assumes good management and agronomic practice. (However, see footnote on previous page.)

(f) The input variables and options for the crop yield models are given in Table 14.1. Most variables are self-explanatory. However, the planting date (PLDATE) option requires amplification. If a computed planting date is

Table 14.1 Crop yield modelling : control variables

```
C                           CROP YIELD MODELLING
C                           --------------------
C
C     VARIABLES
C     ---------
C                 CROP     = SELECTION OF CROP TYPE FOR YIELD MODELLING ( AT
C                            PRESENT MAIZE AND SUGARCANE)
C                 ISTDAY   = DAY ON WHICH CROP IS PLANTED
C                 ISTMO    = MONTH IN WHICH CROP IS PLANTED
C                 LENGTH   = LENGTH OF CROP GROWING SEASON (DAYS)
C                 PLDATE   = OPTION FOR PLANTING DATE TO BE SPECIFIED OR
C                            SELECTED BY COMPUTER FOLLOWING A MINMUM OF
C                            RAINFALL
C
C     CONTROL VARIABLES FOR CROP YIELD MODELLING
C     ------------------------------------------
C
C     COL  1-20  PRINT 'CROP YIELD OPTIONS'
C
C                DO YOU REQUIRE CROP YIELD TO BE ESTIMATED ?
C                     IF YES, CONTINUE WITH QUESTIONS BELOW
C                     IF NO, LEAVE REST BLANK AND CONTINUE WITH NEXT SECTION 7
C                IF NRYLD = 0 THE FOLLOWING OPTIONS ARE NOT REQUIRED AND CAN
C                     BE LEFT BLANK
C     COL     25 SELECT CROP FOR WHICH YIELD IS TO BE ESTIMATED:
C                     IF MAIZE,                             CROP = 1
C                     IF SUGARCANE,                         CROP = 2
C                     IF CROP = 2, THE REMAINING OPTIONS DO NOT APPLY AND CAN
C                     BE LEFT BLANK
C
C                INPUT FOR MAIZE YIELD INFORMATION FOLLOWS
C
C     COL     30 DO YOU WANT TO SPECIFY THE MAIZE PLANTING OR HAVE PLANTING
C                     DATE COMPUTER SELECTED ?
C                     IF PLANTING DATE SPECIFIED,        PLDATE = 1
C                     IF PLANTING DATE COMPUTED,         PLDATE = 0
C                     IF PLDATE = 0 LEAVE REST BLANK
C     COL 34-35  IF PLANTING DATE IS SPECIFIED, IN WHICH MONTH IS MAIZE TO BE
C                     PLANTED (E.G. OCTOBER = 10)          ISTMO =
C     COL 39-40  ON WHICH DAY OF THE MONTH SPECIFIED ABOVE IS MAIZE TO BE
C                     PLANTED (E.G. 9TH = 09)              ISTDAY =
C     COL 43-45  WHAT IS THE LENGTH OF THE GROWING SEASON, IN DAYS ?
C                     (TYPICALLY 150 DAYS)               LENGTH =
```

requested, this is calculated

(i) as occurring after October 1 (before that, low soil temperature retards germination at most locations), and

(ii) on condition that a minimum of 25 mm rainfall has fallen within a period of five consecutive days. This recommendation has been used for many years now and implies that planting takes place after soil moisture has been recharged sufficiently to ensure that germination and some root development take place under favourable conditions. There is an extensive literature in Southern Africa on "optimum" maize planting dates for different regions, related mostly to the apparent "mid-season drought" during the critical flowering period.

(g) In regard to the length of the active growing season, LENGTH, this varies between 130 and 180 days depending on the hybrid and region, but 150 days is an average duration in Southern Africa.

SUGARCANE YIELD MODELS

As early as the 1960s, accumulated results had led to the conclusion that a linear relationship between crop water use (actual evapotranspiration) and sugarcane yield might exist. Thompson (1976), collating overseas results from Hawaii, Australia and Mauritius with those from the South African Sugar Association experiments at Mount Edgecombe, Chakaskraal and Pongola, obtained an equation which, when metricated, may be expressed as

$$Y_c = 9{,}53\ (AET/100) - 2{,}36 \qquad \text{Eq. 5}$$

where

Y_c = annual sugarcane yield ($t.ha^{-1}$), and

AET = annual actual evapotranspiration (mm).

Similarly, an equation was derived by Thompson for tonnes sucrose yielded per hectare (Y_s) which gave

$$Y_s = 22{,}27 + 4{,}841(AET/100) - 0{,}1395(AET/100)^2 \quad \text{Eq. 6}$$

The implication is that approximately 9,5 t cane or 1,33 t sucrose can be produced for each 100 mm water utilized in evapotranspiration by the crop. Such a representation between yield and water use can be used to assess average annual crop yields if annual actual evapotranspiration can be estimated. For annual yield estimates, a July 1 to June 30 growing season is taken for Southern Africa. A cropping factor of 0,8 is applied for each month of the year, following Thompson (1977), and actual evapotranspiration is assumed to decline from the potential when CONST = 0,4.

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CHAPTER 15

OUTPUT OPTIONS

INTRODUCTION

Output options available in the ACRU model consist of daily and monthly summaries of moisture budget components, a separate daily summary for the supplementary irrigation routine, summaries with probability analyses for maize yield, sugarcane yield, runoff and irrigation simulations, plotting options for observed vs simulated runoff and statistical analyses comparing the model's performance of simulated runoff with observed runoff. Output options are given in Table 15.1.

SUMMARY OF DAILY MOISTURE BUDGET COMPONENTS

The daily moisture budget components, all of which have units of mm, are summarized in this option (an example is given in Table 15.2) and consist of

(i) rainfall*,

(ii) effective rainfall* (i.e. rainfall minus interception or stormflow),

(iii) potential evaporation* (i.e. A-pan or its equivalent value),

(iv) potential evapotranspiration from the topsoil* and subsoil* horizons,

(v) actual evapotranspiration from the topsoil* and subsoil* horizons,

(vi) soil moisture contents of both horizons at the end of a day,

(vii) moisture deficits (in relation to porosity moisture contents) for both horizons,

(viii) surplus soil moisture* released from a saturated B-horizon as drainage,

(ix) unsaturated moisture loss from the B-horizon,

(x) the amount of water in the groundwater store,

(xi) baseflow released from the groundwater store*,

(xii) stormflow* (quickflow plus "interflow") released from the stormflow store,

(xiii) total simulated runoff*,

(xiv) observed runoff*, and

(xv) the fraction of plant available soil moisture at which stress sets in.

Components designated with * are summed to give monthly totals.

SUMMARY OF DAILY MOISTURE BUDGET FOR THE SUPPLEMENTARY IRRIGATION ROUTINE

(Example : Table 15.3)

In essence, this daily summary (Table 15.3) differs from the one above in that the soil moisture budget in the supplementary

Table 15.1 Output options : control variables

```
C                                    OUTPUT OPTIONS
C                                    --------------
C
C     VARIABLES
C     ---------
C                  WRIDY   = OPTION FOR PRINTING DAILY SUMMARIES OF MOISTURE
C                            BUDGET COMPONENTS
C                  WRIMO   = OPTION FOR PRINTING MONTHLY SUMMARIES OF MOISTURE
C                            BUDGET COMPONENTS
C                  PRIRR   = OPTION FOR PRINTING SUPPLEMENTARY IRRIGATION INFORMATION
C                            AT DAILY LEVEL
C                  ISUMRY  = OPTION FOR PRINTING STATISTICAL SUMMARY OF SUPPLEMENTARY
C                            IRRIGATION REQUIREMENTS
C                  RSUMRY  = OPTION FOR PRINTING STATISTICAL SUMMARY OF SIMULATED
C                            RUNOFF
C                  WRTYLD  = OPTION FOR ESTIMATING CROP YIELD (MAIZE OR SUGARCANE
C                            AT PRESENT)
C                  IPLOT   = OPTION FOR GRAPHICAL PLOTS OF OBSERVED AND SIMULATED
C                            DAILY RUNOFF
C                  IPLMNO  = OPTION FOR GRAPHICAL PLOTS OF OBSERVED AND SIMULATED
C                            MONTHLY RUNOFF
C                  IPLSTO  = OPTION FOR GRAPHICAL PLOTS OF OBSERVED AND SIMULATED
C                            DAILY SOIL MOISTURE CONTENTS
C                  ICOMPR  = OPTION FOR STATISTICAL SUMMARY OF MODEL PERFORMANCE
C                  LOGVAL  = OPTION FOR TRANSFORMATION OF RUNOFF TO LOGARITHMIC
C                            VALUES
C
C
C                  N.B. OPTIONS WRIDY, WRIMO, WRTYLD AND PRIRR CANNOT PRINT
C                  SIMULTANEOUSLY
C
C
C     COL   1-14   PRINT 'OUTPUT OPTIONS'
C     COL     20   DO YOU REQUIRE A PRINTOUT OF DAILY VALUES OF MOISTURE
C                     BUDGET COMPONENTS ?
C                     IF YES,                                        WRIDY = 1
C                     IF NO,                                         WRIDY = 0
C     COL     21   DO YOU REQUIRE A PRINTOUT OF MONTHLY SUMMARY VALUES OF
C                     MOISTURE BUDGET COMPONENTS ?
C                     IF YES,                                        WRIMO = 1
C                     IF NO,                                         WRIMO = 0
C     COL     22   DO YOU REQUIRE A PRINTOUT OF SUPPLEMENTARY IRRIGATION
C                     INFORMATION AT DAILY LEVEL ?
C                     IF YES,                                        PRIRR = 1
C                     IF NO,                                         PRIRR = 0
C                     N.B. YOU CANNOT ANSWER 'YES' TO THIS AND THE FOLLOWING
C                     OPTION UNLESS YOU SPECIFIED WRIRR = 1 UNDER  'IRRIGATION
C                     REQUIREMENTS'
C     COL     23   DO YOU REQUIRE A STATISTICAL SUMMARY ON SUPPLEMENTARY
C                     IRRIGATION REQUIREMENTS (MONTHLY MEANS, DEVIATIONS,
C                     PROBABILITY) ?
C                     IF YES,                                        ISUMRY = 1
C                     IF NO,                                         ISUMRY = 0
C     COL     24   DO YOU REQUIRE A STATISTICAL SUMMARY OF SIMULATED RUNOFF ?
C                     IF YES,                                        RSUMRY = 1
C                     IF NO,                                         RSUMRY = 0
C     COL     25   DO YOU REQUIRE CROP YIELD ESTIMATIONS FOR EITHER MAIZE OR
C                     SUGARCANE ?
C                     IF YES,                                        WRTYLD = 1
C                     IF NO,                                         WRTYLD = 0
C                     N.B. IF YES, ANSWER RELEVANT QUESTIONS UNDER INPUT
C                     REQUIREMENTS HEADED 'CROP YIELD MODELLING'
C     COL     26   DO YOU REQUIRE A GRAPHICAL PLOT OF DAILY OBSERVED VS
C                     SIMULATED RUNOFFS, ONE MONTH AT A TIME ?
C                     IF YES,                                        IPLOT = 1
C                     IF NO,                                         IPLOT = 0
C     COL     27   DO YOU REQUIRE A GRAPHICAL PLOT OF MONTHLY OBSERVED VS
C                     SIMULATED RUNOFFS, FOR ENTIRE PERIOD OF RECORD ?
C                     IF YES,                                        IPLMNO = 1
C                     IF NO,                                         IPLMNO = 0
C     COL     28   DO YOU REQUIRE A GRAPHICAL PLOT OF OBSERVED VS SIMULATED
C                     SOIL MOISTURE CONTENTS ?
C                     IF YES,                                        IPLSTO = 1
C                     IF NO,                                         IPLSTO = 0
C     COL     29   DO YOU REQUIRE STATISTICAL SUMMARIES OF MODEL PERFORMANCE
C                     (SIMULATED VS OBSERVED RUNOFF) ?
C                     IF NO,                                         ICOMPR = 0
C                     IF YES, ANALYSES FOR DAILY VALUES,             ICOMPR = 1
C                             ANALYSES FOR MONTHLY VALUES,           ICOMPR = 2
C                             ANALYSES FOR BOTH DAILY AND
C                             MONTHLY VALUES,                        ICOMPR = 3
C     COL     30   IF ICOMPR = 1,2 OR 3 , DO YOU REQUIRE VALUES TO BE
C                     TRANSFORMED LOGARITHMICALLY (BASE 10) ?
C                     IF YES,                                        LOGVAL = 1
C                     IF NO,                                         LOGVAL = 0
```

Table 15.2 Daily summary of moisture budget components : an example

WIKI6 ACRU TEST RUN

AREA OF CATCHMENT (KM SQ)	=	3.22
LATITUDE (S)	=	28.31
LONGITUDE (E)	=	31.45
ELEVATION (M)	=	271.00
POTENTIAL EVAPORATION BY DAILY A-PAN DATA		
COEFFICIENT OF DRAINAGE RELEASE	=	.50
COEFFICIENT OF QUICKFLOW RESPONSE	=	.50
COEFFICIENT OF BASEFLOW RESPONSE	=	.02
COEFFICIENT OF INITIAL ABSTRACTION	=	.15
DEPTH OF SOIL IN A-HORIZON (M)	=	.38
DEPTH OF SOIL IN B-HORIZON (M)	=	.46
WILTING POINT OF A-HORIZON (M/M)	=	.135
WILTING POINT OF B-HORIZON (M/M)	=	.135
FIELD CAPACITY OF A-HORIZON (M/M)	=	.245
FIELD CAPACITY OF B-HORIZON (M/M)	=	.245
POROSITY OF SOIL IN A-HORIZON (M/M)	=	.330
POROSITY OF SOIL IN B-HORIZON (M/M)	=	.330
LENGTH OF GROWING SEASON	=	0

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
CROPPING FACTOR	.70	.70	.70	.65	.62	.50	.45	.45	.60	.65	.68	.70
PROP OF ROOTS IN A HORIZON	.70	.70	.70	.80	.85	.85	.85	.85	.85	.75	.70	.70
INTERCEPTION LOSS (MM)	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
TEMP: MEAN MAXIMUM (C)	28.4	27.9	27.5	26.3	23.7	22.1	21.9	22.1	23.6	24.4	25.9	27.7
MEAN MINIMUM (C)	19.5	19.7	18.1	15.4	11.9	8.9	9.3	11.7	14.1	15.0	16.4	18.1

DAILY MOISTURE BUDGET OF MONTH 1 YEAR 1977

DAY	RAIN-FALL	EFFEC-TIVE RAIN	A-PAN EQUIV.	PET A-HOR	PET B-HOR	AET A-HOR	AET B-HOR	SOIL MOIST A-HOR	SOIL MOIST B-HOR	DEFI-CIT A-HOR	DEFI-CIT B-HOR	DRAIN-AGE	UNSAT. DRAIN-AGE	BASE-FLOW STORE	BASE-FLOW	STORM-FLOW	SIMU-LATED RUNOFF	OBSER-VED RUNOFF	STRESS FRAC-TION
1.	30.0	23.2	6.3	3.1	1.3	3.1	1.3	91.9	86.8	1.2	26.2	.00	.00	.00	.000	2.635	2.635	2.255	.4
2.	.0	.0	6.3	2.7	1.2	2.7	1.2	88.8	85.7	4.3	27.0	.00	.00	.00	.000	1.317	1.317	1.473	.4
3.	.0	.0	6.3	3.1	1.3	3.1	1.3	85.5	84.7	7.6	28.0	.00	.00	.00	.000	.659	.659	.965	.4
4.	.0	.0	6.3	3.1	1.3	3.1	1.3	82.1	83.6	11.0	29.1	.00	.00	.00	.000	.329	.329	.785	.4
5.	.0	.0	6.3	3.1	1.3	3.1	1.3	78.9	82.4	14.2	30.3	.00	.00	.00	.000	.165	.165	.656	.4
6.	1.4	.0	6.3	3.1	1.3	3.1	1.3	75.6	81.3	17.5	31.4	.00	.00	.00	.000	.082	.082	.579	.4
7.	.0	.0	6.3	2.7	1.2	2.7	1.1	72.8	80.3	20.3	32.4	.00	.00	.00	.000	.041	.041	.575	.4
8.	.0	.0	6.3	3.1	1.3	3.1	1.2	69.6	79.1	23.5	33.6	.00	.00	.00	.000	.021	.021	.455	.4
9.	.0	.0	6.1	2.1	1.3	3.1	1.1	66.5	78.1	26.6	34.6	.00	.00	.00	.000	.010	.010	.415	.4
10.	1.7	.2	5.7	2.2	1.2	2.5	.9	64.2	77.1	28.9	35.6	.00	.00	.00	.000	.005	.005	.328	.4
11.	.0	.0	5.7	2.4	1.0	1.9	.8	62.3	76.3	30.8	36.4	.00	.00	.00	.003	.003	.003	.355	.4
12.	.0	.0	5.7	2.8	1.2	1.8	.8	60.5	75.5	32.6	37.2	.00	.00	.00	.000	.001	.001	.356	.4
13.	.0	.0	5.7	2.8	1.2	1.5	.8	59.0	74.7	34.1	38.0	.00	.00	.00	.000	.001	.001	.261	.4
14.	.0	.0	5.7	2.8	1.2	1.3	.7	57.7	73.9	35.4	39.8	.00	.00	.00	.000	.000	.000	.234	.4
15.	3.4	1.9	5.7	2.9	1.2	1.1	.7	59.6	73.2	34.5	39.5	.00	.00	.00	.000	.000	.000	.214	.4
16.	.0	.0	5.7	2.4	1.0	1.1	.6	57.5	72.6	35.6	40.1	.50	.09	.00	.000	.000	.000	.207	.4
17.	.0	.0	5.9	2.9	1.2	1.1	.6	55.5	71.9	37.6	40.8	.00	.00	.00	.000	.000	.000	.210	.4
18.	4.1	2.6	5.9	2.9	1.2	.9	.6	58.2	71.3	34.9	41.4	.00	.00	.00	.000	.000	.000	.150	.4
19.	9.1	7.6	5.9	2.5	1.1	1.0	.5	64.7	70.9	28.4	41.8	.00	.00	.00	.000	.000	.000	.283	.4
20.	3.0	1.5	5.9	2.5	1.1	2.0	.5	64.1	70.5	29.0	42.2	.00	.00	.00	.000	.000	.000	.583	.4
21.	.0	.0	5.9	2.5	1.1	1.9	.5	62.1	70.1	31.0	42.6	.00	.00	.00	.000	.000	.000	.370	.4
22.	.0	.0	5.9	2.9	1.2	1.9	.5	60.2	69.7	32.9	43.0	.00	.00	.00	.000	.000	.000	.213	.4
23.	.2	.0	5.9	2.9	1.2	1.5	.5	58.6	69.2	34.5	43.5	.00	.00	.00	.000	.000	.000	.158	.4
24.	49.0	33.9	7.3	3.5	1.5	1.5	.5	90.3	69.4	2.8	43.3	.00	.00	.00	.000	6.284	6.284	2.125	.4
25.	4.6	3.1	7.3	3.2	1.4	3.2	.5	89.6	69.5	3.5	43.2	.00	.00	.00	.000	3.142	3.142	5.468	.4
26.	49.1	25.0	7.3	3.2	1.4	3.2	.5	102.8	78.7	.0	34.0	.00	.00	.00	.000	12.360	12.360	3.355	.4
27.	14.5	10.6	7.3	3.2	1.4	3.2	1.1	101.6	85.1	.0	26.6	.00	.00	.00	.000	7.369	7.369	10.935	.4
28.	1.3	.0	7.3	3.2	1.4	3.7	1.4	95.8	87.4	.0	25.3	.00	.00	.00	.000	3.684	3.684	3.555	.4
29.	68.5	26.4	7.3	3.3	1.4	3.3	1.4	106.0	98.7	.0	14.0	.00	.20	.00	.201	22.174	22.326	9.521	.4
30.	2.9	1.4	7.3	3.2	1.4	3.2	1.4	98.7	102.6	.0	10.1	.00	.29	.00	.222	11.062	11.344	13.330	.4
31.	.0	.0	7.3	3.2	1.4	3.7	1.4	94.3	102.1	.0	10.6	.00	.27	.00	.272	5.531	5.803	3.818	.4
	241.8	138.5	196.3	91.1	39.0	72.7	28.3					.00			.756	76.625	77.581	60.206	

Table 15.3 Daily summary of moisture budget components for supplementary irrigation routine : an example

WLML6 ACRU TEST RUN

```
AREA OF CATCHMENT (KM SQ)                      =    3.32
LATITUDE (S)                                   =   28.31
LONGITUDE (E)                                  =   31.45
ELEVATION (M)                                  =  271.00
POTENTIAL EVAPORATION BY DAILY A-PAN DATA
COEFFICIENT OF DRAINAGE RELEASE                =     .50
COEFFICIENT OF QUICKFLOW RESPONSE              =     .50
COEFFICIENT OF BASEFLOW RESPONSE               =     .02
COEFFICIENT OF INITIAL ABSTRACTION             =     .20
DEPTH OF SOIL IN A-HORIZON (M)                 =     .45
DEPTH OF SOIL IN B-HORIZON (M)                 =     .42
WILTING POINT OF A-HORIZON (M/M)               =    .130
WILTING POINT OF B-HORIZON (M/M)               =    .166
FIELD CAPACITY OF A-HORIZON (M/M)              =    .237
FIELD CAPACITY OF B-HORIZON (M/M)              =    .264
POROSITY OF SOIL IN A-HORIZON (M/M)            =    .362
POROSITY OF SOIL IN B-HORIZON (M/M)            =    .394
LENGTH OF GROWING SEASON                       =     0
```

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
CROPPING FACTOR	.75	.75	.75	.70	.70	.65	.65	.65	.70	.75	.75	.75
FRCN OF ROOTS IN A HORIZON	.70	.70	.70	.80	.85	.85	.85	.85	.85	.95	.70	.70
INTERCEPTION LOSS (MM)	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50
TEMP: MEAN MAXIMUM (C)	28.4	27.9	27.5	26.3	23.7	22.1	21.9	22.1	23.6	24.4	25.9	27.7
MEAN MINIMUM (C)	19.5	19.7	18.1	15.4	11.9	8.9	9.3	11.7	14.1	15.0	16.4	18.1

DAILY MOISTURE BUDGET FOR IRRIGATION ROUTINE FOR MONTH 1 YEAR 1977

DAY	RAIN	PE	ACT-IR	IRRIGATION DEFICIT	IRRIGATION STORMFLOW	EFFECTIVE RAINFALL	INITIAL SOIL STORAGE	SURPLUS RAINFALL	FINAL SOIL STORAGE	IRRIGATION REQUIREMENT
1.	30.0	4.7	4.7	44.7	6.8	23.2	191.4	.0	191.4	.0
2.	.0	3.8	3.8	.0	.0	.0	187.6	.0	187.6	.0
3.	.0	4.7	4.7	.0	.0	.0	182.9	.0	182.9	.0
4.	.0	4.7	4.7	.0	.0	.0	178.2	.0	178.2	.0
5.	.0	4.7	4.7	.0	.0	.0	173.4	.0	173.4	.0
6.	1.4	4.7	4.7	44.1	.0	.0	168.7	.0	217.5	48.8
7.	.0	4.2	4.2	.0	.0	.0	213.3	.0	213.3	.0
8.	.0	4.7	4.7	.0	.0	.0	208.6	.0	208.6	.0
9.	.0	4.7	4.7	.0	.0	.0	203.9	.0	203.9	.0
10.	1.7	4.3	4.3	13.6	.0	.0	199.6	.0	199.6	.0
11.	.0	3.6	3.6	.0	.0	.0	196.0	.0	196.0	.0
12.	.0	4.3	4.3	.0	.0	.0	191.7	.0	191.7	.0
13.	.0	4.3	4.3	.0	.0	.0	187.4	.0	187.4	.0
14.	.0	4.3	4.3	.0	.0	.0	183.1	.0	183.1	.0
15.	3.4	4.3	4.3	34.4	.0	.9	179.8	.0	179.8	.0
16.	.0	3.3	3.3	.0	.0	.0	176.4	.0	176.4	.0
17.	.0	4.4	4.4	.0	.0	.0	172.0	.0	217.5	45.5
18.	4.1	4.4	4.4	.0	4.1	.0	213.1	.0	213.1	.0
19.	9.1	3.5	3.5	4.4	5.3	3.8	213.4	.0	213.4	.0
20.	3.0	3.5	3.5	4.2	.7	2.3	212.1	.0	212.1	.0
21.	.0	3.5	3.5	.0	.0	.0	208.7	.0	208.7	.0
22.	.0	4.4	4.4	.0	.0	.0	204.2	.0	204.2	.0
23.	.2	4.4	4.4	13.3	.0	.0	199.8	.0	199.8	.0
24.	43.0	5.4	5.4	17.7	31.8	16.2	210.6	.0	210.6	.0
25.	4.6	4.5	4.5	6.9	1.0	3.6	209.7	.0	209.7	.0
26.	49.1	4.5	4.5	7.9	40.9	8.3	213.4	.0	213.4	.0
27.	14.5	4.5	4.5	4.1	10.5	4.0	212.9	.0	212.9	.0
28.	1.3	4.5	4.5	4.7	.0	1.3	209.6	.0	209.6	.0
29.	68.9	5.0	5.0	7.9	59.5	8.7	213.3	.0	213.3	.0
30.	2.9	4.5	4.5	4.2	.7	2.2	211.0	.0	211.0	.0
31.	.0	4.5	4.5	.0	.0	.0	206.4	.0	206.4	.0
	[illegible]	135.2	135.2		161.6	74.4		.0		94.3

irrigation routine combines the A- and B-horizon soil moistures.

Additionally, the amount of supplementary irrigation added to the soil profile is given, as are soil moisture contents before irrigation water is added (but after stormflow, if generated) and after irrigation water is added.

MONTHLY SUMMARY OF MOISTURE BUDGET COMPONENTS

(Example : Table 15.4)

Monthly summations of the moisture budget are given for the major components listed in Table 15.2, with values of supplementary irrigation requirements added. The values of soil moisture storages and deficits listed are for the last day of each respective month.

STATISTICAL SUMMARY OF SUPPLEMENTARY IRRIGATION REQUIREMENTS

(Example : Table 15.5)

This statistical summary lists, for each month of the year, as well as for annual totals, the means, standard deviations and coefficients of variability of generated supplementary irrigation requirements. Input information which is relevant to the simulation of irrigation requirements is also listed, for example, cropping factors, the type of scheduling assumed, field efficiency assumed or the method by which potential evaporation has been estimated. The summary further contains a monthly frequency analysis of irrigation requirements for the 5%, (i.e. 1:20 year 'wet' period), 10%, 20%, 33%, 50%, 67%, 80%, 90% and 95% (i.e. 1:20 year 'dry' period) levels of non-occurrence (Table 15.5). This frequency analysis is a useful tool for planning purposes and decision-making when the variables involved are not distributed normally.

Table 15.4 Monthly summary of moisture budget components : an example

U2M1A ACRU TEST RUN

AREA OF CATCHMENT (KM SQ)	=	1.31
LATITUDE (S)	=	29.73
LONGITUDE (E)	=	30.16
ELEVATION (M)	=	1050.00
POTENTIAL EVAPORATION BY DAILY A-PAN DATA		
COEFFICIENT OF DRAINAGE RELEASE	=	.50
COEFFICIENT OF QUICKFLOW RESPONSE	=	.50
COEFFICIENT OF BASEFLOW RESPONSE	=	.02
COEFFICIENT OF INITIAL ABSTRACTION	=	.20
DEPTH OF SOIL IN A-HORIZON (M)	=	.40
DEPTH OF SOIL IN B-HORIZON (M)	=	.41
WILTING POINT OF A-HORIZON (M/M)	=	.272
WILTING POINT OF B-HORIZON (M/M)	=	.272
FIELD CAPACITY OF A-HORIZON (M/M)	=	.385
FIELD CAPACITY OF B-HORIZON (M/M)	=	.385
POROSITY OF SOIL IN A-HORIZON (M/M)	=	.396
POROSITY OF SOIL IN B-HORIZON (M/M)	=	.396
LENGTH OF GROWING SEASON	=	0

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
CROPPING FACTOR	.76	.76	.76	.75	.74	.73	.73	.73	.73	.74	.75	.76
FRAC OF ROOTS IN A HORIZON	.40	.40	.40	.40	.40	.40	.40	.40	.40	.40	.40	.40
INTERCEPTION LOSS (MM)	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00
TEMP: MEAN MAXIMUM (C)	25.0	24.9	24.2	22.5	20.6	19.0	19.2	20.8	22.3	22.6	23.5	24.7
MEAN MINIMUM (C)	14.6	14.6	13.5	10.5	6.6	3.3	3.7	5.8	8.5	10.6	12.1	13.6

MONTHLY SUMMARY OF MOISTURE BUDGET U2M1A ACRU TEST RUN

YEAR	MONTH	RAINFALL	EFFECTIVE RAINFALL	PET	AET	S.M.C. A-HOR	S.M.C. B-HOR	DEF. A-HOR	DEF. B-HOR	DRAIN-AGE	BASE-FLOW	STORM-FLOW	EST. RUNOFF	OBS. RUNOFF	IRRIG REQU.
77	1	159.9	101.6	100.2	83.3	155.5	125.8	.0	29.0	.000	.000	12.8	12.8	9.0	94.8
77	2	47.2	27.0	99.3	69.4	122.3	114.7	31.7	43.2	.000	.000	.7	.7	9.4	41.4
77	3	141.8	97.0	67.6	59.2	151.9	122.7	2.1	35.1	.000	.000	2.7	2.7	8.8	.0
77	4	59.2	26.6	73.7	53.0	139.8	118.5	15.2	39.3	.000	.000	.0	.0	3.5	.0
77	5	18.3	15.3	67.5	38.5	119.6	115.4	34.4	42.4	.000	.000	.0	.0	.5	93.7
77	6	9.7	6.7	61.1	11.7	117.4	112.6	36.6	45.3	.000	.000	.0	.0	.0	46.2
77	7	1.6	.0	72.2	9.3	110.0	111.4	44.0	45.9	.000	.000	.0	.0	.1	45.1
77	8	15.9	4.7	81.1	3.0	111.6	111.9	42.4	45.9	.000	.000	.0	.0	.0	93.8
77	9	73.1	57.3	94.5	12.8	151.1	116.9	2.9	40.9	.000	.000	1.2	1.2	.5	45.6
77	10	113.7	67.4	74.9	51.6	150.7	128.1	.0	29.7	.000	.000	2.1	2.1	1.0	.0
77	11	111.5	66.4	90.5	80.9	150.0	118.9	4.0	38.9	.000	.437	1.8	2.3	4.0	.0
77	12	130.1	78.9	115.6	66.0	150.5	123.3	.0	34.5	.000	.000	10.5	10.5	2.7	100.2
TOTALS		850.0	553.8	998.3	537.6					.000	.437	31.9	32.3	39.5	571.7

MONTHLY SUMMARY OF MOISTURE BUDGET U2M1A ACRU TEST RUN

YEAR	MONTH	RAINFALL	EFFECTIVE RAINFALL	PET	AET	S.M.C. A-HOR	S.M.C. B-HOR	DEF. A-HOR	DEF. B-HOR	DRAIN-AGE	BASE-FLOW	STORM-FLOW	EST. RUNOFF	OBS. RUNOFF	IRRIG REQU.
78	1	238.9	110.5	80.6	80.6	150.3	149.7	3.7	9.2	4.439	8.538	72.4	81.0	48.0	.0
78	2	89.6	44.0	67.6	65.3	152.5	125.6	1.5	32.3	.000	2.149	.2	2.4	23.7	47.7
78	3	102.5	60.2	74.5	61.6	153.2	123.5	.8	34.3	.000	.934	.4	1.4	11.6	.0
78	4	78.0	45.7	57.7	50.6	143.6	128.1	10.4	29.7	.000	.518	3.7	4.2	6.4	.0
78	5	10.4	.0	63.7	40.0	116.5	115.2	17.5	42.6	.000	.272	.0	.3	2.2	47.6
78	6	4.8	1.0	49.9	6.7	111.4	112.7	42.6	45.1	.000	.142	.0	.1	.1	47.2
78	7	32.5	26.4	59.7	22.3	114.7	113.4	39.3	44.4	.000	.075	.0	.1	.4	47.4
78	8	21.9	7.8	62.4	9.3	114.1	112.5	39.9	45.3	.000	.042	.0	.0	.2	47.6
78	9	81.0	52.5	75.9	30.6	132.1	116.5	21.9	41.4	.000	.022	2.3	2.8	.6	46.5
78	10	162.1	107.3	82.7	58.1	154.1	133.6	.0	24.3	.000	.165	12.5	12.6	6.4	.0
78	11	151.2	88.8	72.2	65.8	154.2	143.3	.0	9.5	.000	4.153	14.8	15.0	21.6	46.5
78	12	184.1	107.1	104.0	104.0	154.2	146.8	.0	11.1	.000	4.700	25.5	33.2	12.5	.0
TOTALS		1157.0	651.7	853.9	610.9					4.438	21.715	135.3	157.0	154.1	330.8

Table 15.5 Statistical summary of supplementary irrigation requirements : an example

UZPIO ACRU TEST RUN

LATITUDE (S) = 29.73
LONGITUDE (E) = 30.19
ELEVATION (M) =1050.00
POTENTIAL EVAPORATION BY DAILY A-PAN DATA
IRRIGATION TO FIELD CAPACITY
FIELD EFFICIENCY = 1.00
AVAILABLE SOIL MOISTURE CONTENT AT STRESS THRESHOLD = .50

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
CROPPING FACTOR	.76	.76	.76	.75	.74	.73	.73	.73	.73	.74	.75	.76
PROP OF ROOTS IN A HORIZON	.40	.40	.40	.40	.40	.40	.40	.40	.40	.40	.40	.40
INTERCEPTION LOSS (MM)	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00

IRRIGATION REQUIREMENTS

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANN
MEAN	40.33	31.75	31.87	31.96	46.76	62.02	46.45	71.28	47.36	31.33	41.53	41.28	524.73
STANDARD DEVIATION	35.95	24.61	24.72	39.06	29.65	24.56	29.24	26.39	29.86	24.29	20.47	37.63	135.40
COEFF OF VARIATION	89.13	77.51	77.59	122.22	63.40	39.10	62.95	37.02	63.03	77.58	49.29	91.15	25.80

PROBABILITY ANALYSIS

5.%	.00	.00	.00	.00	2.30	46.27	2.30	45.94	2.32	.00	2.34	.00	333.50
10.%	.00	.00	.00	.00	2.30	46.27	2.30	45.94	2.32	.00	2.34	.00	333.50
20.%	.00	.00	.00	.00	9.19	46.39	9.21	46.20	9.29	.00	9.38	.00	341.52
33.%	.00	.00	.00	.00	45.02	47.00	45.14	47.96	45.52	.00	45.95	.00	387.25
50.%	46.70	46.32	45.79	.00	46.02	47.18	46.07	48.22	46.48	45.90	47.75	45.90	571.65
67.%	48.43	47.37	46.75	47.20	47.24	48.37	46.75	93.79	47.40	46.49	49.98	50.20	577.59
80.%	51.42	47.63	48.74	48.69	47.56	86.92	47.23	95.19	49.12	46.87	51.64	51.21	610.62
90.%	69.22	48.27	49.34	67.65	66.08	94.48	65.39	96.02	67.47	47.64	52.26	70.95	635.59
95.%	82.00	48.69	49.40	81.58	79.91	94.61	79.92	96.37	80.91	48.14	52.41	85.56	654.70

STATISTICAL SUMMARY OF SIMULATED RUNOFF

(Example : Table 15.6)

Both the structure and contents of this summary are similar to those described in the previous section, except that the runoff coefficients used in the simulations are also listed (Table 15.6). This statistical summary would be applied at ungauged locations when simulations of water yield are required for dam design, or when the effects of changes in land use are modelled.

CROP YIELD ESTIMATIONS

(Examples : Tables 15.7 and 15.8)

The ACRU model applies soil moisture budgeting routines to estimate crop yields, one crop at a time. In the case of maize (Table 15.7), the estimated yields by each of the four models described in Chapter 14 are tabulated for each season, as are the planting date (either specified as input or computed) and the number of stress days for the critical flowering period. This information is followed by a statistical summary comprising means, standard deviation and variabilities of estimated maize yields, as well as probabilities of attaining yields at selected levels of recurrence.

The routine for sugarcane is similar to that of maize (Table 15.8). However, the growing season is fixed (July to June) and estimates are given for the sugarcane and sucrose yield models described in Chapter 14.

PLOTTING ROUTINES FOR OBSERVED vs SIMULATED OUTPUT

(Example : Figure 15.1)

Simple plots of observed and simulated values on a matrix printer

Table 15.6 Statistical summary of simulated runoff : an example

U2K18 ACRU TEST RUN

LATITUDE (S) = 29.73
LONGITUDE (E) = 30.16
ELEVATION (M) =1050.00
COEFFICIENT OF DRAINAGE RELEASE = .50
COEFFICIENT OF QUICKFLOW RESPONSE = .50
COEFFICIENT OF BASEFLOW RESPONSE = .02
COEFFICIENT OF INITIAL ABSTRACTION = .20
POTENTIAL EVAPORATION BY DAILY A-PAN DATA

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
CROPPING FACTOR	.76	.76	.76	.75	.74	.73	.73	.73	.73	.74	.75	.76
FRAC OF ROOTS IN A HORIZON	.40	.40	.40	.40	.40	.40	.40	.40	.40	.40	.40	.40
INTERCEPTION LOSS (MM)	3.00	3.00	3.00	3.00	3.00	2.00	3.00	3.00	3.00	3.00	3.00	3.00

SIMULATED RUNOFF (MM)

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANN
MEAN	20.61	13.37	7.71	2.00	2.67	.03	.02	.35	1.14	2.59	9.15	8.99	68.63
STANDARD DEVIATION	30.49	10.90	9.32	2.27	6.35	.06	.03	.82	1.07	4.98	7.22	12.26	48.85
COEFF OF VARIATION	147.96	81.52	120.92	113.94	237.84	174.09	176.80	236.73	93.51	192.28	78.84	136.38	71.18

PROBABILITY ANALYSIS

5.%	2.10	.81	.07	.00	.00	.00	.00	.00	.00	.00	.47	1.85	25.82
10.%	2.10	.81	.07	.00	.00	.00	.00	.00	.00	.00	.47	1.85	25.82
20.%	2.20	1.05	.27	.00	.00	.00	.00	.00	.00	.00	.79	1.90	26.84
33.%	2.70	2.35	1.32	.00	.00	.00	.00	.00	.01	.01	2.24	2.63	32.18
50.%	3.62	10.29	2.70	.00	.01	.00	.00	.00	1.11	.33	7.51	2.71	50.62
67.%	13.00	17.46	4.65	2.92	.11	.00	.00	.02	1.20	.49	10.90	3.25	57.01
80.%	19.59	20.15	11.98	3.97	.24	.04	.02	.04	1.62	1.78	14.13	8.99	82.23
90.%	45.14	23.94	17.86	4.48	6.41	.09	.05	.84	2.18	6.32	16.57	19.54	116.80
95.%	63.05	26.27	20.87	4.66	11.02	.12	.06	1.43	2.49	9.48	17.78	26.35	136.52

Table 15.7 Maize yield estimation : an example

JAAGDAAN MAIZE YIELD

AREA OF CATCHMENT (KM SQ)	=	1.00
LATITUDE (S)	=	29.30
LONGITUDE (E)	=	30.70
ELEVATION (M)	=	1006.00
POTENTIAL EVAPORATION BY DAILY A-PAN DATA		
COEFFICIENT OF DRAINAGE RELEASE	=	.50
COEFFICIENT OF QUICKFLOW RESPONSE	=	.50
COEFFICIENT OF BASEFLOW RESPONSE	=	.02
COEFFICIENT OF INITIAL ABSTRACTION	=	.20
DEPTH OF SOIL IN A-HORIZON (M)	=	.30
DEPTH OF SOIL IN B-HORIZON (M)	=	.70
WILTING POINT OF A-HORIZON (M/M)	=	.139
WILTING POINT OF B-HORIZON (M/M)	=	.135
FIELD CAPACITY OF A-HORIZON (M/M)	=	.243
FIELD CAPACITY OF B-HORIZON (M/M)	=	.245
POROSITY OF SOIL IN A-HORIZON (M/M)	=	.350
POROSITY OF SOIL IN B-HORIZON (M/M)	=	.330
LENGTH OF GROWING SEASON	=	150

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
CROPPING FACTOR	1.00	.95	.65	.50	.50	.50	.50	.40	.40	.50	.65	.95
PROP OF ROOTS IN A HORIZON	.70	.70	.70	.80	.85	.95	.95	.95	.95	.95	.90	.80
INTERCEPTION LOSS (MM)	.80	1.30	1.10	1.00	1.00	.90	.90	.20	.20	.30	.30	.50
TEMP: MEAN MAXIMUM (C)	26.6	24.3	25.1	22.5	19.9	19.2	19.8	20.0	22.5	24.3	23.5	25.1
MEAN MINIMUM (C)	14.7	14.7	14.6	10.3	7.8	5.2	5.5	6.5	9.6	11.1	12.5	12.9

MAIZE YIELD ESTIMATION (T/HA/SEASON)

YEAR	DU PISANI 77	DU PISANI 78	DE JAGER	USA-STEWART	PLANTING DATE	STRESS DAYS
1971/72	4.192	2.409	3.856	4.033	OCTOBER 8	8
1972/73	4.903	1.184	4.739	5.239	OCTOBER 14	14
1973/74	4.720	4.512	4.513	4.930	NOVEMBER 2	3
MEAN	4.605	2.702	4.369	4.734		
STANDARD DEVIATION	.369	1.683	.456	.627		
COEFF OF VARIATION	8.016	62.297	10.492	13.235		

PROBABILITY ANALYSIS

5.%	4.218	1.245	3.889	4.078
10.%	4.218	1.245	3.889	4.078
20.%	4.218	1.245	3.889	4.078
33.%	4.218	1.245	3.889	4.078
50.%	4.456	1.797	4.185	4.481
67.%	4.722	2.430	4.515	4.933
80.%	4.793	3.250	4.603	5.054
90.%	4.848	3.881	4.671	5.147
95.%	4.875	4.194	4.705	5.193

Table 15.8 Sugarcane yield estimation : an example

JAAGBAAN SUGARCANE YIELD

AREA OF CATCHMENT (KM SQ)	=	1.00
LATITUDE (S)	=	29.30
LONGITUDE (E)	=	30.70
ELEVATION (M)	=	1066.00
POTENTIAL EVAPORATION BY DAILY A-PAN DATA		
COEFFICIENT OF DRAINAGE RELEASE	=	.50
COEFFICIENT OF QUICKFLOW RESPONSE	=	.50
COEFFICIENT OF BASEFLOW RESPONSE	=	.02
COEFFICIENT OF INITIAL ABSTRACTION	=	.20
DEPTH OF SOIL IN A-HORIZON (M)	=	.30
DEPTH OF SOIL IN B-HORIZON (M)	=	.70
WILTING POINT OF A-HORIZON (M/M)	=	.135
WILTING POINT OF B-HORIZON (M/M)	=	.135
FIELD CAPACITY OF A-HORIZON (M/M)	=	.245
FIELD CAPACITY OF B-HORIZON (M/M)	=	.245
POROSITY OF SOIL IN A-HORIZON (M/M)	=	.350
POROSITY OF SOIL IN B-HORIZON (M/M)	=	.350
LENGTH OF GROWING SEASON	=	0

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
CROPPING FACTOR	1.00	.55	.65	.50	.50	.50	.50	.40	.40	.50	.65	.55
FROP OF ROOTS IN A HORIZON	.70	.70	.70	.80	.85	.95	.95	.95	.95	.95	.50	.80
INTERCEPTION LOSS (MM)	.80	1.30	1.10	1.00	1.00	.90	.90	.30	.30	.30	.30	.50
TEMP: MEAN MAXIMUM (C)	26.6	24.3	25.1	22.5	19.9	19.2	19.M	20.0	22.5	24.3	23.5	25.1
MEAN MINIMUM (C)	14.7	14.1	14.6	10.3	7.8	5.2	5.5	6.5	9.6	11.1	12.5	12.9

SUGARCANE YIELD ESTIMATION (T/HA/YEAR)

YEAR	SUGAR CANE	SUCROSE
1971/72	68.139	5.478
1972/73	64.649	4.442
1973/74	72.514	6.723
MEAN	68.434	5.540
STANDARD DEVIATION	3.941	1.142
COEFF OF VARIATION	5.758	20.588

PROBABILITY ANALYSIS

5.%	64.824	4.494
10.%	64.824	4.494
20.%	64.824	4.494
33.%	64.824	4.494
50.%	66.394	4.960
67.%	68.183	5.490
80.%	69.807	5.976
90.%	71.201	6.349
95.%	71.858	6.536

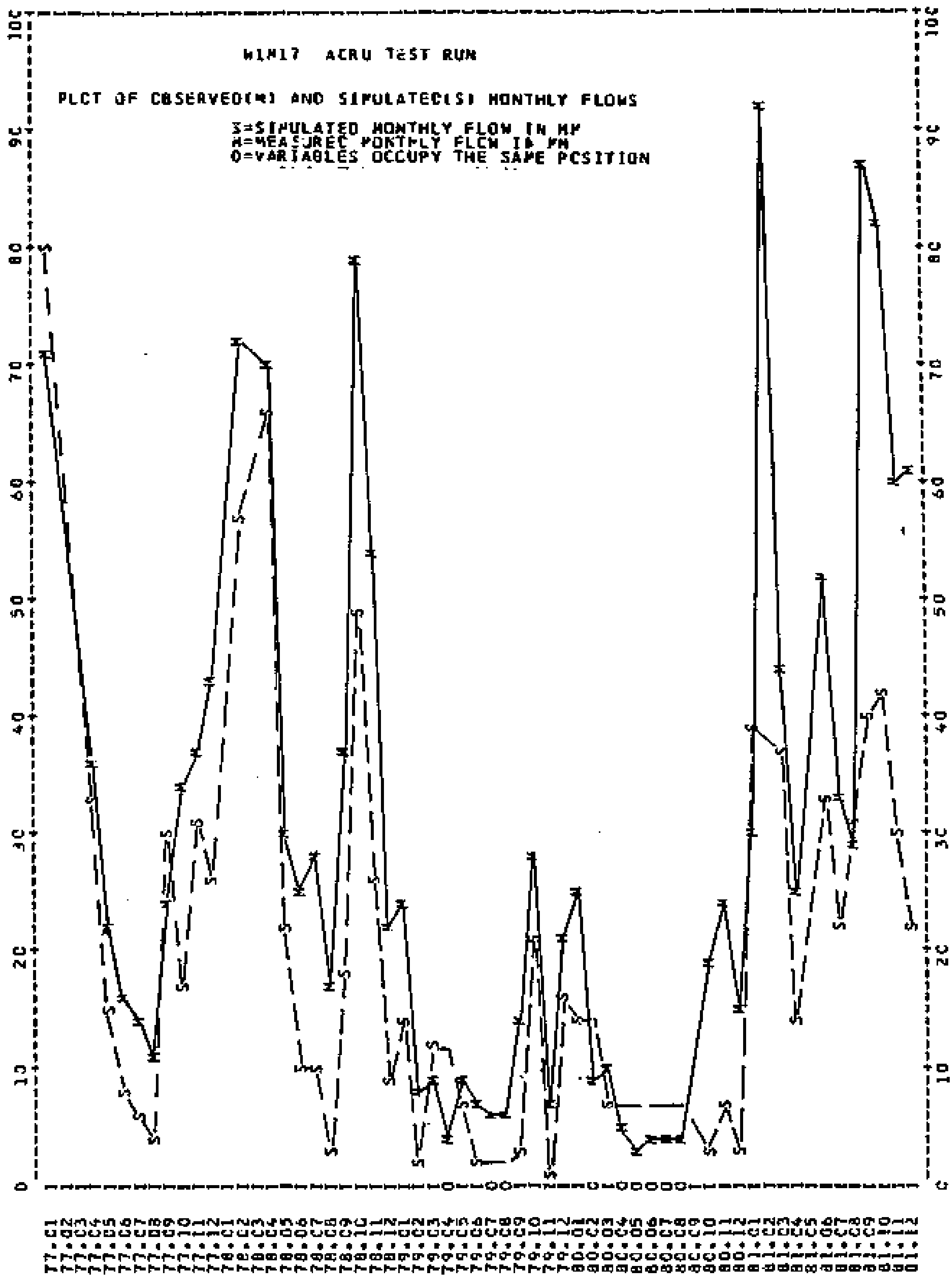

Figure 15.1 Plot of monthly observed vs simulated runoff : an example

have been incorporated as an optional output in the ACRU model. At present this option is available for

(i) daily observed vs simulated runoff, one month at a time,

(ii) monthly observed vs simulated runoff, for the entire period of record under review (Figure 15.1), and

(iii) daily observed vs simulated soil moisture contents for the topsoil and subsoil horizons of a soil profile.

STATISTICAL SUMMARIES OF MODEL PERFORMANCE

The statistical summaries compare simulated and observed runoff, at either

(i) daily level, or

(ii) monthly level

of data. The statistical programs in the ACRU model are adaptations of programs published by Roberts (1978) and include, inter alia, a comparison of means, variances, standard deviations as well as coefficients of determination and efficiency (Chapter 3) and the regression equation between observed and simulated runoffs. Warnings are given if systematic errors are detected in runoff simulations. Examples are given in Chapter 16.

REFERENCE

Roberts, P.J.T. 1978. A comparison of the performance of selected conceptual models of the rainfall-runoff process in semi-arid catchments near Grahamstown. Rhodes University, Grahamstown, Hydrological Research Unit. Report 1/78.

CHAPTER 16

MODEL PERFORMANCE

The performance of the ACRU model was tested on four catchments in Natal for which daily climatic data as well as soils and land use information were readily available. The catchments are

(i) U2M18, a steep, predominantly forested catchment at Cedara (Schulze, 1979),

(ii) V1M28, a small, flat, short grassveld catchment at DeHoek (Schulze, 1983),

(iii) W1M16, at 3,22 km^2 the largest of the catchments tested, located in Zululand and predominantly medium grassveld (Hope and Mulder, 1979), and

(iv) W1M17, a smaller Zululand catchment, again predominantly grassveld (Hope and Mulder, 1979).

The performances of the model as reported in this chapter were TESTED ON INITIAL RUNS, i.e. all soils (depth, retention constants) and land use (cropping factor, proportion of roots in A-horizon, interception loss) variables were calculated directly from information contained in the references cited above and from other relevant literature, with no changes made for improved goodness of fit. All the observed rainfall and runoff data were taken from data files, while evaporation data were obtained from either published material (Zululand; Hope et al, 1981) or from computer printout provided by the Agrometeorology Section of the Department of Agriculture, Cedara. The ACRU model was tested for the period 1977-82 (inclusive) for U2M18, 1977-May 1983 for V1M28, 1977-79 for W1M16 and 1977-81 for W1M17, a period which contained the severe Zululand floods of 1977 as well as the drought of the early 1980's.

The statistics of model performance for each of the four test catchments are given for monthly runoff in Tables 16.1 to 16.4 with runoff units, where relevant, given in mm. Results from the three grassveld catchments are highly satisfactory.

(a) For V1M28 both Coefficients of Determination (D) and Efficiency (E) are 0,948 (Table 16.2). While the model over-estimates means (12,1 vs 10,5 mm per month) the deviations are conserved (27,1 vs 27,5 mm). The model over-estimates in the lower ranges and perusal of the daily and monthly printouts point to over-estimations, particularly in spring, when rainfall intensities are ususally very low and the catchment responds very slowly after dry winters.

(b) Statistics of model performance for monthly runoff on catchment W1M16 are generally excellent. Not only does Table 16.3 show D and E values to be highly satisfactory at 0,972 and 0,975 respectively, but means and deviations are conserved excellently and the regression coefficient is 0,999.

(c) Although land use and soils for W1M17 are similar to those of W1M16, the goodness of fit statistics (Table 16.4), while still considered satisfactory, do not match up to those of W1M16. The ACRU model under-estimates runoff on this catchment (monthly means 37,7 vs 45,2 mm), but deviations are conserved well (66,4 vs 63,9 mm). The under-estimation occurs primarily in the lower values (base constant -7,7 mm); but "design" values are simulated well (regression coefficient 1,004).

(d) The least satisfactory performance of a "first" run was

Table 16.1 Statistics of performance of monthly values, U2M18

U2M18 ACRU TEST RUN

STATISTICS OF PERFORMANCE OF ACRU MODEL

A COMPARISON OF SIMULATED AND OBSERVED FLOWS
FOR MONTHLY VALUES

TOTAL OBSERVED FLOWS	=	390.262
TOTAL SIMULATED FLOWS	=	411.753
MEAN OF OBSERVED FLOWS	=	5.420
MEAN OF SIMULATED FLOWS	=	5.719
CORRELATION COEFFICIENT	=	.833
STUDENTS T VALUE	=	12.583
REGRESSION COEFFICIENT	=	1.075
BASE CONSTANT FOR REGRN. EQN.	=	-.106
STANDARD ERROR OF SIMULATED FLOW	=	54.741
VARIANCE OF OBSERVED FLOW	=	84.676
VARIANCE OF SIMULATED VALUES	=	140.573
STANDARD DEVIATION OF X VALUES	=	9.202
STANDARD DEVIATION OF Y VALUES	=	11.856
PERCENTAGE DIFFERENCE IN STANDARD DEVIATION	=	-28.846
COEFFICIENT OF DETERMINATION	=	.693
COEFFICIENT OF EFFICIENCY	=	.509

###CAUTION### SYSTEMATIC ERROR DETECTED ###

Table 16.2 Statistics of performance of monthly values, V1M28

V1M28 ACRU TEST RUN

STATISTICS OF PERFORMANCE OF ACRU MODEL

A COMPARISON OF SIMULATED AND OBSERVED FLOWS
FOR MONTHLY VALUES

TOTAL OBSERVED FLOWS	=	805.224
TOTAL SIMULATED FLOWS	=	935.008
MEAN OF OBSERVED FLOWS	=	10.457
MEAN OF SIMULATED FLOWS	=	12.143
CORRELATION COEFFICIENT	=	.973
STUDENTS T VALUE	=	36.863
REGRESSION COEFFICIENT	=	.986
BASE CONSTANT FOR REGRN. EQN.	=	1.827
STANDARD ERROR OF SIMULATED FLOW	=	54.311
VARIANCE OF OBSERVED FLOW	=	735.202
VARIANCE OF SIMULATED VALUES	=	755.827
STANDARD DEVIATION OF X VALUES	=	27.115
STANDARD DEVIATION OF Y VALUES	=	27.492
PERCENTAGE DIFFERENCE IN STANDARD DEVIATION	=	-1.393
COEFFICIENT OF DETERMINATION	=	.948
COEFFICIENT OF EFFICIENCY	=	.948

NO SYSTEMATIC ERRORS DETECTED

Table 16.3 Statistics of performance of monthly values, W1M16

W1M16 ACRU TEST RUN

STATISTICS OF PERFORMANCE OF ACRU MODEL

A COMPARISON OF SIMULATED AND OBSERVED FLOWS
FOR MONTHLY VALUES

TOTAL OBSERVED FLOWS	=	1412.967
TOTAL SIMULATED FLOWS	=	1416.222
MEAN OF OBSERVED FLOWS	=	39.249
MEAN OF SIMULATED FLOWS	=	39.340
CORRELATION COEFFICIENT	=	.986
STUDENTS T VALUE	=	34.077
REGRESSION COEFFICIENT	=	.999
BASE CONSTANT FOR REGRN. EQN.	=	.137
STANDARD ERROR OF SIMULATED FLOW	=	72.656
VARIANCE OF OBSERVED FLOW	=	5406.091
VARIANCE OF SIMULATED VALUES	=	5549.275
STANDARD DEVIATION OF X VALUES	=	73.526
STANDARD DEVIATION OF Y VALUES	=	74.493
PERCENTAGE DIFFERENCE IN STANDARD DEVIATION	=	-1.316
COEFFICIENT OF DETERMINATION	=	.972
COEFFICIENT OF EFFICIENCY	=	.975

NO SYSTEMATIC ERRORS DETECTED

Table 16.4 Statistics of performance of monthly values, W1M17

W1M17 ACRU TEST RUN

STATISTICS OF PERFORMANCE OF ACRU MODEL

A COMPARISON OF SIMULATED AND OBSERVED FLOWS
FOR MONTHLY VALUES

TOTAL OBSERVED FLOWS	=	2714.156
TOTAL SIMULATED FLOWS	=	2261.615
MEAN OF OBSERVED FLOWS	=	45.236
MEAN OF SIMULATED FLOWS	=	37.694
CORRELATION COEFFICIENT	=	.963
STUDENTS T VALUE	=	27.309
REGRESSION COEFFICIENT	=	1.004
BASE CONSTANT FOR REGRN. EQN.	=	-7.735
STANDARD ERROR OF SIMULATED FLOW	=	135.106
VARIANCE OF OBSERVED FLOW	=	4083.086
VARIANCE OF SIMULATED VALUES	=	4410.526
STANDARD DEVIATION OF X VALUES	=	63.899
STANDARD DEVIATION OF Y VALUES	=	66.412
PERCENTAGE DIFFERENCE IN STANDARD DEVIATION	=	-3.932
COEFFICIENT OF DETERMINATION	=	.928
COEFFICIENT OF EFFICIENCY	=	.922

###CAUTION### SYSTEMATIC ERROR DETECTED ###

achieved on Cedara's forested catchment U2M18 (Table 16.1). Means of simulated monthly flows compare well with observed values (5,7 vs 5,4 mm), but deviations are not conserved (28% difference). Consequently the D and E coefficients have been reduced to 0,693 and 0,509 respectively. High flows would be estimated well (regression coefficient 1,075) but low flows are under-estimated slightly.

Perusal of individual days' and months' simulations shows that the ACRU1 model can still be refined considerably. Much scatter at daily levels of data may be attributed to rainfall intensity's not being accounted for in ACRU1 at present. This is an important area for future research in terms of generalizing typical intensities at monthly level and incorporating results in, say, estimates of initial abstraction. The model also tends to under-estimate runoff in dry years, possibly because the cropping factor (hence evapotranspiration and moisture deficits) is not adjusted for extended periods of stress.

The individual days' simulations are furthermore fraught with data problems - a single rainfall event may extend over two days of data, intensity and duration are not accounted for, because runoff responds to rainfall with a lag, the runoff responses frequently appear one day out of phase with rainfall. These are problems inherent in all daily models.

A major long term improvement could, hopefully, be brought about with a daily model by taking a distributed rather than a lumped modelling approach, and this is particularly the case in catchments where vastly different land uses and soils occur on a catchment, as on U2M18.

The ACRU model has given highly satisfactory results on initial runs. The model needs, however, to be tested on more catchments in diverse hydrological environments and this is seen as an immediate priority.

REFERENCES

Hope, A.S. and Mulder, G.J. 1979. Hydrological investigations of small catchments in the Natal coastal belt and the role of physiography and landuse in the rainfall-runoff process. University of Zululand, Kwa Dlangezwa, Series B No. 2. 283 pp.

Hope, A.S., Mulder, G.J. and Sands, R.M. 1981. Temperature and evaporation data for the Zululand research catchments. University of Zululand, Kwa Dlangezwa, Zululand Hydrology Project, Report 1/81, 43 pp.

Schulze, R.E. 1979. Field studies, data processing, techniques and models for applied hydrological research, Vol. 1. University of Natal, Pietermaritzburg, Department of Agricultural Engineering, ACRU Report No. 7, 423 pp.

Schulze, R.E. 1983. The DeHoek/Ntabamhlope and Cathedral Peak Hydrological Catchments. University of Natal, Pietermaritzburg, Department of Agricultural Engineering, ACRU Report No. 18, 63 pp.

APPENDIX 1

COMPUTER PROGRAM OF THE ACRU1 HYDROLOGICAL SIMULATION MODEL

R.E. Schulze, E. Murgatroyd, W.J. George and C.B. Schultz

Updating and improvements to the ACRU model are an ongoing process. Latest available listings may be obtained from

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```
      DIMENSION AET(32),AETIR(32),AET1(32),AET2(32),APAN(12,32),
     *ASOEV(32),ASOEVD(32),ATRAN1(32),ATRAN2(32),ATRANS(32),
     *AWC1(32),AWC2(32),CAY(12),CAYD(12,32),CDATA(70,4),CONSTA(32),
     *CORPAN(12),CV(13),D(12),DAYS(12),DEF1(32),DEF2(32),DEF1BR(32),
     *DEF2BR(32),DIRRIG(70,13),DL(12),DNO(32),DPE(32),E(12),ELAID(32),
     *ERFL(32),ERFLIR(32),ESRFL(32),EXX(32),FACTOR(12),
     *FF(6),FFS(4),FMT(6),HEAD(17),IDAY(32),IWEIR(6),KSMDAY(32),
     *MNPLV(240),MOIAAP(12),OBSQMX(480),OBSQX(4000),OBSTO1(32)
     *OBSTO2(32),PAN(32),PARAM(12,32),PCENT(9),PCTILE(9,12),PERC(32),
     *PLINT(32),PLSTRS(32),PORFR(32),POSOEV(32),POTRAN(32),POTR1(32),
     *POTR2(32),PP(6),PP1(32),PP2(32),PRAIN(6),QUICKF(32),RAIN(32),
     *REDAR(32),REDSA(32),REQIR(32),RFL(32),RFLNET(32),ROOTA(12),
     *ROOTB(12),RUN(32),RUNCD(32),SDATA(70,13),SIMQM(480),SIMQT(4800),
     *SIMSQ(32),SMD(32),SMDIR(32),SMOBS1(32),SMOBS2(32),SMOBS3(32)
     *SMST01(32),SMST02(32),SMST03(32),SMST10(32),SMST30(32),SMST60(32),
     *SM10(32),SM30(32),SM60(32),STD(13),STRFL(32),STOIR(32),STOIRO(32),
     *STORMQ(32),STO1(32),STO2(32),STO1BR(32),STO2BR(32),STOIR(32),
     *STRMCO(32),STRMFL(32),SURIR(32),SUR1(32),SUR2(32),SWTRA(11),
     *SYBL(6),SYBLO(4),T(12),TAET(12),TAETIR(12),TAET1(12),TAET2(12),
     *TAPAN(12),TASOEV(12),TDISCH(12),TDPE(12),TERAIN(12),TET(12),
     *TE1(12),TE2(12),T1(12),TIRRFL(12),TMAX(12),TMAXD(32),TMIN(12)
      DIMENSION TMIND(32),TMITD(12),TMLIN(12),TPLINT(12),TPOSEV(12),
     *TPOTR1(12),TPOTR2(12),TPTRAN(12),TRAIN(12),TREQIR(12),
     *TRQIR(12),TRUN(12),TQUICK(12),TSTORM(12),TSTWR(12),TSTREM(12),
     *TSUR(12),TSURIR(12),TTRANS(12),TTRAN1(12),TTRAN2(12),VALUE(9),
     *VEGINT(32),WPFCPD(3,11),X(70),XMEAN(13),XXX(12)
      CHARACTER EQIN*19(5),IRRTYP*18(3),ISTID*8,LUSE*4,SMONTH*9(12)
      COMMON/PETEMP/TEMP,TMAX,TMIN,EQPET,DL,D,LINWIN,ELEV,ALAT
      COMMON/HDGMTH/HEAD
      COMMON/PREVDI/SOIL1,SOIL2,PLINTC,RFLC,RCO,STCO,SOILI,EFPPT
      COMMON/LDVALS/STOIR,PLINT,RUNCO,STRMCO,RFL,E,ERFL
      COMMON/PRINT/DEF1,DEF2,STO1,STO2
      COMMON/COUNT/I,IYR,NDYM,IYEAR,K
      COMMON/PRNTMO/TRAIN,TERAIN,TDPE,TAET,TPOSEV,TASOEV,TPOTR1,TPOTR2,
     *TTRAN1,TTRAN2,TPTRAN,TTRANS,TSUR,TRUN,TQUICK,TDISCH,TSTREM,TRQIR
      COMMON/PRTDLY/MOIST,DNO,PP1,PP2,DPE,AET1,AET2,AWC1,AWC2,OBSTO1,
     *OBSTO2,RUN,QUICKF,SIMSQ,STRMFL,REQIR,CONSTA,PORFR,APAN,SUR2,PERC,
     *PRIRR,EVTR,CAYD,POSOEV,ASOEV,POTR1,POTR2,ATRAN1,ATRAN2
      COMMON/TOTALS/TE1,TE2,TAET1,TAET2,TAPAN
      COMMON/IRRIG/AETIR,SMDIR,STOIR,ERFLIR,STOIRO,SURIR,TAETIR,TSTOIR,
     *TIRRFL,TSURIR,TREQIR
      COMMON/MAIZE/PLDATE,LENGTH
 9876 CONTINUE
C-----------------------------------------------------------------------
C
C       ACRU MODEL - DAILY VERSION - SEPTEMBER,1984.
C
C-----------------------------------------------------------------------
C
C       OPTIONS & DEFINITIONS:
C
C       ALAT   = LATITUDE (DEGREES & DECIMALS OF DEGREES)
C       AREA   = AREA OF CATCHMENT IN KM SQ
C       COFRU  = COEFFICIENT OF RUNOFF I.E. FRACTION OF WATER BELOW ROOT ZONE
C                THAT RUNS OFF ON A PARTICULAR DAY
C       COIA   = COEFF OF INITIAL ABSTRACTION FOR STORMFLOW SUBMODEL
C       CONST  = FRACTION OF SOIL MOISTURE AT WHICH AE < PE
C       CRLEPO = CRITICAL LEAF WATER POTENTIAL. IF TO BE USED, A VALUE IS
C                ENTERED. IF NOT, A BLANK IS READ
C
C       DEPAHO = DEPTH OF A HORIZON IN METRES
C       DEPBHO = DEPTH OF B HORIZON IN METRES
C       E      = MONTHLY POTENTIAL EVAPORATION (MM)
C       ELEV   = ELEVATION ABOVE MEAN SEA LEVEL (METRES)
C       EQPET  = OPTIONS FOR THREE TEMPERATURE BASED EQUATIONS FOR
C                ESTIMATION OF POTENTIAL EVAPOTRANSPIRATION IF A-PAN VALUES .
C                UNAVAILABLE
C                1 = LINACRE
C                2 = BLANEY CRIDDLE
C                3 = THORNTHWAITE
C                4 = DAILY A-PAN DATA
C                5 = MONTHLY A-PAN DATA
C       EVTR   = OPTION FOR ESTIMATING EVAPORATION AND TRANSPIRATION SEPARATELY
C                IF EVTR = 1  E + T ARE COMBINED
C                        = 2  E + T ARE CALCULATED SEPARATELY
C       FC1    = SOIL MOISTURE CONTENT AT FIELD CAPACITY FOR A HORIZON
C       FC2    = SOIL MOISTURE CONTENT AT FIELD CAPACITY FOR B HORIZON
C       ICOMPR = OPTION TO STATISTICALLY COMPARE SIMULATED AND OBSERVED
C                VALUES OF STREAMFLOW. IS ONLY ALLOWED IF OBSQ = 1.
C                IF ICOMPR = 0  THIS OPTION IS OMITTED
C                          = 1  AN ANALYSIS IS DONE FOR DAILY FLOWS
C                          = 2  AN ANALYSIS IS DONE OF MONTHLY FLOWS
C                          = 3  ANALYSES ARE PERFORMED FOR DAILY AND MONTHLY
C                               FLOWS.
C       IOBSQ  = OPTION TO PRINT SIMULATED AND OBSERVED DATA
C                IF IOBSQ = 1  OBSERVED FLOW DATA IS READ IN
C                         = 0  NO OBSERVED DATA IS TO BE READ IN
C       IPLOT  = OPTION TO GRAPHICALLY PLOT OBSERVED VS SIMULATED FLOW
C                THIS OPTION SHOULD ONLY BE USED IF IOBSQ = 1
C                IF IPLOT = 1  GRAPH IS PRODUCED
C                         = 0  NO GRAPH IS PRODUCED
C       ISUMRY = OPTION TO PRINT A SUMMARY OF IRRIGATION REQUIREMENTS
C                IF ISUMRY = 0  NO SUMMARY IS PRODUCED
C                          = 1  SUMMARY IS PRODUCED
C       LINWIN = IDENTIFICATION TO DETERMINE ZONE OF THE SITE
C                (USED TO FIND WIND FACTOR FOR LINACRE EQUATION)
C                0 = WIND FACTOR UNKNOWN - ASSUME = 15.
C                1 = COASTAL
C                2 = INLAND CONTINENTAL
C                3 = INLAND MARITIME
C       LOGVAL = OPTION TO USE LOGARITHMIC FLOW VALUES IN STATISTICAL
C                COMPARISON OF SIMULATED AND OBSERVED STREAMFLOWS. THIS
C                REDUCES THE 'WEIGHT' GIVEN TO HIGH FLOWS. IT CAN ONLY
C                BE USED IF ICOMPR = 1,2 OR 3.
C                IF LOGVAL = 0  ACTUAL VALUES ARE USED.
C                          = 1  LOGVALUES ARE USED.
C       MONTHLY TOTALS : -
C                TSUR   = SOIL MOISTURE SURPLUS
C                TE1    = POTENTIAL EVAPORATION FROM LAYER 1
C                TE2    = POTENTIAL EVAPORATION FROM LAYER 2
C                TAET   = TOTAL ACTUAL EVAPOTRANSPIRATION FROM BOTH LAYERS
C                TAET1  = A.E. OF LAYER 1
C                TAET2  = A.E. OF LAYER 2
C                TRQIR  = SUPPLEMENTARY IRRIGATION REQUIREMENT
C                TRUN   = PERCOLATION AND DEEP DRAINAGE
C                TSTORM = TOTAL STORMFLOW
C                TDISCH = TOTAL STORMFLOW, PERCOLATION & DRAINAGE
C                TSTREM = OBSERVED RUNOFF
C                TDPE   = OBSERVED A-PAN EVAPORATION FOR MONTH
C                TPLINT = PLANT INTERCEPTION
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C        PAM    = PLANT AVAILABLE MOISTURE
C        PAW1   = PLANT AVAILABLE WATER IN A HORIZON
C        PAW2   = PLANT AVAILABLE WATER IN B HORIZON
C        PLDATE = PLANTING DATE OPTION
C                 IF PLDATE = 0  COMPUTED PLANTING AFTER 25 MM OF RAINFALL
C                                IN 5 DAYS
C                           = 1  SPECIFIED DAY (MONTH, DAY) IS GIVEN
C                 ISTMO  = BEGINNING MONTH OF PLANTING IF DATE OPTION IS
C                          SPECIFIED
C                 ISTDAY = BEGINNING DAY OF PLANTING DATE IF DATE IS SPECIFIED
C                 LENGTH = LENGTH OF MAIZE GROWING SEASON (DAYS)
C        PO1    = SOIL MOISTURE CONTENT AT POROSITY FOR A HORIZON
C        PO2    = SOIL MOISTURE CONTENT AT POROSITY FOR B HORIZON
C        PPTCOR = CORRECTION FACTOR FOR PRECIPITATION DATA
C                 IF PPTCOR = 0  NO CORRECTION FACTOR USED
C                           = 1  CORRECTION FACTOR USED
C        PPTINF = OPTION TO READ PRECIPITATION DATA FROM CARDS OR FILE 16.
C                 OR IN A STRING FORMAT (FILE 21.)
C                 IF PPTINF = 0  DATA READ FROM CARDS
C                           = 1  DATA READ FROM FILE 16.
C                           = 2  DATA READ FROM FILE 21.
C        RSUMRY = OPTION TO PRINT A SUMMARY OF SIMULATED RUNOFF
C                 IF RSUMRY = 0  NO SUMMARY IS PRINTED
C                           = 1  SUMMARY IS PRINTED
C        SAT    = FRACTION BY WHICH SOIL POROSITY EXCEEDS PLANT
C                 AVAILABLE MOISTURE, I.E. POROSITY FRACTION
C        SCHED  = OPTION FOR THE TYPE OF SUPPLEMENTARY IRRIGATION SCHEDULING .
C                 1 = PLANNED DEFICIT TO 80% PLANT AVAILABLE WATER
C                 2 = IRRIGATION TO FIELD CAPACITY
C                 3 = FIXED AMOUNT OF WATER TO BE IRRIGATED, AMTIR
C      -          AMTIR  = THE AMOUNT TO BE IRRIGATED (MM) AND IS USED WHEN
C                          OPTION 3 IS SPECIFIED
C        STOR   = PLANT AVAILABLE MOISTURE OF PROFILE
C        TPAW   = TOTAL PLANT AVAILABLE WATER
C        WP1    = SOIL MOISTURE CONTENT AT WILTING POINT FOR A HORIZON
C        WP2    = SOIL MOISTURE CONTENT AT WILTING POINT FOR B HORIZON
C        WRIDY  = DAILY PRINTOUT OPTION:       0 = NO,  1 = YES
C        WRIMO  = MONTHLY PRINTOUT OPTION:     0 = NO,  1 = YES
C        WRIRR  = IRRIGATION PRINTOUT OPTION:  0 = NO,  1 = YES
C        WRTYLD = GRAIN YIELD PRINTOUT OPTION: 0 = NO,  1 = YES
C                 CROP   = THE OPTION FOR SELECTING A CROP IF WRTYLD = 1
C                 1 = MAIZE
C                 2 = SUGARCANE
C
C
C        ------------------------------------------------------------------
C
C        DATA STATEMENTS
C
         DEFINE FILE 16(AREADA,,120)
         DATA(SYMLO(I),I=1,2)/'A','B'/
         DATA(SYML(I),I=1,4)/'1','2','A','B'/
         DATA(FMT(I),I=1,6)/'(12X','/F9.','2,2X','         ','        ','     '/
         DATA PCENT/5.,10.,20.,33.,50.,67.,80.,90.,95./
         DATA DAYS/31.,29.,31.,30.,31.,30.,31.,31.,30.,31.,30.,31./
         DATA EQTN/'LINACRE','BLANEY CRIDDLE','THORNTHWAITE',
        *'DAILY A-PAN DATA','MONTHLY A-PAN DATA'/
         DATA IRRTYP/'TO PLANNED DEFICIT','TO FIELD CAPACITY',
        *'BY FIXED AMOUNT'/
         DATA SMONTH/'JANUARY','FEBRUARY','MARCH','APRIL','MAY','JUNE','JUL

        *Y','AUGUST','SEPTEMBER','OCTOBER','NOVEMBER','DECEMBER'/
         DATA WFFCFO/.272,.185,.396,  .177,.270,.434,  .033,.091,.417,
        *.055,.135,.491,  .095,.207,.412,  .133,.330,.486,  .148,.255,.330,
        *.197,.310,.391,  .308,.366,.432,  .239,.331,.539,  .250,.367,
        *.473/
         DATA SWTRRA/3.5,4.5,3.3,3.8,4.2,4.2,4.5,5.0,4.0,3.4,3.7/
C
C        ------------------------------------------------------------------
C
C        INPUT VARIABLES
C
C         LOCATIONAL INPUT
         READ(5,103)HEAD,AREA,ELEV,ALAT,ALONG
   103   FORMAT(4(/),1X,17A2,2X,F5.2,1X,F6.1,2(1X,F5.2))
C
C        OUTPUT OPTIONS
C
         READ(5,555)WRIDY,WRIMO,PRIRR,ISUMRY,RSUMRY,WRTYLD,IPLOT,IPLMNQ,
        *IPLSTO,ICOMPR,LOGVAL
   555   FORMAT(5(/),3(5X,F1.0),6X,I1,2(6X,F1.0),5(6X,I1))
         WRITE(6,*)'WRIDY=',WRIDY,'ISUMRY=',ISUMRY
C         RAINFALL CONTROL OPTIONS
         READ(5,104)PPTINF,PPTCOR
   104   FORMAT(5(/),6X,F1.0,3X,F4.2)
         WRITE(6,*)'PPTINF=',PPTINF
C         EVAP CONTOL OPTIONS
         READ(5,550)PANDAT,PANMON,PANCOR,EQPET,TEMP,LINWIN,EVTR
   550   FORMAT(5(/),5(6X,F1.0),4X,I3,6X,F1.0)
         WRITE(6,*)'PANDAT=',PANDAT
         IF(PANCOR.EQ.1)THEN
         READ(5,1103)(CORPAN(I),I=1,12)
  1103   FORMAT(5(/),12(1X,F4.2))
         ELSE
         READ(5,1102)A
  1102   FORMAT(5(/),2X)
         ENDIF
C         READ IN 12 VALUES OF MEAN MAX & MIN TEMPS (IF TEMP = 1)
         IF(TEMP.EQ.1)THEN
         READ(5,102)(TMAX(I),I=1,12),(TMIN(I),I=1,12)
   102   FORMAT(5(/),12(1X,F5.1),/12(1X,F5.1))
         ELSE
         READ(5,700)B
   700   FORMAT(6(/),2X)
         ENDIF
C        FOR THORNTHWAITE PE OPTION, READ IN DAYLENGTH FACTOR, DL(I) FOR EACH
C        MONTH ACCORDING TO LATITUDE
         READ(5,100)(DL(I),I=1,12)
   100   FORMAT(5(/),12(1X,F4.2))
C        FOR BLANEY CRIDDLE PE OPTION, READ IN DAYLIGHT FRACTION ACCORDING TO
C        LATITUDE
         READ(5,605)(D(I),I=1,12)
   605   FORMAT(5(/),12(1X,F4.3))
C         SOILS OPTIONS & INFORMATION
         READ(5,551)PEDINF,PEDDEP,ITEXT,MOIST,DEPAMO,DEPBMO,FC1,FC2,WP1,WP2
        *,PO1,PO2
   551   FORMAT(5(/),2(6X,F1.0),2(6X,I1),2(2X,F5.2),6(1X,F4.3))
C         VEGETATION OPTIONS & INFORMATION
         READ(5,552)CONST,CRLEPO
   552   FORMAT(5(/),1X,F4.0,2X,F5.2)
C         READ IN CROP FACTORS FOR ET EQUATIONS
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      READ(5,806)(CAY(I),I=1,12)
  806 FORMAT(5(/),12(1X,F4.2))
C      READ IN 12 VALUES OF PROPORTION OF ROOTS IN 'A' HORIZON
      READ(5,807)(ROOTA(I),I=1,12)
  807 FORMAT(5(/),12(1X,F4.2))
      DO 808 I=1,12
  808 ROOTB(I) = 1.0 - ROOTA(I)
C      READ IN 12 MONTHLY VALUES OF INTERCEPTION LOSS
      READ(5,809)(VEGINT(I),I=1,12)
  809 FORMAT(5(/),12(1X,F4.2))
C      READ IN RUNOFF CONTROL VARIABLES
      READ(5,553)IOBSQ,IOBSUN,SHDDEP,COFRU,COIA,RESPOF,BFRESP
  553 FORMAT(5(/),2(6X,I1),6X,F1.0,2(2X,F4.2),2(2X,F5.2))
C      IRRIGATION REQUIREMENTS
      READ(5,554)WRIRR,SCHED,EFFIRR,CONSTI,PLADEF,AMTIR
  554 FORMAT(5(/),2(5X,F1.0),2(3X,F4.2),2X,F5.2,3X,F5.1)
C      CROP YIELD VARIABLES
      READ(5,115)CROP,PLDATE,ISTDAY,ISTMO,LENGTH
  115 FORMAT(5(/),2(6X,F1.0),2(5X,I2),4X,I3)
C     CHECK FOR ERRORS IN SELECTION OF FLOW OPTIONS.
      IF((IOBSQ.EQ.0).AND.(ICOMPR.NE.0))THEN
      WRITE(6,*)'OPTION ERROR, ICOMPR REQUESTED WITHOUT FLOW DATA'
      STOP
      END IF
C
C     -----------------------------------------------------------------
C
C     PREPARE FOR AND CALL SUBROUTINE WHICH DOES HARMONIC ANALYSIS
C     12 MONTHLY VALUES ARE ENTERED AND THE SUBROUTINE RETURNS 365 DAILY VALUES
C
      DO 873 I=1,12
      XXX(I)=CAY(I)
  873 CONTINUE
      CALL HARMON(XXX,PARAM)
      DO 874 I=1,12
      NDYM=IFIX(DAYS(I))
      DO 875 J=1,NDYM
      CAYD(I,J)=PARAM(I,J)
  875 CONTINUE
  874 CONTINUE
C
C     -----------------------------------------------------------------
C
C     DEFINE AMOUNT OF STORAGES IN A AND B HORIZONS
C
      IF(PEDINF.EQ.1.)GO TO 1701
      IF(PEDDEP-2.)1713,1714,1705
 1713 DEPAHO=0.3
      DEPBHO=0.8
      GO TO 1706
 1714 DEPAHO=0.2
      DEPBHO=0.2
      GO TO 1706
 1705 DEPAHO=0.3
      DEPBHO=0.5
 1706 WP1=WPFCPO(1,ITEXT)
      WP2=WP1
      FC1=WPFCPO(2,ITEXT)
      FC2=FC1
      PO1=WPFCPO(3,ITEXT)
      PO2=PO1
 1701 SMWP1=WP1*DEPAHO*1000.
      SMWP2=WP2*DEPBHO*1000.
      SMFC1=FC1*DEPAHO*1000.
      SMFC2=FC2*DEPBHO*1000.
      SMPO1=PO1*DEPAHO*1000.
      SMPO2=PO2*DEPBHO*1000.
      PAW1=SMFC1-SMWP1
      PAW2=SMFC2-SMWP2
      TPAW=PAW1+PAW2
      SMPAW=SMFC1+SMFC2
      SMWPT=SMWP1+SMWP2
      ALFASO=SWTRRA(ITEXT)
      UPLISO=9.*((ALFASO-3.)**0.42)
C
C     -----------------------------------------------------------------
C
C     INITIALIZATIONS
C
C     CROP YIELD MODELS
      IYEAR=0
      LMN=0
      LM=0
C
C     COUNTERS FOR OBJECTIVE FUNCTION PACKAGE
      NDYTAL = 0
      MNTALY = 1
C
C     STORAGES OF SOIL MOISTURE AND INTERCEPTION
      SOILI=TPAW*0.5+SMWPT
      SOIL1=PAW1*0.5+SMWP1
      SOIL2=PAW2*0.5+SMWP2
      PLINTC=0.0
      RFLC=0.0
      EFPPT=0.0
      DYSIRA=0.0
      SULSU=0.0
      SUECD=0.0
      KCO=0.0
      STCO=0.0
C
C     PE FOR DECEMBER OF PREVIOUS YEAR
      ETDE=150.
C
C     -----------------------------------------------------------------
C
C     WRITE GENERAL HEADING
C
      WRITE(6,105) HEAD
  105 FORMAT(1H1,39X,17A2,/40X,40('=')/)
      WRITE(6,107)AREA,ALAT,ALONG,ELEV,EQTN(EQPET)
  107 FORMAT(5X,'AREA OF CATCHMENT  (KM SQ)',11X,'=',F7.2,/5X,'LATITUDE
     *(S)',25X,'=',F7.2,/5X,'LONGITUDE (E)',24X,'=',F7.2,/5X,'ELEVATION
     *(M)',24X,'=',F7.2,/5X,'POTENTIAL EVAPORATION BY ',A19)
      WRITE(6,111)BFRESP,RESPOF,COFRU,COIA,DEPAHO,DEPBHO,WP1,WP2,FC1,
     *FC2,PO1,PO2,LENGTH
  111 FORMAT(5X,'COEFFICIENT OF DRAINAGE RELEASE',6X,'=',F7.2,/5X,'COEFF
     *ICIENT OF QUICKFLOW RESPONSE',4X,'=',F7.2,/5X,'COEFFICIENT OF BASE
     *FLOW RESPONSE',5X,'=',F7.2,/5X,'COEFFICIENT OF INITIAL ABSTRACTION
     *',3X,'=',F7.2,/5X,'DEPTH OF SOIL IN A-HORIZON (M)',7X,'=',F7.2,/5X
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```
     *,'DEPTH OF SOIL IN B-HORIZON (M)',7X,'=',F7.2,/5X,'WILTING POINT O
     *F A-HORIZON (M/M)',5X,'=',F8.3,/5X,'WILTING POINT OF B-HORIZON (M/
     *M)',5X,'=',F8.3,/5X,'FIELD CAPACITY OF A-HORIZON (M/M)',4X,'=',F8.
     *3,/5X,'FIELD CAPACITY OF B-HORIZON (M/M)',4X,'=',F8.3,/5X,'POROSIT
     *Y OF SOIL IN A-HORIZON (M/M)',2X,'=',F8.3,/5X,'POROSITY OF SOIL IN
     * B-HORIZON (M/M)',2X,'=',F8.3,/5X,'LENGTH OF GROWING SEASON',11X,
     *'=',I5)
      WRITE(6,112)
  112 FORMAT(//,30X,'JAN',3X,'FEB',3X,'MAR',3X,'APR',3X,'MAY',3X,
     *'JUN',3X,'JUL',3X,'AUG',3X,'SEP',3X,'OCT',3X,'NOV',3X,'DEC')
      WRITE(6,113) (CAY(I),I=1,12)
  113 FORMAT(/1X,'CROPPING FACTOR',11X,12(2X,F4.2))
      WRITE(6,114) (ROOTA(I),I=1,12)
  114 FORMAT(1X,'PROP OF ROOTS IN A HORIZON',12(2X,F4.2))
      WRITE(6,188)(VEGINT(I),I=1,12)
  188 FORMAT(1X,'INTERCEPTION LOSS (MM)',4X,12(1X,F5.2))
      IF(PANCOR.EQ.1.)WRITE(6,1104)(CORPAN(I),I=1,12)
 1104 FORMAT(1X,'PAN CORRECTION FACTOR',5X,12F6.2)
      WRITE(6,5200) (TMAX(I),I=1,12)
 5200 FORMAT(1X,'TEMP: MEAN MAXIMUM (C)',4X,12(2X,F4.1))
      WRITE(6,5201) (TMIN(I),I=1,12)
 5201 FORMAT(1X,6X,'MEAN MINIMUM (C)',4X,12(2X,F4.1))
C
C     ------------------------------------------------------------------
C
C     PE ROUTINE USING TEMPERATURE-BASED EQUATIONS
C
      IF(EQPET.LE.3.)CALL PETEMP(T,TI,ANHEI,A,E,FACTOR,THLIN,THITD)
C
C     ------------------------------------------------------------------
C
C     INITIALIZE ANNUAL TOTALS TO ZERO
C
  200 CALL INITAN(SUMRA,SUMERA,SUMPE,SUMPE1,SUMPE2,SUMAE,SUMAE1,SUMAE2,
     *SUMET,SUMINT,SUMSU,SUMIR,SUMRU,SUMQU,SFLOW,SUMST,STAET,STPET,
     *STCAN,TOTAET,TOTPET,TOTCAN)
      LNN=LNN+1
C
C     ------------------------------------------------------------------
C
C     WRITE HEADING FOR MONTHLY PRINTOUT OPTION
C
      IF(WRIMO.EQ.1.)CALL MDGHTR
      IYEAR=IYEAR+1
C
C     ------------------------------------------------------------------
C     CHECK WHETHER MONTHLY A-PAN VALUES TO BE READ IN. THESE ARE READ IN FOR
C     12 MONTHS OF THE YEAR IN JANUARY
      IF(PANMON.EQ.1.AND.I.EQ.1)READ(5,715)KYR,(E(I),I=1,12)
  715 FORMAT(I2,1X,12F4.1)
C
C*****************************************************************************
C
C     START OF MAIN DO LOOP - AT MONTHLY LEVEL WITH DAILY CALCS WITHIN EACH
C     LOOP
C
      DO 2 I=1,12
C
C     ------------------------------------------------------------------
C
C     INITIALIZE DAILY ARRAYS
C
      CALL INITDY(SMD,STORMD,ERFL,ERFLIR,PLINT,STOIR,RAIN,RFL,STRFL,
     *STRMFL,THIND,THAXD,APAN,PAN,DPE,SMOBS1,SMOBS2,SMOBS3,SMSTO1,
     *SMSTO2,SMSTO3,OBSTO1,OBSTO2,IDAY)
C
C     ------------------------------------------------------------------
C
C     READ IN DAILY RAINFALL DATA ONE MONTH AT A TIME
C     WHERE:  IUNIT DISTINGUISHES BETWEEN METRIC MM AND ENGLISH INCHES,
C                   IF IUNIT = 1, UNITS ARE ENGLISH
C                   IF IUNIT = 0, UNITS ARE METRIC
C             ISTID IS THE RAINGAUGE IDENTIFICATION,
C             NDAY  IS THE NUMBER OF DAYS WITH RAIN,
C             IYR   IS THE YEAR,
C             MO    IS THE MONTH.
C
C     CHECK WHETHER DATA TO BE READ FROM CARDS OR FILE
      IF(PPTINF-1.)116,117,118
C
C     READ DATA FROM CARDS
C
  116 READ(5,101)ISTID,IUNIT,IYR,MO,NDAYS,(IDAY(L),RAIN(L),L=1,11)
  101 FORMAT(6A1,I1,3I2,1X,11(I2,F4.1))
C     CHECK FOR END OF RUN - DATA TERMINATES WITH BLANK LINE/CARD
      IF(IYR.EQ.0)GO TO 99
      IF(MO.NE.I)GO TO 228
C     IF THERE ARE MORE THAN 11 RAIN DAYS IN A MONTH, A SECOND/THIRD CARD/LINE
C     IS READ
      IF(NDAYS.GT.11)THEN
      READ(5,101)ISTID,IUNIT,IYR,MO,NDAYS,(IDAY(L),RAIN(L),L=12,22)
      IF(MO.NE.I)GO TO 228
      IF(NDAYS.GT.22)THEN
      READ(5,101)ISTID,IUNIT,IYR,MO,NDAYS,(IDAY(L),RAIN(L),L=23,31)
      IF(MO.NE.I)GO TO 228
      ENDIF
      ENDIF
      GO TO 233
C     MESSAGE TO INDICATE MONTH OUT OF SEQUENCE
  228 WRITE(6,1111)IYR,MO
 1111 FORMAT(1X,'ERROR IN RAINFALL DATA,YEAR 19',I2,' MONTH ',I2)
      STOP
C
C
C     READ DATA FROM FILE 16
C
  117 READ(16,1000,END=99)ISTID,IUNIT,IYR,MO,NDAYS,(IDAY(L),RAIN(L),
     *L=1,13)
 1000 FORMAT(6A1,I1,3I2,13(I2,F5.1))
      IF(NDAYS.GT.13)READ(16,1000)ISTID,IUNIT,IYR,MO,NDAYS,(IDAY(L),
     *RAIN(L),L=14,26)
      IF(NDAYS.GT.26)READ(16,1002)ISTID,IUNIT,IYR,MO,NDAYS,(IDAY(L),
     *RAIN(L),L=27,31)
 1002 FORMAT(6A1,I1,3I2,5(I2,F5.1))
C
  233 IF(IUNIT.EQ.1)THEN
C     CONVERT RAINFALL FROM INCHES TO MM
      DO 236 L=1,NDAYS
  236 RAIN(L)=RAIN(L)*25.4
      ENDIF
```

```
      IF(NDAYS.GT.0)THEN
      DO 238 L=1,NDAYS
      K=IDAY(L)+1
      RFL(K)=RAIN(L)
  238 CONTINUE
      ENDIF
C
C     ------------------------------------------------------------------------
C
C     IF IOBSD = 1, THEN READ IN DAILY RUNOFF DATA ONE MONTH AT A TIME
C     (3 CARDS PER MONTH ARE USED)
C
      IF(IOBSQ.EQ.1)THEN
      NDAE = 0
      READ(5,3601)ICRD,IWEIR,MO,(STRMFL(KDAY),KDAY=1,10)
 3601 FORMAT(1X,I1,6A1,I2,10F7.2)
      IF(ICRD.NE.1)GO TO 38
      READ(5,3602)ICRD,(STRMFL(KDAY),KDAY=11,21)
 3602 FORMAT(1X,I1,1X,11F7.2)
      IF(ICRD.NE.2)GO TO 38
      READ(5,3604)ICRD,(STRMFL(KDAY),KDAY=22,(IFIX(DAYS(MO))))
 3604 FORMAT(1X,I1,1X,10F7.2)
      IF(ICRD.NE.3)GO TO 38
C
C     CONVERT STREAMFLOW TO MM/DAY
      NDAE = IFIX(DAYS(MO))
      DO 37 ICON=1,NDAE
      IF(IOBSUN.LE.1)THEN
      STRMFL(ICON)=STRMFL(ICON)/(AREA*1000.)
      ELSE
      STRMFL(ICON)=STRMFL(ICON)*60.*60.*24./(AREA*1000.)
      ENDIF
   37 CONTINUE
      ENDIF
      GO TO 36
   38 WRITE(6,3603)
 3603 FORMAT(1X,'ERROR IN RUNOFF DATA')
      STOP
   36 CONTINUE
C
C     ------------------------------------------------------------------------
C
C     CHECK WHETHER DAILY A-PAN VALUES TO BE READ IN
C
      IF(PANDAY.EQ.1)THEN
      IF(EOPET.NE.4)THEN
      READ(5,1704)
 1704 FORMAT(/)
      ELSE
      E(I)=0.0
      NDYM=IFIX(DAYS(MO))
      READ(5,6003)KYR,MO,(APAN(I,L),L=2,20)
 6003 FORMAT(2I2,19F4.1)
C     TWO CARDS/LINES OF A-PAN VALUES REQUIRED FOR 31 DAYS CHECK WHETHER
C     BOTH CARDS/LINES ARE GIVEN
      IF(KYR.NE.IYR.OR.I.NE.MO)GO TO 2281
      READ(5,6004)KYR,MO,(APAN(I,L),L=21,32)
 6004 FORMAT(2I2,12F4.1)
      IF(KYR.NE.IYR.OR.I.NE.MO)GO TO 2281
C     DAILY VALUES OF A-PAN EVAP ARE SUMMED TO GIVE A MONTHLY VALUE
      DO 708 K=2,(NDYM+1)
  708 E(I)=E(I)+APAN(I,K)
      ENDIF
      ENDIF
      GO TO 2283
 2281 WRITE(6,2282)KYR,MO
 2282 FORMAT(1X,'ERROR IN PAN EVAP DATA,YEAR 19',I2,'  MONTH ',I2)
 2283 CONTINUE
C
C     ------------------------------------------------------------------------
C
C     READ IN DAILY SOIL-MOISTURE VALUES IF OPTION FOR OBSERVED
C     SOIL-MOISTURE INPUT IS 1
C
      IF(MOIST.NE.1)GO TO 3000
      KSM=1
      JSM=5
 3002 READ(5,3003)NSMDYS,LUSE,KSMYR,KSMMN,(KSMDAY(L1),SM10(L1),
     *SM30(L1),SM60(L1),L1=KSM,JSM)
 3003 FORMAT(I2,A4,2I2,5(I2,3F4.1))
C     CHECK FOR ERRORS IN SEQUENCE OF DATA
      IF(KSMYR.NE.IYR.OR.KSMMN.NE.MO)WRITE(6,3008)
 3008 FORMAT(1X,'ERROR IN SEQUENCE OF OBSERVED MOISTURE DATA')
      KSM=KSM+5
      JSM=JSM+5
C     CHECK FOR FURTHER CARDS OF SOIL MOISTURE DATA
      IF((JSM-5).LT.NSMDYS)GO TO 3002
C     CALCULATE THE AVERAGE SOIL MOISTURE IN EACH STORAGE LAYER
      DO 3000 I1=1,NSMDYS
      K1=KSMDAY(I1)+1
      SMST10(K1)=SM10(I1)
      SMST30(K1)=SM30(I1)
      SMST60(K1)=SM60(I1)
      OBSTO1(K1)=(SMST10(K1)+SMST30(K1))/2
      OBSTO2(K1)=(SMST30(K1)+SMST60(K1))/2
 3000 CONTINUE
      IF(PPTINF.NE.2)GO TO 1119
C
C     ************************************************************************
C     DATA READ FROM FILE 21.
C     ************************************************************************
C
 1119 IF(EOPET.EQ.4.)E(I)=0.0
      DO 3001 L=1,31
      READ(21,1120,END=99)ISTID,IYR,MO,IDAY(L),RAIN(L),TMAXD(L),
     *TMIND(L),PAN(L),STRFL(L),SMOBS1(L),SMOBS2(L),SMOBS3(L)
 1120 FORMAT(A8,3I2,4(F5.1,1X),F7.3,1X,3(F5.1,1X))
      K=IDAY(L)+1
      RFL(K)=RAIN(L)
      STRMFL(K)=STRFL(L)
      APAN(I,K)=PAN(L)
      E(I)=E(I)+APAN(I,K)
      SMSTO1(K)=SMOBS1(L)
      SMSTO2(K)=SMOBS2(L)
      SMSTO3(K)=SMOBS3(L)
      OBSTO1(K)=(SMSTO1(K)+SMSTO2(K))/2.
      OBSTO2(K)=(SMSTO2(K)+SMSTO3(K))/2.
      DAYS(2)=28.
      IF(MOD(IYR,4).EQ.0)DAYS(2)=29.
      IF(IFIX(DAYS(MO)).EQ.IDAY(L))GO TO 1121
```

```
 3081 CONTINUE
 1121 NDYM=IFIX(DAYS(MO))
C
C     ------------------------------------------------------------------------
C
C     IF ONLY MONTHLY PE IS GIVEN (DERIVED FROM TEMPERATURES),
C     THIS PE IS FIRST SMOOTHED BY A WEIGHTED INTERPOLATION TO 5-DAY
C     (PENTAD) VALUES WHICH ARE THEN CONVERTED TO DAILY PE VALUES
C
 1119 IF(EQPET.EQ.4)GO TO 707
C     SETTING OF VALUES FOR JANUARY
      IF(I.EQ.1)THEN
      ELM=ETDE
      ENM=E(I+1)
      ELSE
C     SETTING VALUES FOR DECEMBER
      IF(I.EQ.12)THEN
      ENM=E(1)
      ELM=E(I-1)
      ELSE
      ENM=E(I+1)
      ELM=E(I-1)
      ENDIF
      ENDIF
C     ESTABLISH PENTAD VALUES. PP=E FOR PENTAD
      IF(E(I).GE.ELM)THEN
      PP(1)=(ELM+(E(I)-ELM)*7./12.)/6.
      PP(2)=(ELM+(E(I)-ELM)*9./12.)/6.
      PP(3)=(ELM+(E(I)-ELM)*11./12.)/6.
      ELSE
      PP(1)=(E(I)+5./12.*(ELM-E(I)))/6.
      PP(2)=(E(I)+3./12.*(ELM-E(I)))/6.
      PP(3)=(E(I)+1./12.*(ELM-E(I)))/6.
      ENDIF
      IF(E(I).LE.ENM)THEN
      PP(4)=(E(I)+(ENM-E(I))*1./12.)/6.
      PP(5)=(E(I)+(ENM-E(I))*3./12.)/6.
      PP(6)=(E(I)+(ENM-E(I))*5./12.)/6.
      ELSE
      PP(4)=(ENM+(E(I)-ENM)*11./12.)/6.
      PP(5)=(ENM+(E(I)-ENM)*9./12.)/6.
      PP(6)=(ENM+(E(I)-ENM)*7./12.)/6.
      ENDIF
C     WEIGHT PENTAD PE TO TALLY WITH MONTHLY VALUES
      FRPP=0.0
      DO 321 J=1,6
  321 FRPP=FRPP+PP(J)
      FRPP=FRPP/E(I)
      DO 322 J=1,6
  322 PP(J)=PP(J)/FRPP
C     CONVERT PENTAD VALUES OF PE TO DAILY VALUES, BECAUSE PREVIOUS
C     DAYS VALUES HAVE TO BE KNOWN DAY NUMBERS RANGE FROM 2 TO 32
C     INSTEAD OF 1 TO 31
      NOST=2
      NOEN=6
      DO 333 J=1,5
      DO 332 K=NOST,NOEN
  332 DPE(K)=PP(J)/5.
      NOST=NOST+5
      NOEN=NOEN+5

  333 CONTINUE
      GO TO(334,335,334,336,334,336,334,334,336,334,336,3341,MO
  334 NDYM=31
      NDYP=6
      GO TO 337
  335 NDYM=28
      NDYP=3
      GO TO 337
  336 NDYM=30
      NDYP=5
  337 CONTINUE
      DO 338 K=27,(NDYM+1)
  338 DPE(K)=PP(6)/NDYP
      DO 717 K=1,(NDYM+1)
      APAN(I,K)=DPE(K)
      DPE(K)=DPE(K)*CAY(I)
  717 CONTINUE
  707 CONTINUE
C
C     ------------------------------------------------------------------------
C
C     SET STORAGES FROM PREVIOUS DAYS' READINGS
C
      CALL PREVDY(STO1,STO2,PLINT,RFL,ERFL,DEF1,DEF2,RUNCO,STRMCO,STOIR)
C
C     ------------------------------------------------------------------------
C
C     INITIALIZE TOTALS OF SURPLUS, AET, IRRIG. REQ., RUNOFF FOR THE
C     MONTH TO ZERO
C
      CALL INITMO(TSUP,TE1,TE2,TDPE,TAET,TAET1,TAET2,TET,TPOIR,TRUN,
     *TERAIN,TRAIN,TSTORM,TQUICK,TDISCH,TSTREM,TPLINT,TAETIK,TSTOIK,
     *TIRRFL,TSURIP,TREDIP,TAPAN,NOIRAP,TPOBEV,TASOEV,TPOTR1,TPOTR2,
     *TTRAN1,TTRAN2,TPTRAN,TTRANS)
C
C     ------------------------------------------------------------------------
C
C     CALCULATION OF DAILY WATER BALANCE; NDYM=NO DAYS IN MONTH
C
      DO 60 K=2,(NDYM+1)
C
C     CHECK WHETHER DAILY PE AND RAINFALL HAVE TO BE CORRECTED FOR A
C     SYSTEMATIC ERROR
C
      IF(PANCOR.EQ.1)APAN(I,K)=APAN(I,K)*CORPAN(I)
      IF(PPTCOR.EQ.1)RFL(K)=RFL(K)*PPTCOR
C     CONVERT PAN EVAPORATION TO CROP POTENTIAL EVAPOTRANSPIRATION
C
      DPE(K)=APAN(I,K)*CAYD(I,K-1)
C     CALCULATION OF CONST, THE FRACTION OF P.A.M. AT WHICH STRESS SETS IN
C     IF CRITICAL LEAF WATER POTENTIAL IS NOT USED,A FIXED VALUE OF
C     'CONST' IS USED
C     IF CRITICAL LEAF WATER POTENTIAL OF CROP USED IN CALCULATION,
C     'CONST' IS A VARIABLE FOR THE DAY AND IT IS CALCULATED HERE
C
      IF(CRLEPO.NE.0.)CONST=0.94+0.26*CRLEPO/(APAN(I,K))
      IF(CONST.LT.0.1)CONST=0.1
C     APPORTION POTENTIAL EVAPOTRANSPIRATION TO A AND B HORIZONS
C     BEFORE THIS IS DONE, THE INTERCEPTED WATER OF THE PREVIOUS DAY
C     FIRST HAS TO BE EVAPORATED AT POTENTIAL RATE - FROM THE INTERCEPTION
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```
C       STORAGE, WHICH IS 0.5 INTERCEPTION LOSS
C
        IF(PFL(K-1).GT.0.)THEN
        DPE(K)=(APAN(I,K)-0.5*PLINT(K-1))*CAYD(I,K-1)
        IF(DPE(K).LT.0.02)DPE(K)=0.02
        PLINT(K)=0.5*PLINT(K-1)-APAN(I,K)
        ENDIF
        PP1(K)=DPE(K)*ROOTA(I)
        PP2(K)=DPE(K)*ROOTB(I)
C
C       ------------------------------------------------------------------------
C
C       CALCULATE ACTUAL EVAPOTRANSPIRATION (AET)
C       AET CAN EQUAL PE,BUT IS LESS IF AVAILABLE SOIL MOISTURE IS
C       LESS THAN FRACTION,I.E.IF STRESS HAS SET IN
C
C       CHECK WHETHER EVAPORATION AND TRANSPIRATION TO BE ESTIMATED SEPARATELY
C       (EVTR = 2) OR TOGETHER (EVTR = 1)
C
        IF(EVTR.EQ.1.)THEN
C       CALCULATE AET AS ONE VALUE
C
C       CALCULATION OF AET FOR A HORIZON
C
        IF(STO1(K-1).GE.(PAW1*CONST+SMWP1))THEN
C       NO STRESS SITUATION , THEREFORE AE=PE FOR DAY
        AET1(K)=PP1(K)
        ELSE
C       STRESS SITUATION, THEREFORE AE<PE
        AET1(K)=PP1(K)*(STO1(K-1)-SMWP1)/(PAW1*CONST)
        ENDIF
        STO1(K)=STO1(K-1)-AET1(K)
C
C       CALCULATION OF AET FOR B HORIZON
C
        IF(STO2(K-1).GE.(PAW2*CONST+SMWP2))THEN
        AET2(K)=PP2(K)
        ELSE
        AET2(K)=PP2(K)*(STO2(K-1)-SMWP2)/(PAW2*CONST)
        ENDIF
        AET(K)=AET1(K)+AET2(K)
        STO2(K)=STO2(K-1)-AET2(K)
C
C        CHECK FOR OVERALL STRESS
        IF(AET(K).GE.(0.5*DPE(K)))THEN
        PLSTRS(K)=0.0
        ELSE
        PLSTRS(K)=1.0
        ENDIF
        ENDIF
C
        IF(EVTR.EQ.2.)THEN
C
C       CALCULATE TRANSPIRATION AND SOIL EVAPORATION SEPARATELY BY THE RITCHIE
C       (1972) APPROACH
C
C       FIRST CALCULATE LEAF AREA INDEX FOR THE DAY FROM CROPPING FACTOR
C       (WITH 0.3 < CAYD < 1.06)
        IF(CAYD(I,K-1).LT.0.3)CAYD(I,K-1)=0.3
        IF(CAYD(I,K-1).GT.1.06)CAYD(I,K-1)=1.06
        EXX(K)=1.-(CAYD(I,K-1)-0.3)*(1./0.75)
        ELAID(K)=1.32+1.29*SIN(30*EXX(K)+137.3)-0.78*SIN(60*EXX(K)+133.6)
C       CALCULATE POTENTIAL SOIL EVAPORATION
        POSOEV(K)=APAN(I,K)*EXP(ELAID(K)*(-0.4))
        IF(POSOEV(K).GT.APAN(I,K))POSOEV(K)=APAN(I,K)
C       CALCULATE ACTUAL SOIL EVAPORATION BY THE RITCHIE ROUTINE
        IF(SUESU.LT.UPLISO)THEN
          IF(ERFL(K-1).GE.SUESU)THEN
          SUESU=0.0
          ELSE
          SUESU=SUESU-ERFL(K-1)
          ENDIF
        ELSE
          IF(ERFL(K-1).GE.SUESD)THEN
          ESRFL(K-1)=ERFL(K-1)-SUESD
          SUESU=UPLISO-ESRFL(K-1)
          IF(ESRFL(K-1).GT.UPLISO)SUESU=0.0
          ELSE
          GO TO 8003
          ENDIF
        ENDIF
        SUESU=SUESU+POSOEV(K)
        IF(SUESU.GT.UPLISO)THEN
          ASOEV(K)=POSOEV(K)-0.4*(SUESU-UPLISO)
          SUESD=0.6*(SUESU-UPLISO)
          DYSIRA=(SUESD/ALFASO)**2
        ELSE
          ASOEV(K)=POSOEV(K)
        ENDIF
        GO TO 9001
  8003  DYSIRA=DYSIRA+1
        ASOEV(K)=ALFASO*SQRT(DYSIRA)-ALFASO*SQRT(DYSIRA-1)
        IF(ERFL(K-1).GT.0.0)THEN
          ASOEVD(K)=0.8*ERFL(K-1)
          IF(ASOEVD(K).LE.ASOEV(K))ASOEVD(K)=ASOEV(K)*ERFL(K-1)
          IF(ASOEVD(K).GT.POSOEV(K))ASOEVD(K)=ASOEV(K)
          ASOEV(K)=ASOEVD(K)
        ELSE
          IF(ASOEV(K).GT.POSOEV(K))ASOEV(K)=POSOEV(K)
        ENDIF
        SUESD=SUESD+ASOEV(K)-ERFL(K-1)
        DYSIRA=(SUESD/ALFASO)**2
C       CALCULATE TOTAL POTENTIAL TRANSPIRATION
  9001  POTRAN(K)=APAN(I,K)-POSOEV(K)
C       APPORTION TOTAL POTENTIAL TRANSPIRATION TO A- AND B-HORIZONS
        POTR1(K)=POTRAN(K)*ROOTA(I)
        POTR2(K)=POTRAN(K)*ROOTB(I)
C       CALCULATE AET (ASOEV + ATRANS) FOR A-HORIZON
C
C       CHECK FOR WATER STRESS IN A-HORIZON
        IF(STO1(K-1).GE.(PAW1*CONST+SMWP1))THEN
C       NO STRESS, THEREFORE ACTUAL = POTENTIAL TRANSPIRATION
        ATRAN1(K)=POTR1(K)
        ELSE
C       STRESS SITUATION, THEREFORE ACTUAL < POTENTIAL TRANSPIRATION
        ATRAN1(K)=POTR1(K)*(STO1(K-1)-SMWP1)/(PAW1*CONST)
        ENDIF
        AET1(K)=ATRAN1(K)+ASOEV(K)
        STO1(K)=STO1(K-1)-AET1(K)
C       CALCULATE AET FOR B-HORIZON
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```
      IF(STO2(K-1).GT.(PAW2*CONST+SMWP2))THEN
      ATRAN2(K)=POTR2(K)
      ELSE
      ATRAN2(K)=POTR2(K)*(STO2(K-1)-SMWP2)/(PAW2*CONST)
      ENDIF
      AET2(K)=ATRAN2(K)
      STO2(K)=STO2(K-1)-AET2(K)
      AET(K)=AET1(K)+AET2(K)
      ATRANS(K)=ATRAN1(K)+ATRAN2(K)
C     CHECK FOR STRESS
      IF(ATRANS(K).GE.(0.5*POTRAN(K)))THEN
      PLSTRS(K)=0.0
      ELSE
      PLSTRS(K)=1.0
      ENDIF
      ENDIF
C
C     CALCULATIONS OF AET FOR IRRIGATION REQUIREMENTS
C
      IF(WKIRR.EQ.1.)THEN
      IF(STOIR(K-1).GE.(TPAW*CONST+SMWPT))THEN
      AETIR(K)=DPE(K)
      ELSE
      AETIR(K)=DPE(K)*(STOIR(K-1)-SMWPT)/(TPAW*CONST)
      ENDIF
      ENDIF
      STOIR(K)=STOIR(K-1)-AETIR(K)
C
C     ---------------------------------------------------------------------------
C
C     CALCULATE SOIL STORAGE, FIRST FOR DRY LAND THEN FOR IRRIGATION
C     CONDITIONS. START WITH TOP SOIL LAYER.
      IF(RFL(K).GT.0.)GO TO 359
      ERFL(K)=0.0
      PLINT(K)=0.0
      STORMQ(K)=0.0
C
C     ABSTRACT INTERFLOW FROM PREVIOUS DAY
      QUICKF(K)=STRMCO(K-1)*RESPQF
      STRMCO(K)=STRMCO(K-1)-QUICKF(K)
      ERFLIR(K)=0.0
      STOIR(K)=0.0
      GO TO 1741
  359 CONTINUE
C
C     FOR NON-IRRIGATED CONDITIONS, FIRST ABSTRACT STORMFLOW BY SCS-SMB
C     MODEL IF RAINFALL IS GREATER THAN OR EQUAL TO 1 MM FOR THE DAY.
C     THIS ABSTRACTION INCLUDES INTERCEPTION.
      IF(RFL(K).LE.1.)GO TO 251
C     DETERMINE WHETHER ONLY A- OR BOTH HORIZONS ARE TO BE USED IN
C     CALCULATING DEFICITS
      IF(SMDDEP.LE.1.)THEN
      SMD(K)=SMPO1-STO1(K)
      ELSE
      SMD(K)=(SMPO1-STO1(K))+(SMPO2-STO2(K))
      ENDIF
      IF(SMD(K).LT.0.)SMD(K)=0.01
C     CHECK THAT NET RAINFALL > INITIAL ABSTRACTION
      IF(PLINT(K).GT.0.)THEN
      RFLNET(K)=RFL(K)-(VEGINT(I)-PLINT(K))

      ELSE
      RFLNET(K)=RFL(K)-VEGINT(I)
      ENDIF
      IF(RFLNET(K).LE.COIA*SMD(K))GO TO 251
      STORMQ(K)=(RFLNET(K)-COIA*SMD(K))**2/(RFLNET(K)-COIA*SMD(K)
     *+SMD(K))
      ERFL(K)=RFLNET(K)-STORMQ(K)
      QUICKF(K)=RESPQF*(STORMQ(K)+STRMCO(K-1))
      STRMCO(K)=(1.-RESPQF)*(STORMQ(K)+STRMCO(K-1))
      PLINT(K)=VEGINT(I)
      GO TO 741
C
C     ABSTRACT INTERCEPTED RAINFALL TO OBTAIN DAILY EFFECTIVE RAINFALL
C     AND INTERCEPTION LOSS
C
  251 CONTINUE
      STORMQ(K)=0.1
      QUICKF(K)=STRMCO(K-1)*RESPQF
      STRMCO(K)=STRMCO(K-1)-QUICKF(K)
      IF(RFL(K).GE.VEGINT(I))THEN
      ERFL(K)=RFL(K)-VEGINT(I)
      PLINT(K)=VEGINT(I)
      ELSE
      ERFL(K)=0.0
      PLINT(K)=RFL(K)
      ENDIF
  741 CONTINUE
C
C     FOR IRRIGATED CONDITIONS ALSO ABSTRACT STORMFLOW BY SCS-SMB
C     MODEL AS ABOVE FOR ANY AMOUNT OF RAINFALL AND THEN CALCULATE SOIL
C     STORAGE FOR IRRIGATION ROUTINE
      IF(WKIRR.EQ.0.)GO TO 254
      SMDIR(K)=SMPAW-STOIR(K-1)
C
C     CHECK THAT RAINFALL > INITIAL ABSTRACTION
      IF(RFL(K).GT.COIA*SMDIR(K))THEN
      STOIR(K)=(RFL(K)-COIA*SMDIR(K))**2/(RFL(K)-COIA*SMDIR(K)+
     *SMDIR(K))
      ERFLIR(K)=RFL(K)-STOIR(K)
      ELSE
      IF(RFL(K).EQ.0.)THEN
      ERFLIR(K)=0.0
      ELSE
      IF(RFL(K).GE.VEGINT(I))THEN
      ERFLIR(K)=RFL(K)-VEGINT(I)
      ELSE
      ERFLIR(K)=0.1
      ENDIF
      ENDIF
      ENDIF
 1741 CONTINUE
      STOIR(K)=STOIR(K)+ERFLIR(K)
      STOIRO(K)=STOIR(K)
C
C     IRRIGATION SOIL STORAGE ROUTINE ENDS
C
C
C     CONTINUE WITH SOIL STORAGE CALCULATIONS
  254 STO1(K)=STO1(K)-ERFL(K)
C
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C       CHECK STATE OF SOIL STORAGES
        IF(STO1(K).LE.SMWP1)THEN
C       STORAGE IS NOW BELOW WILTING POINT
C       IF STORAGE IS BELOW WILTING POINT, IT IS SET TO SOIL MOISTURE
C       STORAGE AT WILTING POINT
        SUR1(K)=0.0
        DEF1(K)=PAW1
        STO1(K)=SMWP1
        ELSE
C       IF STORAGE IS NOW POSITIVE,CONTINUE CALCULATION OF SOIL MOISTURE
        IF(STO1(K).GT.SMFC1)THEN
C       STORAGE IS NOW IN EXCESS OF PLANT AVAILABLE MOISTURE
        SUR1(K)=STO1(K)-SMFC1
C       A FRACTION OF THIS SURPLUS WATER NOW REMAINS IN SURFACE. THE
C       REMAINDER DRAINS TO NEXT HORIZON
        DEF1(K)=0.0
        STO1(K)=SMFC1+(1.-0.5)*SUR1(K)
        SUR1(K)=0.5*SUR1(K)
        ELSE
C       STORAGE IS NOW BETWEEN CAPACITY AND WILTING POINT
        STO1(K)=STO1(K)
        SUR1(K)=0.0
        DEF1(K)=SMFC1-STO1(K)
        ENDIF
        ENDIF
C
C       CALCULATE SOIL MOISTURE BALANCE FOR LOWER SOIL LAYER
C
        STO2(K)=STO2(K)+SUR1(K)
        IF(STO2(K).LE.SMWP2)THEN
        SUR2(K)=0.0
        DEF2(K)=PAW2
        STO2(K)=SMWP2
        RUN(K)=RUNCO(K-1)*COFRU
        RUNCO(K)=RUNCO(K-1)-RUN(K)
        ELSE
C       CHECK WHETHER STORAGE IN LAYER 2 EXCEEDS PAW OF LAYER 2,IF SO,
C       SATURATED DEEP PERCOLATION OCCURS
        IF(STO2(K).GT.SMFC2)THEN
        SUR2(K)=STO2(K)-SMFC2
C       AGAIN A FRACTION OF SURPLUS WATER PERCOLATES OUT AND FRACTION
C       REMAINS
        RUNCO(K)=RUNCO(K-1)+BFRESP*SUR2(K)
        RUN(K)=RUNCO(K)*COFRU
        RUNCO(K)=RUNCO(K)-RUN(K)
        DEF2(K)=0.0
        STO2(K)=SMFC2+(1.-BFRESP)*SUR2(K)
        SUR2(K)=SUR2(K)-BFRESP*SUR2(K)
        ELSE
C       STORAGE IN LAYER 2 NOW BETWEEN CAPACITY AND ZERO
        STO2(K)=STO2(K)
        SUR2(K)=0.0
        RUN(K)=RUNCO(K-1)*COFRU
        RUNCO(K)=RUNCO(K-1)-RUN(K)
        DEF2(K)=SMFC2-STO2(K)
        ENDIF
        ENDIF
C
C       SOIL MOISTURE VALUES ARE NOW SET BEFORE UNSATURATED REDISTRIBUTION
C       CAN TAKE PLACE
        STO1BR(K)=STO1(K)
        STO2BR(K)=STO2(K)
        DEF1BR(K)=DEF1(K)
        DEF2BR(K)=DEF2(K)
C
C       UNSATURATED SOIL MOISTURE REDISTRIBUTION
C       SOIL MOISTURE REDISTRIBUTION IS A FUNCTION OF SOIL MOISTURE
C       GRADIENT.  GRADIENT IS EXPRESSED AS A PROPORTION OF SOIL
C       MOISTURE CONTENT TO PLANT AVAILABLE WATER.
C       FRSMA=FRACTION OF SOIL MOISTURE IN A HORIZON
C
        FRSMA=STO1(K)/SMFC1
        FRSMB=STO2(K)/SMFC2
        FRSMC=((SMFC2-SMWP2)/2.+SMWP2)/SMFC2
C       DOWNWARD UNSATURATED REDISTRIBUTION - ONLY IF ALL HORIZONS ARE BELOW
C       FIELD CAPACITY
        IF(SMFC1.GT.STO1(K).AND.SMFC2.GT.STO2(K))THEN
C       CHECK WHETHER  A HORIZON IS MORE MOIST THAN B HORIZON
        IF(FRSMA.GE.FRSMB)THEN
C       REDISTRIBUTION FACTOR A TO B IS A 2% PER DAY (REFAB)
        REFAB=0.02
        REDAB(K)=STO1(K)*REFAB*(FRSMA-FRSMB)
C       RESET SOIL MOISTURE FOR A AND B HORIZONS
        STO1(K)=STO1(K)-REDAB(K)
        STO2(K)=STO2(K)+REDAB(K)
        REDBA(K)=0.0
        DEF1(K)=SMFC1-STO1(K)
        DEF2(K)=SMFC2-STO2(K)
        ELSE
C       UPWARD REDISTRIBUTION IF B HORIZON MORE MOIST THAN A HORIZON
        REFBA=0.01
        REDBA(K)=REFBA*STO2(K)*(FRSMB-FRSMA)
        STO1(K)=STO1(K)+REDBA(K)
        STO2(K)=STO2(K)-REDBA(K)
        REDAB(K)=0.0
        DEF1(K)=SMFC1-STO1(K)
        DEF2(K)=SMFC2-STO2(K)
        ENDIF
        ENDIF
C       IF B HORIZON IS MOISTER THAN 50% PAW, UNSATURATED PERCOLATION TAKES
C       PLACE OUT OF 'B' INTO GROUNDWATER ZONE
        PERCFC=0.02
        IF(FRSMB.GT.FRSMC)THEN
        PERC(K)=STO2(K)*PERCFC*(FRSMB-FRSMC)
        STO2(K)=STO2(K)-PERC(K)
        DEF2(K)=SMFC2-STO2(K)
C       ADJUST RUNOFF = SATURATED + UNSATURATED RUNOFF
        RUN(K)=RUN(K)+PERC(K)
        ELSE
        PERC(K)=0.0
        ENDIF
C       CONVERT PAW TO WATER CONTENT EXPRESSED AS VOL WATER/VOL SOIL
        AWC1(K)=STO1(K)
        AWC2(K)=STO2(K)
C
C       CALCULATE FRACTION OF SOIL MOISTURE TO POROSITY
C
        PORFR(K)=STO1(K)/SMPO1
C
C       ---------------------------------------------------------------------
```

```
C
C       CALCULATE RUNOFF FOR DAY
        SIMSO(K)=QUICKF(K)+RUN(K)
C
C       ------------------------------------------------------------------------
C
C       IRRIGATION REQUIREMENTS ARE NOW CALCULATED
C       CHECK STATE OF SOIL STORAGES
C
        IF(WRIPR.EQ.0.)GO TO 411
        IF(STOIR(K).LE.SMWPT)THEN
C
C       IF BELOW WILTING POINT IRRIGATE
        REQIR(K)=TPAW/EFFIRR
        STOIR(K)=STOIR(K)+REQIR(K)
        SURIR(K)=0.0
        ENDIF
        GO TO 512
C
C       CHECK WHETHER SOIL STORAGE IS ABOVE FIELD CAPACITY
        IF(STOIR(K).GT.SMPAW)THEN
        SURIR(K)=0.5*(STOIR(K)-SMPAW)
        REQIR(K)=0.0
        STOIR(K)=SMPAW+0.5*SURIR(K)
        ELSE
C
C       STORAGE IS NOW BETWEEN WILTING POINT AND FIELD CAPACITY
        SURIR(K)=0.0
        STOIR(K)=STOIR(K)
        IF(STOIR(K).GT.(TPAW*CONSTI+SMWPT))THEN
C       STORAGE IS NOW ABOVE STRESS THRESHOLD, THEREFORE NO IRRIGATION
C       IS REQUIRED
        REQIR(K)=0.0
        ELSE
C       STORAGE IS NOW BETWEEN FIELD CAPACITY AND WILTING POINT,
C       THEREFORE IRRIGATION IS REQUIRED
C       CHECK WHAT TYPE OF IRRIGATION SCHEDULING IS TO BE USED
        IF(SCHED-2)5101,5100,5102
C       SCHEDULE IS A PLANNED DEFICIT TO E.G. 0.8 FIELD CAPACITY
 5101   REQIR(K)=(TPAW*PLADEF+SMWPT-STOIR(K))/EFFIRR
        STOIR(K)=TPAW*PLADEF+SMWPT
        GO TO 512
C       SCHEDULE IS TO IRRIGATE TO FIELD CAPACITY
 5100   REQIR(K)=(TPAW+SMWPT-STOIR(K))/EFFIRR
        STOIR(K)=TPAW+SMWPT
        GO TO 512
C       SCHEDULE IS TO IRRIGATE A FIXED AMOUNT (E.G. 25MM), AMTIR
 5102   REQIR(K)=AMTIR
        STOIR(K)=STOIR(K)+AMTIR*EFFIRR
        ENDIF
        ENDIF
  512   CONTINUE
        NOIRAP(I)=NOIRAP(I)+1
  411   CONTINUE
C
C       DAILY FLOW VALUES ARE STORED IN ARRAYS FOR LATER USE
C       IN STATISTICAL PACKAGE
        IF((ICOMPR.EQ.1).OR.(ICOMPR.EQ.3))THEN
        NDYTAL = NDYTAL+1
        OBSQY(NDYTAL) = STRMFL(K)
        SIMQY(NDYTAL) = SIMSO(K)
        END IF
C       MONTHLY VALUES OF THE WATER BALANCE ARE NOW TOTALLED PER DAY
C
        CONSTA(K)=CONST
        TRAIN(I)=TRAIN(I)+RFL(K)
        TERAIN(I)=TERAIN(I)+ERFL(K)
        TE1(I)=TE1(I)+PP1(K)
        TE2(I)=TE2(I)+PP2(K)
        TDPE(I)=TDPE(I)+DPE(K)
        TAPAN(I)=TAPAN(I)+APAN(I,K)
        TSUR(I)=TSUR(I)+SUR2(K)
        TRUN(I)=TRUN(I)+RUN(K)
        TSTORM(I)=TSTORM(I)+STORMQ(K)
        TQUICK(I)=TQUICK(I)+QUICKF(K)
        TAET2(I)=TAET2(I)+AET2(K)
        TAET1(I)=TAET1(I)+AET1(K)
        TAET(I)=TAET(I)+AET(K)
        TET(I)=TET(I)+ATRANS(K)
        TPOSEV(I)=TPOSEV(I)+POSOEV(K)
        TASOEV(I)=TASOEV(I)+ASOEV(K)
        TPOTR1(I)=TPOTR1(I)+POTR1(K)
        TPOTR2(I)=TPOTR2(I)+POTR2(K)
        TTRAN1(I)=TTRAN1(I)+ATRAN1(K)
        TTRAN2(I)=TTRAN2(I)+ATRAN2(K)
        TPTRAN(I)=TPTRAN(I)+POTRAN(K)
        TTRANS(I)=TTRANS(I)+ATRANS(K)
        TREQIR(I)=TREQIR(I)+REQIR(K)
        TSTREM(I)=TSTREM(I)+STRMFL(K)
        TDISCH(I)=TRUN(I)+TQUICK(I)
        TPLINT(I)=TPLINT(I)+PLINT(K)
        TAETIR(I)=TAETIR(I)+AETIR(K)
        TSTOIR(I)=TSTOIR(I)+STOIR(K)
        TIRRFL(I)=TIRRFL(I)+ERFLIR(K)
        TSURIR(I)=TSURIR(I)+SURIR(K)
        TREQIR(I)=TREQIR(I)+REQIR(K)
C       DNO = PENTAD NUMBERS, 1 - 6
        DNO(K)=K-1
C
C       ------------------------------------------------------------------------
C
C       CROP YIELD ROUTINES
C
        IF(WRTYLD.EQ.0.)GO TO 60
C
        IF(CROP.EQ.1.)CALL MZPREP(RRAIN,TRRAIN,LSTART,LDAY,IRIMO,ISTDAY,
       *NSTRES,MSDAYS,TOTAET,TOTPET,LGROW,STAET,STPET,ATRANS,RFL)
C
        IF(CROP.EQ.2.)CALL CNPREP(I,K,STCAN,TOTCAN,AET1,AET2,PLINT)
C
C       ------------------------------------------------------------------------
C
   60   CONTINUE
C
C       THIS IS END OF DAILY MOISTURE BUDGET LOOP
C
C       ------------------------------------------------------------------------
C
C        MONTHLY FLOW VALUES ARE STORED IN ARRAYS FOR LATER USE IN THE
C        STATISTICAL PACKAGE.
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C
      IF((ICOMPR.EQ.2).OR.(ICOMPR.EQ.3).OR.(IPLMNO.EQ.1))THEN
      MNTALY = MNTALY+1
      OBSOMX(MNTALY) = TSTREM(I)
      SIMOMY(MNTALY) = TDISCH(I)
      MNPLV(MNTALY)=(IYR*100)+I
      END IF
C
C     ------------------------------------------------------------------
C
C     OPTION FOR PRINTING DAILY MOISTURE BUDGET WITH MONTHLY SUB-TOTALS
C
      IF(WRIDY.EQ.1.)CALL PRTDLY
C
C     ------------------------------------------------------------------
C
C     OPTION FOR OUTPUT OF DAILY GRAPHICAL PLOT
C
C
C.....PLOTTING SECTION.....
C.....FOR USING STAT-PACK OF UNIV-NATAL TO PRESENT
CC....PLOT OF SIMULATED AND OBSERVED DAILY STREAMFLOWS
CC....IPLOT MUST = 1    IF NOT NEEDED IPLOT MUST = 0
      IF(IPLOT.NE.1)GO TO 9643
      WRITE(6,7010)HEAD
      IND=0
      IS=0
      WRITE(6,9201)I,IYR
 9201 FORMAT(1X,34X,' HYDROGRAPH OF OBSERVED(M) AND SIMULATED(S) DAILY
     *FLOWS',//,50X,'MONTH = ',I2,'   YEAR = ',I2,//,50X,'S = SIMULATED F
     *LOW IN MM',//,50X,'M = MEASURED FLOW IN MM'//)
CC....WRITE HEADINGS FOR Y-AXIS
      WRITE(6,9202)
 9202 FORMAT(1X,'                                   0         10        20        30
     *        40        50        60        70        80        90        1
     *00')
      WRITE(6,9203)
 9203 FORMAT(24X,10('---------+'))
      DO 9204 IPL=2,NDYM+1
      Y=FLOAT(IPL-1)
      FF(1) = STRMFL(IPL-1)
      FF(2) = SIMSO(IPL)
C
 9204 CONTINUE
      WRITE(6,9203)
      WRITE(6,9202)
C
CC....PLOT SIMULATED AND OBSERVED SOIL MOISTURE
CC....IPLSTO MUST = 1    IF NOT NEEDED IPLSTO MUST = 0
 9643 IF(IPLSTO.NE.1)GO TO 9343
      WRITE(6,7010)
      IND=0
      IS=0
      WRITE(6,9301)I,IYR
 9301 FORMAT(1X,34X,'PLOT OF OBSERVED(M) AND SIMULATED(S) SOIL MOISTURE
     *STORAGE',//,50X,'MONTH = ',I2,'   YEAR = ',I2
     *,//,50X,'1=SIMULATED MOISTURE IN STORAGE 1',/
     *,50X,'2=SIMULATED MOISTURE IN STORAGE 2'/
     *50X,'A=OBSERVED MOISTURE IN A HORIZON'/
     *50X,'B=OBSERVED MOISTURE IN B HORIZON'/
     *50X,'0=VARIABLES OCCUPY THE SAME POSITION',//)
CC....WRITE HEADINGS FOR Y-AXIS
      WRITE(6,9202)
      WRITE(6,9203)
      DO 9304 IPL=2,NDYM+1
      Y=FLOAT(IPL-1)
      FFS(1)=AWC1(IPL)
      FFS(2)=AWC2(IPL)
      FFS(3)=OBSTO1(IPL)
      FFS(4)=OBSTO3(IPL)
      CALL PLOT1(IND,IS,Y,SYBL,FFS,4,FMT)
 9304 CONTINUE
      WRITE(6,9203)
      WRITE(6,9202)
 9343 CONTINUE
C
C     ------------------------------------------------------------------
C
C     OPTION FOR PRINTING MONTHLY MOISTURE BUDGET WHEN DAILY VALUES NOT
C     REQUESTED
C
      IF(WRIMO.EQ.1.AND.WRIDY.EQ.0.)CALL PRNTMO
C
C     ------------------------------------------------------------------
C
C     SUMMATION OF ANNUAL TOTALS
C
      CALL ANSUMS(I,SUMRA,SUMPE,SUMPE1,SUMPE2,SUMERA,SUMAE,SUMAE1,
     *SUMAE2,SUMET,SUMIR,SUMSU,SUMRU,SUMQU,SUMINT,SFLOW,SDATA,DIRRIG,
     *SUMST,LMN,TRAIN,TDPE,TE1,TE2,TERAIN,TAET,TAET1,TAET2,TET,TRQIR,
     *TSUR,TRUN,TQUICK,TPLINT,TDISCH,TSTREM)
C
C     ------------------------------------------------------------------
C
C     SOIL MOISTURE VALUES OF LAST DAY OF MONTH ARE STORED FOR USE ON FIRST DAY
C     OF NEXT MONTH OR YEAR
C
      CALL LDVALS(SOIL1,SOIL2,SOILI,PLINTC,RCO,STCO,RFLC,EFPPT,ETDE)
C
C     ------------------------------------------------------------------
C
C     END OF MAIN LOOP
C
    2 CONTINUE
C
C     ------------------------------------------------------------------
C
      SDATA(LMN,13)=SFLOW
      DIRRIG(LMN,13)=SUMIR
C
C     THE MONTHLY MOISTURE BUDGET HAS NOW BEEN ESTABLISHED - GIVE TOTALS
C
      IF(WRTYLD.EQ.0.)GO TO 611
      IF(WRIMO.EQ.1.OR.WRIDY.EQ.1.OR.WRIRR.EQ.1.)WRITE(6,515)
  515 FORMAT(1X,120('-'))
      IF(WRIDY.EQ.1.)THEN
      WRITE(6,632)SUMRA,SUMERA,SUMPE,SUMPE1,SUMPE2,SUMAE1,SUMAE2,
     *SUMSU,SUMRU,SUMQU,SFLOW,SUMST
  632 FORMAT(1X,'ANNUAL TOTALS',/14('-'),/3X,F6.1,F5.1,F6.1,5X,4F5.1,
     *21X,F7.2,9X,4F7.3)
      ENDIF
```

```
      IF(WRIMO.EQ.1.)THEN
      WRITE(6,511)SUMRA,SUMERA,SUMPE,SUMAE,SUMSU,SUMRU,SUMOU,
     *SFLOW,SUMST,SUMIR
  511 FORMAT(1X,'TOTALS',4X,F8.1,F9.1,2F7.1,37X,F7.3,F8.3,4F7.1)
      ENDIF
C
C     ------------------------------------------------------------------
C
C     CROP YIELD MODELS
C
  611 IF(WRTYLD) 378,378,379
  379 IF(CROP-1.)386,386,385
C
C     MAIZE YIELD MODEL
C
  386 IF(IYEAR-2) 378,382,380
  382 WRITE(6,5000)
 5000 FORMAT(//45X,'MAIZE YIELD ESTIMATION (T/HA/SEASON)'/45X,
     *36('-')/)
      WRITE(6,5001)
 5001 FORMAT(16X,'YEAR',4X,'DU PISANI 77',4X,'DU PISANI 78',6X,'DE JAGER
     *',2X,'USA-STEWART',8X,'PLANTING DATE',14X,'STRESS DAYS'/)
  380 TOTAET=TOTAET+ENDAET
      TOTPET=TOTPET+ENDPET
      YLDDP=TOTAET/92.
      YLDUSA=0.01845*TOTAET-3.0825
      YLDP78=0.88**NSTRES*4575.0*TOTPET/434.4/1000.
      YLDDJ=30.*(TOTAET-100.)*.45/1000.
      IYRA=IYR-1
      IF(WRTYLD)393,378,393
  393 IF(PLDATE)614,613,614
  613 WRITE(6,5002)IYRA,IYR,YLDDP,YLDP78,YLDDJ,YLDUSA,SMONTH(LSTAPT),
     *LDAY,NSTRES
 5002 FORMAT(13X,'1 ',I2,'/',I2,3X,F10.3,6X,F10.3,5X,F10.3,3X,F10.3,
     *11X,A9,I3,17X,I3)
      GO TO 378
  614 WRITE(6,5002)IYRA,IYR,YLDDP,YLDP78,YLDDJ,YLDUSA,SMONTH(ISTMO),
     *ISTDAY,NSTRES
  378 ENDAET=STAET
      ENDPET=STPET
      IF(IYEAR.EQ.1) GO TO 200
      LM=LM+1
      XMDP=XMDP+YLDDP
      CDATA(LM,1)=YLDDP
      CDATA(LM,2)=YLDP78
      CDATA(LM,3)=YLDDJ
      CDATA(LM,4)=YLDUSA
      GO TO 200
C
C     SUGAR CANE MODEL
C
  385 IF(WRTYLD)387,390,387
  387 IF(IYEAR-2)390,391,392
  391 WRITE(6,5050)
 5050 FORMAT(//45X,'SUGAR CANE YIELD ESTIMATION (T/HA/YEAR)'/45X,
     *39('-')/)
      WRITE(6,5051)
 5051 FORMAT(39X,'YEAR',13X,'SUGAR CANE',11X,'SUCROSE'//)
  392 TOTCAN=TOTCAN+ENDCAN
      AESUC=TOTCAN/100.
      YLDCAN=9.5*AESUC-2.36
      YLDSUC=-23.7+4.841*AESUC-0.1395*(AESUC**2.)
      IF(YLDSUC)234,789,789
  234 YLDSUC=0.
  789 IYRA=IYR-1
      IF(WRTYLD)394,390,394
  394 WRITE(6,5052)IYRA,IYR,YLDCAN,YLDSUC
 5052 FORMAT(37X,'19',I2,'/',I2,2(10X,F10.3))
  390 ENDCAN=STCAN
      IF(IYEAR.EQ.1)GO TO 200
      LM=LM+1
      CDATA(LM,1)=YLDCAN
      CDATA(LM,2)=YLDSUC
      GO TO 200
C
C     AT THIS STAGE THE PROGRAM HAS GONE THROUGH THE ENTIRE DATA SET.
C     STATISTICAL ROUTINES/OPTIONS FOLLOW
C     CALL STATISTICAL SUBROUTINE FOR CROP YIELD MODELS IF REQUIRED
   99 IF(WRTYLD)699,777,699
  699 IF(CROP-1.)799,799,899
  799 DO 125 I=1,4
      DO 126 J=1,LM
  126 X(J)=CDATA(J,I)
      N=LM
      CALL STAT(X,N,AVE,SDEV,CVAR,VALUE)
      XMEAN(I)=AVE
      STD(I)=SDEV
      CV(I)=CVAR
      DO 1137 J=1,9
 1137 PCTILE(J,I)=VALUE(J)
  125 CONTINUE
      WRITE(6,6000)(XMEAN(I),I=1,4)
 6000 FORMAT(/16X,'MEAN',3X,F10.3,6X,F10.3,5X,F10.3,3X,F10.3)
      WRITE(6,6001)(STD(I),I=1,4)
 6001 FORMAT(/2X,'STANDARD DEVIATION',3X,F10.3,6X,F10.3,5X,F10.3,3X,
     *F10.3)
      WRITE(6,6002)(CV(I),I=1,4)
 6002 FORMAT(/2X,'COEFF OF VARIATION',3X,F10.3,6X,F10.3,5X,F10.3,3X,
     *F10.3)
      WRITE(6,6076)
      DO 139 J=1,9
      WRITE(6,6113)PCENT(J),(PCTILE(J,I),I=1,4)
 6113 FORMAT(/16X,F3.0,'%',3X,F10.3,6X,F10.3,5X,F10.3,3X,F10.3)
  139 CONTINUE
      GO TO 777
  899 DO 127 I=1,2
      DO 128 J=1,LM
  128 X(J)=CDATA(J,I)
      N=LM
      CALL STAT(X,N,AVE,SDEV,CVAR,VALUE)
      XMEAN(I)=AVE
      STD(I)=SDEV
      CV(I)=CVAR
      DO 1138 J=1,9
 1138 PCTILE(J,I)=VALUE(J)
  127 CONTINUE
      WRITE(6,6060)(XMEAN(I),I=1,2)
 6060 FORMAT(/40X,'MEAN',2(10X,F10.3))
      WRITE(6,6061)(STD(I),I=1,2)
 6061 FORMAT(/26X,'STANDARD DEVIATION',2(10X,F10.3))
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      WRITE(6,6062)(CV(I),I=1,2)
 6062 FORMAT(/26X,'COEFF OF VARIATION',2(10X,F10.3))
      WRITE(6,6076)
      DO 140 J=1,9
      WRITE(6,6063)PCENT(J),(PCTILE(J,I),I=1,2)
 6063 FORMAT(/40X,F3.0,'%',2(10X,F10.3))
  140 CONTINUE
C
C     CHECK WHETHER RUNOFF SUMMARY IS REQUIRED
  777 LMN=LMN-1
      IF(RSUMRY)129,779,129
  129 DO 133 I=1,13
      DO 132 J=1,LMN
  132 X(J)=SDATA(J,I)
      N=LMN
      CALL STAT(X,N,AVE,SDEV,CVAR,VALUE)
      XMEAN(I)=AVE
      STD(I)=SDEV
      CV(I)=CVAR
      DO 135 J=1,9
  135 PCTILE(J,I)=VALUE(J)
  133 CONTINUE
      WRITE(6,105)HEAD
      WRITE(6,106)ALAT,ALONG,ELEV,RFRESP,RESPOF,COFRU,COTA,EQTN(EQPET)
  106 FORMAT(/5X,'LATITUDE (S)',33X,'=',F7.2,/5X,'LONGITUDE (E)',32X,'='
     *,F7.2,/5X,'ELEVATION (M)',33X,'=',F7.2,/5X,'COEFFICIENT OF DRAINAG
     *E RELEASE',4X,'=',F7.2,/5X,'COEFFICIENT OF QUICKFLOW RESPONSE',3X,
     *'=',F7.2,/5X,'COEFFICIENT OF BASEFLOW RESPONSE',3X,'=',F7.2,/5X,
     *'COEFFICIENT OF INITIAL ABSTRACTION =',F7.2,/5X,'POTENTIAL EVAPORA
     *TION BY ',A19)
      WRITE(6,112)
      WRITE(6,113)(CAY(I),I=1,12)
      WRITE(6,114)(ROOTA(I),I=1,12)
      WRITE(6,188)(VEGINT(I),I=1,12)
      WRITE(6,6070)
 6070 FORMAT(//52X,'SIMULATED RUNOFF (MM)'/52X,21('-')/)
      WRITE(6,6071)
 6071 FORMAT(24X,'JAN',5X,'FEB',5X,'MAR',5X,'APR',5X,'MAY',5X,'JUN',
     *5X,'JUL',5X,'AUG',5X,'SEP',5X,'OCT',5X,'NOV',5X,'DEC',5X,'ANN'/)
      WRITE(6,6072)(XMEAN(I),I=1,13)
 6072 FORMAT(/16X,'MEAN',12F8.2,F9.2)
      WRITE(6,6073)(STD(I),I=1,13)
 6073 FORMAT(/2X,'STANDARD DEVIATION',12F8.2,F9.2)
      WRITE(6,6074)(CV(I),I=1,13)
 6074 FORMAT(/2X,'COEFF OF VARIATION',12F8.2,F9.2)
      WRITE(6,6076)
 6076 FORMAT(//52X,'PROBABILITY ANALYSIS'/52X,20('-')/)
      DO 136 J=1,9
      WRITE(6,6075)PCENT(J),(PCTILE(J,I),I=1,13)
 6075 FORMAT(/16X,F3.0,'%',12F8.2,F9.2)
  136 CONTINUE
C
C     CHECK WHETHER IRRIGATION SUMMARY IS REQUIRED
  779 IF(ISUMRY)142,146,142
  142 DO 143 I=1,12
      DO 144 J=1,LMN
  144 X(J)=DIRRIG(J,I)
      N=LMN
      CALL STAT(X,N,AVE,SDEV,CVAR,VALUE)
      XMEAN(I)=AVE
      STD(I)=SDEV
      CV(I)=CVAR
      DO 145 J=1,9
  145 PCTILE(J,I)=VALUE(J)
  143 CONTINUE
      WRITE(6,105)HEAD
      WRITE(6,166)ALAT,ALONG,ELEV,EQTN(EQPET),IRRTYP(SCHED),EFFIRR,
     *CONSTI
  166 FORMAT(/5X,'LATITUDE (S)',40X,'=',F7.2,/5X,'LONGITUDE (E)',39X,'='
     *,F7.2,/5X,'ELEVATION (M)',39X,'=',F7.3,/5X,'POTENTIAL EVAPORATION
     *BY ',A19,/5X,'IRRIGATION ',A18,/5X,'FIELD EFFICIENCY',36X,'=',F7.2
     *,/5X,'AVAILABLE SOIL MOISTURE CONTENT AT STRESS THRESHOLD =',F7.2)
      WRITE(6,112)
      WRITE(6,113)(CAY(I),I=1,12)
      WRITE(6,114)(ROOTA(I),I=1,12)
      WRITE(6,188)(VEGINT(I),I=1,12)
      WRITE(6,6080)
 6080 FORMAT(//51X,'IRRIGATION REQUIREMENTS'/51X,23('-')/)
      WRITE(6,6071)
      WRITE(6,6072)(XMEAN(I),I=1,13)
      WRITE(6,6073)(STD(I),I=1,13)
      WRITE(6,6074)(CV(I),I=1,13)
      WRITE(6,6076)
      DO 146 J=1,9
      WRITE(6,6075)PCENT(J),(PCTILE(J,I),I=1,13)
  146 CONTINUE
C-----------------------------------------------------------------------
C          TESTS OF MODEL PERFORMANCE
C-----------------------------------------------------------------------
C          CHECK WHICH OPTIONS ARE REQUESTED
      IF(ICOMPR.EQ.0)GO TO 999
      IF(ICOMPR.EQ.1.OR.ICOMPR.EQ.3)THEN
C     PERFORM COMPARISON OF DAILY FLOWS
      WRITE(6,7010)HEAD
 7010 FORMAT('1',1X,1H1,//,50X,20A2,//)
      CALL OBJFUN(OBSQX,SIMQY,NDYTAL,LOGVAL,1)
      IF(ICOMPR.EQ.1)GO TO 999
      ENDIF
C     PERFORM COMPARISON OF MONTHLY FLOWS
      WRITE(6,7012)HEAD
 7012 FORMAT('1',1X,1H1,//,40X,20A2,//)
      CALL OBJFUN(OBSQMX,SIMQMY,MNTALY,LOGVAL,2)
  999 CONTINUE
C
C.....PLOTTING SECTION.....
CC....FOR PLOT USING STAT-PACK OF UNIV-NATAL TO PRESENT
CC....GRAPHS OF SIMULATED AND OBSERVED MONTHLY FLOWS,
CC....IPLMNQ MUST = 1    IF NOT NEEDED IPLMNQ MUST = 0
      IF(IPLMNQ.NE.1)GO TO 9443
      WRITE(6,7010)HEAD
       WRITE(6,9401)
 9401 FORMAT(1X,34X,'PLOT OF OBSERVED(M) AND SIMULATED(S) MONTHLY FLOWS
     *',//,50X,'S=SIMULATED MONTHLY FLOW IN MM'/
     *50X,'M=MEASURED MONTHLY FLOW IN MM'/
     *50X,'0=VARIABLES OCCUPY THE SAME POSITION',//)
CC....WRITE HEADINGS FOR Y-AXIS
      WRITE(6,9202)
      WRITE(6,9203)
      DO 9404 IPL=1,MNTALY
      Y=(FLOAT(MNPLO(IPL)))/100
```

```
      FF(1)=OBSDMX(IPL)
      FF(2)=SIMDMY(IPL)
      CALL PLOT1(IND,IS,Y,SYBLG,FF,2,FMT)
 9494 CONTINUE
      WRITE(6,9203)
      WRITE(6,9202)
 9443 CONTINUE
      STOP
      DEBUG SUBCHK
      AT 9E-6
      END
C     ------------------------------------------------------------------
C
C     END OF PROGRAM.   SUBROUTINES FOLLOW.
C
C     ------------------------------------------------------------------
C
C     PE ROUTINE
C
      SUBROUTINE PETEMP(T,TI,ANHEI,A,E,FACTOR,THLIN,THITD)
C
      DIMENSION T(12),THAX(12),THIN(12),TI(12),E(12),DL(12),D(12),
     *FACTOR(12),THLIN(12),THITD(12),WINDFA(12,3),DAYS(12)
      COMMON/PETEMP/TEMP,THAX,THIN,EQPET,DL,D,LINWIN,ELEV,ALAT
      DATA DAYS/31.,28.,31.,30.,31.,30.,31.,31.,30.,31.,30.,31./
      DATA WINDFA/19.,18.8,18.7,17.,14.8,14.6,15.4,18.7,20.4,20.7,
     *20.,20.,  14.,13.,12.5,11.8,12.3,11.8,12.6,15.5,15.7,17.,16.,
     *15.,  13.,12.,12.,10.2,10.6,10.7,11.,12.3,13.,13.,12.,12./
C
      IF(TEMP.EQ.0.)THEN
      WRITE(6,10)
   10 FORMAT(//1X,'YOU HAVE MADE AN ERROR - YOU CANNOT REQUEST A TEMPERA
     *TURE BASED P.E. METHOD WITHOUT TEMPERATURE')
      STOP
      ENDIF
C
C     CALCULATE MEAN TEMPERATURES
C
      DO 20 I=1,12
   20 T(I)=(THAX(I)+THIN(I))/2.
C     SELECTION PE EQUATION (BY EQPET)
      IF(EQPET.EQ.3.)THEN
C     THORNTHWAITE METHOD
C     CALCULATE ANNUAL HEAT INDEX (ANHEI) AND MONTHLY TEMPERATURE INDEX (TI)
      ANHEI=0.0
      DO 30 I=1,12
      TI(I)=(T(I)/5.0)**1.514
   30 ANHEI=ANHEI+TI(I)
C     CALCULATE THE INDEX A
      A=0.49+0.0179*ANHEI-0.000077*ANHEI**2.0+0.000000675*ANHEI**3.0
C     CALCULATE MONTHLY VALUES OF POTENTIAL EVAP. E(I) IN MM
      DO 40 I=1,12
   40 E(I)=16.0*((10.0*T(I)/ANHEI)**A)*DL(I)
      ENDIF
      IF(EQPET.EQ.2.)THEN
C     BLANEY CRIDDLE METHOD
      DO 50 I=1,12
      E(I)=(0.142*T(I)+1.095)*(T(I)+17.8)*D(I)*10.0
      IF(T(I).LE.3.)E(I)=1.38*(T(I)+17.8)*D(I)*10.0
   50 CONTINUE
      ENDIF
      IF(EQPET.EQ.1.)THEN
C     LINACRE METHOD
C     SELECT WIND FACTOR FOR LINACRE EQUATION. IF NO REGIONAL FACTOR
C     IS KNOWN, THE LINACRE VALUE OF 15 IS ASSUMED.
      DO 60 I=1,12
      IF(LINWIN.EQ.0)FACTOR(I)=15.
      IF(LINWIN.EQ.1)FACTOR(I)=WINDFA(I,1)
      IF(LINWIN.EQ.2)FACTOR(I)=WINDFA(I,2)
      IF(LINWIN.EQ.3)FACTOR(I)=WINDFA(I,3)
      THLIN(I)=T(I)+0.006*ELEV
      THITD(I)=0.0023*ELEV+0.37*T(I)+0.53*(THAX(I)-THIN(I))+0.35*
     *(T(1)-T(7))-10.9
      IF(THITD(I).LT.4.)THITD(I)=4.
      E(I)=(500.*THLIN(I)/(100.-ALAT)+FACTOR(I)*THITD(I))/(80.-T(I))*
     *DAYS(I)
   60 CONTINUE
      ENDIF
      RETURN
      END
C
C     ------------------------------------------------------------
C
C     INITIALIZE ANNUAL TOTALS TO ZERO
C
      SUBROUTINE INITAN(SUMRA,SUMERA,SUMPE,SUMPE1,SUMPE2,SUMAE,SUMAE1,
     *SUMAE2,SUMET,SUMINT,SUMSU,SUMIR,SUMRO,SUMOU,SFLOW,SUMST,STAET,
     *STPET,STCAN,TOTAET,TOTPET,TOTCAN)
C
      SUMRA=0.0
      SUMERA=0.0
      SUMPE=0.0
      SUMPE1=0.0
      SUMPE2=0.0
      SUMAE=0.0
      SUMAE1=0.0
      SUMAE2=0.0
      SUMET=0.0
      SUMINT=0.0
      SUMSU=0.0
      SUMIR=0.0
      SUMRU=0.0
      SUMOU=0.0
      SFLOW=0.0
      SUMST=0.0
      STAET=0.0
      STPET=0.
      STCAN=0.
      TOTAET=0.0
      TOTPET=0.0
      TOTCAN=0.
      RETURN
      END
C
C     ------------------------------------------------------------------
C
C     WRITE HEADING FOR MONTHLY PRINTOUT OPTION
C
      SUBROUTINE HDGMTH
C
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```
      DIMENSION HEAD(17)
      COMMON/MDGMTH/HEAD
C
      WRITE(6,10)HEAD
   10 FORMAT(//5X, 'MONTHLY SUMMARY OF MOISTURE BUDGET',5X,20A2)
      WRITE(6,20)
   20 FORMAT(5X,60('-'))
      WRITE(6,30)
   30 FORMAT(20X,'EFFECTIVE',13X,2(1X,'S.M.C.'),2(3X,'DEF.'),3X,'DRAIN-'
     *,2X,'BASE-',2X,'STORM-',2X,'EST.',3X,'OBS.',2X,'IRRIG')
      WRITE(6,40)
   40 FORMAT(1X,'YEAR',1X,'MONTH',1X,'RAINFALL',1X,'RAINFALL',3X,'PE',
     *4X,'AET',2X,'A-HOR',2X,'B-HOR',2X,'A-HOR',2X,'B-HOR',5X,'AGE',4X,
     *'FLOW',2X,'FLOW',2X,'RUNOFF',1X,'RUNOFF',2X,'REQU.'/)
      RETURN
      END
C
C     ------------------------------------------------------------------
C
C     INITIALIZE DAILY ARRAYS
C
      SUBROUTINE INITDY(SMD,STORMQ,ERFL,ERFLIR,PLINT,STQIR,RAIN,RFL,
     *STRFL,STRMFL,TMIND,TMAXD,APAN,PAN,DPE,SMOBS1,SMOBS2,SMOBS3,
     *SMSTO1,SMSTO2,SMSTO3,OBSTO1,OBSTO2,IDAY)
C
C     NOTE:  32 DAYS PER MONTH USED TO ENABLE CALCULATIONS TO
C     INCLUDE VALUES OF LAST DAY OF PREVIOUS MONTH
C
      DIMENSION APAN(12,32),PAN(32),DPE(32),ERFL(32),ERFLIR(32),
     *PLINT(32),IDAY(32),OBSTO1(32),OBSTO2(32),RAIN(32),RFL(32),SMD(32),
     *SMOBS1(32),SMOBS2(32),SMOBS3(32),SMSTO1(32),SMSTO2(32),SMSTO3(32),
     *STORMQ(32),STQIR(32),STRFL(32),STRMFL(32),TMAXD(32),TMIND(32)
C
      DO 10 K=1,32
      SMD(K)=0.0
      STORMQ(K)=0.0
      ERFL(K)=0.0
      ERFLIR(K)=0.0
      PLINT(K)=0.0
      STQIR(K)=0.0
      RAIN(K)=0.0
      RFL(K)=0.0
      STRFL(K)=0.0
      STRMFL(K)=0.0
      TMIND(K)=0.0
      TMAXD(K)=0.0
      APAN(I,K)=0.0
      PAN(K)=0.0
      DPE(K)=0.0
      SMOBS1(K)=0.0
      SMOBS2(K)=0.0
      SMOBS3(K)=0.0
      SMSTO1(K)=0.0
      SMSTO2(K)=0.0
      SMSTO3(K)=0.0
      OBSTO1(K)=0.0
      OBSTO2(K)=0.0
   10 IDAY(K)=0
      RETURN
      END
C
C     ------------------------------------------------------------------
C
C     SET STORAGES FROM PREVIOUS DAYS' READINGS
C
      SUBROUTINE PREVDY(STO1,STO2,PLINT,RFL,ERFL,DEF1,DEF2,RUNCO,
     *STRMCO,STQIR)
C
      DIMENSION STO1(32),STO2(32),PLINT(32),RFL(32),ERFL(32),DEF1(32),
     *DEF2(32),RUNCO(32),STRMCO(32),STQIR(32)
      COMMON/PREVDY/SOIL1,SOIL2,PLINTC,RFLC,RCO,STCO,SOILI,EFPPT
C
      K=2
      STO1(K-1)=SOIL1
      STO2(K-1)=SOIL2
      PLINT(K-1)=PLINTC
      RFL(K-1)=RFLC
      ERFL(K-1)=EFPPT
      DEF1(K-1)=0.0
      DEF2(K-1)=0.0
      RUNCO(K-1)=RCO
      STRMCO(K-1)=STCO
      STQIR(K-1)=SOILI
      RETURN
      END
C
C     ------------------------------------------------------------------
C
C     INITIALIZE TOTALS OF SURPLUS,AET,IRRIG.REQ.,RUNOFF FOR THE MONTH
C     TO ZERO
C
      SUBROUTINE INITMO(TSUR,TE1,TE2,TDPE,TAET,TAET1,TAET2,TET,TRQIR,
     *TRUN,TERAIN,TRAIN,TSTORM,TQUICK,TDISCH,TSTREM,TPLINT,TAETIR,
     *TSTQIR,TIRRFL,TSURIR,TPEQIR,TAPAN,NOIRAP,TPOSEV,TASDEV,TPOTR1,
     *TPOTR2,TTRAN1,TTRAN2,TPTRAN,TTRANS)
C
      DIMENSION TSUR(12),TE1(12),TE2(12),TDPE(12),TAET(12),TAET1(12),
     *TAET2(12),TET(12),TRQIR(12),TRUN(12),TERAIN(12),TRAIN(12),
     *TSTORM(12),TQUICK(12),TDISCH(12),TSTREM(12),TPLINT(12),TAETIR(12),
     *TSTQIR(12),TIRRFL(12),TSURIR(12),TPEQIR(12),TAPAN(12),NOIRAP(12),
     *TPOSEV(12),TASDEV(12),TPOTR1(12),TPOTR2(12),TTRAN1(12),TTRAN2(12),
     *TPTRAN(12),TTRANS(12)
C
      DO 10 I=1,12
      TSUR(I)=0.0
      TE1(I)=0.0
      TE2(I)=0.0
      TDPE(I)=0.0
      TAET(I)=0.0
      TAET1(I)=0.0
      TAET2(I)=0.0
      TET(I)=0.0
      TRQIR(I)=0.0
      TRUN(I)=0.0
      TERAIN(I)=0.0
      TRAIN(I)=0.0
      TSTORM(I)=0.0
      TQUICK(I)=0.0
      TDISCH(I)=0.0
      TSTREM(I)=0.0
```

```
      TPLINT(I)=0.0
      TAETIR(I)=0.0
      TSTOIR(I)=0.0
      TIRRFL(I)=0.0
      TSURIR(I)=0.0
      TREQIR(I)=0.0
      TAPAN(I)=0.0
      TPOSEV(I)=0.0
      TASDEV(I)=0.0
      TPOTR1(I)=0.0
      TPOTR2(I)=0.0
      TTRAN1(I)=0.0
      TTRAN2(I)=0.0
      TPTRAN(I)=0.0
      TTRANS(I)=0.0
   10 NDIRAF(I)=0
      RETURN
      END
C
C     ----------------------------------------------------------------------
C
C     MAIZE YIELD MODEL
C
      SUBROUTINE MZPREP(PRAIN,TPRAIN,LSTART,LDAY,ISTMO,ISTDAY,NSTRES,
     *MSDAYS,TOTAET,TOTPET,LGROW,STAET,STPET,ATRANS,RFL)
C
      DIMENSION AET1(32),AET2(32),APAN(12,32),ATRANS(32),AWC1(32),
     *AWC2(32),CONSTA(32),DNO(32),DPE(32),OBSTO1(32),OBSTO2(32),
     *PERC(32),PORFR(32),PP1(32),PP2(32),PRAIN(6),QUICKF(32),REQIR(32),
     *RFL(32),RUN(32),SINSQ(32),STRAFL(32),SUR2(32)
      COMMON/COUNT/I,IYR,NDYM,IYEAR,K
      COMMON/PRTDLY/MOIST,DNO,PP1,PP2,DPE,AET1,AET2,AWC1,AWC2,OBSTO1,
     *OBSTO2,RUN,QUICKF,SINSQ,STRAFL,REQIR,CONSTA,PORFR,APAN,SUR2,PERC,
     *PRIRR,EVTR,CAYD,POSDEV,ASDEV,POTR1,POTR2,ATRAN1,ATRAN2
      COMMON/MAIZE/PLDATE,LENGTH
C
C     CHECK WHETHER START OF GROWING SEASON GIVEN
C     IF NOT GIVEN CALCULATE NOW
      IF(PLDATE)250,256,250
  256 IF(ISTMO)250,262,250
  262 IF(I-10)60,243,266
  266 IF(I-12) 243,263,263
  263 ISTMO=12
      ISTDAY=35
      GO TO 250
  243 DO 245 J=2,6
      IF(K-J) 246,244,247
  244 PRAIN(J)=RFL(K)
  245 CONTINUE
  246 IF(I-10) 249,249,247
  247 DO 248 J=1,5
  248 PRAIN(J)=PRAIN(J+1)
      PRAIN(6)=RFL(K)
C     TOTAL PLANTING RAIN HAS TO BE 25MM ACCUMULATED OVER
C     5 DAYS
  249 TPRAIN=PRAIN(2)+PRAIN(3)+PRAIN(4)+PRAIN(5)+PRAIN(6)
      IF(TPRAIN-25.)60,60,255
  255 ISTMO=I
      ISTDAY=K-1
C     CALCULATE AET FOR GRAIN YIELD EQUATIONS
  250 IF(IYEAR-2)675,676,676
  676 IF(I-ISTMO)678,678,673
  678 IF(LGROW-LENGTH)677,673,673
  673 IF(PLDATE)695,257,695
  257 LSTART=ISTMO
      LDAY=ISTDAY
      ISTMO=0
      ISTDAY=0
      NSTRES=MSDAYS
      MSDAYS=0
      DO 258 J=1,6
  258 PRAIN(J)=0.0
      GO TO 60
  695 IF(MSDAYS)60,60,696
  696 NSTRES=MSDAYS
      MSDAYS=0
      GO TO 60
C     SUMMATE PE AND AE FOR BOTH SOIL LAYERS
  677 IF(EVTR.EQ.1.)TOTAET=TOTAET+AET1(K)+AET2(K)
      IF(EVTR.EQ.2.)TOTAET=TOTAET+ATRANS(K)
      TOTPET=TOTPET+PP1(K)+PP2(K)
      LGROW=LGROW+1
C     CALCULATE NUMBER OF STRESS DAYS FOR DU PISANI 1978 MODEL
      GO TO 679
  675 IF(I-ISTMO)60,670,672
  670 IF(K-(ISTDAY+1))60,671,672
  671 LGROW=0
  672 IF(EVTR.EQ.1.)STAET=STAET+AET1(K)+AET2(K)
      IF(EVTR.EQ.2.)STAET=STAET+ATRANS(K)
      STPET=STPET+PP1(K)+PP2(K)
      LGROW=LGROW+1
  679 IF(LGROW-70)60,690,690
  690 IF(LGROW-100)691,691,60
C     CHECK FOR STRESS DAY
  691 IF(AET1(K)-0.5*PP1(K))684,60,60
  684 IF(AET2(K)-0.5*PP2(K))685,60,60
  685 MSDAYS=MSDAYS+1
   60 RETURN
      END
C
C     ----------------------------------------------------------------------
C
C     SUGAR CANE YIELD ESTIMATE
C
      SUBROUTINE CNPREP(I,K,STCAN,TOTCAN,AET1,AET2,PLINT)
C
      DIMENSION AET1(32),AET2(32),PLINT(32)
C
C     ACTUAL EVAPOTRANSPIRATION (INCLUDING INTERCEPTED WATER) IS SUMMED
C     TO GIVE AN ESTIMATE OF SUGAR CANE YIELD.
C     TOTCAN = TOTAL FROM JANUARY TO JUNE
C     STCAN = TOTAL FROM JULY TO DECEMBER
C
      IF(I.GE.7)STCAN=STCAN+AET1(K)+AET2(K)+PLINT(K)
      IF(I.LT.7)TOTCAN=TOTCAN+AET1(K)+AET2(K)+PLINT(K)
      RETURN
      END
C
C     ----------------------------------------------------------------------
C
```

```
C     OPTION FOR PRINTING DAILY MOISTURE BUDGET WITH MONTHLY SUB-TOTALS
C
      SUBROUTINE PRTDLY
C
      DIMENSION AETIR(32),AET1(32),AET2(32),APAN(12,32),ASOEV(32),
     *ATRAN1(32),ATRAN2(32),AWC1(32),AWC2(32),
     *CAYD(12,32),CONSTA(32),DEF1(32),DEF2(32),DNO(32),DPE(32),
     *E(12),ERFL(32),ERFLIR(32),OBSTO1(32),OBSTO2(32),PERC(32),
     *PLINT(32),PORFR(32),POSOEV(32),POTR1(32),POTR2(32),PP1(32),
     *PP2(32),QUICKF(32),REQIR(32),RFL(32),
     *RUN(32),RUNCO(32),SIMSQ(32),SMDIR(32),STOIR(32),STOIRO(32),
     *STO1(32),STO2(32),STOIR(32),STRMCO(32),STRMFL(32),SURIR(32),
     *SUR2(32),TAET(12),TAETIR(12),TAET1(12),TAET2(12),TAPAN(12),
     *TASOEV(12),TDISCH(12),TDPE(12),TERAIN(12),TE1(12),TE2(12),
     *TIRRFL(12),TPOSEV(12),TPOTR1(12),TPOTR2(12),TRTRAN(12),TQUICK(12),
     *TRAIN(12),TREQIR(12),TRQIR(12),TRUN(12),TSTQIR(12),TSIPER(12),
     *TSUR(12),TSURIR(12),TTRANS(12),TTRAN1(12),TTRAN2(12)
      COMMON/LDVALS/STOIR,PLINT,RUNCO,STRMCO,RFL,E,IRFL
      COMMON/PRINT/DEF1,DEF2,STO1,STO2
      COMMON/COUNT/I,IYR,NDYM,IYEAR,K
      COMMON/PRNTMO/TRAIN,TERAIN,TDPE,TAET,TPOSEV,TASOEV,TPOTR1,TPOTR2,
     *TTRAN1,TTRAN2,TRTRAN,TTRANS,TSUR,TRUN,TQUICK,TDISCH,TSTREM,TRQIR
      COMMON/PRTDLY/MOIST,DNO,PP1,PP2,DPE,AET1,AET2,AWC1,AWC2,OBSTO1,
     *OBSTO2,RUN,QUICKF,SIMSQ,STRMFL,REQIR,CONSTA,PORFR,APAN,SUR2,PERC,
     *PRIRR,EVTR,CAYD,POSOEV,ASOEV,POTR1,POTR2,ATRAN1,ATRAN2
      COMMON/TOTALS/TE1,TE2,TAET1,TAET2,TAPAN
      COMMON/IRRIG/AETIR,SMDIR,STOIR,ERFLIR,STOIRO,SURIR,TAETIR,TSTQIR,
     *TIRRFL,TSURIR,TREQIR
C
C     CHECK IF DAILY OUTPUT TO INCLUDE OBSERVED SOIL-MOISTURE DATA
      IF(MOIST.EQ.1.AND.PRIRR.EQ.0.)THEN
      WRITE(6,10)I,IYR
   10 FORMAT(1H1,1X,'DAILY MOISTURE BUDGET OF MONTH ',I2,', YEAR ',I2,//
     *1X,'DAY RAIN ERAIN PE1  PE2 APAN AE1 AE2 STO1 AWC1 OST1 STO2 AWC2
     *OST2 DEF1 DEF2 BSFLO RUNCO STORM SIMSQ OBSERQ IRR CONST PORFR')
      DO 30 K=2,(NDYM+1)
      WRITE(6,20)DNO(K),RFL(K),ERFL(K),PP1(K),PP2(K),DPE(K),AET1(K),
     *AET2(K),STO1(K),AWC1(K),OBSTO1(K),STO2(K),AWC2(K),OBSTO2(K),
     *DEF1(K),DEF2(K),RUN(K),RUNCO(K),QUICKF(K),SIMSQ(K),STRMFL(K-1),
     *REQIR(K),CONSTA(K),PORFR(K)
   20 FORMAT(1X,F3.0,5F5.1,2F4.1,10F5.1,F6.3,2F7.3,F5.1,F5.2,F4.2)
   30 CONTINUE
      WRITE(6,170)
      WRITE(6,40)TRAIN(I),TERAIN(I),TE1(I),TE2(I),TDPE(I),TAET1(I),
     *TAET2(I),TRUN(I),TQUICK(I),TDISCH(I),TSTREM(I),TRQIR(I)
   40 FORMAT(1X,3X,5F5.1,2F4.1,40X,F5.1,5X,F6.3,2F7.3,F5.1)
      ENDIF
C     - - - - - - - - - - - - - - - - - - - - - - - - - -
      IF(MOIST.EQ.0.AND.PRIRR.EQ.0.AND.EVTR.EQ.1.)THEN
      WRITE(6,50)I,IYR
   50 FORMAT(/1X,'DAILY MOISTURE BUDGET OF MONTH ',I2,', YEAR 19',I2,/,
     *45('-')/)
      WRITE(6,60)
   60 FORMAT(9X,'EFFEC-',31X,'SOIL  SOIL  DEF- DEF-',7X,'UNSAT BASE',
     *11X,'SIMU-   OBSER- STRESS')
      WRITE(6,70)
   70 FORMAT(5X,'RAIN TIVE A-PAN  CROP PET  PET  AET  AET MOIST MOIST IC
     *IT ICIT DRAIN DRAIN FLOW BASE  STORM LATED   VED   FRAC-')
      WRITE(6,80)
   80 FORMAT(1X,'DAY FALL RAIN EQUIV  FACT "A"  "B"  "A"  "B" A-HOR B-HO
     *R "A"  "B"  -AGE  -AGE STORE FLOW  FLOW  RUNOFF  RUNOFF TION'/)
      DO 100 K=2,(NDYM+1)
      WRITE(6,90)DNO(K),RFL(K),ERFL(K),APAN(I,K),CAYD(I,K-1),PP1(K),
     *PP2(K),AET1(K),AET2(K),STO1(K),STO2(K),DEF1(K),DEF2(K),SUR2(K),
     *PERC(K),RUNCO(K),RUN(K),QUICKF(K),SIMSQ(K),STRMFL(K-1),CONSTA(K)
   90 FORMAT(1X,F3.0,2F5.1,1X,F5.1,1X,F5.3,F4.1,3F5.1,2F6.1,2F5.1,1X,
     *3F5.2,F6.3,3F7.3,F4.1)
  100 CONTINUE
      WRITE(6,170)
      WRITE(6,110)TRAIN(I),TERAIN(I),TAPAN(I),TE1(I),TE2(I),TAET1(I),
     *TAET2(I),TSUR(I),TRUN(I),TQUICK(I),TDISCH(I),TSTREM(I)
  110 FORMAT(4X,2F5.1,F6.1,5X,F5.1,3(1X,F4.1),23X,F5.2,10X,F6.3,3F7.3)
      ENDIF
C     - - - - - - - - - - - - - - - - - - - - - - - - - -
      IF(MOIST.EQ.0.AND.PRIRR.EQ.0.AND.EVTR.EQ.2.)THEN
      WRITE(6,50)I,IYR
      WRITE(6,190)
  190 FORMAT(9X,'EFFEC-',11X,'SOIL EVAP TRANSPIRATION  SOIL  SOIL  DEF-
     *DEF-',7X,'UNSAT BASE',12X,'SIMU- OBSER- STRESS')
      WRITE(6,200)
  200 FORMAT(5X,'RAIN TIVE A-PAN  CROP',9X,'POT POT ACT ACT MOIST MOIST
     *ICIT ICIT DRAIN DRAIN FLOW BASE STORM LATED  VED   FRAC-')
      WRITE(6,210)
  210 FORMAT(1X,'DAY FALL RAIN EQUIV  FACT POT ACT "A" "B" "A" "B" A-HOR
     * B-HOR "A" "B"  -AGE  -AGE STORE FLOW FLOW RUNOFF RUNOFF TION'/)
      DO 230 K=2,(NDYM+1)
      WRITE(6,220)DNO(K),RFL(K),ERFL(K),APAN(I,K),CAYD(I,K-1),POSOEV(K),
     *ASOEV(K),POTR1(K),POTR2(K),ATRAN1(K),ATRAN2(K),STO1(K),STO2(K),
     *DEF1(K),DEF2(K),SUR2(K),PERC(K),RUNCO(K),RUN(K),QUICKF(K),
     *SIMSQ(K),STRMFL(K-1),CONSTA(K)
  220 FORMAT(1X,F3.0,2F5.1,1X,F5.1,1X,F5.3,2F4.1,1X,4F4.1,2F6.1,2F5.1,
     *1X,3F5.2,4F6.3,F4.1)
  230 CONTINUE
      WRITE(6,170)
      WRITE(6,240)TRAIN(I),TERAIN(I),TAPAN(I),TPOSEV(I),TASOEV(I),
     *TPOTR1(I),TPOTR2(I),TTRAN1(I),TTRAN2(I),TSUR(I),TRUN(I),TQUICK(I),
     *TDISCH(I),TSTREM(I)
  240 FORMAT(4X,2F5.1,F6.1,5X,F5.1,5F4.1,23X,F5.2,10X,F5.2,F6.2,
     *1X,2F6.3)
      ENDIF
C     - - - - - - - - - - - - - - - - - - - - - - - - - -
      IF(PRIRR.EQ.1.)THEN
      WRITE(6,120)I,IYR
  120 FORMAT(/1X,'DAILY MOISTURE BUDGET FOR IRRIGATION ROUTINE FOR MONTH
     * ',I2,' YEAR 19',I2)
      WRITE(6,130)
  130 FORMAT(57X,'INITIAL',13X,'FINAL')
      WRITE(6,140)
  140 FORMAT(22X,'IRRIGATION',2X,'IRRIGATION',2X,'EFFECTIVE',3X,'SOIL',
     *4X,'SURPLUS',5X,'SOIL',3X,'IRRIGATION',/1X,'DAY',1X,'RAIN',3X,
     *'PE',1X,'AET-IR',3X,'DEFICIT',4X,'STORMFLOW',3X,'RAINFALL',2X,
     *'STORAGE',2X,'RAINFALL',2X,'STORAGE',1X,'REQUIREMENT'/)
      DO 160 K=2,(NDYM+1)
      WRITE(6,150)DNO(K),RFL(K),DPE(K),AETIR(K),SMDIR(K),STQIR(K),
     *ERFLIR(K),STOIRO(K),SURIR(K),STOIR(K),REQIR(K)
  150 FORMAT(1X,F3.0,2F5.1,F6.1,3X,F6.1,5X,F6.1,6X,F6.1,3(4X,F6.1,
     *3X,F6.1))
  160 CONTINUE
      WRITE(6,170)
  170 FORMAT(1X,130('-'))
```

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      WRITE(6,180)TRAIN(I),TDPE(I),TAETIR(I),TSTOIR(I),TIRREL(I),
     *TSURIP(I),TRSOIR(I)
  180 FORMAT(4X,2F5.1,F6.1,14X,F6.1,6X,F6.1,2(13X,F6.1))
      ENDIF
      RETURN
      END
C
C     ------------------------------------------------------------------
C
C     OPTION FOR PRINTING MONTHLY MOISTURE BUDGET WHEN DAILY VALUES NOT
C     REQUESTED
C
      SUBROUTINE PRNTMO
C
      DIMENSION TRAIN(12),TERAIN(12),TDPE(12),TAET(12),STO1(32),
     *STO2(32),DEF1(32),DEF2(32),TSUR(12),TRUN(12),TQUICK(12),
     *TDISCH(12),TSTREM(12),TROIR(12),TPOSEV(12),TASDEV(12),TPOTR1(12),
     *TPOTR2(12),TTRAN1(12),TTRAN2(12),TPTRAN(12),TTRANS(12)
      COMMON/COUNT/I,IYR,NDYM,IYEAR,K
      COMMON/PRINT/DEF1,DEF2,STO1,STO2
      COMMON/PRNTMO/TRAIN,TERAIN,TDPE,TAET,TPOSEV,TASDEV,TPOTR1,TPOTR2,
     *TTRAN1,TTRAN2,TPTRAN,TTRANS,TSUR,TRUN,TQUICK,TDISCH,TSTREM,TROIR
C
      WRITE(6,10)IYR,I,TRAIN(I),TERAIN(I),TDPE(I),TAET(I),STO1(NDYM+1),
     *STO2(NDYM+1),DEF1(NDYM+1),DEF2(NDYM+1),TSUR(I),TRUN(I),TQUICK(I),
     *TDISCH(I),TSTREM(I),TROIR(I)
   10 FORMAT(1X,I3,3X,I3,2X,F7.1,F9.1,2F7.1,4F7.1,2F8.3,4F7.1)
      RETURN
      END
C
C     ------------------------------------------------------------------
C
C     SUMMATION OF ANNUAL TOTALS
C
      SUBROUTINE ANSUMS(I,SUMRA,SUMPE,SUMPE1,SUMPE2,SUMERA,SUMAE,SUMAE1,
     *SUMAE2,SUMET,SUMIR,SUMSU,SUMRU,SUMQU,SUMINT,SFLOW,SDATA,DIRRIG,
     *SUMST,LMN,TRAIN,TDPE,TE1,TE2,TERAIN,TAET,TAET1,TAET2,TET,TROIR,
     *TSUR,TRUN,TQUICK,TPLINT,TDISCH,TSTREM)
C
      DIMENSION TRAIN(12),TDPE(12),TE1(12),TE2(12),TERAIN(12),TAET(12),
     *TAET1(12),TAET2(12),TET(12),TROIR(12),TSUR(12),TRUN(12),
     *TQUICK(12),TPLINT(12),TDISCH(12),TSTREM(12),SDATA(70,13),
     *DIRRIG(70,13)
C
      SUMRA=SUMRA+TRAIN(I)
      SUMPE=SUMPE+TDPE(I)
      SUMPE1=SUMPE1+TE1(I)
      SUMPE2=SUMPE2+TE2(I)
      SUMERA=SUMERA+TERAIN(I)
      SUMAE=SUMAE+TAET(I)
      SUMAE1=SUMAE1+TAET1(I)
      SUMAE2=SUMAE2+TAET2(I)
      SUMET=SUMET+TET(I)
      SUMIR=SUMIR+TROIR(I)
      SUMSU=SUMSU+TSUR(I)
      SUMRU=SUMRU+TRUN(I)
      SUMQU=SUMQU+TQUICK(I)
      SUMINT=SUMINT+TPLINT(I)
      SFLOW=SFLOW+TDISCH(I)
      SDATA(LMN,I)=TDISCH(I)
      DIRRIG(LMN,I)=TROIR(I)
      SUMST=SUMST+TSTREM(I)
      RETURN
      END
C
C     ------------------------------------------------------------------
C
C     SOIL MOISTURE VALUES OF LAST DAY OF MONTH OR YEAR ARE STORED
C     FOR USE ON FIRST DAY OF NEXT MONTH OR YEAR
C
      SUBROUTINE LDVALS(SOIL1,SOIL2,SOILI,PLINTC,RCO,STCO,RFLC,EFPPT,
     *ETDE)
C
      DIMENSION STO1(32),STO2(32),STOIR(32),PLINT(32),RUNCO(32),
     *STRMCO(32),RFL(32),ERFL(32),E(12),DEF1(32),DEF2(32)
      COMMON/LDVALS/STOIR,PLINT,RUNCO,STRMCO,RFL,E,ERFL
      COMMON/PRINT/DEF1,DEF2,STO1,STO2
      COMMON/COUNT/I,IYR,NDYM,IYEAR,K
C
      SOIL1=STO1(NDYM+1)
      SOIL2=STO2(NDYM+1)
      SOILI=STOIR(NDYM+1)
      PLINTC=PLINT(NDYM+1)
      RCO=RUNCO(NDYM+1)
      STCO=STRMCO(NDYM+1)
      RFLC=RFL(NDYM+1)
      EFPPT=ERFL(NDYM+1)
      ETDE=E(12)
      RETURN
      END
C
C     ------------------------------------------------------------------
C
C     366 DAILY VALUES ARE CALCULATED FROM 12 MONTHLY VALUES USING HARMONIC
C     ANALYSIS
C
      SUBROUTINE HARMON(XXX,PARAM)
      DIMENSION XXX(12),A(6),B(6),IDA(12),PARAM(13,32),XA(6),XB(6)
      DATA(IDA(IMO),IMO=1,12)/31,28,31,30,31,30,31,31,30,31,30,31/
      AM=0.0
      DO 9 J=1,12
      A(J)=0.0
    8 B(J)=0.0
    9 CONTINUE
      XXX(1)=XXX(1)*0.982
      XXX(2)=XXX(2)*1.087
      XXX(3)=XXX(3)*0.982
      XXX(4)=XXX(4)*1.015
      XXX(5)=XXX(5)*0.982
      XXX(6)=XXX(6)*1.015
      XXX(7)=XXX(7)*0.982
      XXX(8)=XXX(8)*0.982
      XXX(9)=XXX(9)*1.015
      XXX(10)=XXX(10)*0.982
      XXX(11)=XXX(11)*1.015
      XXX(12)=XXX(12)*0.982
      DO 35 I=1,12
   35 AM=AM+XXX(I)
      AM=AM/12.0
      DO 40 J=1,6
```

```
      DO 50 I=1,12
      XA(J)=XA(J)+XXX(I)*COS(30*I*J*.01744)
      XB(J)=XB(J)+XXX(I)*SIN(30*I*J*.01744)
   50 CONTINUE
      XA(J)=XA(J)/6
      XB(J)=XB(J)/6
      IF(J.EQ.6)THEN
      XA(J)=XA(J)/2
      XB(J)=XB(J)/2
      ENDIF
      A(J)=SQRT((XA(J))**2+(XB(J))**2)
      B(J)=57.3*ATAN(XA(J)/XB(J))
   40 CONTINUE
      N=-1
      DO 104 IMO=1,12
      DO 103 IDAY=1,IDA(IMO)
      N=N+1
      R=.5+N/30.44
      PARAM(IMO,IDAY)=FOURIE(R,A,B,AM)
  103 CONTINUE
  104 CONTINUE
      RETURN
      END
C
      REAL FUNCTION FOURIE(R,A,B,AM)
      DIMENSION A(6),B(6)
      REAL R
      FOURIE=AM+A(1)*SIN((30*R+B(1))*.01744)+A(2)*SIN((60*R+B(2))*.0174
     *4)+A(3)*SIN((90*R+B(3))*.01744)+A(4)*SIN((120*R+B(4))*.01744)+A(5
     *)*SIN((150*R+B(5))*.01744)+A(6)*SIN((180*R+B(6))*.01744)
      RETURN
      END
C
C     ------------------------------------------------------------------
C
C       SUBROUTINE TO PERFORM STATISTICAL CALCULATIONS ON DATA
C
      SUBROUTINE STAT(X,N,AVE,SDEV,CVAR,VALUE)
      DIMENSION X(70),VALUE(9),PCPT(9)
      DATA PCPT/5.,10.,20.,33.,50.,67.,80.,90.,95./
C
C     THIS SUBROUTINE CALCULATES THE MEAN, STANDARD DEVIATION AND
C     COEFFICIENT OF VARIATION.
      XTOT=0.
      SSX=0.
      DO 1 J=1,N
      XTOT=XTOT+X(J)
      SSX=SSX+X(J)**2.
    1 CONTINUE
      XL=FLOAT(N)
      SDEV=SQRT((SSX-(XTOT**2./XL))/(XL-1.))
      AVE=XTOT/XL
      CVAR=(SDEV/AVE)*100.
C
C     SORT VALUES IN ASCENDING ORDER
      NX=N-1
      DO 6 J=1,NX
      LEAST=J
      NB=J+1
      DO 5 K=NB,N
      IF(X(K)-X(LEAST))4,4,5
    4 LEAST=K
    5 CONTINUE
      XTEMP=X(LEAST)
      X(LEAST)=X(J)
      X(J)=XTEMP
    6 CONTINUE
C
C     CALCULATE MEDIAN AND PERCENTAGE POINTS
      DO 15 J=1,9
      EVENT=XL/100.*PCPT(J)
      IF(EVENT-1)7,8,8
    7 EVENT=1.05
    8 JK=IFIX(EVENT)
      DECPL=EVENT-FLOAT(JK)
      VALUE(J)=X(JK)+(X(JK+1)-X(JK))*DECPL
   15 CONTINUE
   16 RETURN
      END
C     ------------------------------------------------------------------
C
      SUBROUTINE OBJFUN(XX,YY,N,L,IOPTN)
C     PACKAGE FOR MEASURES OF MODEL PERFORMANCE
C     BASED ON WORK OF P.J.T.ROBERTS(1978) AND ADAPTED FOR USE IN THE
C     ACRU MODEL BY C.B.SCHULTZ WITH EXTRA ADDITIONS AS RECOMMENDED
C     BY PROF.R.E.SCHULZE,NOV.,1983.
C     THE MEAN,STANDARD DEVIATION,VARIANCE,CORRELATION COEFFICIENT,
C     COEFFICIENT OF DETERMINATION,COEFFICIENT OF MODEL EFFICIENCY,
C     STUDENT'S T VALUE REGRESSION COEFFICIENT AND BASE CONSTANT OF
C     OF REGRESSION EQUATION ARE PROVIDED FOR SIMULATED AND OBSERVED
C     FLOW VALUES. THE PRESENCE OF SYSTEMATIC ERRORS IS ALSO INDICATED
C     THE PACKAGE CAN BE USED FOR MONTHLY OR DAILY EVALUATIONS
C     DEPENDING ON OPTIONS CHOSEN IN THE MAIN PROGRAM.
C         IF ICOMPR = 0   THIS PACKAGE IS OMITTED.
C         IF ICOMPR = 1   AN ANALYSIS IS DONE FOR DAILY FLOWS
C         IF ICOMPR = 2   AN ANALYSIS IS DONE FOR MONTHLY FLOWS
C         IF ICOMPR = 3   ANALYSES ARE DONE FOR DAILY AND MONTHLY FLOWS
C     AN OPTION ALSO EXISTS FOR THE USE OF LOG. VALUES SHOULD THE
C     USER WISH TO PREVENT GIVING TOO MUCH WEIGHT TO HIGH FLOWS
C         IF LOGVAL = 0 ACTUAL VALUES ARE USED
C         IF LOGVAL = 1 LOGARITHMIC FLOW VALUES ARE USED
C     ******************************************************************
      DIMENSION XX(4000),YY(4000)
 9876 CONTINUE
C     INITIALIZATIONS
      SXY=0.
      SYSQ=0.
      SXSQ=0.
      SUMT=0.
      SUMY=0.
      SUMM=0.
      SXMY=0.
      DO 10 I=1,N
      IF (L.NE.1) GO TO 5
C     ------------------------------------------------------------------
C     CONVERT TO LOG VALUES IF REQUESTED.
C     ------------------------------------------------------------------
      XX(I)=XX(I)*1000.
      YY(I)=YY(I)*1000.
      IF (XX(I).LT.1.0)XX(I)=1.1
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```
      IF (YY(I).LT.1.0) YY(I)=1.0
      XVAL=ALOG10(XX(I))
      YVAL=ALOG10(YY(I))
      GO TO 6
    5 XVAL=XX(I)
      YVAL=YY(I)
C     ------------------------------------------------------------------
C     CALCULATE ARRAY TOTALS,SUM OF SQUARES AND SUM OF CROSS PRODUCTS
C     ------------------------------------------------------------------
    6 SUMX=SUMX+XVAL
      SUMY=SUMY+YVAL
      XSQ=XVAL**2.0
      YSQ=YVAL**2.0
      SXSQ=SXSQ+XSQ
      SYSQ=SYSQ+YSQ
      PXY=XVAL*YVAL
      SPXY=SPXY+PXY
   10 CONTINUE
C     ----------------------------------------------------------------
C     CHECK FOR ZERO ARRAYS
C     ----------------------------------------------------------------
      IF ((SUMX.GT.0.).AND.(SUMY.GT.0.)) GO TO 20
      AMENX=0.
      AMENY=0.
      CCOF=0.
      TTEST=0.
      RECO=0.
      BASE=0.
      SDEVY=0.
      VARY=0.
      SDY=0.
      VARX=0.
      SDX=0.
      EVAL=0.
      SDIF=0.
      GO TO 30
C     ----------------------------------------------------------------
C     CALCULATE MEAN,STD.DEVIATION,VARIANCE,CORRELATION COEFFICIENT
C     STUDENT'S T VALUE,REGRESSION COEFFICIENT AND BASE CONSTANT OF
C     REGRESSION EQUATION.
C     ----------------------------------------------------------------
   20 AMENX=SUMX/FLOAT(N)
      AMENY=SUMY/FLOAT(N)
      AX=SXSQ-((SUMX**2.0)/FLOAT(N))
      AY=SYSQ-((SUMY**2.0)/FLOAT(N))
      TOP=SPXY-((SUMX*SUMY)/FLOAT(N))
      CCOF=TOP/((AX*AY)**0.5)
      NCC=N-2
      BNC=FLOAT(NCC)
      TTEST=CCOF*(BNC**0.5)/((1.0-(CCOF*CCOF))**0.5(
      RECO=TOP/AX
      BASE=AMENY-(RECO*AMENX)
      SDEVY=(AY**0.5)*((1.0-(CCOF*CCOF))**0.50)
      VARY=(SYSQ/NCC)-(AMENY*AMENY)
      VARX=(SXSQ/NCC)-(AMENX*AMENX)
      SDX=VARX**0.5
      SDY=VARY**0.5
      DO 50 J=1,N
      XMMX=(XX(J)-AMENX)*(XX(J)-AMENX)
      XMY=(XX(J)-YY(J))*(XX(J)-YY(J))
      SXMMX=SXMMX+XMMX
      SXMY=SXMY+XMY
C     ----------------------------------------------------------------
C     CALCULATE COEFFICIENT OF DETERMINATION AND COEFFICIENT OF
C     MODEL EFFICIENCY.
C     ----------------------------------------------------------------
   50 CONTINUE
      CODETR = CCOF*CCOF
      EVAL = (SXMMX - SXMY)/SXMMX
      SDIF = ((SDX-SDY)/SDX)*100.0
C     ----------------------------------------------------------------
C     CHECK FOR SYSTEMATIC ERRORS.
C     ----------------------------------------------------------------
      ISYSER = 1
      IF(EVAL.LT.CODETR)ISYSER = -1
C     ----------------------------------------------------------------
C     OUTPUT OF STATISTICS OF MODEL PERFORMANCE
C     ----------------------------------------------------------------
      WRITE(6,420)
  420 FORMAT (1H0,42X,'STATISTICS OF PERFORMANCE OF ACRU MODEL'
     *,/,42X,39('-'),//,40X,'A COMPARISON OF SIMULATED AND OBSERVED FLOW
     *S',//)
      IF(IOPTN.EQ.1) WRITE(6,430)
  430 FORMAT(1X,52X,'FOR DAILY VALUES',//)
      IF(IOPTN.EQ.2) WRITE(6,431)
  431 FORMAT(1X,52X,'FOR MONTHLY VALUES',//)
      IF(L.EQ.1)WRITE(6,405)
  405 FORMAT(1X,12X,'LOG VALUES ARE USED THROUGHOUT',//)
      WRITE (6,414) SUMX,SUMY
  414 FORMAT(1X,14X,'TOTAL OBSERVED FLOWS ',23X,'=',F10.3,
     *//,1X,14X,'TOTAL SIMULATED FLOWS',23X,'=',F10.3,/)
      WRITE(6,421) AMENX,AMENY,CCOF,TTEST,RECO,BASE,SDEVY,VARX,VARY
  421 FORMAT (1X,14X,'MEAN OF OBSERVED FLOWS',22X,'=',F10.3,//
     *,1X,14X,'MEAN OF SIMULATED FLOWS                      =',F10.3,//
     *,1X,14X,'CORRELATION COEFFICIENT                      =',F10.3,//
     *,1X,14X,'STUDENTS T VALUE                             =',F10.3,//
     *,1X,14X,'REGRESSION COEFFICIENT                       =',F10.3,//
     *,1X,14X,'BASE CONSTANT FOR REGRN. EQN.                =',F10.3,//
     *,1X,14X,'STANDARD ERROR OF SIMULATED FLOW             =',F10.3,//
     *,1X,14X,'VARIANCE OF OBSERVED FLOW                    =',F10.3,//
     *,1X,14X,'VARIANCE OF SIMULATED VALUES                 =',F10.3,/)
      WRITE(6,422)SDX,SDY,SDIF,CODETR,EVAL
  422 FORMAT (1X,14X,'STANDARD DEVIATION OF X VALUES',13X,' =',F10.3,//
     *,1X,14X,'STANDARD DEVIATION OF Y VALUES               =',F10.3,//
     *,1X,14X,'PERCENTAGE DIFFERENCE IN STANDARD DEVIATION  =',F10.3,//
     *,1X,14X,'COEFFICIENT OF DETERMINATION                 =',F10.3,//
     *,1X,14X,'COEFFICIENT OF EFFICIENCY                    =',F10.3,//)
      IF(ISYSER)35,40,40
   40 WRITE(6,440)
  440 FORMAT(1X,14X,'NO SYSTEMATIC ERRORS DETECTED',//).
      GO TO 30
   35 WRITE(6,435)
  435 FORMAT(1X,14X,'***CAUTION*** SYSTEMATIC ERROR DETECTED ***')
   30 RETURN
      DEBUG SUBCHK
      AT 9876
      END
```