ANTECEDENT SOIL IN DESIGN RUNOFF VOLUME ESTIMATION

By SJ Dunsmore, RE Schulze & EJ Schmidt

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TABLE OF CONTENTS

TABLE OF CONTENTS (continued)

LIST OF TABLES

LIST OF TABLES (continued)

LIST OF TABLES (continued) Page

LIST OF FIGURES

LIST OF FIGURES (continued) Page

LIST OF FIGURES (continued) Page

LIST OF FIGURES (continued) Page

TERMINOLOGY

In the context of this report, the term design flood is used when neither flood volume or peak discharge are referred to specifically. The research results presented in this report refer to a daily runoff depth in response to a daily rainfall depth. Thus in the application of extreme value distributions to an annual maximum series of daily runoff and rainfall data, the daily design runoff depth and daily design rainfall depth for various probabilities of exceedance are derived. The daily runoff depth assuming uniform runoff response over the entire catchment area and given in the unit millimeters, was used throughout the report in preference to a runoff volume, to allow direct comparison of runoff per unit area between catchments and of runoff per unit rainfall between days. Unless otherwise specified runoff depths are for total flows as measured at the gauging weir which is the sum of stormflow or quick-flow, i.e. the direct runoff response, consisting of both surface and subsurface runoff, for a given rainfall event and baseflow which is the delayed subsurface response due to previous events.

1. INTRODUCTION

The South African Institute of Civil Engineers (1983) estimated the annual costs of building hydraulic structures on small catchments in South Africa at approximately R300 000 000. The expenditure due to overdesign and repairs of these structures is estimated to be a considerable proportion of this amount (Schulze, 1984a). The improvement of design flood volume and peak discharge estimation procedures is therefore vital.

It is usually due to the economics of design that engineers use simplified models involving averaged values for an entire catchment of spatially variable factors such as rainfall, slope and soil values. Since no practical model can account for all causative factors with certainty, situations arise where one or more methods present good results for some events, and yet cannot represent the runoff process adequately for other events on the same catchment. Similarly, the use of a different methods may improve these predictions while at the same time deteriorating other estimates which were satisfactory initially (Hiemstra and Reich, 1967). Hence, the choice of the design method is critical and often a problem.

One characteristic common to most design methods, however, is the assumption that the design flood will have the same return period as the design storm which produces it (Chapter 3). The use of average catchment conditions in many methods is based on the premise that a design flood with a return period approximately equal to the design storm will be produced (Cordery, 1970).It has, however, been long realised that this will not necessarily be the case in practice. Average catchment conditions are difficult to define on ungauged catchments, and factors such as initial and continuing abstractions from the rainfall depth may cause the return periods of the design storm and the resulting flood to differ (Cordery, 1970).

Many researchers have proposed that antecedent catchment wetness is one of the major factors influencing runoff generation from a rainfall event (Chapter 2). The extent of its significance, especially under design conditions, is at present unknown (Chapter 3). In current design procedures the antecedent wetness is either represented as a partial function of antecedent rainfall, such as in the SCS model (Chapter 4), or indirectly by a constant such as in the Rational method (Chapter 3). These representations, which are then considered as constants on each catchment, have been shown to vary from storm to storm (eg. Hjelmfelt, 1983, and French, Pilgrim and Laurenson, 1974, respectively), and much of this variation has been attributed to the inadequate representation of the antecedent catchment wetness.

In this study, two hydrological models for use on small catchments have been selected for comparison of their simulated daily runoff volume output for "design" events with corresponding observed daily runoff volume. Although an estimate of "design" peak discharge is usually also required, it is generally assumed there is a close association between the peak and the runoff volume and the results of this study are thus not limited to runoff volume determinations alone. The SCS model was chosen as it has been adapted for use in South Africa and is at present one of the more popular models in design flood estimation. The ACRU model was selected as it utilises the basic SCS runoff volume procedure, but also because it applies a conceptually based and more complex representation of the soil moisture balance. By comparing the output from the two models to recorded runoff events on a number of catchments representing humid, sub-humid and arid regions, a better understanding of the relationship between rainfall, runoff and antecedent soil moisture may be obtained.

Using these data, maximum daily rainfall and runoff series were generated for each catchment and a log-Normal extreme value distribution was fitted to each series enabling a study to be made of the daily rainfall and runoff frequencies. In addition, the same data were analysed to determine whether the simulated antecedent soil moisture component played a statistically significant role in the production of daily runoff from daily rainfall. A review of some of the concepts and theories related to the generation of runoff from rainfall, are first considered in the following chapter.

2. ANTECEDENT SOIL MOISTURE IN THE RAINFALL-RUNOFF PROCESS

It is intuitive that two identical storm events occurring on two catchments identical in every way, except that one is initially wet and the other dry, are likely to produce runoff events with different hydrograph characteristics. The catchment antecedent wetness is, in fact, considered by many to be one of the most influential factors in the rainfall-runoff process (eg. Richardson, Baird and Smerdon, 1969; Cordery, 1971; Hope, 1980). To obtain a better understanding of the importance of the antecedent soil moisture (ASM), some of the concepts and observations concerning this factor will be reviewed.

2.1 Concepts of stormflow

Hope (1980) grouped the theories of stormflow into two broad categories, namely

(a) those based on the infiltration and overland flow theory of runoff developed by Horton in 1933, and
(b) those based on the unit source area theories, which include the variable source area and the partial area theories.

The Horton theory is based on the assumption that stormflow is generated by rainfall excess, which is the rainfall failing to infiltrate the soil surface resulting in overland flow (Horton, 1933). Stormflow is thus conceived as widespread sheetflow, and the theory implies that most rainfall events exceed the infiltration capacity (Freeze, 1972). The model may thus be applicable to areas having low infiltration capacities and high intensity storms (Ward, 1975), and to areas of sparse vegetation cover, as in arid areas where sodic soils exhibit rapid crusting (Ward,1984).

The unit source area theories associate one or more of the following principles;

(a) the production of stormflow in a catchment is non-uniform,
(b) stormflow is not necessarily surface flow but may be derived from subsurface flow, or a combination of the two,
(c) the production of stormflow occurs only from certain areas of a catchment and not the whole catchment (Hope, 1980).

Freeze (1972) states that sole reliance on the Hortonian theory overemphasises the role of overland flow. He maintains that channel and subsurface flow are more amenable to deterministic modelling in that they provide more suitable representations of reality.

The variable source area theory concentrates on the role of subsurface stormflow in producing saturated overland flow. If the subsurface flow from upslope sources exceeds the transmitting capacity of the soil at a point, this water will rise to the surface to produce surface flow and so increase the area under surface flow. Hence, the portion of the catchment yielding stormflow shrinks and swells, depending on rainfall amount and antecedent soil moisture condition (Hewlett and Hibbert, 1967).

The partial area theory is based on the presumption that only certain portions of a catchment are effective in producing stormflow (Hope, 1980). Betson (1964) found that not only did storm runoff tend to occur from only a small part of the catchment, but that the size of the contributing area did not change under normal conditions. Dunne and Black (1970) noticed that storm runoff was only produced on small areas of the catchment slope where the water table reached the surface. They added that subsurface stormflow was not an important contributor to the total storm runoff.

Each of these theories has an application in practice, and the extent to which they can be applied is dependent on the particular catchment's characteristics such as relief, aspect, soil types and depths and rainfall characteristics. It is likely that a combination of these processes will apply to most catchments. Freeze (1980) suggests that the Horton mechanism is more common on the upslope sections of a catchment, while the partial area mechanism is more likely to be found on the flatter areas near channels. In a review of stormflow theories, Ward (1982) summarises these conflicting concepts (Figure 2.1), and he maintains that "...everyone except Horton may be seen to be partially correct most of the time"(Ward, 1982; p26).

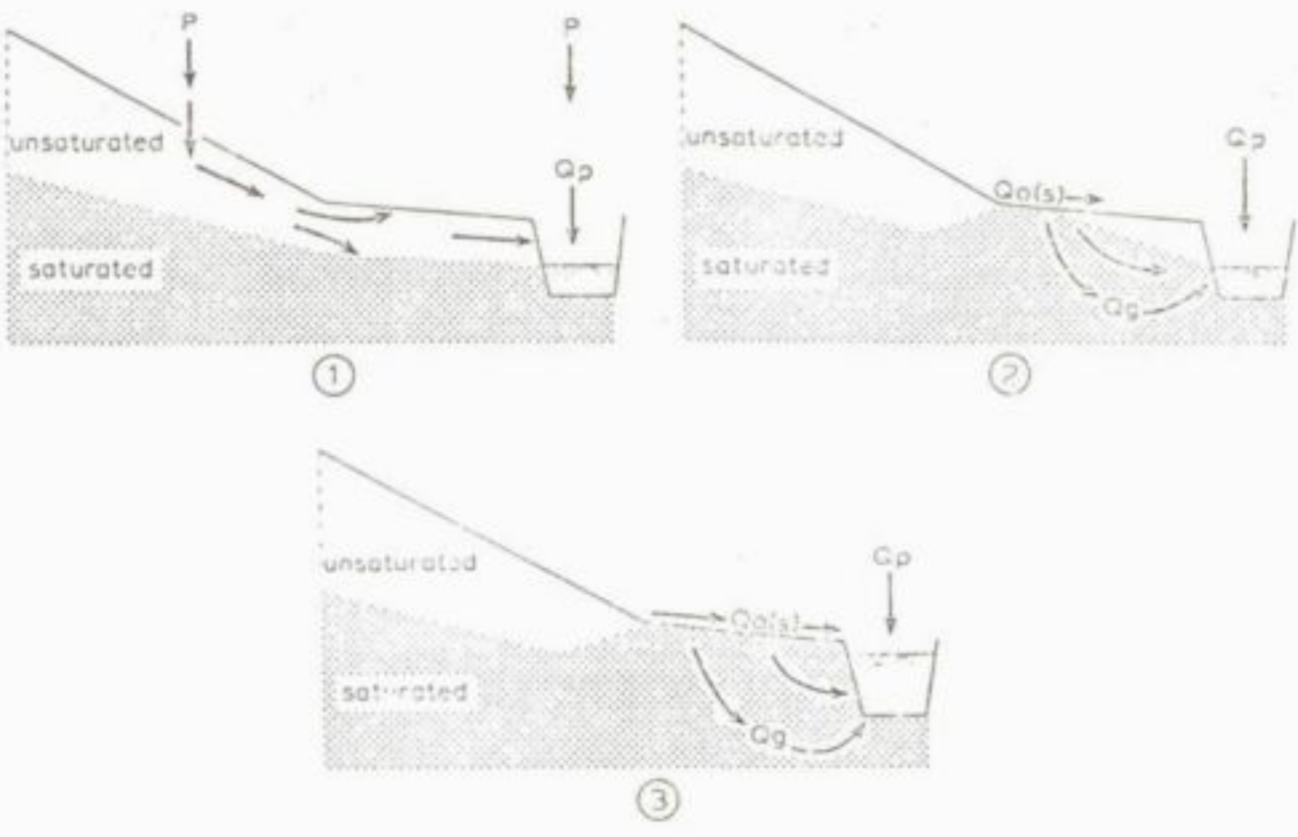


Figure 2.1 An integrated view of the response of streamflow to precipitation. Qp is direct precipitation onto the water surface, Qo(s) is saturated overland flow, and Qg is subsurface flow (Ward, 1982)

2.2 The effect of antecedent soil moisture on runoff

The theories of stormflow are based on the observations of the researchers cited and those of previous studies carried out in the field. In considering antecedent soil moisture, the question arises as to whether its effect on runoff response, especially with regards events approaching "design magnitude", is significant enough to be incorporated in modelling procedures.

The effects of ASM on the infiltration rate was described by Philip (1957) as being significant over a short period of time. As shown in Figure 2.2, different soil moisture levels will generate different infiltration curves, and as time increases, the curves tend towards a common asymptote, namely that infiltration capacity for a saturated soil. However, Philip maintains that at all times during infiltration the wetting front advances more rapidly for a higher initial soil moisture condition, resulting in a more rapid transmission of subsurface moisture. In a discussion of the Hortonian theory of infiltration, Betson (1964) suggested that if the infiltration curve of a catchment could be assumed constant for given soil and cover types, then antecedent soil moisture could be used to predict the initial infiltration capacity for a storm event.

In terms of statistical significance , Hills (1971) noted that initial soil moisture is the most significant soil based factor in the production of runoff. The other factors included soil bulk density and soil ecological status. Henninger, Petersen and Engman (1976) compared initial

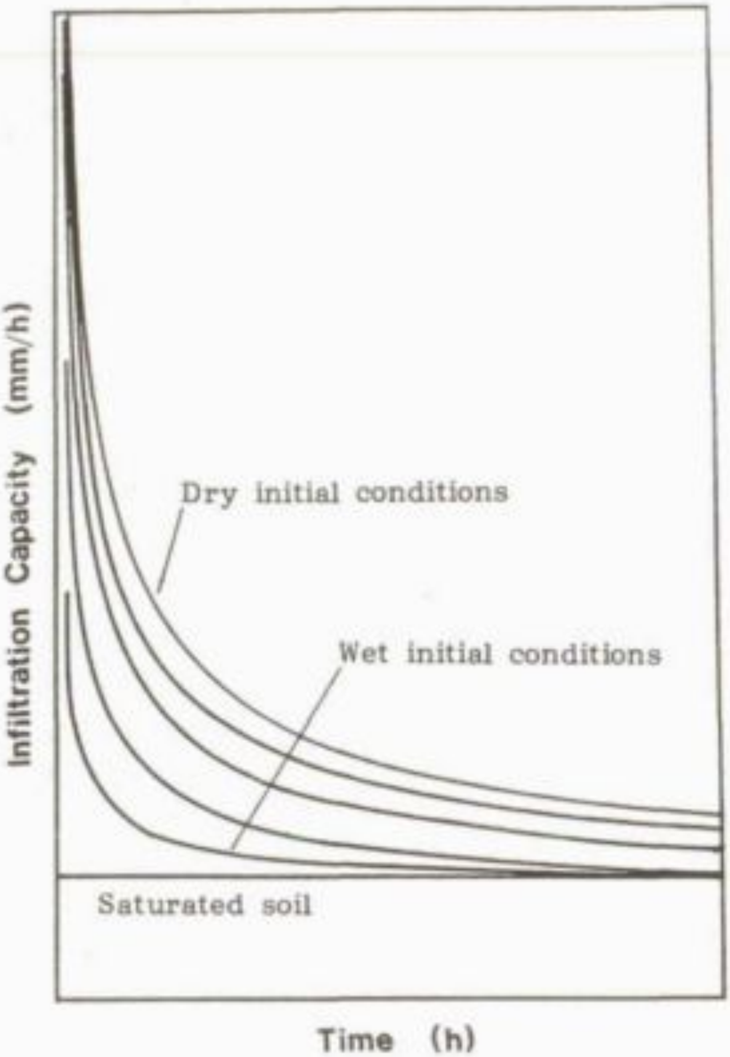


Figure 2.2 The influence of initial moisture content on infiltration rate (after Philip, 1957)

soil moisture contents to an index derived from cumulative weighted pan evaporation, and showed that while the latter made no significant contribution to runoff generation, that made by the soil moisture component was highly significant.

Under British conditions, it has been found that runoff volume (Q) can be estimated by subtracting the antecedent soil moisture deficit (SMD) from the storm rainfall, viz.

$$Q = R - SMD \qquad \ldots 2.1$$

where R is daily rainfall (Mandeville, O'Connell, Sutcliffe and Nash, 1970). SMD can be calculated from a water balance between daily rainfall and Penman estimate of actual evapotranspiration, assuming a catchment under certain percentages of short and long rooted vegetation and riparian areas.

Lynch, Corbett and Sopper (1977) noted that changes in high antecedent moisture levels gave rise to significant changes in storm runoff, maximum peakflow and total storm runoff. From regression analyses on the data they obtained a good linear relationship between ASM and total stormflow.

Kavvas and Delleur (1984) performed a periodic statistical analysis of daily streamflow data in Indiana, USA. In their model they assumed the runoff to be a function of level of soil storage and time since the beginning of the hydrograph. Among other findings, their study showed that;

(a) the persistence properties of daily flows depend on the initial storage state of the catchment, and
(b) if the daily streamflow process is modelled as the release from a linear catchment storage, this release should depend on the state of the storage.

It would appear that there is an important place for antecedent soil moisture in the process of modelling runoff response. The problem then arises as to how to represent such a component in the model. The paucity of data requires the ASM to be simulated on a continuous basis, to be estimated for an event, or to be represented by an index of sorts.

2.3 The representation of antecedent soil moisture

The modelling of soil moisture in a catchment is a complex process, the main problem arising from its temporal and spatial variability. The main causes of this variability rest with both static factors, such as topography, soil series and vegetation cover, and dynamic factors such as amount and nature of the rainfall (Reynolds, 1970). Henninger et al. (1976), noticed that soil moisture varied significantly between soil series, and that the differences between moisture levels varied inconsistently with time.

Probably the most common procedure of side-stepping this problem in modelling is to adopt an "averaged" catchment condition. In lumped models, the catchment parameters are summarised as weighted means and the parameter values are then considered homogeneous, enabling the use of more simple moisture accounting techniques. Linsley, Kohler and Paulhus (1958) felt that the approach of employing catchment accounting techniques applied on a daily basis could yield very good results of runoff prediction, but the lack of computing facilities at that time made the process laborious. This gave rise to the development of indices of the antecedent moisture status, and parameters such as base flow in the stream prior to the storm, days since the last rain and other similar indices were explored (Linsley, 1967).

In 1951, Kohler and Linsley predicted that the rate at which moisture is depleted from a catchment is roughly proportional to the amount of moisture in storage. They developed an index based on an exponential depletion of the soil moisture between periods of rainfall. The index is given by

$$API_t = API_o \cdot k^t \qquad \ldots\ 2.2$$

where API_o is the initial antecedent precipitation index, API_t is the reduced value after t days, and k is a recession factor. API_t is theoretically dependent on the rainfall over an infinite period, but if a reasonable initial value is chosen the calculated index should be close to the true value (Linsley et al., 1958).

Because of its simplicity, many researchers have incorporated the API method into their models as a means of representing the antecedent soil moisture. Richardson et al. (1969) renamed it the antecedent retention index (ARI) in their fine time interval model developed to simulate runoff hydrographs. In the design situation, Cordery (1970) used an API to determine initial loss during design storms to investigate the effects of such losses on the return period of the design flood.

The Natural Environment Research Council (NERC,1975) defined a catchment wetness index (CWI) in their runoff model based on a five day API and a soil moisture deficit (SMD) as follows ;

$$CWI = 125 + API_5 - SMD \qquad \text{... 2.3}$$

where the constant 125 ensures a positive value of CWI. Lynch and Corbett (1982) utilised a catchment's antecedent flow rate as an index of the catchment moisture status. They hypothesised that the measured baseflow prior to the storm would give a better indication of the average catchment condition since its amount is dependent on all the hydrologic processes involved in the rainfall-runoff conversion.

In all cases, the antecedent moisture condition, represented by an index, proved to have a significant effect on stormflow generation. The API is, however, only an approximation of the soil moisture status (Linsley, 1967). Research by Kohler and Richards (1962) on techniques of calculating soil moisture produced the concept of two soil moisture levels with the upper being depleted by evapotranspiration at the potential rate and the lower at a rate proportional to the ratio of the residual soil moisture to the total capacity of the lower zone. In addition they developed the concept of multicapacity accounting, based on the premise that the average soil moisture deficiency for the catchment is best derived by weighting the simultaneous values obtained by separate calculations with different assumed storage capacities.

The modelling of soil moisture incorporates the estimation of the potential and actual evapotranspiration as well as the modelling of the moisture redistribution in the root zone (Nixon, Lawless and McCormick, 1972). Schulze (1984b) describes a soil moisture model based on these premises, and accounts for both saturated redistribution and unsaturated redistribution of soil moisture movement.

In the literature therefore, antecedent soil moisture has either been represented by an index, usually based on antecedent precipitation, or by estimations from budgeting techniques. Whatever the method used, the researchers have concluded that the role of antecedent soil moisture in the rainfall-runoff process is an important one. The question now arises as to how important it is in design flood estimation.

3. DESIGN FLOOD ESTIMATION

In South Africa flow records for small catchments, eg. up to 15 km² (Witwatersrand Hydrological Research Unit, 1972), are generally scarce and often only cover a short period of time. Where flow records are available they can be used to estimate design flows in ungauged catchments of similar climate, land use and physiography in the local area. However, in most cases parametric methods are used in which the design flows are estimated on the basis of catchment characteristics and local rainfall data. Rainfall records are more widely available than runoff records and usually cover a longer period of record (Larson and Reich, 1973). Once a record of runoff events has been simulated from the rainfall record a frequency analysis may then be performed on the simulated record and the event corresponding to the design frequency of occurrence can then be obtained.

An immediate problem facing an engineer in the design of a structure which is affected by the hydrology of a catchment is the selection of an appropriate flood estimation technique. Recent years have seen increasing numbers of design techniques becoming available, and yet, despite considerable research being conducted on these techniques, little information is available on the general effects of catchment modification on flood control (Campbell, Ward and Middleton, 1986). The selection of a design method then becomes a difficult task and the designer may not always be confident of the results obtained from the method which has been chosen.

3.1 Choice of method

Apart from the cost of applying a design method, the two main factors affecting the engineer's choice of method are the input data required and the accuracy of the output desired. Frequently the design methods are applied using insufficient data, and although the engineer is usually aware of these deficiencies, he is seldom able to estimate their effects on the results produced. Furthermore, even with adequate data, it is not always possible to assess the accuracy of the hydrological design (Campbell et al, 1986).

The results from a survey conducted by Campbell et al (1986) showed that the main problems associated with the use of flood estimation techniques are the availability of adequate data, the lack of familiarity with the different techniques and the lack of perception of accuracy. They noted that although there is a marked tendency to move away from the Rational method, there is general concern about the suitability and accuracy of all the techniques currently in common use.

3.2 Methods in common practice in South Africa

The Witwatersrand Hydrological Reserach Unit (1972), the Natal Provincial Administration (NPA) design manual (1981), and the National Transport Commission (NTC) road drainage manual (1983) each recommend that the use of statistical methods be preferred to the design methods mentioned below if suitable historical rainfall and flow records exist. However, since in South Africa such data are scarce for small catchments, methods of estimating design floods from design rainfall must be employed. From their survey on the use of flood estimation techniques in South Africa, Campbell et al (1986) state that although the Rational method is still the most commonly used method, the uses of the Time-Area, SCS and Kinematic methods are on the increase. A summary of their results is shown in Table 3.1.

Table 3.1 Statistics on the use of flood estimation techniques on small catchments in South Africa (after Campbell et al. 1986)

Question	Rational method (%)	Time-area (%)	SCS (%)	Kinematic (%)	Other (%)
Use of technique*	90	34	30	10	26
Reason for use**					
Easy to use	85	61	56	27	57
Not familiar with other techniques	18	17	9	9	7
Technique sufficiently accurate	55	50	38	18	46
Where used**					
Land-use					
- Urban	80	64	44	36	39
- Agricultural	52	58	75	45	71
- Veld	57	64	66	27	75
- Afforested	28	31	50	9	50
- Mining	15	19	19	9	14
- Other	16	10	12	18	25
Catchment size					
- 0 to 1 km^2	64	47	66	55	36
- 1 to 10 km^2	85	64	69	64	46
- 10 to 100 km^2	34	55	44	45	75
Type of analysis**					
Peak flow	81	72	67	73	68
Runoff volume	42	59	42	64	57
Storm hydrograph	12	38	28	55	57
Problems with technique**					
Insufficient data	35	25	28	18	43
Lack of computer	4	11	0	0	7
Not familiar with technique	0	3	6	27	0
Other	9	11	28	9	25

Based on : * Percentage of respondents using flood estimation techniques
** Percentage of respondents using this technique

3.2.1 The Rational method

Although the Rational method was developed initially for urban usage, it has become widely used on small rural catchments (French, Pilgrim and Laurenson, 1974). In the formula

$$q_p = cIA \qquad \ldots 3.1$$

q_p is the peak discharge resulting from a storm of mean rainfall intensity, I, on a catchment of area A. The runoff coefficient, c, represents many factors influencing the rainfall-runoff relationship and reflects that part of the storm rainfall contributing to the peak flood (NTC, 1983). It has to account for catchment properties such as soil type and topography and conditions such as land-use, plant cover and antecedent wetness. Although considered a constant for a particular catchment, it has been shown to increase with increasing rainfall intensity (Schaake, Geyer and Knapp, 1967; French et al., 1974). The NTC road drainage manual maintains that there is no objective theoretical method for determining c, and as a result the subjective aspects of engineering judgement and experience play a large role in the successful application of this method (NTC, 1983). The method can be used to estimate quickflow volume by assuming a triangular hydrograph with time to peak and recession time equal to the concentration time of the catchment (NPA, 1981).

3.2.2 The SCS method

This method was first introduced to South African practitioners by Reich in 1962, but it was not until the publication of an adaptation of the model for South African conditions and graphical solutions by Schulze and Arnold (1979) that the method became a popular design flood estimation technique. It is recommended by both the NPA design manual (1981) and the NTC road drainage manual (1983) for use on catchments up to $10km^2$. This method will be further discussed in Chapter 4.

3.2.3 The Time-Area method

In this method as in the Kinematic and Rational methods, overland flow is assumed to be the sole source of storm runoff, where surface losses such as ponding and infiltration are abstracted from the rainfall to determine the excess rain which is routed over the catchment (Watson, 1981). Pondage is treated as an initial abstraction and is dependent on slope and land- use (Middelton, Ward, Haan and van Schalkwyk, 1985), while infiltration is accounted for on the basis of the Horton (1933) equation

$$f_c = f \quad + (f_0 - f \quad) e^{-kt} \qquad \ldots 3.2$$

where f_c is the infiltration capacity at time t, f_0 and f are the infiltration capacities at time t = o and t = , and k is a recession constant (Watson, 1981). Therefore, the three parameters that have to be estimated are f_0, f and k. These parameters may vary not only between catchments but they may also vary between storms. Their determination in the model is based on the SCS soil and antecedent soil moisture groupings.

Tests conducted by Watson show that the method is more suited to urban than rural catchments although he considered the comparisons of computed with observed hydrographs in rural catchments as generally satisfactory. Middleton et al. (1985), state the main disadvantage as being that the surface and channel velocities are assumed constant with time, and subsurface stormflow is ignored. They claim that peak discharges may be over-estimated because of the simplified routing procedures that are employed. In addition, criticisms levelled by Hawkins (1978) at the SCS method of antecedent moisture determination due to oversimplified procedures could, for the same reasons, be aimed at this method.

3.2.4 The Kinematic method

Middleton et al. (1985), define the kinematic equations as simplified versions of the dynamic equations of motion. The equations can be solved for overland or sheet flow and channel flow, and can be used in design for predicting runoff hydrographs from a catchment.

The method is based on two equations which are derived from the principles of conservation of mass and momentum. The component of note in these equations is that termed the net lateral inflow rate and is given by

$$q(x,t) = r(x,t) - i(x,t) \qquad \ldots 3.3$$

where $r(x,t)$ and $i(x,t)$ denote the rainfall rate and infiltration rate as functions of time, t, and space, x (Woolhiser, 1982). Woolhiser states that the amount, and temporal and spatial distributions of the lateral inflow exert the most significant influence on the runoff hydrograph, and so considers errors in estimating infiltration the most serious in catchment response simulation.

In applying the kinematic equations to a complex catchment, the user must first decide on a method of spatial representation of the catchment. Secondly, the parameters of hydraulic resistance and infiltration must be selected. Finally, the selection of the appropriate numerical methods is required to solve the equations. This method can only really be solved by computer although graphical solutions for simple catchments have been published (Green and Stephenson, 1982). Disadvantages lie in the difficulty of understanding the methodology and in the amount of input data required (Middleton et al., 1985). However, the method has been shown to give good results but is more suited to urban catchments where the selection of infiltration and hydraulic resistance parameters are easier.

From the above discussion it would seem, therefore, that one of the main problems facing the engineer at present is the choice of the design method. The lack of familiarity with the different techniques and the difficulty in determining the accuracy of the results could be largely due to the degree of subjectivity involved in the estimation of some of the input parameters.

3.3 Rainfall and runoff frequency

The main criterion in the choice of a design flood magnitude should be the desired lifetime of the structure involved. Considerations of the economics of construction, maintenance and risk of failure within the desired lifetime will affect the choice of the return period used in design. Most designers tend to use rainfall return periods as a basis for their flood predictions, thereby avoiding the fact that the resulting floods could have considerably different return periods (Hiemstra and Reich, 1967). It appears to be usual to expect that the flood peak will have the same design return period as the design storm from which it was derived (Cordery, 1970).

In examining concurrently observed return periods for rainfall and resultant flood peak discharge, Hiemstra and Reich (1967) chose 134 floods from 45 catchments in various areas throughout the USA and produced the results shown in Figure 3.1. No apparent relationship between the return periods of the corresponding events seem to exist, and they concluded that to predict an event of a particular return period on the basis of the rainfall event is "futile".

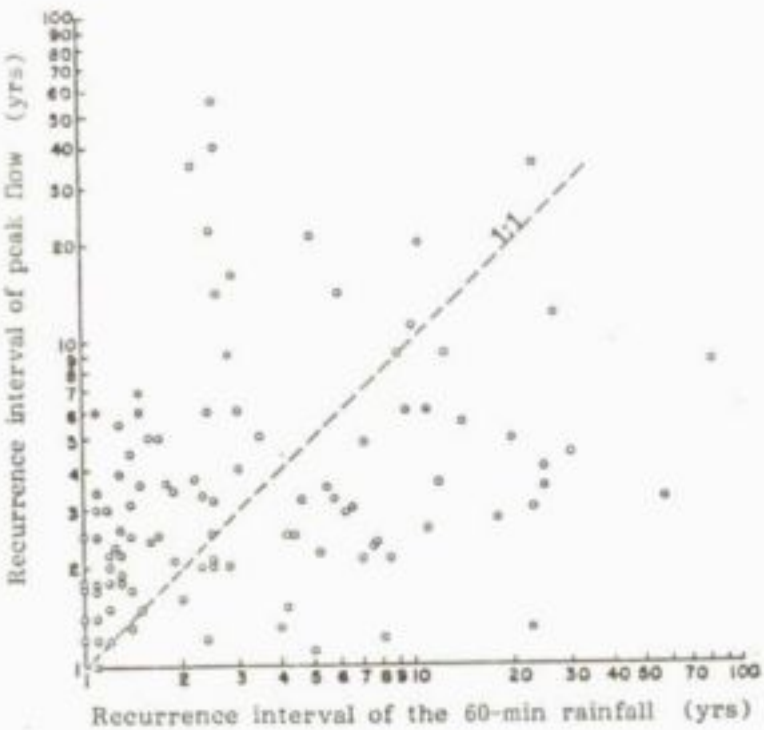


Figure 3.1 Peak flow recurrence intervals vs. recurrence intervals of associated 60 minute rainfalls (after Larson and Reich, 1973)

In their experimental examination of the Rational method, Schaake et al. (1967) made an attempt to study the assumption that the frequency of occurrence of the calculated flood peak is the same as that for the design storm intensity. This assumption is implied in the method and their results showed that it is "approximately correct".

Larson and Reich (1973) decided that the analysis represented in Figure 3.1 was not sufficiently sensitive to reveal the true nature of the relationship. In their approach they prepared a rank correlation diagram using rainfall and flow records from 20 small catchments. Using this, they determined that although the rainfall and runoff ranks were mostly unequal, there was a strong tendency toward equal ranking (Figure 3.2). Hence, they concluded,

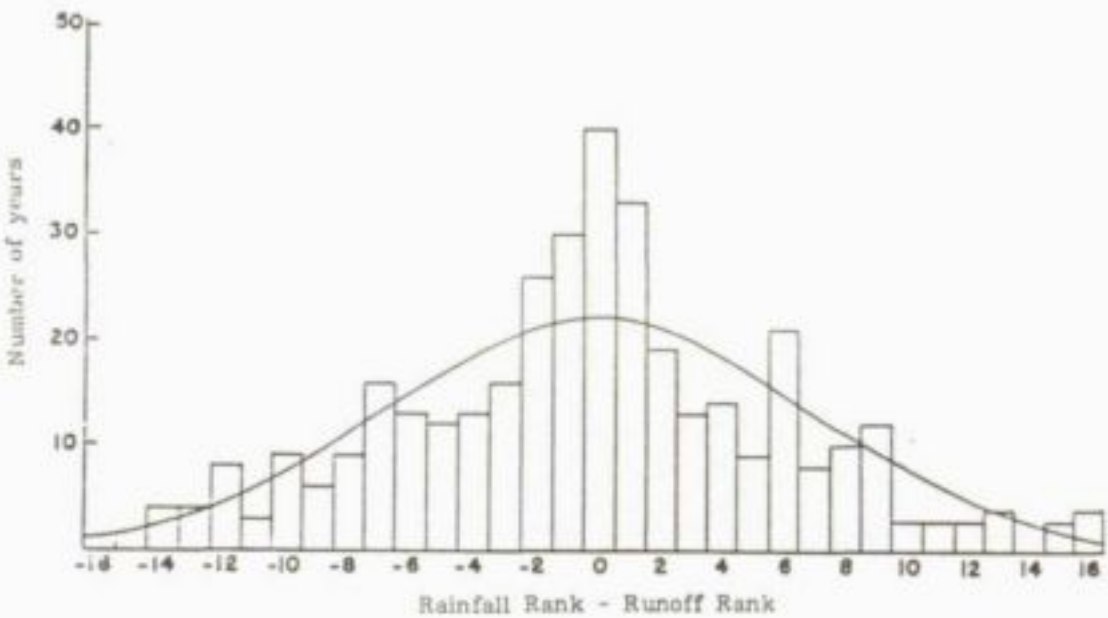


Figure 3.2 Distribution of the difference between rainfall and peak runoff ranks for test catchments in Pennsylvania, USA (after Larson and Reich, 1973)

that even though there is a wide variation between the two ranks, it is appropriate to assume that a design storm will produce a design flood of equal return period in the catchments considered.

It would appear, therefore, that the assumption of equal ranking for corresponding rainfall and runoff events is one that is acceptable for present design methods such as the Rational and SCS procedures. However, with an increasing demand for structures to be built on small ungauged catchments, the total expenditure is now considerable (Cordery and Webb, 1974). Hence, the need for more accurate predictions is emphasized, with the result that a closer look is now being taken at possible causal relationships.

3.4 Association of antecedent soil moisture and design runoff

From their studies of the Rational method, Schaake et al. (1967) observed that the dimensionless runoff coefficient, c, used in the formula as a constant representing catchment runoff potential, usually varies from storm to storm. They suggested that to account for this variability, the derivation of c would require some measure of the antecedent conditions. Similarly, Reich (1970) found that although no usable relation could be found between the extreme value statistics of rainfall and floods, there is a causal linkage. He implied that further research into the effects of antecedent moisture and time or season of the year may reveal some relationship between ASM and design runoff.

If one assumes that the flood peak is a function of other independent variables as well as rainfall, and if the probability distributions of these variables are known, then the probability distribution of the flood peak will be an integration of these distributions (Hiemstra, 1969). Cordery

(1970) claims that factors such as initial loss, continuing loss and storm duration would introduce joint probabilities which might cause the return period of the design flood to be different from that of the design storm. Hughes (1977) recognised that a given runoff volume can be produced by any of a number of rainfall volumes, depending on the loss rate. He describes the number of events which could produce that runoff volume as being finite and mutually exclusive, and that each of these events involves the simultaneous occurrence of a given loss rate and a given rainfall. Hence, the probability of occurrence of a given runoff volume due to a specific rainfall volume will be proportional to the joint probabilites of the rainfall amount and the loss rate, which is expressed by the antecedent moisture condition (Hughes, 1977).

Various attempts at determining a design flood prediction method have indicated the importance of an index of antecedent soil moisture. Packman and Kidd (1980) determined critical design values of antecedent catchment wetness for various catchments, and found that the higher the catchment's mean annual precipitation (MAP) the higher the design value of antecedent wetness. In their investigations of the relation between design storm and flood frequencies, Beaudoin, Rouselle and Marchi (1983) noted that the antecedent soil moisture condition is a major factor affecting the return period of the peak flow.

Diaz-Granados, Valdes and Bras (1984) derived a joint probability density function of storm duration and intensity which is sensitive to a mean initial soil moisture. They noticed that the antecedent soil moisture component in arid areas could be represented adequately by a mean value, a situation not true for humid areas. Cordery (1970), on the other hand, found that in areas of Australia with a MAP of greater than 1270 mm the effect of antecedent moisture condition on storm runoff becomes insignificant.

The role of ASM in design has therefore been recognised as a potentially highly significant factor in affecting the outcome of a design storm event. In fact, it has been stated that next to the amount and distribution of the rainfall, the antecedent moisture condition of the catchment is the most important controlling factor in storm runoff production (Cordery, 1971; Foroud and Broughton, 1981).

In using a bi-variate normal distribution to describe joint probabilities of rainfall depth and antecedent soil moisture Hughes (1985) notes the following:

(a) Although the importance of antecedent soil moisture in design runoff estimation has been realised, its representation is still based on available data and facilities.
(b) There are a large number of combinations of rainfall and antecedent soil moisture for the same joint probability, but not all will produce flood conditions. Hence, some cutoff level is required to ensure conditions to be considered for design purposes.
(c) If an output hydrograph is required then the rainfall input must be represented by such descriptors as storm duration, depth and profile, but for estimations of flood volume, storm depth and antecedent condition may suffice.
(d) The problem still exists as to how to incorporate these aspects into a technique which is realistic under practical design situations.

From the above review it becomes evident that much has yet to be learnt about the influence of ASM on design runoff generation. It remains to be seen whether effects of the storm characteristics, such as duration, intensity and profile, overshadow the significance of ASM, or whether the lumped modelling approach utilising only rainfall amounts and average catchment conditions is adequate in enabling the detection of effects of ASM on stormflow production. In addition, for purposes of design practice, it must be determined whether any trends exist between areas of similar and differing climate, to enable confident application of a design method in ungauged areas.

In the following chapter two models are described. With respect to this study they are essentially the same, except that one provides a more sophisticated account of antecedent soil moisture conditions. By comparing each model's estimates of runoff events to observed runoff events it is hoped that some light may be shed on some of the above mentioned problems.

4. DESCRIPTIONS OF MODELS USED

Two models were used to determine the significance of antecedent soil moisture in the estimation of design daily runoff depth from small catchments. In both models daily runoff is a function of the initial moisture status of the soil, but the determination of this moisture is very different between the two models. The first model to be discussed is that developed by the Soil Conservation Service (SCS) of the United States Department of Agriculture (USDA) as presented in the National Engineering Handbook, Section 4 (NEH-4, 1972), while the second is the more recent ACRU model developed by Schulze (1984b).

4.1 The SCS Model

The model described in NEH-4 (1972) was adapted to South African conditions by Schulze and Arnold (1979) for the estimation, in design practice, of the flood volume and rate of runoff resulting from a given rainfall event. Although a detailed description of the model is given by Schulze and Arnold (1979), a brief summary of those aspects used in this research will be given.

The SCS equation for the estimaton of stormflow volume is given by

$$Q = \frac{(P - I_a)^2}{(P - I_a) + S} \quad \text{for } I_a < P \qquad \ldots 4.1$$

where P is the total storm rainfall, I_a is the initial abstraction which can be defined in terms of S, the potential maximum soil moisture retention, by a coefficient c of S (NEH-4, 1972).

Hence

$$P = \frac{(P - cS)^2}{P - cS + S} \qquad \ldots 4.2$$

Although the coefficient c has been found to be dependent on such factors as rainfall amount, duration and intensity, drainage density and catchment slope (Schulze, George, Arnold and Mitchell, 1984), as well as season and antecedent moisture condition (Schulze and Arnold, 1979) it was felt that a value of 0.2, as suggested by NEH-4 (1972), would usually be used in design practice. Hence c was set at 0.2 for all applications of the SCS model in this research project.

S is an index of soil moisture deficit and is related to soil properties, land use and soil moisture status (Schulze, 1984b). For purposes of its determination it is defined as a function of a runoff Curve Number (CN), namely

$$S = \frac{25400}{CN} - 254 \qquad \ldots 4.3$$

CN, a dimensionless value ranging between zero and 100, is first derived for so-called "average" soil moisture status according to soil type and vegetation cover conditions. Thereafter it is adjusted according to the catchment wetness which is based on the total five-day antecedent rainfall. According to the time of year, a catchment is classified into antecedent moisture condition (AMC) groups, either as "wet" (AMC III), "dry" (AMC I) or "average" (AMC II). This classification and examples of CN adjustment are given in Table 4.1.

Table 4.1 Standard SCS antecedent moisture classification and Curve Number adjustment, with corresponding S in brackets (Schulze, 1984b)

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)

For the purpose of computer programming simplicity the Curve Number was adjusted according to the following equations derived by Sobhani (1976) :

$$CN_I = CN_{II}/(2.334 - 0.01334\ CN_{II}) \qquad \ldots 4.4$$

$$CN_{III} = CN_{II}/(0.4036 + 0.0059\ CN_{II}) \qquad \ldots 4.5$$

Major criticism has been aimed at this standard SCS method of accounting for antecedent moisture status by Hawkins (1978), who states that the discrete AMC classes should be more continuous, since with minor changes in antecedent rainfall at critical values they promote sudden shifts of CN with resulting "quantum jumps" in the calculated runoff. An example is given by Schulze (1982) who calculated that for a rainfall of 50.8 mm and a CN value of 80, the estimated stormflow is 2.8 mm, 14.2 mm and 29.5 mm for the AMC groups I, II and III respectively. A review of the method and further criticisms are given by Schulze (1982). However, irrespective of the model's weaknesses, it remains as one of the more popular design tools used on small (0 - 10 km²) catchments (SRK, 1984).

4.2 The ACRU Model

4.2.1 Concepts and structure of ACRU

The version of the ACRU model used in this research is the ACRU1 model presented by Schulze (1984b), but with somewhat modified output options added specifically for this research. ACRU1 was developed around the following basic aims (Schulze, 1984b) :

(a) It is a "conceptual physical" model; conceptual in that it assumes a one-dimensional system where the important processes are idealised and included in discrete time units; physical in that the ability of the soil to store and transmit water is represented explicitly and that vegetation water used is simulated realistically.

(b) It is a multi-purpose and multi-component model outputting either simulated runoff, supplementary irrigation requirements or seasonal crop yields for maize or sugarcane.

(c) It is a small catchments lumped model for use on catchment areas under 10 km^2.

(d) The model has daily time steps and uses daily input of climatic data such as rainfall and potential evaporation.

(e) The ACRU1 model was developed on the basis of daily multi-soil-layer moisture budgeting and is essentially an actual evapotranspiration model.

A summary of the concepts of the model in terms of input and objectives is given in Figure 4.1. As mentioned above, the hydrology of the ACRU1 model is focussed on the moisture budgeting on a daily time step, and the separation and redistribution of moisture in the soil profile is depicted

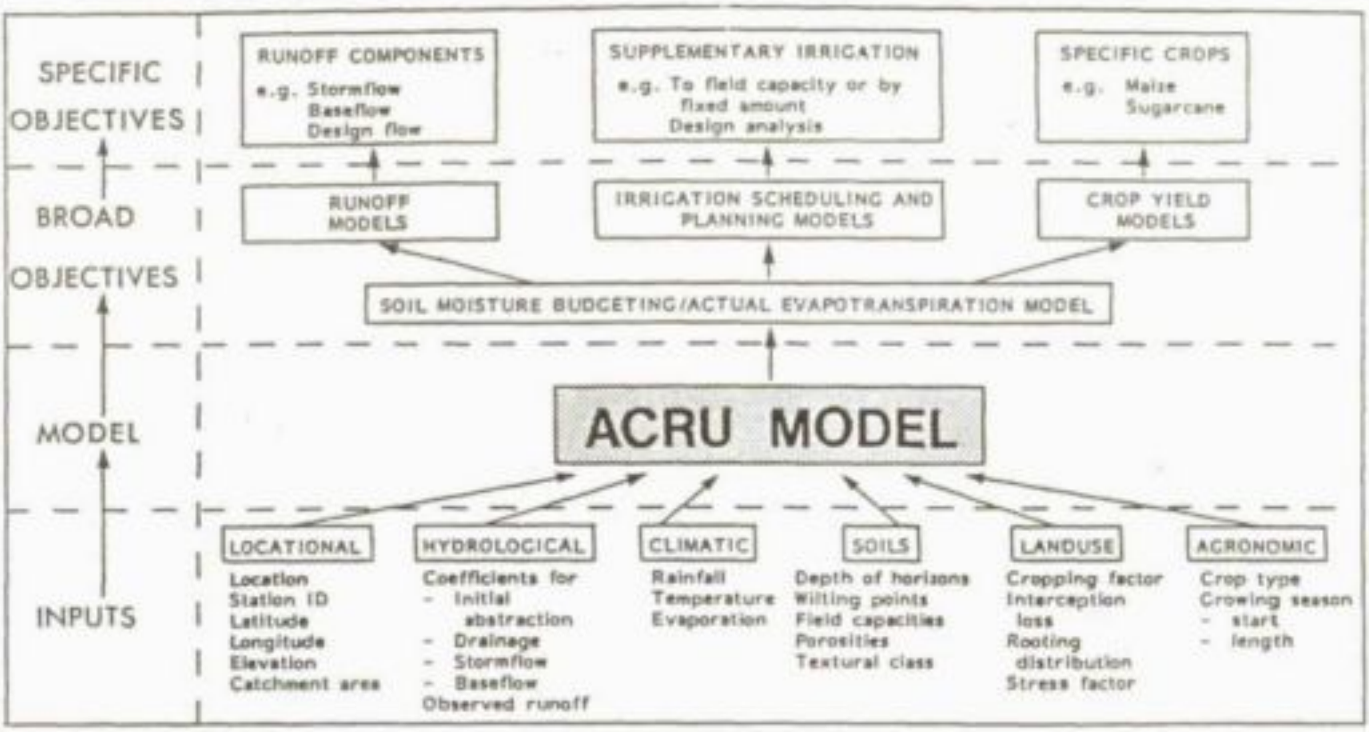


Figure 4.1 The ACRU1 model : concepts (Schulze, 1984b)

in Figure 4.2. Rainfall which is not abstracted as interception or direct runoff, enters into the A-horizon. Should the moisture in the A-horizon reach field capacity any further precipitation would drain into the B-horizon. Vertical drainage out of the system takes place once the B-horizon exceeds its field capacity. Evapotranspiration, which is dependant on atmospheric and vegetation demand, takes place from previously intercepted rainfall and simultaneously from the A- and B-horizons depending on rooting distribution and whether or not the vegetation is under moisture stress. In addition, saturated and unsaturated moisture redistribution may occur depending upon relative moisture gradients (Figure 4.2).

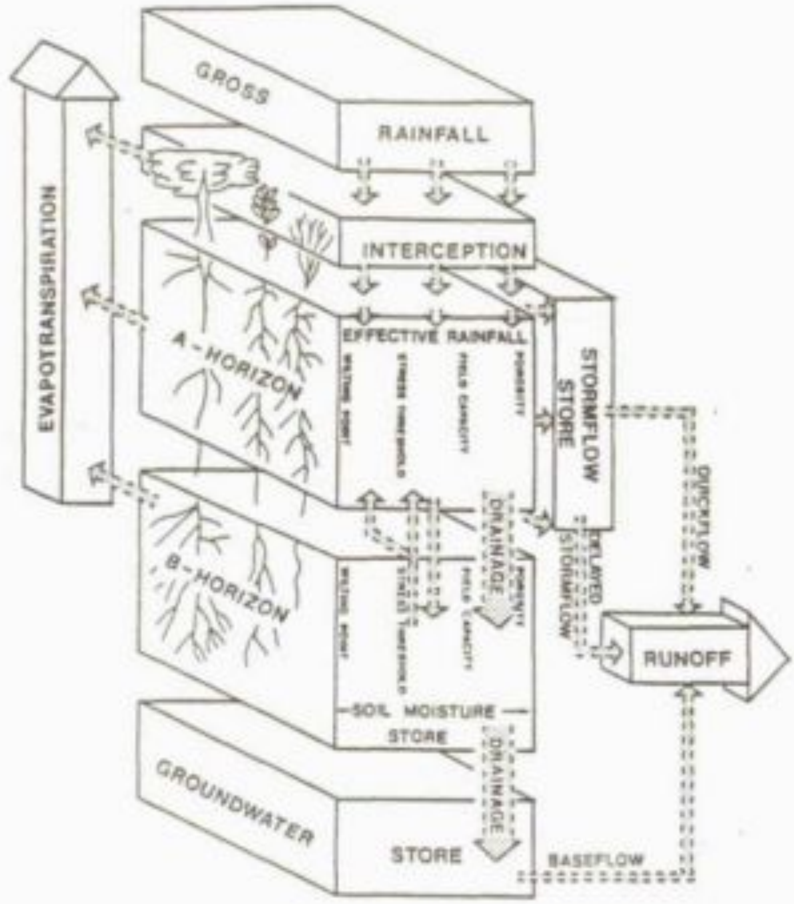


Figure 4.2 The ACRU1 model : general structure (Schulze, 1984b)

4.2.2 Input information

The model requires an input of daily rainfall from a representative gauge in or near the catchment to enable the various hydrological processes to be simulated. The quality of rainfall data is therefore of prime importance if accurate simulations are desired. However, the quality of the output is also very dependent upon the availability and accuracy in measurement of the various parameters listed in Table 4.2.

Table 4.2 Catchment information parameters in the ACRU model

Parameter	Parameter Label
Climatic Information	
Monthly mean of maximum air temperatures (°C)	TMAXD(I) , I=1,12
Monthly mean of mimimum air temperatures (°C)	TMIND(I) , I=1,12
Soils Information	
Depth of A-horizon (m)	DEPAHO
Depth of B-horizon (m)	DEPBHO
Wilting point of A-horizon (m/m)	WP1
Wilting point of B-horizon (m/m)	WP2
Field capacity of A-horizon (m/m)	FC1
Field capacity of B-horizon (m/m)	FC2
Porosity of A-horizon (m/m)	PO1
Porosity of B-horizon (m/m)	PO2
Vegetation Information	
Cropping factor	CAY(I) , I=1,12
Proportion of roots in the A-horizon	ROOTA(I) , I=1,12
Interception loss (mm)	VEGINT(I) , I=1,12
Runoff Parameters	
Coefficient of initial abstraction	COIAM(I) , I=1,12
Catchment curve number	CN2
Coefficient of quickflow response	RESPQF
Coefficient of drainage release	BFRESP
Coefficient of baseflow response	COFRU
Coefficient of drainage from A to B-horizons	ABRESP
Effective depth of runoff response (m)	SMDDEP

Being a moisture budgeting and actual evapotranspiration model, the accurate estimation of potential evaporation (PE) is vital. At best, PE is estimated from an input of daily A-pan values, and at worst is estimated from equations using monthly means of maximum and minimum temperatures (Table 4.2). Several temperature based equations for the estimation of potential evaporation are available in ACRU1. The equation selected for this research was that of Linacre's (1977), namely

$$PE = \frac{500T_m(100 - ALAT) + LINWIN(T_a - T_d)D_{mi}}{(80 - T_a)} \quad \ldots 4.6$$

where

PE = potential evaporation rate (mm/month)

LINWIN = wind factor

T_m = $T_a + 0.006$ ELEV, with

ELEV = elevation above sea level (m)

T_a = mean temperature (°C)

D_{mi} = number of days in the month

ALAT = latitude in degrees

$T_a - T_d$ = $0.0023\ ELEV + 0.37\ T_a + 0.53R + 0.53\ R_{an} - 10.9$ (°C)

R = mean daily range of temperature (°C), and

R_{am} = difference between the mean temperature of the hottest and coldest months of the year (°C).

This equation was chosen on the basis of results obtained by Clemence and Schulze (1982) and Schulze (1983) in that it provided better estimates of PE than the other well known temperature based methods.

The monthly value of PE provided by the equation is then transformed into daily values by a weighted interpolative technique which considers the PE values of the previous and following months. Pentad values of PE are then calculated and each day within a pentad are assumed to have equal values of daily PE (Schulze, 1984b).

With regard to soils information input, the soil profile comprises two "active" horizons in terms of root development and moisture extraction through evapotranspiration, and a groundwater store which is active only in the sense that it stores water draining below the effective rooting depth and releases this water slowly as baseflow (Figure 4.2). It is otherwise undefined pedologically. The three moisture retention constants which have to be determined are the porosity value (PO), the field capacity (FC) and the wilting point (WP) as shown in Table 4.2. Moisture in excess of the WP value is available to plants, and hence to evapotranspiration; moisture in excess of the FC value is available for saturated drainage; moisture between FC and WP may be redistributed according to soil water gradients between the two "active" horizons (Schulze, 1984b).

The occurrence of saturated soil moisture redistribution is determined as follows (Schulze, 1984b) : Saturated soil moisture redistribution may occur from one horizon to a lower horizon if the moisture level in the first horizon is above FC and greater than that of the lower horizon. This rate of drainage is exponential and can be set at a fraction of remaining excess water per day by the variable ABRESP and BFRESP for A to B and B to groundwater movements respectively (Table 4.2).

Information required on the catchments and land use and cover is described by the monthly variables CAY, VEGINT and ROOTA (Table 4.2). The cropping factor, CAY, is the coefficient by which the daily A-pan, or equivalent, value is multiplied to provide an estimation of the potential evapotranspiration under certain cover conditions. Its values therefore reflect on growth stages and canopy coverage.

Values of interception loss, VEGINT, in millimeters per rainday, are required for each month of the year in order to account for differences in interception losses with growth stages or dormancy. Similarly, twelve monthly values of ROOTA, the proportion of roots in the A-horizon, are required since soil moisture extracation takes place simulataneously from both horizons and in proportion to the rooting distributions. The fraction ROOTA varies seasonally and determines to a large degree at what rates the drying of the soil takes place in the two active horizons (Schulze, 1984b).

4.2.3 Runoff simulation by ACRU

As shown in Figure 4.2 output in the form of runoff consists of a daily stormflow depth and a daily baseflow depth component. The baseflow component is derived from a groundwater store which is recharged by drainage from the lower active soil horizons (Schulze, 1984b). Two response coefficients in the model, the first, ABRESP (Table 4.2), determining the rate of drainage from the A- to the B-horizon, and the second, BFRESP, determining the rate of drainage from the B-horizon to the groundwater store are determined subjectively at present since no readily available data are obtainable in Southern Africa. However, Schulze (1984b) suggests values around 0.5 for both coefficients, increasing with coarsness in soil texture.

A third coefficient, the baseflow response coefficient, COFRU, determines the rate at which water in the groundwater store is released as baseflow per day. Again, no data are available for this coefficient and from experience with the model Schulze (1984b) suggests a value of 0.02 as a starting value for small catchments. However, for the catchments considered in this project, these coefficients were varied according to catchment characteristics. For example, if it was apparent that baseflow was a major likely contributor to the observed flow then the values of COFRU and possibly BFRESP would be increased.

The ACRU1 models' daily stormflow estimation is based on the SCS stormflow equation (Equation 4.2) with some conceptual differences as noted by (Schulze, 1984b) :

(a) Rainfall intercepted by the vegetation is deducted from the total rainfall amount before being applied to Equation 4.2, and is therefore not considered part of the initital abstractions in the SCS model.

(b) The potential maximum retention of the soil, S, is calculated as a soil moisture deficit with respect to the soils porosity level, and hence the SCS Curve Number method is not considered at all.

(c) The depth of soil for which the moisture deficit is considered can be varied in the model in an attempt to account for different runoff producing mechanisms. For example, for predominantly short vegetation which is shallow rooted the deficit of a shallow soil layer may be more representative of the runoff mechanism, whereas, for taller, thicker vegetation cover with deeper roots a deeper effective soil may be considered. This variable is represented by SMDDEP in Table 4.2.

(d) A coefficient of quickflow response, RESPQF, has been included in the model to account for any lagged response caused by, for example, catchment size, soils with high or low interflow potential, as well as vegetation and stream channel patterns which may affect the response of a catchment to stormflow.

4.2.4 Modifications to the ACRU1 Model

Modifications to the model as presented by Schulze (1984b) have taken the form of additions of subroutines which then use the existing output of the model. The subroutines added are as follows:

(a) The subroutine SCS calculates the daily stormflow depth for each day of rainfall. The total five-day antecedent rainfall is calculated from the continuous daily rainfall record. The antecedent moisture grouping is determined according to season and the Curve Number for the average catchment condition (CN-II), which is read in with the other catchment input (Table 4.2), is adjusted according to the Sobhani (1976) Equations 4.4 and 4.5. The value of S is then calculated (Equation 4.3) and finally the daily stormflow depth is determined (Equation 4.2). This procedure is outlined in the flowchart in Figure 4.3.

It was also decided that, since continuous daily rainfall data are not always available for design purposes and that most practitioners apply CN-II to obtain their estimates of stormflow, the subroutine also outputs daily stormflow depth estimations for average catchment conditions.

(b) Subroutine RANK selects and ranks the five highest events in each year, for all years of record, of either rainfall, observed daily runoff depth or ACRU simulated daily runoff, depending on the option chosen. Irrespective of which option is chosen for ranking, corresponding values of the other two options, as well as the antecedent soil moisture deficit, the SCS daily runoff estimates and month of occurrence are stored by the subroutine for listing and use by other subroutines.

(c) Subroutines AMS and PDS each make use of the array of data generated by the subroutine RANK. Subroutine AMS considers only the maximum events of each year to generate an annual maximum series while subroutine PDS generates a partial duration series from the array by considering the highest N (= number of years of record) events. For each series the plotting positions are calculated for each event using the Weibull formula

$$P = \frac{m}{N+1} \qquad \text{... 4.7}$$

where P is the probability of occurrence, N is the number of years of record and m is the rank (from largest to smallest) of the event. In both subroutines, only the quantity ranked in the subroutine RANK is actually considered in the series.

(d) Three extreme value distribution programs have been adapted for use in the ACRU model. The subroutines GUMBEL (representing the Type 1 Extreme Distribution), LOGN (representing the two parameter Log-Normal Distribution), and LOGP (representing the three-parameter Log-Pearson Distribution) were adapted from Fortran programs presented by Kite (1977).

Data generated in the subroutine AMS is read into the selected extreme value subroutine and is fitted to the distribution. Therefore, depending on the option selected for ranking in RANK, either rainfall, observed daily runoff or ACRU simulated daily runoff is fitted to the distribution. A special case occurs when rainfall is selected for ranking and the SCS subroutine is used. Here the annual maximum rainfall series and the corresponding observed, ACRU and SCS runoff series are fitted to the selected distribution for comparison.

4.3 Discussion

The SCS procedure as described in this chapter corresponds to the original model described by the NEH-4 (1972). Even though many modifications to the model have been suggested, this is the version used in design practice (eg. NPA, 1981; NTC, 1983); hence the reason for its selection in this study.

For the purpose of this project, the ACRU model is viewed as an application of the SCS model with a more sophisticated representation of the soil moisture status. By comparing the performance of and the output from both models, it may be observed how the estimates of daily runoff are affected by antecedent soil moisture, and in doing so antecedent moisture data will be obtained, enabling any relationship between soil moisture and observed flow to be studied.

It must be noted here that, at this stage, the ACRU model is presently under continuous development and testing. Relationships between model parameters, such as the runoff coefficients, and catchment characteristics are still under research. However, with careful consideration of the catchment characteristics, it is believed that the values assumed for these parameters will be reasonable. A list of the catchments and their characteristics used in this study is summarised in the folowing chapter.

5. CATCHMENT AND DATA DESCRIPTIONS

Catchments representing a range of climates and sizes were required which had relatively long periods of recorded rainfall and streamflow. Since adequate flow records are scarce in South Africa it was decided to make use of available flow records for catchments in the USA. Six experimental catchments ranging in size from 1.2 to 10.4 km^2 and representing humid, sub-humid and arid regions were selected from those catchments maintained by the Agricultural Research Service (ARS) of the United States Department of Agriculture (USDA) for research purposes. The selected catchments are listed in Table 5.1 and their locations are shown in Figure 5.1.

Table 5.1 Catchments used in study

Location	ARS No.	Latitude	Longitude	Altitude (m)	Area (km^2)	MAP (mm)	MAR (mm)	Yrs on record
Coshocton	26 30	40°22' N	81°46' W	320	1.23	975	345	29
	26 35	40°23' N	81°49' W	335	10.40	975	294	29
Hastings	44 01	40°16' N	98°16' W	597	1.95	600	85	29
	44 03	40°18' N	98°16' W	585	8.44	600	71	29
Safford	45 01	32°55' N	109°48' W	1020	2.10	225	9.1	31
	45 03	32°55' N	109°48' W	1120	3.09	225	2.6	31

Input of rainfall and streamflow to the ACRU and SCS models are required as lumped daily values and since five of the six catchments have more than one rainfall measuring station, each set of daily rainfall measurements was weighted by the Thiessen polygon method to provide a catchment mean (Table 5.2). Data, other than rainfall and streamflow, required as input to the ACRU model, are listed in Table 4.2. To estimate daily evapotranspiration rates the model requires either daily pan estimates of evaporation or mean monthly maximum and minimum temperatures (Section 4.2.2). For the Coshocton catchments daily A-pan data were obtained from a meteorological station situated between catchments 2630 and 2635. Monthly means of daily maximum and

Table 5.2 Available Rainfall and Streamflow data

ARS Catchment No.	Raingauge No.	Years of Record	Weighting (%) by Gauge	Weighting equation for Rainfall ( ) denotes raingauge No.	Period and length of concurrent data (years)
2630	108	1938 - 1978	58		
	113	1940 - 1969	22	RAIN=0.58(108)+0.22(113)+0.20(116)	1941 to 1969 = 29
	116	1941 - 1970	20		
	Weir: OH-196	1938 - 1978			
2635	027	1938 - 1971	50		
	039	1943 - 1971	8	RAIN=0.50(027)+0.08(039)+0.42(091)	1943 to 1971 = 29
	091	1940 - 1971	42		
	Weir: OH-095	1943 - 1971			
4401	B36	1939 - 1967	100	RAIN=1.00(B36)	1939 to 1967 = 29
	Weir: W-3	1939 - 1967			
4403	B36	1939 - 1967	42	RAIN=0.42(B36)+0.58(C31)	1939 to 1967 = 29
	C31	1938 - 1967	58		
	Weir: W-8	1938 - 1967			
4501	R02	1939 - 1969	69	RAIN=0.69(R02)+0.31(R03)	1939 to 1969 = 31
	R03	1939 - 1975	31		
	Weir: W-I	1939 - 1969			
4503	R09	1939 - 1969	46	RAIN=0.46(R09)+0.54(R11)	1939 to 1969 = 31
	R11	1939 - 1971	54		
	Weir: W-IV	1939 - 1969			

Figure 5.1 Locations of the selected catchments

minimum temperatures were obtained for the Hastings catchments from a six year period of record (Table 5.3). Temperature values for the Safford catchments were obtained from isotherms mapped by Baker (1936) for the region (Table 5.4).

Table 5.3 Monthly means of maximum and minimum temperatures (°C) for Hastings, averaged for the years 1962 to 1967 (data from USDA-ARS, 1968; 1970; 1971; 1972a; 1972b; 1973)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Maximum	0.4	3.4	8.6	17.1	24.1	27.1	30.9	29.2	23.4	20.7	11.5	3.3
Minimum	-12.8	-2.8	-4.2	3.8	10.4	15.2	18.3	15.4	10.8	5.7	-2.2	-8.8

Table 5.4 Monthly means of maximum and minimum temperatures (°C) for Safford (from Baker, 1936)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Maximum	13.9	15.6	16.7	22.8	27.8	33.3	33.9	33.3	28.3	23.9	17.2	12.8
Minimum	-3.9	-1.1	1.1	3.3	6.7	11.1	17.2	16.7	11.7	5.6	1.1	-3.9

A description of the soils in each of the catchments was obtained from various USDA-ARS publications of which the USDA-ARS (1957) and the USDA-ARS (1968) provided most of the information shown in Tables 5.5 to 5.7. Additional information on the Coshocton soils (USDA-ARS ,1975) and the Hastings soils (USDA-ARS, 1973) provided further insight to soil types and their distributions, enabling detailed estimates of the soil depth and moisture parameters to be made at these two locations (Tables 5.5 to 5.6). Such detailed information on the Safford soils was not, however, available. The soil descriptions given by USDA-ARS (1957) could not be found amongst the descriptions given by the USDA-ARS (1968) for the area. An attempt was then made to match the soil types from the descriptions given by USDA-ARS (1957) to those presented by the USDA-ARS (1968) and the soil moisture constants for each soil type selected were averaged to obtain the final set of values as shown in Table 5.7.

Table 5.5 Soils input for Coshocton catchments 2630 and 2635

Catchment	Soils Description*	Soils Type	Area* (%)	DEPAHO (m)	DEPBHO (m)	WP1 (m/m)	WP2 (m/m)	FC1 (m/m)	FC2 (m/m)	PO1+ (m/m)	PO2+ (m/m)
2630	topsoil - silt loam to stoney loam texture, 0.15-0.20 m deep, moderate fine crumb structure	Keene silt loam (shallow phase)	20	.15	.46	.152	.215	.373	.370	.486	.436
	subsoil - moderate permeability, medium internal drainage, no impeding layer	Keene silt loam	10	.20	.53	.145	.232	.354	.359	.486	.486
		Muskingham silt loam	13	.20	.64	.135	.152	.329	.287	.486	.486
		Muskingham stoney loam	30	.18	.58	.069	.046	.231	.150	.412	.412
		Mixed silt loams	27	.18°	.56°	.133+	.133+	.330+	.330+	.486	.486
		Weighted values		.18	.56	.119	.136	.311	.281	.464	.464
2635	topsoil - silt loams, loams & stoney loams, 0.15 - 0.20 m deep, moderate fine crumb structure.	Keene silt loam	21	.20	.53	.145	.232	.354	.359	.486	.486
	subsoil - moderate permeability, medium internal drainage, no impeding layer	Keene silt loam (shallow phase)	13	.15	.46	.152	.215	.373	.370	.486	.486
		Muskingham silt loam	11	.20	.64	.135	.152	.329	.287	.486	.486
		Mixed silt loams **	19	.18°	.53°	.133+	.133+	.330+	.330+	.486	.486
		Mixed stoney loams	28	.18°	.53°	.69+	.046+	.231+	.150+	.412	.412
		Mixed loams	8	.18°	.53°	.177+	.177+	.270+	.270+	.434	.434
		Weighted values		.18	.53	.124	.146	.308	.281	.461	.461

* USDA-ARS (1957)
\+ Schulze (1984b)
** as for Muskingham stoney loam, USDA-ARS (1968)
° mean soil depths assumed
All other data obtained from USDA-ARS (1968)

Table 5.6 Soils input for Hastings catchments 4401 and 4403

Catchment	Soils Description*	Soils Type	Area** (%)	DEPAHO (m)	DEPBHO (m)	WP1 (m/m)	WP2 (m/m)	FC1 (m/m)	FC2 (m/m)	PO1+ (m/m)	PO2+ (m/m)
4401	topsoil - silt loam texture, medium to fine crumb structure; silty clay loam texture, medium to fine granular structure. 24% 0-0.13 m deep, 61% 0.13-0.20 m deep, 15% > 0.20 m deep subsoil - permeability - moderately slow 58%, moderate 31%, slow 11%: medium internal drainage	Colby silt loam	10.3	.20	.00	.207	.207	.411	.411	.486	.486
		Crete silt loam *	11.0	.36	.38	.228	.264	.383	.386	.486	.486
		Hastings silt loam	43.7	.23	.51	.228	.264	.383	.386	.486	.486
		Hastings silty clay loam	10.9	.13	.30	.255	.265	.391	.403	.432	.432
		Holdrege silt loam	9.4	.18	.51	.230	.233	.406	.405	.486	.486
		Nuckolls silt loam	1.9	.23	.46	.197	.220	.370	.359	.486	.486
		Nuckolls silty clay loam	2.3	.10	.28	.217	.214	.362	.365	.432	.432
		Judson silt loam **	9.6	.25	1.12	.132	.148	.354	.341	.486	.486
		Weighted values		.22	.47	.213	.219	.382	.341	.474	.424
4403	topsoil - silt loam - 86%; silty clay - 11%; silt loam silty clay loam complex - 3%; 22% < 0.13m; 58% 0.13-0.20m, 20% > 0.20m deep subsoil - permeability - moderately slow 56% moderate 41%, slow 3%	Colby silt loam	11.1	.20	.00	.207	.207	.411	.411	.486	.486
		Crete silt loam *	2.6	.36	.38	.228	.264	.383	.386	.486	.486
		Hastings silt loam	44.7	.23	.51	.228	.264	.383	.386	.486	.486
		Hastings silty clay loam	7.1	.13	.30	.253	.265	.391	.403	.432	.432
		Holdrege silt loam	14.5	.18	.51	.230	.233	.406	.405	.486	.486
		Nuckolls silty clay loam	3.3	.10	.28	.217	.214	.362	.365	.432	.432
		Judsons silt loam **	11.8	.25	1.12	.132	.148	.354	.341	.486	.486
		Mixed silt loam	4.9	.17	.48	.133+	.133+	.330+	.330+	.486+	.486
		Weighted values		.21	.50	.212	.209	.383	.338	.480	.460

* USDA-ARS (1957)
** USDA-ARS (1973)

* As for Hastings silt loam, USDA-ARS (1973)
All other moisture data from USDA-ARS (1968)

\+ Schulze (1984b)
** No recognised B horizon but very deep A horizons (USDA-ARS, 1968) split into two horizons.

Table 5.7 Soils input for Safford catchments 4501 and 4503

Catchment	Soils Description*	Soils Type	DEPAHO (m)	DEPBHO (m)	WP1 (m/m)	WP2 (m/m)	FC1 (m/m)	FC2 (m/m)	PO1 (m/m)	PO2 (m/m)
4501	topsoil - stoney gravelly loam and sandy loam, granular 0-0.56 m deep subsoil - stoney, gravelly silty loam; slowly permeable Impervious hardpan at 0.58 m	Unnamed "02" gravelly sandy loam - pit (a)	.48	.23	.055	.058	.107	.110	.412	.412
		- pit (b)	.04	.02	.036	.069	.116	.113	.412	.412
		Unnamed "03" gravelly sandy loam	.04	.55	.052	.053	.087	.106	.412	.412
		Unnamed "07" gravelly sandy loam	.05	.43	.053	.089	.120	.128	.412	.412
		Unnamed "08" gravelly sandy loam - pit (a)	.14	.22	.073	.095	.100	.131	.412	.412
		- pit (b)	.13	.24	.178	.199	.245	.268	.412	.412
		Unnamed "09" gravelly sandy loam	.20	.18	.105	.111	.167	.164	.412	.412
		Unnamed "12" stoney sandy loam	.05	.41	.057	.122	.123	.212	.412	.412
		Weighted values	.14°	.36°	.070	.100	.133	.209	.412	.412
4503**	topsoil - 0.08 to 0.15 m, sandy loam, loose granular subsoil - light sandy clay loam blocky, compact weakly cemented in places, moderately to slowly permeable	A-horizon = sandy loam B-horizon = sandy clay loam	.13°°	.41°°	.095	.148	.207	.255	.412	.330
		Unnamed "02" gravelly sandy loam	.05	.62	.071	.066	.165	.165	.412	.330
		Unnamed "08" v. gravelly sandy loam	.14	.45	.073	.094	.131	.144	.412	.330
		Weighted values	.11	.49	.080	.103	.168	.188	.412	.335

* USDA-ARS (1957)
** Soils given by USDA-ARS (1957) are not described in USDA-ARS (1968). Therefore soils slected from USDA-ARS (1968) were chosen on basis of description in given in USDA-ARS (1957).

\++ soil descriptions given in USDA-ARS (1957) did not suit any of those given in USDA-ARS (1968). Moisture values were therefore those recommended by Schulze (1984b) for sandy and sandy clay loams.

° arithmetic mean of the above mentioned depths
°° means assumed from depths of soils in Safford, Arizona (USDA-ARS, 1968)

Vegetation type and distribution for the Coshocton catchments (Table 5.8) were obtained from the USDA-ARS (1963) and similar information was found for the Hastings catchments (Table 5.9) in USDA-ARS (1973). In contrast to the relatively dense vegetation at Coshocton and Hastings, both the Safford catchments were bare over 75 to 90 per cent of their areas, and what vegetation there was consisted mostly of shrubs (USDA-ARS, 1957).

Table 5.8 Vegetation type and per cent distribution for the Coshocton catchments (USDA-ARS, 1963)

Catchment	2630				2635			
Years	1945	1957	1959	mean(%)	1945	1957	1959	mean(%)
Maize +	7.2	4.0	0.0	4.0	7.0	9.0	9.5	8.5
Wheat *	0.7	12.0	9.5	7.0	9.0	11.0	10.5	10.2
Meadow °	35.3	23.0	27.4	29.0	20.2	19.0	19.6	19.6
Pasture °	24.2	28.0	30.1	27.0	22.0	19.8	19.2	20.3
Idle land °	-	-	-	-	6.0	5.0	5.0	5.3
Woodland	27.9	28.0	28.0	28.0	31.8	31.8	31.8	31.8
Farmyards/Roads	4.7	5.0	5.0	5.0	4.0	4.4	4.4	4.3

\+ Maize cut by September 23
* Wheat cut by July, followed by meadow
° Meadow consists of legumes, grass and weeds,
pasture consists of grass and weeds of same height
idle land consists of grass and weeds of varying height
(USDA-ARS, 1963)

Table 5.9 Vegetation type and per cent distribution for the Hastings catchments (USDA-ARS, 1973)

Catchment	4401			4403			
Years	1938-55	1957-67	mean(%)	1938-46	*1955-60	1961-67	mean(%)
Maize	27.6	7.5	19.8	28.0	12.5	3.8	14.8
Sorghum	3.1	21.2	10.3	4.7	15.4	22.5	14.2
Oats/Barley	16.8	1.2	10.6	13.2	2.4	1.9	5.8
Wheat	24.7	20.2	22.9	18.8	18.3	17.2	18.1
Fallow	3.3	18.5	9.4	4.2	13.5	17.2	11.6
Lucerne	1.5	2.1	1.7	2.1	8.7	8.6	6.6
Pasture	15.6	18.3	16.7	17.6	20.7	20.8	19.7
Meadow	1.7	4.0	2.6	4.7	2.9	2.9	3.5
Sudan +	2.5	3.1	2.7	3.3	1.4	2.2	2.3
Farmyards/Roads	3.1	3.7	3.3	3.1	4.2	3.0	3.4

* yrs 1947-54 not on record
\+ includes millet and drilled sorghum

The ACRU model requires vegetation information in the form of monthly mean values of the crop factor, the proportion of roots in the A-horizon and rainfall interception loss (Table 4.2). Crop factors were assigned to each land cover type in each catchment as shown in Tables 5.10 and 5.11. These values were then weighted according to the mean percentage areas of the different land uses determined in Tables 5.8 and 5.9. Crop factors for the Safford catchments were assigned the monthly values as shown in Table 5.12.

Averaged monthly values of rooting depth, represented as a proportion of the roots in the A-horizon, are given in Table 5.13 Monthly values of daily interception loss, envisaged as the difference between gross rainfall and net rainfall entering the soil on a rainday, are given for each catchment in Table 5.14. These factors were all estimated on the basis of crop type, stage of growth in each month and climate.

Table 5.10 Crop factors for the Coshocton catchments

Land Use	2630* %	2635* %	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Maize	4.0	8.5	.35	.35	.40	.40	.55	.65	.80	.90	.80	.40	.40	.35
Wheat	7.0	10.2	.35	.35	.35	.45	.70	.95	.65	.45	.45	.40	.40	.35
Meadow	29.0	19.6	.40	.40	.55	.75	.85	.85	.85	.85	.80	.75	.50	.40
Pasture	27.0	20.3	.40	.40	.55	.75	.85	.85	.85	.85	.80	.75	.50	.40
Idle land	0.0	5.3	.40	.40	.55	.75	.85	.85	.85	.85	.80	.75	.50	.40
Woodland	28.0	31.8	.40	.40	.40	.40	.50	.70	.75	.75	.75	.60	.40	.40
Farmyards/ Roads	5.0	4.3	.30	.30	.30	.30	.30	.30	.30	.30	.30	.30	.30	.30
2630			.39	.39	.48	.59	.70	.78	.78	.77	.74	.65	.45	.39
2635			.39	.39	.46	.56	.67	.77	.77	.76	.73	.62	.44	.39

* Percentages from Table 5.8

Table 5.11 Crop factors for the Hastings catchments

Land Use	4401* %	4403* %	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Maize	19.8	14.9	.35	.35	.40	.40	.55	.65	.80	.90	.80	.40	.40	.35
Sorghum °	10.3	14.2	.40	.40	.40	.40	.40	.70	.90	.80	.50	.40	.40	.40
Oats/Barley	10.6	5.8	.40	.35	.35	.45	.75	.80	.65	.45	.45	.45	.45	.45
Wheat	22.9	18.1	.35	.35	.35	.45	.70	.95	.65	.45	.45	.40	.40	.35
Fallow	9.4	11.6	.50	.50	.50	.50	.50	.50	.50	.50	.50	.50	.50	.50
Lucerne °	1.7	6.6	.50	.50	.50	.65	.85	.85	.85	.85	.85	.65	.50	.50
Pasture °	16.7	19.7	.40	.40	.55	.75	.85	.85	.85	.85	.80	.75	.50	.40
Meadow °	2.6	3.5	.40	.40	.55	.75	.85	.85	.85	.85	.80	.75	.50	.40
Sudan °	2.7	2.3	.40	.40	.40	.50	.75	.90	.70	.50	.40	.40	.40	.40
Farmyards/ Roads	3.3	3.4	.30	.30	.30	.30	.30	.30	.30	.30	.30	.30	.30	.30
4401			.39	.38	.42	.50	.66	.76	.73	.66	.60	.49	.44	.40
4403			.44	.40	.44	.52	.65	.75	.74	.68	.61	.51	.44	.41

* Percentages from Table 5.9
° Values derived from Doorenbos and Pruitt (1977)

Table 5.12 Crop factors for the Safford catchments

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
4501/3	0.45	0.45	0.45	0.45	0.45	0.50	0.50	0.50	0.50	0.45	0.45	0.45

Table 5.13 Proportion of roots in the A-horizon, ROOTA(I)

Catchment	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2630	.98	.98	.95	.65	.60	.60	.60	.60	.65	.75	.90	.98
2635	.98	.98	.90	.60	.60	.60	.60	.60	.60	.70	.90	.98
4401	.95	.95	.90	.80	.70	.70	.70	.70	.80	.80	.90	.95
4403	.95	.95	.90	.80	.70	.70	.70	.70	.80	.80	.90	.95
4501	.90	.90	.90	.90	.90	.90	.90	.90	.90	.90	.90	.90
4503	.90	.90	.90	.90	.90	.90	.90	.90	.90	.90	.90	.90

Table 5.14 Vegetation interception loss, VEGINT(I), in mm/day

Catchment	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2630	.90	.90	1.00	1.20	1.30	1.45	1.20	1.35	1.45	1.45	.90	.90
2635	.90	.90	1.00	1.20	1.30	1.45	1.20	1.35	1.45	1.45	.90	.90
4401	.80	.80	.50	.50	1.10	1.10	1.10	1.10	1.00	.80	.80	.80
4403	.80	.80	.50	.50	1.10	1.10	1.10	1.10	1.00	.80	.80	.80
4501	.30	.30	.30	.30	.30	.30	.30	.30	.30	.30	.30	.30
4503	.30	.30	.30	.30	.30	.30	.30	.30	.30	.30	.30	.30

The remaining input required by the ACRU model are the runoff coefficients listed in Table 5.15. With the exception of the SCS Curve Number (CN2), each of the factors was assigned initial values. These were subsequently altered in accordance with the catchments' response characteristics. For example, all the selected catchments have moderate to high quickflow response factors (RESPQF) by virtue of their areas being small, their storm rainfall amounts being relatively high (in the case of the Coshocton and Hastings catchments), or their vegetation being sparse (as in the Safford catchments). The coefficients of drainage (ABRESP and BFRESP) were based on the soils descriptions, namely moderate to well drained soils with moderate to rapid permeability at Coshocton, moderate to well drained soils at Hastings, and well to excessively well drained soils for Safford (USDA-ARS, 1968) with an impervious hardpan in catchment 4501 (USDA-ARS, 1957). The coefficient of baseflow response (COFRU) was set at 2 per cent for all the catchments as suggested by Schulze (1984b), but the continuous baseflow observed on the Coshocton catchments suggested a higher value. COFRU was then set at 5 per cent for the Coshocton catchments 2630 and 2635.

The effective depth for runoff response (SMDDEP) was initially set equal to the depth of the A-horizon. Then by comparing the output of estimated streamflow to the observed streamflow it was increased if the model was over-estimating stormflow or decreased if underestimating stormflow.

Table 5.15 Runoff coefficients for each catchment

Catchment	2630	2635	4401	4403	4501	4503
Coeff. of quickflow response (RESPQF)	0.70	0.60	0.95	0.70	1.00	1.00
Coeff. of drainage from A to B horizons (ABRESP)	0.80	0.50	0.50	0.80	0.50	0.80
Coeff. of drainage release (BFRESP)	0.80	0.80	0.50	0.20	0.05	0.50
Coeff. of baseflow response (COFRU)	0.05	0.05	0.02	0.02	0.02	0.02
Effective depth for runoff response (SMDDEP)	0.18	0.18	0.30	0.30	0.14	0.30
Curve Number (CN2)	74*	75⁺	78*	75*	79*	80

The Curve Numbers shown in Table 5.15 were obtained from Schmidt, Schulze and Dunsmore (1985) or from Schulze (1982) with the exception of the Curve Number derived for catchment 4503. The hydrological soil grouping for the catchment was obtained from Table 7.1 in NEH-4 (1972) and the Curve Number was derived as a mean of that for fallow land and poor pastured land.

It should be noted here that the application of the ACRU and SCS models on all the selected catchments was performed with both the design hydrologist and the research hydrologist in mind. Although an attempt was made to select the best input data from all available references, neither model was calibrated any more than a designer would have done with the same references. Questions may arise as to the determination of the runoff coefficients in Table 5.15, and here again these values were determined on the basis of the observed data, catchment characteristics and recommendations published by Schulze (1984b).

Both the ACRU and SCS models now have to be tested on each catchment in order to obtain and compare levels of performance. The following chapter describes the criteria selected for judging the models' performance and discusses the results for each catchment.

6. MODEL PERFORMANCE

In order to study the influence of the soil moisture deficit on the production of stormflow, it was first necessary to check the performance of the ACRU model in terms of water balance and daily runoff depth. The Model performance statistics selected are shown in Table 6.1. The values of total observed and simulated daily flows give an indication of the overall efficiency of the model's water balance technique. Agreement in the means and standard deviations are considered useful criteria in judging a models predictability (Aitken, 1973). However, to obtain an indication of how well the estimated values fit the observed values, and whether any systematic errors in the estimations exist, functions such as the correlation and regression coefficients as well as the coefficients of determination and efficiency have been used.

In addition to determining the performance of the ACRU model in simulating daily runoff, the above statistics will also be obtained for the SCS model. These statistics will represent the SCS model's performance in simulating daily runoff depths from rainfall amounts exceeding some threshold level, and will be compared to similar statistics obtained for ACRU simulations under the same conditions.

6.1 Statistics of model performance

The statistics of performance of stormflow simulation by the ACRU model on the six catchments are listed in Tables 6.1 to 6.3, and a review of model performance on each catchment is as follows :

(a) On catchment 2630 it was noticed that high daily flows during the winter months were not well simulated by the model, resulting in the large discrepancy between the

Table 6.1 Statistics of performance of the ACRU model on the Coshocton catchments

Statistics of daily flows	2630 Months 1-12	2630 Months 4-11	2635 Months 1-12	2635 Months 4-11
Total observed flows (mm)	10 022	4 615	8 539	3 855
Total simulated flows (mm)	5 959	3 397	7 259	3 626
Mean of observed flows (mm)	.946	.652	.806	.545
Mean of simulated flows (mm)	.563	.480	.687	.512
Standard deviation of observed flows (mm)	2.541	2.087	2.175	1.703
Standard deviation of simulated flows (mm)	1.976	1.979	1.669	1.620
Percentage difference in standard deviation	22.227	5.131	23.293	4.886
Correlation coefficient	.808	.851	.805	.863
Regression coefficient	.627	.807	.619	.825
Base constant for regression equation	-.031	-.046	.186	.063
Coefficient of determination	.652	.725	.650	.745
Coefficient of efficiency	.629	.708	.645	.736

total flows (Table 6.1). These high flows were attributed mainly to snowmelt since the observed flow events were often greater than the recorded rainfall event which produced a total months flows greater than the total months rainfall.

Periods of snowmelt appeared to occur during the months December to March, and since most of the important storm events occurred in summer, it was decided to consider only the months April through November in the analysis. For these months the resulting simulated daily flows can be seen to be far more in agreement with the observed flows. The percentage difference in standard deviation dropped from 22.2 to 5.1 percent.

Table 6.2 Statistics of performance of the ACRU model on the Hastings catchments

Statistics of daily flows	4401 Months 1-12	4401 Months 4-11	4403 Months 1-12	4403 Months 4-11
Total observed flows (mm)	2 467	2 287	2 067	1 927
Total simulated flows (mm)	2 319	2 292	2 136	2 104
Mean of observed flows (mm)	.233	.323	.195	.272
Mean of simulated flows (mm)	.220	.326	.202	.297
Standard deviation of observed flows (mm)	2.203	2.656	1.761	2.111
Standard deviation of simulated flows (mm)	2.047	2.496	1.723	2.098
Percentage difference in standard deviation	7.076	6.035	2.169	.571
Correlation coefficient	.913	.925	.826	.841
Regression coefficient	.848	.868	.808	.836
Base constant for regression equation	.021	.043	.052	0440
Coefficient of determination	.834	.855	.682	.707
Coefficient of efficiency	.834	.855	.659	.683

The correlation coefficient improved from a 0.808 to 0.851, and the regression equation moved closer to the 1:1 line. For both runs the coefficient of efficiency is slightly less than the coefficient of determination, indicating a small bias in the estimates. However, the coefficients are sufficiently close to 1.0 to consider the model to perform well on this catchment during the summer months.

(b) The above situation also holds true for catchment 2635. By ignoring the months of December to March the statistics were improved markedly, especially the agreement between the means and standard deviations of the observed and simulated daily flows, and in the increase of the coefficients of determination and efficiency.

Table 6.3 Statistics of performance of the ACRU model on the Safford catchments

Statistics of daily flows	4501 Months 1-12	4501 Months 7-10	4503 Months 1-12	4503 Months 6-9
Total observed flows (mm)	283	273	80	80
Total simulated flows (mm)	361	248	208	126
Mean of observed flows (mm)	.025	.072	.007	.021
Mean of simulated flows (mm)	.032	.066	.018	.033
Standard deviation of observed flows (mm)	.488	.832	.144	.248
Standard deviation of simulated flows (mm)	.450	.715	.317	.520
Percentage difference in standard deviation	7.672	14.010	-120.579	-109.529
Correlation coefficient	.765	.821	.522	.549
Regression coefficient	.705	.706	1.152	1.150
Base constant for regression equation	.014	.015	.010	.009
Coefficient of determination	.585	.674	.273	.301
Coefficient of efficiency	.561	.672	-2.569	-2.093

Again these two coefficients are very close, indicating good agreement and a regression equation approximating the 1:1 relationship well. Hence, the model shows good output on this catchment for the months April to November.

(c) Table 6.2 gives the statistics of performance of the model on the Hastings catchments. Again, the ACRU model simulates daily streamflows well, especially on the smaller catchment 4401, where the coefficient of efficiency equals the high coefficient determination of 0.855 implying that there is no systematic bias in the model output.

Unlike the Coshocton catchments, snowmelt does not appear to be a problem at Hastings, as can be seen by the close agreement between the total observed and simulated daily flows for the months January to December. By disregarding months December to March the statistics were improved, although these improvements were not nearly as marked as those for the Coshocton catchments.

(d) The runoff regime on the arid Safford catchments is somewhat different, particularly to Coshocton. It was determined for catchment 4501 that 87 percent of the observed runoff events, from the 31 years of record, occurred during the months July to October. Over the same length of time, catchment 4503 received 88 percent of its runoff events during the months June to September. On the other hand, the ACRU model was estimating runoff from various rainfall events outside of these months more often than runoff actually occurred. Hence, since the number of flows observed for these catchments is low, the number of estimated events was proportionately much greater and it was decided to include only those months mentioned above in which the majority of runoff events occurred (Table 6.3).

The statistics show a general improvement, however slight, when only the selected months are considered. Overall, the model shows reasonable performance on catchment 4501, with fair agreement between the total flows and between the standard deviations of those flows. Considering the episodic nature of rainfall on arid catchments the coefficient of determination of 0.674 may be considered good with a coefficient of efficiency of 0.672 showing little bias in the output.

The statistics for catchment 4503, however, reflect a poor simulation of the water yield, with the model tending to overestimate runoff events. This is illustrated not only by a comparison of the total flows, but also by the large difference between the standard deviations of the observed and simulated flows. The coefficient of efficiency is negative, a result which can be attributed mainly to the poor simulation of low flows, and the prediction of flow when no runoff actually occurred. The model's performance on this catchment is therefore considered relatively poor.

6.2 Discussion of results

Initial sensitivity tests performed on the ACRU model by Weddepohl (1985) revealed that, other than to rainfall, the model is most sensitive to the soils parameters; particularly the depth of the A-horizon (DEPAHO), the porosity (PO), field capacity (FC) and wilting point (WP) of the soil; also to the cropping factor, CAY(I). Since the selected catchments were maintained for research, their descriptions have been generally well documented. Hence the selected values of the above mentioned parameters (Chapter 5) are considered to be representative for each of the catchments.

The exceptions are the Safford catchments, where, as mentioned in Chapter 5, all but the soil characteristics are well described. It appears from the statistics shown in Table 6.3 that the simulated water yield for catchment 4501 is not too far in error and hence the soils' moisture parameters selected as in Table 5.7 may be assumed to be reasonable. However, for catchment 4503, adequate soils information appeared even more scant than for 4501, and it is felt that it is the estimates of the soil moisture parameters that are a probable source of error in the estimation of the catchment's water yield.

It would seem, however, that catchment 4503 is difficult to model regardless of the lack of adequate soils data, as will be shown in the following section. It remains now to compare the performance of the ACRU model to the performance of the SCS model and in doing so to obtain a "feel" for the difference in the representation by the models of a catchment's antecedent wetness.

6.3 Comparison of ACRU and SCS model performance

The purpose of this section is to study and compare both of the models in the socalled design situation. In other words the daily simulated runoff depth from both models resulting from the higher rainfall events are compared statistically. Only the months selected as shown in Tables 6.1 and 6.3 are considered for the Coshocton and Safford catchments respectively. Table 6.2 shows that, at Hastings, there is little difference between the daily simulations for the selected months and for the whole year. Hence, at Hastings the months January to December are considered in the following analysis. In addition a threshold value of rainfall was selected arbitrarily at 20 mm per day for the humid and sub-humid catchments and 10 mm per day for the arid catchments.

In practice, a designer using the SCS model will not always be able to obtain adequate representative rainfall data, with the result that Curve Number adjustment according to antecedent precipitation is not always possible. He may then choose to design under "average" catchment conditions using the Curve Number II. It was therefore decided to apply the SCS model with both an adjusted Curve Number (SCS-adj) and a fixed Curve Number II (SCS-II) for all events, and in doing so obtain a feel of the success of the designer's choice.

The statistics of performance of the models applied to each catchment are listed in Tables 6.4 to 6.6. On catchment 2630 the ACRU model yields a good overall simulated water yield and has the lowest difference in standard deviation between the observed and estimated flows. Although the base constant in the regression equation is high for the ACRU model, the slope is much closer to unity than for either of the other methods. The coefficient of determination for the ACRU estimates is markedly higher than that of either of the SCS estimates and there appears to be little systematic bias in its output.

The statistics show similar trends for catchment 2635. The ACRU model overestimates the total flow by as much as the SCS-II method underestimates, a result also reflected in the means. The SCS-II method, however, provides a better representation of the flow variance with a percentage difference between the observed and simulated standard deviations of only 9.6 per cent as opposed to a 17.2 percent difference shown by the ACRU model. The coefficients of determination and efficiency exhibited by the ACRU model are still markedly higher than those of either of the two SCS methods, with a similar regression equation as for catchment 2630.

Table 6.4 Statistics of performance of the ACRU and SCS models for daily rainfall amounts above 20 mm at Coshocton

Statistics of daily flows	2630 Months 4-11			2635 Months 4-11		
	ACRU	SCS-adj	SCS-II	ACRU	SCS-adj	SCS-II
Total observed flows (mm)	1 248	1 248	1 248	989	989	989
Total simulated flows (mm)	1 583	273	709	1 298	273	696
Mean of observed flows (mm)	5.496	5.496	5.496	4.052	4.052	4.052
Mean of simulated flows (mm)	6.976	1.203	3.126	5.319	1.121	2.851
Standard deviation of observed flows (mm)	8.744	8.744	8.744	7.108	7.108	7.108
Standard deviation of simulated flows (mm)	7.853	4.785	6.310	5.886	4.713	6.422
Percentage difference in standard deviation	10.399	45.279	27.836	17.194	33.695	9.644
Correlation coefficient	.883	.683	.750	.889	.631	.756
Regression coefficient	.791	.374	.542	.736	.418	.683
Base constant for regression equation	2.626	-.851	.150	2.336	-.573	.082
Coefficient of determination	.780	.466	.563	.791	.398	.572
Coefficient of efficiency	.751	.206	.489	.755	.226	.522

Statistics on the Hastings catchments show that the ACRU model performs better than either SCS method in terms of both water yield, goodness of fit of and model efficiency, especially on the smaller catchment 4401 (Table 6.5). This is particularly shown in the low percentage differences in the standard deviations and in the small differences between the coefficients of determination and efficiency.

Table 6.5 Statistics of performance of the ACRU and SCS models for daily rainfall amounts above 20 mm at Hastings

Statistics of daily flows	4401 Months 1-12 ACRU	SCS-adj	SCS-II	4403 Months 1-12 ACRU	SCS-adj	SCS-II
Total observed flows (mm)	1 869	1 869	1 869	1 156	1 156	1 156
Total simulated flows (mm)	1 789	664	1 254	1 337	504	945
Mean of observed flows (mm)	8.458	8.458	8.458	5.694	5.694	5.694
Mean of simulated flows (mm)	8.095	3.005	5.673	6.586	2.480	4.657
Standard deviation of observed flows (mm)	12.268	12.268	12.268	9.515	9.515	9.515
Standard deviation of simulated flows (mm)	11.637	9.153	9.396	9.982	8.810	9.436
Percentage difference in standard deviation	5.138	25.392	23.405	-4.912	7.407	.826
Correlation coefficient	.905	.754	.872	.858	.774	.778
Regression coefficient	.858	.562	.668	.900	.717	.772
Base constant for regression equation	.834	-1.752	.025	1.463	-1.602	.263
Coefficient of determination	.819	.568	.760	.735	.600	.605
Coefficient of efficiency	.816	.370	.697	.690	.462	.548

On catchments 2630, 2635 and 4401, the SCS-adj method has performed comparatively poorly. In all cases water yield was severely underestimated and the method exhibited low coefficients of determination and efficiency. Conversly, the SCS-II method generated more realistic flow estimates and showed much higher model efficiencies. This situation changes somewhat on catchment 4403 where the SCS-adj statistics are much closer to the SCS-II statistics. Water yield is better simulated by the SCS-II method, and although the SCS-adj method produces a similarly high coefficient of determination of 0.600, there exists a greater bias in the output of that method.

Table 6.6 lists the statistics from the Safford catchments. The threshold rainfall level was decreased to 10 mm here in an attempt to increase the number of events included in the statistics. On catchment 4501 the ACRU model again generates the best water yield with good agreement between the total observed and simulated flows, as well as between the standard deviations of those flows. The regression

Table 6.6 Statistics of performance of the ACRU and SCS models for daily rainfall amounts above 10 mm at Safford

Statistics of daily flows	4501 Months 7-10			4503 Months 6-9		
	ACRU	SCS-adj	SCS-II	ACRU	SCS-adj	SCS-II
Total observed flows (mm)	261	261	261	72	72	72
Total simulated flows (mm)	247	15	107	123	19	181
Mean of observed flows (mm)	2.006	2.006	2.006	.607	.607	.607
Mean of simulated flows (mm)	1.902	.119	.820	1.035	.159	1.524
Standard deviation of observed flows (mm)	4.056	4.056	4.056	1.260	1.260	1.260
Standard deviation of simulated flows (mm)	3.405	.753	2.144	2.763	.834	3.553
Percentage difference in standard deviation	16.059	81.447	47.147	-119.221	33.799	-181.924
Correlation coefficient	.776	.414	.786	.477	.321	.469
Regression coefficient	.651	.077	.416	1.046	.212	1.323
Base constant for regression equation	.595	-.035	-.013	.399	.031	.721
Coefficient of determination	.602	.172	.618	.228	.103	.220
Coefficient of efficiency	.598	-.099	.466	-2.829	-.141	-5.837

equations show that the ACRU output is closest to a 1:1 line with a regression coefficient of 0.651. However there is little difference in the coefficients of determination of the ACRU and SCS-II models, although there appears to be noticeable systematic error present in the SCS-II output. Again, the SCS-adj method fares poorly on this catchment.

On catchment 4503, all the models appear to perform inadequately. In all cases the coefficients of determination are low and the coefficients of efficiency are negative. Both the ACRU and SCS-II models overestimate, although judging by the regression coefficients the ACRU model almost approximates unity. However, the differences in standard deviation are high with the SCS-adj method producing the lowest at 34 per cent.

6.4 Concluding remarks

It has been shown by the statistics presented in Tables 6.1 to 6.3 that the ACRU model is performing satisfactorily on all but the Safford catchment 4503. Emphasis is placed here on the differences between the totals and between the standard deviations of the observed and simulated flows, as these functions reflect the model's ability to represent the moisture storage levels of the catchment.

In comparing the ACRU model to the SCS model it was found that the ACRU model performed better on all catchments except 4503, on which all the methods simulated poorly. It was also found that on these catchments the use of a Curve Number II in the SCS model gave much improved flow estimates than that using a Curve Number adjusted to account for antecedent rainfall.

It may also be seen that there appears to be a definite trend of the performance of the ACRU model with respect to catchment size. Irrespective of climate, the model performed better on the smaller of the two catchments in each area. In addition, the modelling of arid catchments is more difficult than on the humid and sub-humid catchments.

7. DESIGN FLOOD FREQUENCY

In order to estimate the 5-year return period flood event on a small catchment the procedure in design practice is to obtain an annual maximum rainfall series of rainfall duration representative of the critical response time of the catchment, and then to fit a frequency distribution to these data and determine the storm amount corresponding to the 20 per cent exceedence probability. This rainfall amount is then applied to some method which estimates the flow resulting from such a storm magnitude and this flow volume is then assumed to have a frequency interval of 5 years.

7.1 Equal ranking for rainfall and runoff events

As discussed in Chapter 3, this assumption of equal return periods for a design storm and its resultant runoff response is causing some concern among researchers. In an attempt to study the validity of this assumption a maximum daily rainfall series (MRS) and a maximum observed daily runoff series (MFS) were generated for each catchment for the selected months described in Chapter 6. In addition, the daily runoff corresponding with the events in the MRS were used to generate a separate runoff series which shall be denoted MFS_r. The MRS and MFS_r for the catchments in each region are listed in Tables 7.1 to 7.3. The first and second rank columns in each list gives the ranking of the events in the MRS and the MFS_r respectively, where the largest event attains the rank number one. The third rank column presents the rankings of the events in the MFS_r as they are ranked in the MFS. It must be noted here that the above maximum series are derived in a similar manner to an annual maximum series. The difference lies in the fact that on the Coshocton and Safford catchments not all the months of the

Table 7.1 Maximum rainfall series (MRS) and corresponding daily runoff series (MFS_r) in mm for the Coshocton catchments ($rank_r$ denotes the ranking of the MFS_r and $rank_a$ gives the ranking according to the maximum observed daily runoff series MFS)

2630 Months 4-11					2635 Months 4-11				
MRS	rank	MFS_r	$rank_r$	$rank_a$	MRS	rank	MFS_r	$rank_r$	$rank_a$
115.9	1	69.2	1	1	143.1	1	65.4	1	1
115.2	2	37.4	4	4	104.2	2	29.3	3	3
84.2	3	36.1	5	5	85.3	3	40.2	2	2
81.1	4	39.6	3	+	71.0	4	16.3	7	+
79.7	5	29.9	6	6	61.0	5	18.4	6	8
65.9	6	8.2	10	+	59.5	6	3.5	18	+
63.2	7	4.1	13	28	57.4	7	1.8	2	+
60.9	8	8.2	11	+	49.5	8	26.2	5	+
60.7	9	49.8	2	2	49.1	9	28.7	4	4
59.6	10	4.1	14	+	49.0	10	1.9	22	+
50.8	11	2.8	16	+	47.7	11	15.4	8	11
50.5	12	3.4	15	+	47.4	12	0.9	25	+
48.0	13	4.3	12	+	47.1	13	4.9	16	25
48.0	14	2.8	17	+	45.8	14	10.7	11	16
47.1	15	1.1	25	+	45.3	15	8.0	13	+
46.6	16	2.0	20	+	44.3	16	2.5	19	+
45.6	17	2.0	21	+	43.7	17	12.8	10	+
45.5	18	2.6	18	+	43.2	18	0.8	26	+
45.2	19	1.3	24	+	42.1	19	2.3	20	+
44.3	20	2.2	19	+	42.0	20	0.5	27	+
43.2	21	12.8	8	+	41.8	21	13.7	9	13
41.0	22	8.6	9	+	41.2	22	1.6	24	+
37.2	23	0.8	27	+	41.1	23	7.0	14	+
36.7	24	19.5	7	10	38.8	24	6.5	15	+
34.6	25	0.9	26	+	37.7	25	0.2	29	+
33.8	26	2.0	22	+	36.8	26	9.4	12	18
33.0	27	1.5	23	+	33.9	27	4.9	17	25
32.4	28	0.6	28	+	32.0	28	0.5	28	+
32.0	29	0.5	29	+	30.0	29	2.0	21	+

\+ events not in observed maximum flood series

year are included in the analysis. The series derived on these two catchments are therefore not strictly annual series, and for the sake of simplicity all the series (including those for Hastings) generated in this study will be referred to as maximum series.

From the rankings listed in Tables 7.1 to 7.3, it appears that the rank of the rainfall event seldom equals that of the corresponding runoff event. While the largest storm produced the largest runoff response on three out of the six catchments, the fact that on the remaining catchments the largest runoff response was produced by the second, third and eighth ranked storms show that the assumption of equal ranking for even the largest events does not necessarily

Table 7.2 Maximum rainfall series (MRS) and corresponding daily runoff series (MFS_r) in mm for the Hastings catchments ($rank_r$ denotes the ranking of the MFS_r and $rank_a$ gives the ranking according to the maximum observed daily runoff series MFS)

4401 Months 1-12					4403 Months 1-12				
MRS	rank	MFS_r	$rank_r$	$rank_a$	MRS	rank	MFS_r	$rank_r$	$rank_a$
140.0	1	81.1	1	1	150.8	1	65.0	2	2
103.6	2	81.1	2	2	135.7	2	74.9	1	1
103.6	3	56.3	4	+	106.4	3	29.8	3	+
97.0	4	76.9	3	3	87.3	4	29.3	4	5
87.7	5	19.9	11	13	80.9	5	6.7	21	+
77.0	6	14.7	17	20	77.6	6	10.2	12	21
75.7	7	45.8	5	5	65.2	7	22.2	5	8
66.5	8	44.3	6	6	63.2	8	6.7	22	+
63.5	9	30.7	7	7	62.5	9	16.8	6	+
59.9	10	4.7	26	+	61.0	10	7.5	19	+
59.2	11	12.5	18	+	60.4	11	2.5	25	+
58.9	12	20.6	10	12	60.3	12	12.6	7	17
56.6	13	18.3	12	14	60.0	13	5.3	23	+
54.9	14	17.1	14	16	59.1	14	8.6	16	+
53.3	15	20.7	9	11	59.0	15	10.5	11	+
52.6	16	4.4	27	+	55.5	16	9.2	14	+
50.8	17	10.3	19	+	51.5	17	9.9	13	22
50.0	18	10.2	20	22	51.2	18	9.0	15	23
47.0	19	10.1	21	+	50.8	19	7.9	18	+
45.7	20	17.8	13	15	47.4	20	1.1	26	+
45.7	21	6.0	25	+	46.9	21	8.6	17	+
45.0	22	15.3	16	18	46.4	22	11.5	9	19
43.4	23	16.1	15	17	45.8	23	12.6	8	18
42.8	24	22.9	8	9	45.1	24	7.3	20	26
42.7	25	7.0	23	27	43.7	25	10.8	10	20
40.9	26	9.8	22	25	42.7	26	1.0	27	+
33.6	27	2.5	28	29	32.4	27	0.4	28	+
32.0	28	6.7	24	28	29.8	28	0.0	29	+
31.5	29	2.0	29	+	27.5	29	4.7	24	27

+ events not in observed maximum flood series

hold true. It can also be seen from the third rank column that many of the events in the MFS_r are not included in the MFS. This indicates that the maximum rainfall events in each year do not necessarily produce the maximum runoff events for that year.

To obtain a clearer perspective of the relationship between rainfall rank and runoff rank the corresponding values were plotted and are shown in Figures 7.1 to 7.6. It may be seen that on all the catchments the scatter of points about the line of equal rank appears to be random. There is, however, a tendency for the lower ranked rainfall events to generate low ranked runoff events and for the higher ranked rainfall events to generate high ranked runoff events.

Table 7.3 Maximum rainfall series (MRS) and corresponding daily runoff series (MFS_r) in mm for the Safford catchments ($rank_r$ denotes the ranking of the MFS_r and $rank_a$ gives the ranking according to the maximum observed daily runoff series MFS)

4501 Months 7-10					4503 Months 6-9				
MRS	rank	MFS_r	$rank_r$	$rank_a$	MRS	rank	MFS_r	$rank_r$	$rank_a$
54.7	1	16.8	3	3	68.1	1	4.0	3	+
45.9	2	18.3	2	2	54.5	2	1.0	14	16
42.6	3	30.3	1	1	47.0	3	4.1	2	4
40.3	4	9.6	5	5	45.5	4	0.0	24	+
40.1	5	12.6	4	4	44.2	5	0.0	25	+
33.5	6	1.3	22	23	38.6	6	0.0	26	+
31.3	7	7.4	10	10	33.0	7	3.8	5	6
30.6	8	1.0	23	24	31.0	8	7.1	1	1
28.4	9	2.3	17	18	30.7	9	3.2	6	7
27.6	10	8.7	6	6	28.9	10	0.0	27	+
27.5	11	3.5	14	16	28.5	11	0.0	28	+
27.1	12	0.3	26	29	28.4	12	1.8	10	10
26.4	13	0.9	24	25	28.4	13	2.0	8	9
25.7	14	7.8	8	8	27.9	14	0.4	16	+
24.5	15	1.6	20	21	27.7	15	0.2	20	25
22.7	16	4.3	13	14	26.9	16	2.0	9	+
22.5	17	7.8	9	9	25.6	17	3.9	4	5
22.3	18	3.2	16	17	25.6	18	0.1	22	+
22.1	19	5.8	12	+	24.9	19	1.2	12	13
21.3	20	8.1	7	7	24.7	20	1.7	11	11
19.1	21	6.5	11	12	23.4	21	2.3	7	8
19.0	22	0.0	29	+	23.4	22	0.3	18	+
18.9	23	0.0	30	+	22.9	23	1.1	13	14
17.6	24	1.6	21	22	20.8	24	0.1	23	+
15.9	25	3.5	15	+	19.7	25	0.0	29	+
14.8	26	0.9	25	+	19.4	26	0.0	30	+
13.5	27	1.7	19	20	18.6	27	0.2	21	+
13.2	28	0.0	19	20	18.6	28	0.0	31	+
12.6	29	1.8	18	+	15.2	29	0.6	15	20
11.2	30	0.3	27	30	12.3	30	0.3	19	23
10.0	31	0.2	28	31	11.1	31	0.4	17	+

+ events not in observed maximum flood series

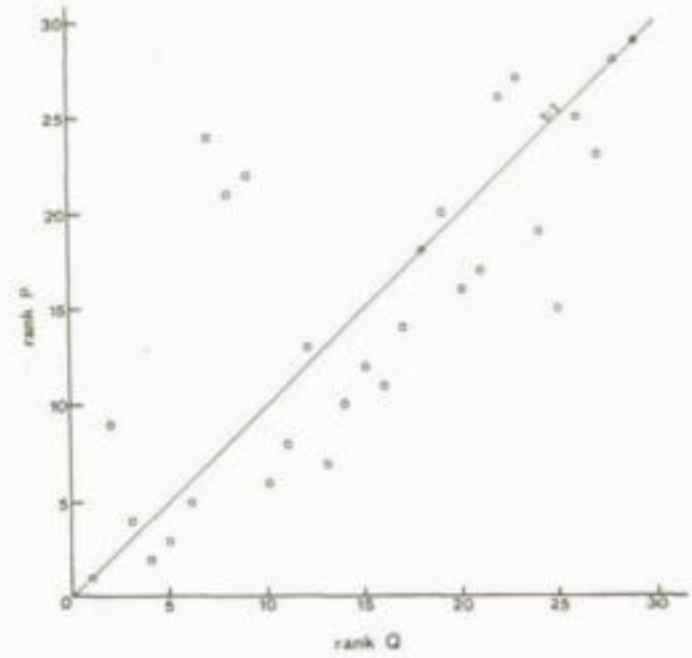


Figure 7.1 Plot of storm rainfall rank against storm runoff rank for Coshocton 2630

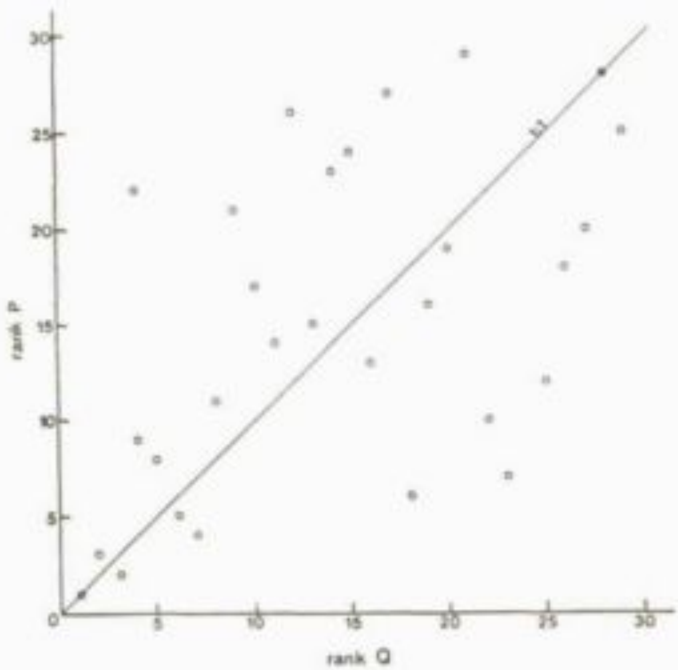


Figure 7.2 Plot of storm rainfall rank against storm runoff rank for Coshocton 2635

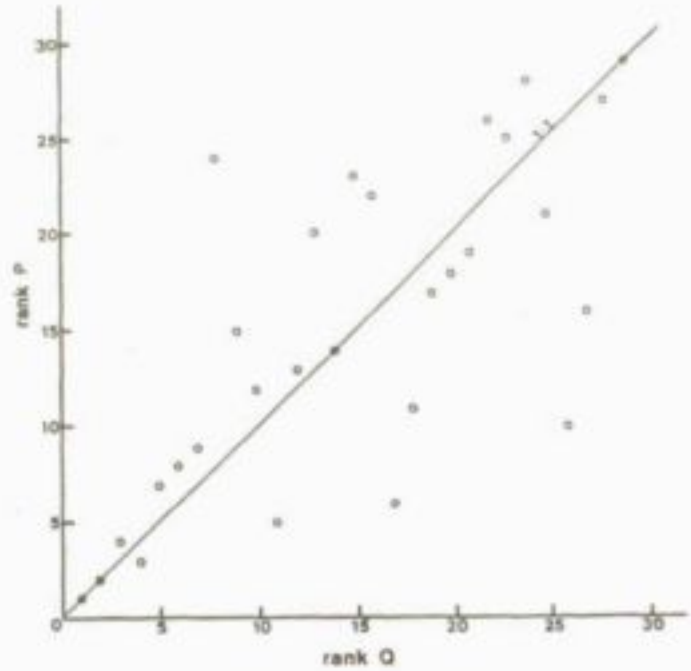


Figure 7.3 Plot of storm rainfall rank against storm runoff rank for Hastings 4401

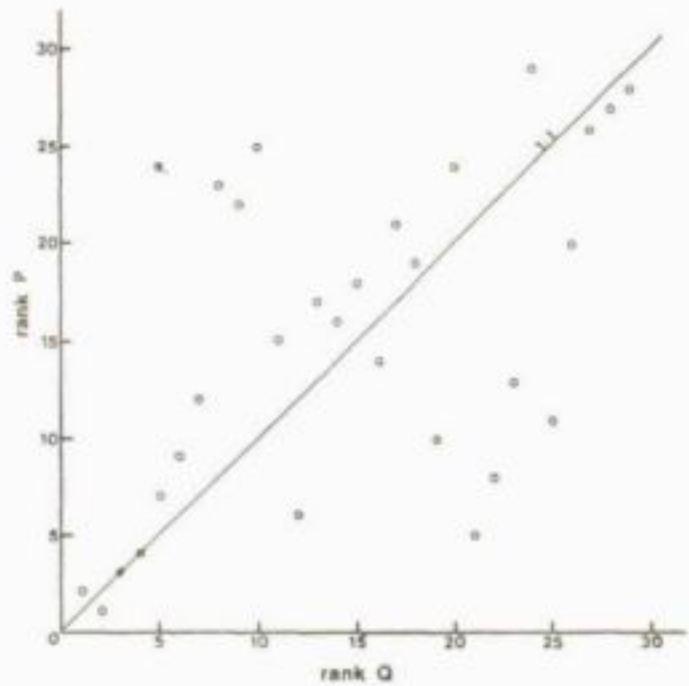


Figure 7.4 Plot of storm rainfall rank against storm runoff rank for Hastings 4405

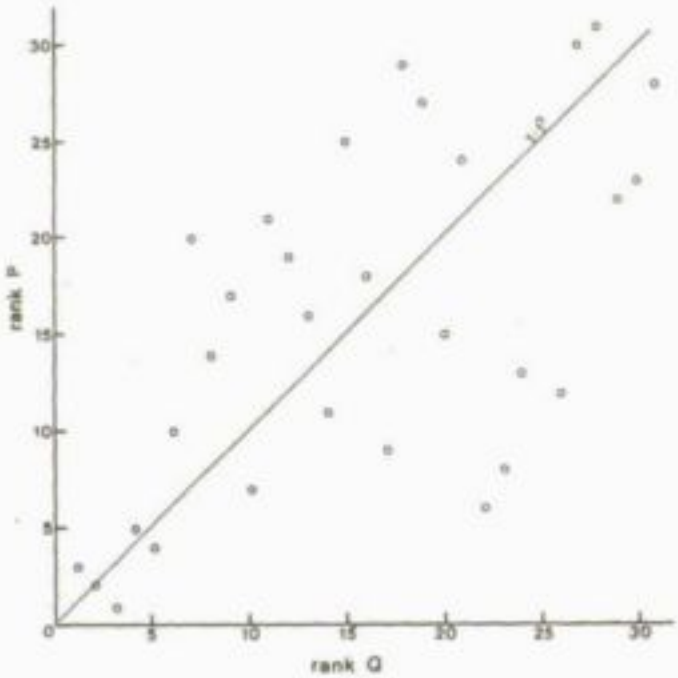


Figure 7.5 Plot of storm rainfall rank against storm runoff rank for Safford 4501

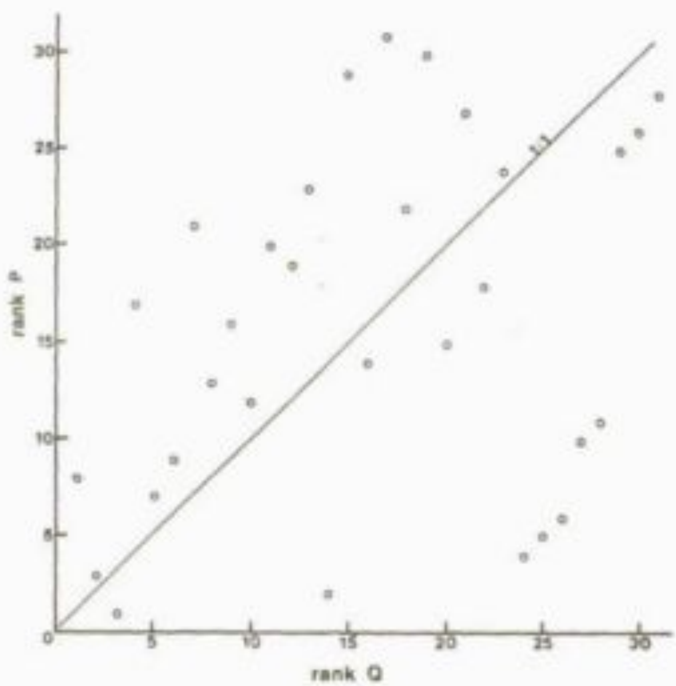


Figure 7.6 Plot of storm rainfall rank against storm runoff rank for Safford 4503

7.2 Association of the T-year daily rainfall with the T-year daily runoff

The next step was to fit to each of the series generated for each catchment a log-Normal frequency distribution and to generate the magnitudes of the 2-year to the 100-year return periods of each series. These magnitudes, listed in Table 7.4, were then plotted on log-probability paper as shown in Figures 7.7 to 7.12. From these plots it is apparent in all cases that the slope of the line corresponding to the distribution of the observed maximum daily runoff series, Q(f), is flatter than that of Q(r). The point of convergence of the two lines occurs at a return period not less than the 50-year frequency. Hence, on all the catchments in this

Table 7.4 The extreme value magnitudes of rainfall and daily runoff on each catchment (Q(r) are the magnitudes of daily runoff corresponding with the maximum rainfall series (MFS_r) and Q(f) are the magnitudes from the observed maximum daily runoff series (MFS). All values in mm)

Return Period (yrs)	2	5	10	20	50	100
2630						
Rainfall	50.2	70.2	83.4	96.2	112.9	125.6
Q(r)	7.0	17.2	27.4	40.3	62.1	83.0
Q(f)	14.7	26.8	36.7	47.6	63.7	77.4
2635						
Rainfall	47.5	68.2	82.4	96.3	114.8	129.0
Q(r)	7.2	16.4	25.1	35.9	53.5	69.7
Q(f)	11.9	22.0	30.5	39.8	53.8	65.7
4401						
Rainfall	56.1	78.4	93.3	107.5	126.7	141.2
Q(r)	16.8	33.7	48.4	65.3	91.4	114.4
Q(f)	19.5	36.7	50.9	66.8	90.7	111.2
4403						
Rainfall	56.8	81.5	98.5	115.1	137.2	154.3
Q(r)	8.7	19.6	30.0	42.6	63.2	82.2
Q(f)	14.8	27.6	38.3	50.2	68.1	83.4
4501						
Rainfall	23.2	32.8	45.6	53.9	60.2	73.4
Q(r)	3.4	7.7	11.7	16.6	24.6	32.0
Q(f)	3.7	8.0	12.0	16.9	24.7	31.8
4503						
Rainfall	26.5	37.4	44.8	52.1	61.6	68.9
Q(r)	0.8	1.9	2.9	4.2	6.3	8.3
Q(f)	1.1	2.3	3.5	5.0	7.3	9.4

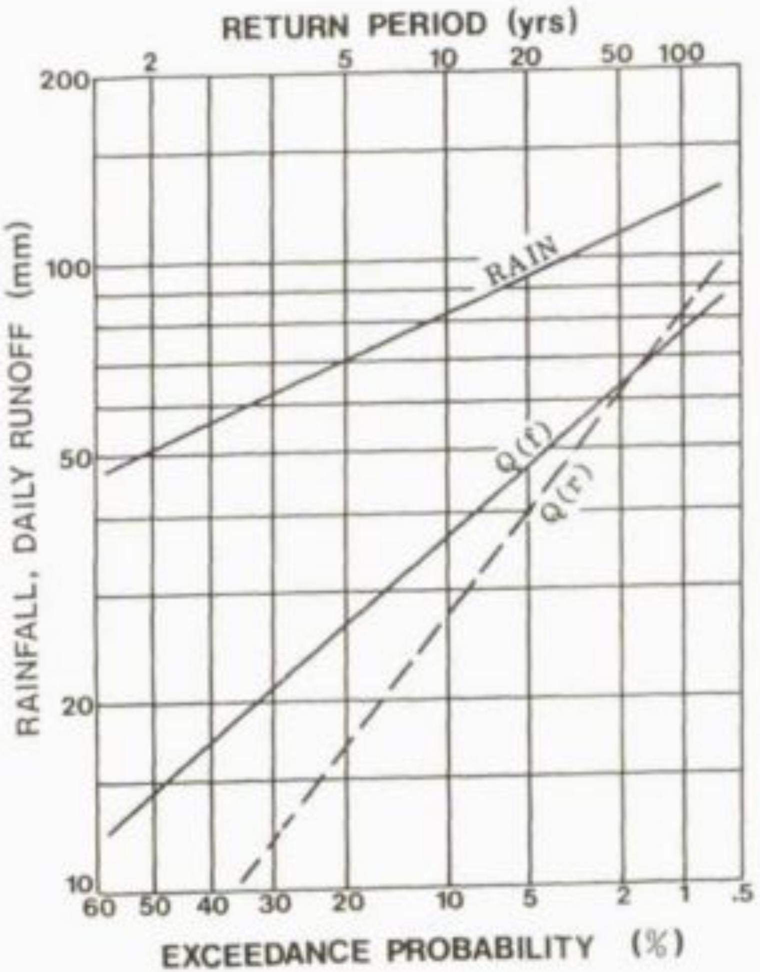


Figure 7.7 Log-Normal frequency distribution of maximum rainfall series, RAIN, the daily runoff series resulting from the rainfall series, Q(r), and the maximum observed daily runoff series, Q(f), for Coshocton 2630

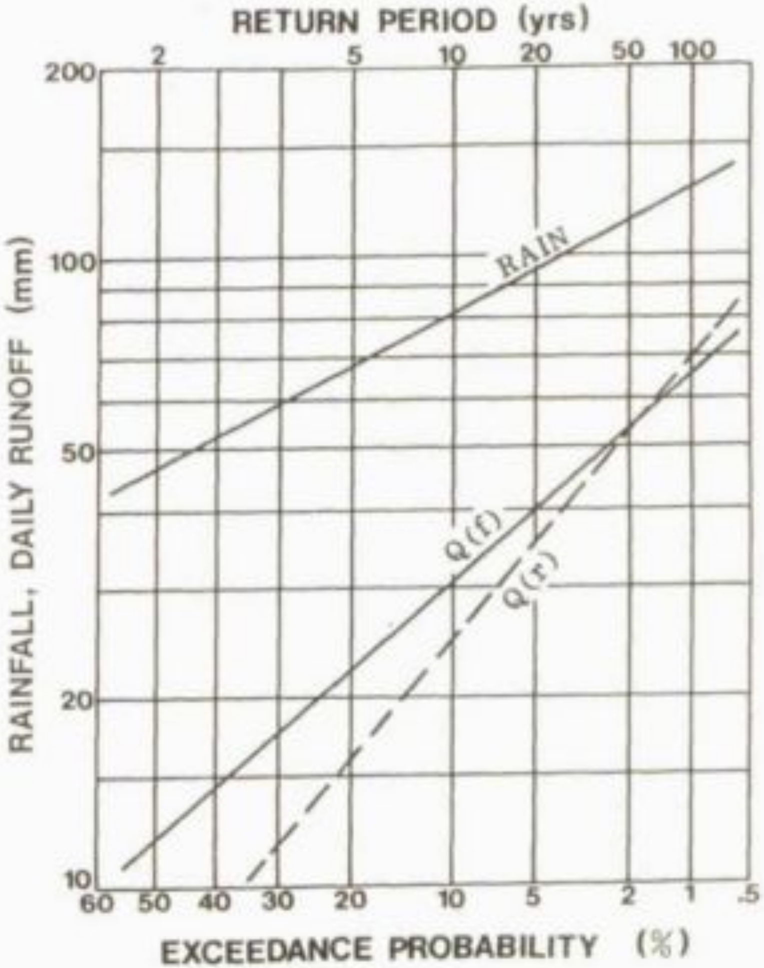


Figure 7.8 Log-Normal frequency distribution of maximum rainfall series, RAIN, the daily runoff series resulting from the rainfall series, Q(r), and the maximum observed daily runoff series, Q(f), for Coshocton 2635

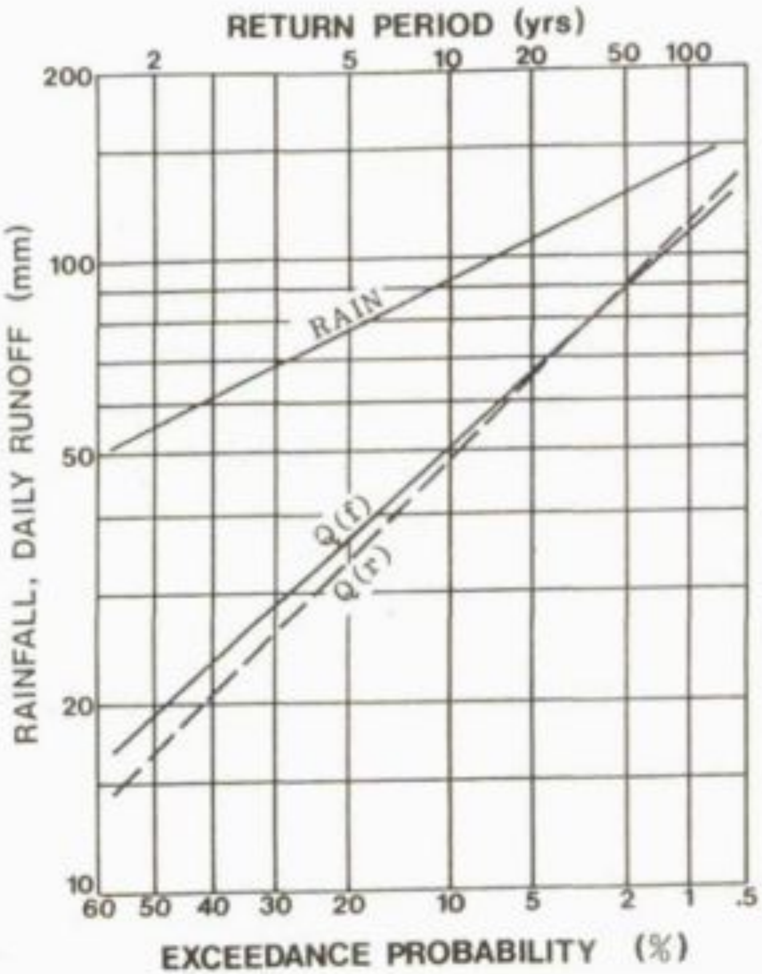


Figure 7.9 Log-Normal frequency distribution of maximum rainfall series, RAIN, the daily runoff series resulting from the rainfall series, Q(r), and the maximum observed daily runoff series, Q(f), for Hastings 4401

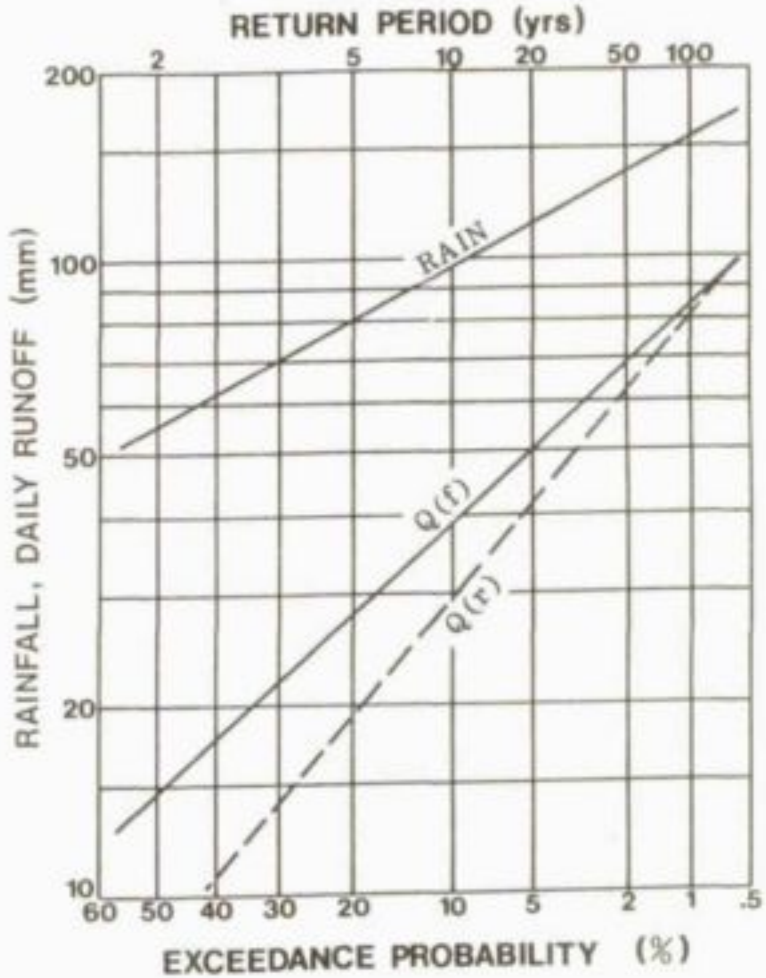


Figure 7.10 Log-Normal frequency distribution of maximum rainfall series, RAIN, the daily runoff series resulting from the rainfall series, Q(r), and the maximum observed daily runoff series, Q(f), for Hastings 4403

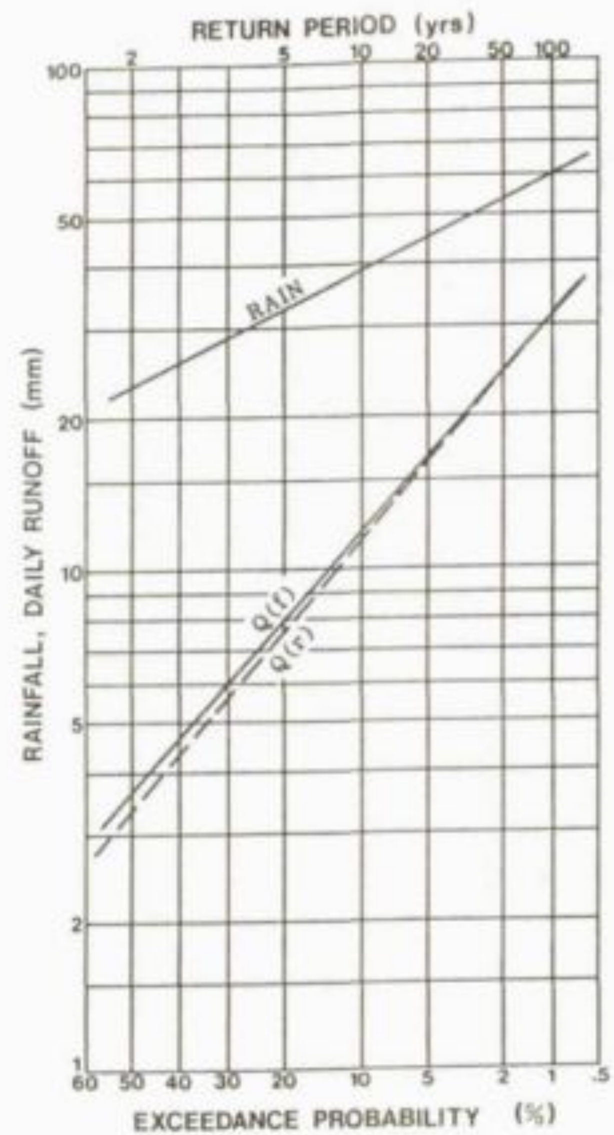


Figure 7.11 Log-Normal frequency distribution of maximum rainfall series, RAIN, the daily runoff series resulting from the rainfall series, Q(r), and the maximum observed daily runoff series, Q(f), for Safford 4501

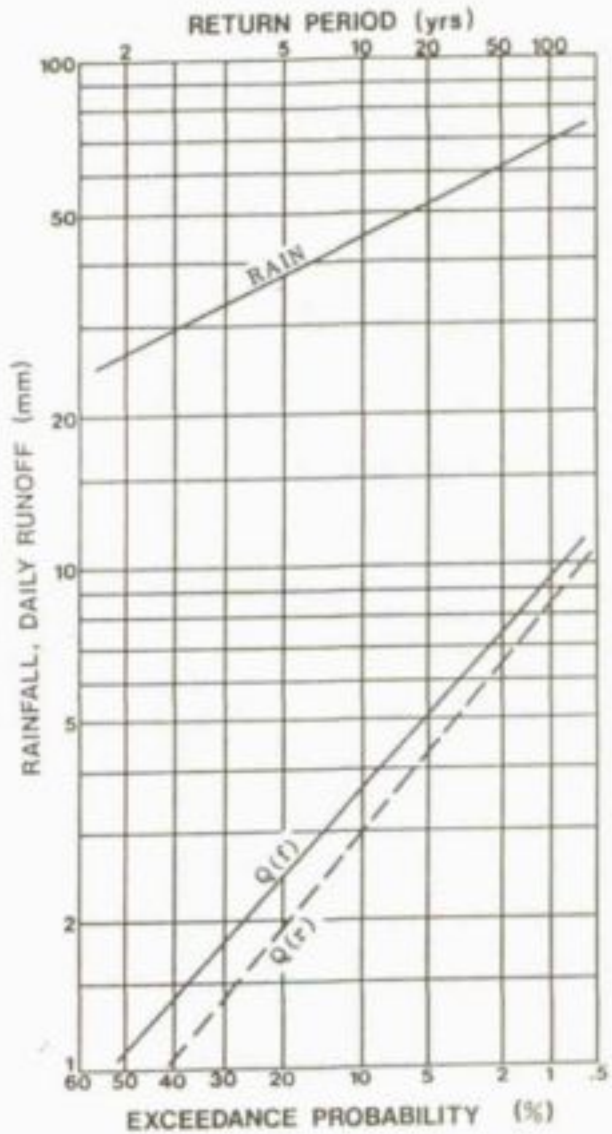


Figure 7.12 Log-Normal frequency distribution of maximum rainfall series, RAIN, the daily runoff series resulting from the rainfall series, Q(r), and the maximum observed daily runoff series, Q(f), for Safford 4503

study the frequency distribution of the observed maximum daily runoff series produced extreme events which were larger in magnitude than those of the corresponding daily runoff series corresponding with the maximum rainfall series for return periods up to 50 years.

The cause of the above result is attributed to the fact that the maximum daily rainfall event in any year may not produce the maximum daily flood volume. However, these results show that even if the design method could provide an accurate estimate of the flood generated by the T-year storm, which in turn is derived from an annual maximum series, the result would still be an underestimate of the true T-year flood. The underestimation may only be small but, for example, the difference between the 10-year flood volumes predicted for catchment 2635 (10.4 km^2) is just over 5 mm, which over a 10 km^2 catchment gives a discrepency of 50 000 m^3.

The problem, however, still remains whether the T-year daily rainfall will generate the T-year daily runoff. In comparing the design values in Table 7.4 with the series in Tables 7.1 to 7.3 various storm events and the corresponding floods were selected and their respective return periods were determined according to the frequency distributions in Figures 7.7 to 7.12 and noted in Table 7.5. Only the highest eight rainfall events were considered for selection as it was found that these events tended to cover the full range of return periods shown in Table 7.4.

As may now be expected, the return period calculated from the MFS for a given magnitude of daily runoff is lower than that calculated from the MFS_r for the same magnitude of daily runoff, with only exceptions occurring at high return periods. The same cannot be said for the relationship between the rainfall return periods and either of thedaily runoff return periods. There appears to be no consistency as to whether the return period of the daily runoff depth is greater or less than that of the rainfall event producing it.

Table 7.5 Selected daily rainfall events, their return periods (T-rain), and the corresponding daily runoff depths (Q) and the return periods according to the series generated by the maximum rainfall series, T(r), and according to the maximum daily runoff series, T(f)

Catchment	RAIN (mm)	T-rain (yrs)	Q (mm)	T(r) (yrs)	T(f) (yrs)
2630	115.9	55	69.2	67	67
	115.2	55	37.4	17	10
	81.1	10	39.6	20	13
	79.7	9	29.9	13	6
	65.9	4	8.2	2.5	1.3
2635	143.1	200	65.4	77	100
	104.1	30	29.3	14	9
	85.3	13	40.2	25	20
	61.0	3.6	18.4	5.7	3.6
	49.5	2.3	26.2	11	6.7
4401	140.0	100	81.1	33	29
	103.6	15	81.1	33	29
	103.6	15	56.3	14	12
	87.7	8	19.9	2.4	2.1
	66.5	3	44.3	8.7	7.7
4403	150.8	77	65.0	56	40
	135.7	40	74.9	77	59
	106.4	13	29.8	10	6
	80.9	5	6.7	1.6	1.2
	65.2	2.8	22.2	5.6	3.3
4501	54.7	55	16.8	21	20
	45.9	20	18.3	25	25
	42.6	14	30.3	83	83
	40.3	10	9.6	7.1	6.7
	33.5	5	1.3	1.2	1.16
4503	68.1	100	4.0	18	13
	54.5	28	1.0	2.4	1.9
	47.0	14	4.1	20	14
	45.5	10	.0	1.0	1.0
	31.0	2.7	7.1	63	50

To determine the T-year design flood depth for a catchment the best method is to determine, from available flow records, an annual maximum daily runoff series, to fit some frequency distribution to this series and thus obtain an estimate of the T-year event. However, without representative flow data this procedure cannot be used and until now the designer has relied on an annual maximum daily rainfall series with some method of converting the T-year rainfall amount into a corresponding daily design flood amount. The above discussion shows that no matter how accurate the method of conversion from rainfall to runoff is, this design procedure will produce results which cannot be relied upon in terms of design magnitudes for given recurrence intervals.

7.3 Comparison of ACRU and SCS large event simulations

An additional step in this analysis was to compare the maximum observed daily runoff series with the maximum simulated daily runoff series generated by both the ACRU and SCS models for each catchment (Table 7.6). A log-Normal frequency distribution was fitted to each series and the results are plotted in Figures 7.13 to 7.18. Table 7.6 shows that, overall, the ACRU model gives a better simulation than either SCS method of the maximum daily runoff series for each catchment, with the exception of catchment 4503. On the humid Coshocton catchments the ACRU model appears to underestimate the highest events, while on the Hastings catchments the model over-estimates the highest events. The remainder of the simulated flood series on all four of the above mentioned catchments appears to be in relatively close agreement with the observed series on each catchment. On the Safford catchment 4501 the ACRU model again produces a comparatively good maximum daily runoff series although it does underestimate the highest runoff depth by almost one third.

The SCS-II method appears to simulate the larger runoff depths better than those in the middle and lower ranges, which tend to be underestimated on all catchments except 4503. The SCS-adj method also appears to simulate the larger runoff events better than the smaller ones, but in all cases the simulations are underestimated. On catchment 4503 both the ACRU and SCS-II methods overestimate all simulations in the series while the SCS-adj method underestimates all simulations.

The simulated distributions (Figures 7.13 to 7.18) resulting from ACRU estimates can be seen to be in close agreement with the observed distributions on all but the Saffod catchment 4503. Even at the 50-year return period there is a maximum discrepency of only 16 % (catchment 2635) between the simulated and observed daily runoff depths. The distri-

Table 7.6 Observed and generated maximum series of daily runoff depths

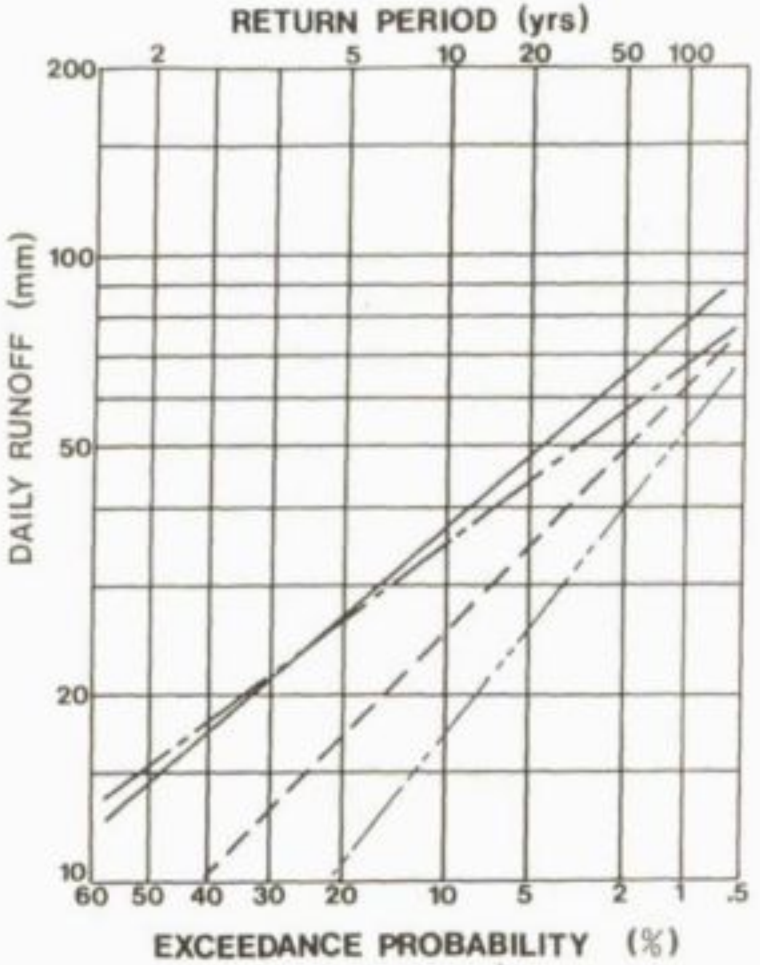
Catchment 2630				Catchment 2635				Catchment 4401			
Q-OBS (mm)	Q-ACRU (mm)	Q-SCS-adj (mm)	Q-SCS-II (mm)	Q-OBS (mm)	Q-ACRU (mm)	Q-SCS-adj (mm)	Q-SCS-II (mm)	Q-OBS (mm)	Q-ACRU (mm)	Q-SCS-adj (mm)	Q-SCS-II (mm)
69.24	58.79	44.82	51.33	65.38	61.32	55.76	75.50	81.06	100.49	80.04	80.04
49.82	49.75	28.29	50.79	40.16	33.00	35.62	44.29	81.05	74.30	76.79	49.53
41.83	41.18	25.32	28.29	29.27	32.46	15.95	30.54	76.86	62.87	42.18	49.53
37.44	39.58	21.92	26.24	28.71	21.23	15.08	21.07	58.99	45.87	37.12	44.29
36.08	32.79	19.51	25.32	26.43	18.08	10.65	15.08	45.82	40.81	25.92	37.12
29.90	31.18	19.19	16.82	23.08	17.86	8.81	14.24	44.34	37.29	21.08	29.24
28.04	27.15	13.90	15.28	21.23	16.97	8.06	13.09	30.68	34.19	20.76	28.32
22.45	22.01	12.30	14.01	18.39	16.53	7.92	9.05	28.69	32.83	17.51	21.98
20.65	20.70	9.30	13.90	18.03	16.14	7.92	8.86	25.88	28.03	16.99	20.01
19.48	18.11	7.37	13.31	16.17	14.53	6.64	8.81	22.90	26.24	14.21	17.72
18.27	16.78	6.41	8.89	15.45	14.52	5.61	8.20	22.31	22.61	12.79	17.28
18.21	15.48	5.25	8.75	13.69	14.26	5.41	8.06	20.80	18.72	12.50	17.09
15.85	14.37	3.20	7.61	13.68	12.80	5.21	7.92	19.91	18.35	11.05	15.69
15.39	14.10	2.02	7.61	13.67	12.61	5.10	7.34	18.34	18.30	10.34	14.67
13.65	13.70	1.67	7.22	13.45	12.50	4.36	7.12	17.79	15.83	9.78	13.73
13.24	12.59	1.42	7.01	10.74	12.06	4.26	6.68	17.06	15.28	9.00	13.33
12.83	12.31	1.18	6.58	10.10	11.37	3.28	6.43	16.12	14.53	8.53	12.30
11.48	11.82	.95	6.54	9.38	11.21	1.91	6.22	15.31	14.31	8.22	11.86
11.42	10.92	.78	6.42	9.36	10.36	1.83	5.77	15.26	13.82	7.44	10.23
10.63	10.87	.50	6.05	8.94	9.40	1.11	5.73	14.67	13.77	4.58	9.55
8.93	10.76	.36	5.61	8.76	9.08	.97	5.65	11.03	11.60	3.44	9.55
7.09	10.16	.28	4.77	6.12	9.00	.42	5.41	10.20	9.83	2.16	9.19
6.78	9.63	.21	3.45	5.14	8.66	.32	5.37	10.00	9.27	1.69	8.39
6.63	8.59	.18	3.29	5.08	8.27	.32	4.49	9.85	7.75	1.63	8.10
5.72	8.42	.14	2.65	4.94	6.83	.32	4.09	9.83	7.64	1.02	8.05
5.56	7.37	.03	2.42	4.87	6.49	.19	3.78	9.48	6.24	.84	7.19
4.89	7.23	.00	2.20	4.75	6.38	.11	2.83	6.99	5.52	.50	4.09
4.12	5.55	.00	2.04	3.12	5.89	.00	2.28	6.73	2.93	.49	3.50
3.60	5.25	.00	1.94	2.98	4.42	.00	1.75	2.53	2.27	.00	3.32

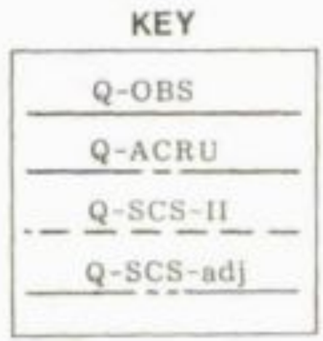
Table 7.6 continued

Catchment 4403 Q-OBS (mm)	Q-ACRU (mm)	Q-SCS-adj (mm)	Q-SCS-II (mm)
74.92	83.87	82.00	82.00
64.97	67.77	69.34	69.34
36.91	48.32	37.75	45.97
36.22	31.33	31.94	31.94
29.28	26.14	23.01	27.53
28.69	25.32	18.67	25.32
28.43	23.26	16.91	17.53
22.21	22.07	14.09	14.35
22.12	20.28	10.38	15.94
20.76	19.18	9.06	15.08
17.33	17.64	8.36	14.75
16.15	17.40	7.83	14.69
15.11	16.87	7.16	14.52
14.83	14.46	6.15	14.05
14.02	13.22	6.11	13.96
13.54	12.39	4.78	12.07
12.58	11.69	4.67	10.02
12.55	11.23	2.53	9.87
11.54	10.11	2.11	9.68
10.82	10.02	1.75	8.06
10.18	7.24	1.30	7.83
9.87	7.16	1.05	7.61
8.96	7.11	1.03	7.34
8.80	6.44	.68	7.03
7.79	6.06	.65	6.43
7.30	4.29	.62	6.01
4.67	1.99	.23	2.39
3.88	1.69	.00	1.70
.90	1.21	.00	1.17

Catchment 4501 Q-OBS (mm)	Q-ACRU (mm)	Q-SCS-adj (mm)	Q-SCS-II (mm)
30.31	21.67	7.61	15.61
18.29	17.25	2.97	10.50
16.77	15.47	2.43	8.76
12.59	13.29	1.20	7.61
9.65	11.70	.73	7.52
8.66	7.81	.44	4.57
8.07	7.41	.02	3.71
7.77	6.71	.00	3.45
7.75	6.62	.00	2.69
7.36	6.26	.00	2.43
7.20	5.50	.00	2.40
6.46	4.74	.00	2.28
4.67	4.56	.00	2.07
4.25	4.24	.00	1.87
3.63	3.42	.00	1.54
3.48	3.18	.00	1.10
3.23	2.83	.00	1.06
2.28	2.70	.00	1.01
1.79	2.63	.00	.97
1.73	2.44	.00	.81
1.65	2.20	.00	.43
1.63	1.64	.00	.41
1.26	1.40	.00	.41
.96	1.06	.00	.23
.87	.79	.00	.08
.65	.65	.00	.02
.59	.48	.00	.00
.35	.34	.00	.00
.31	.15	.00	.00
.31	.04	.00	.00
.18	.00	.00	.00

Catchment 4503 Q-OBS (mm)	Q-ACRU (mm)	Q-SCS-adj (mm)	Q-SCS-II (mm)
7.12	20.66	7.92	25.81
6.89	12.92	3.57	16.59
4.31	9.18	1.82	12.03
4.07	8.41	1.30	11.17
3.89	7.90	.51	10.44
3.81	4.93	.07	7.50
3.22	4.37	.01	4.92
2.30	4.04	.00	4.09
2.03	3.01	.00	3.98
1.85	2.69	.00	3.29
1.73	2.33	.00	3.15
1.46	2.22	.00	3.11
1.17	1.99	.00	3.11
1.09	1.71	.00	2.94
1.03	1.63	.00	2.87
.97	1.44	.00	2.60
.83	1.25	.00	2.18
.73	1.12	.00	2.18
.66	1.00	.00	1.97
.61	.89	.00	1.91
.43	.69	.00	1.54
.33	.64	.00	1.54
.32	.59	.00	1.41
.20	.54	.00	.92
.15	.15	.00	.70
.05	.12	.00	.64
.02	.07	.00	.50
.01	.00	.00	.21
.00	.00	.00	.09
.00	.00	.00	.00
.00	.00	.00	.00





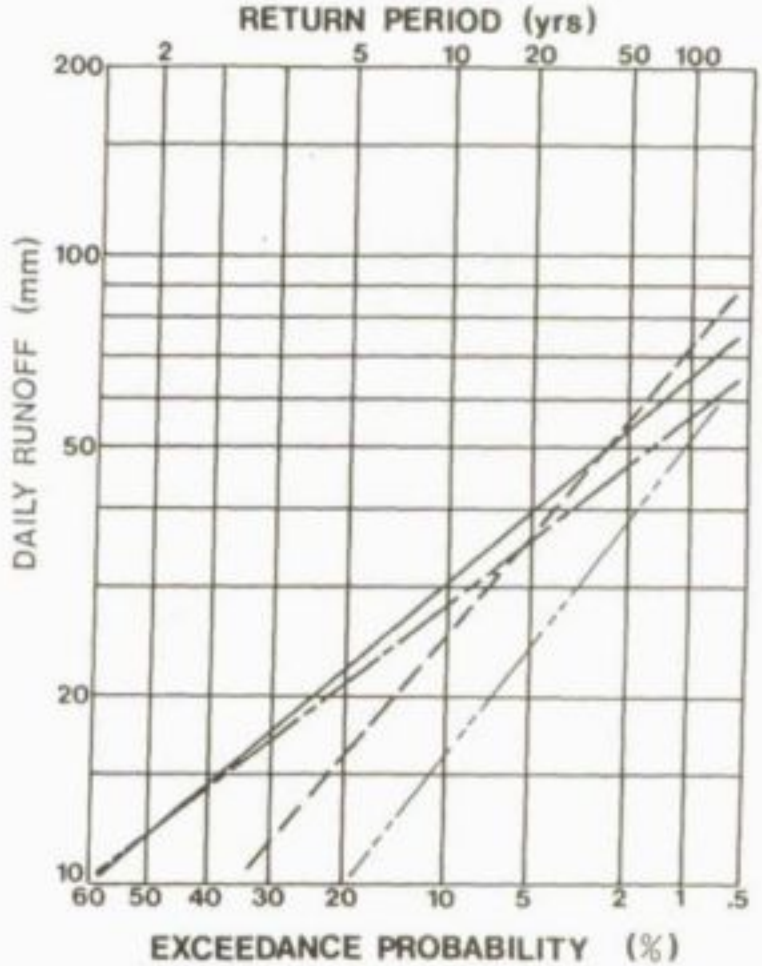


Figure 7.13 Log-Normal plots of maximum daily runoff series for observed data (Q-OBS), and from ACRU (Q-ACRU) and SCS (Q-SCS-adj and SCS-II) simulations for Coshocton 2630

Figure 7.14 Log-Normal plots of maximum daily runoff series for observed data (Q-OBS), and from ACRU (Q-ACRU) and SCS (Q-SCS-adj and SCS-II) simulations for Coshocton 2635

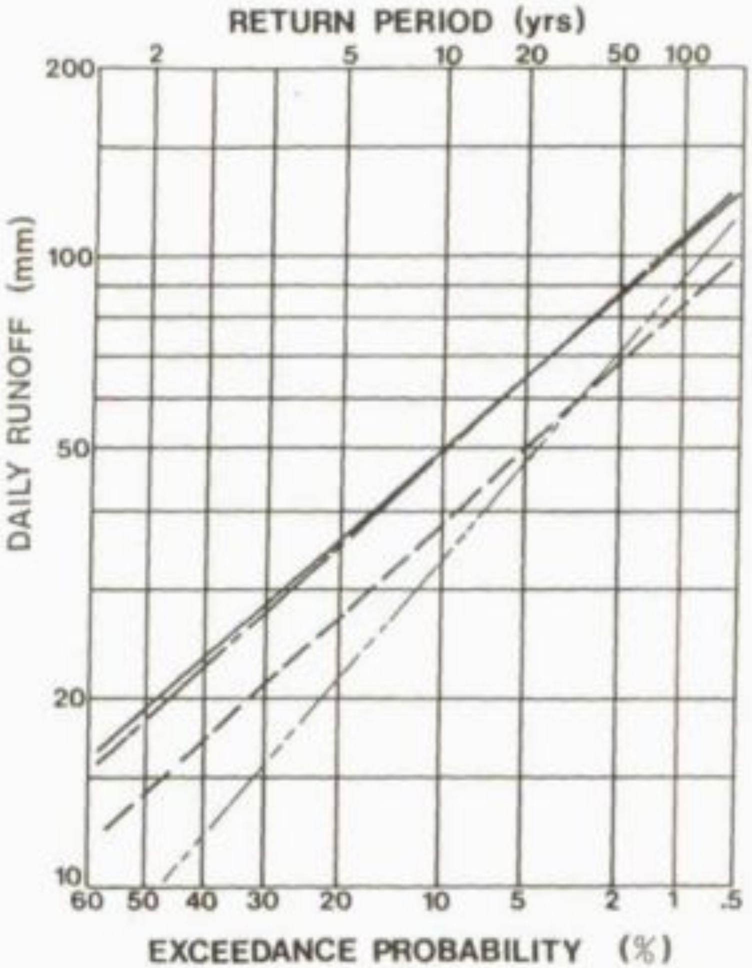
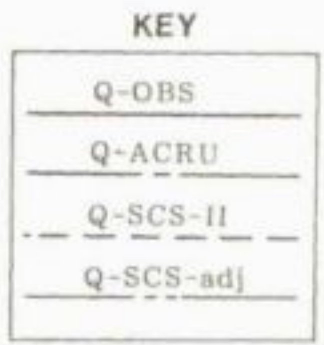


Figure 7.15 Log-Normal plots of maximum daily runoff series for observed data (Q-OBS), and from ACRU (Q-ACRU) and SCS (Q-SCS-adj and SCS-II) simulations for Hastings 4401



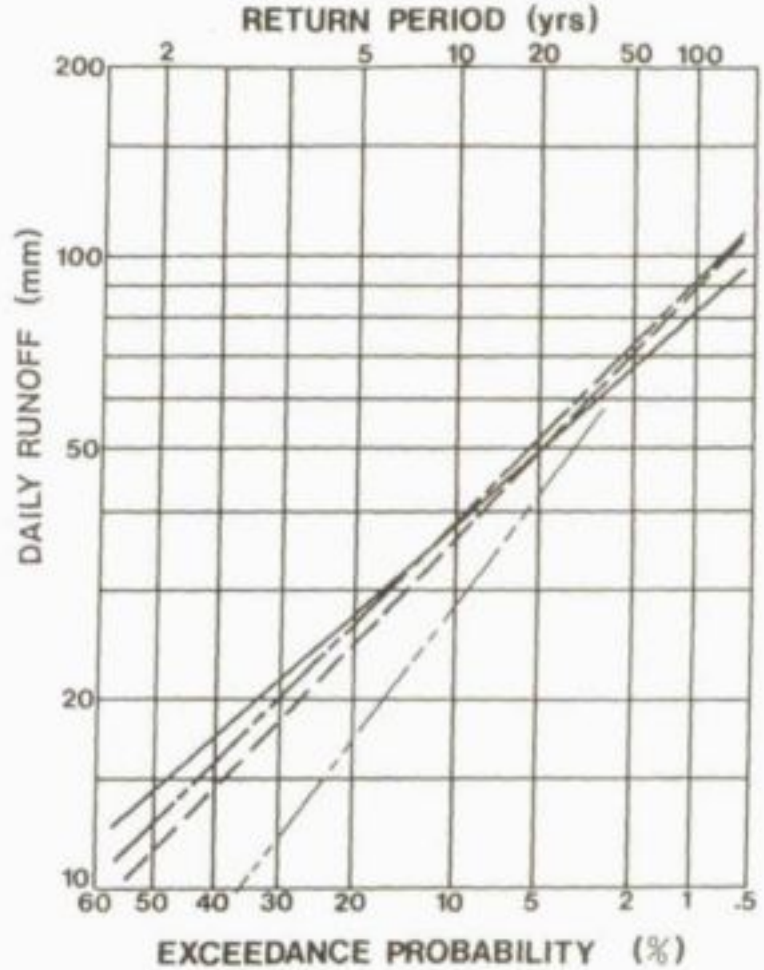
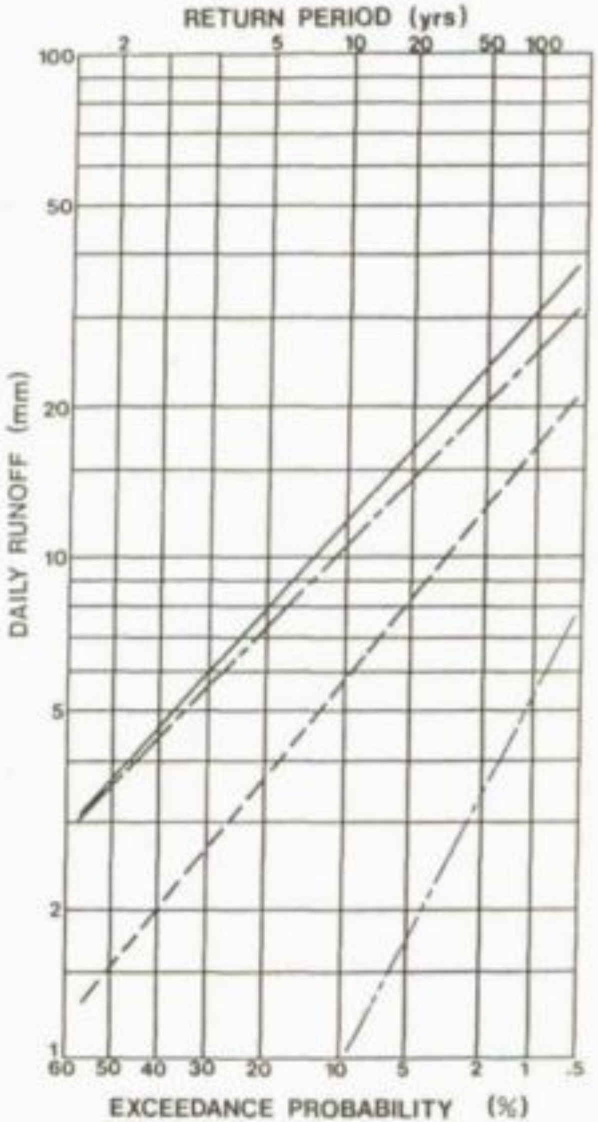
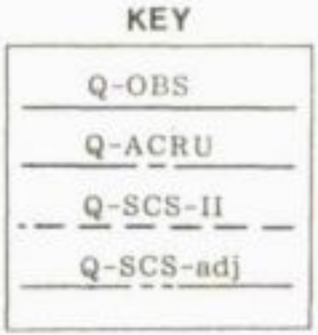


Figure 7.16 Log-Normal plots of maximum daily runoff series for observed data (Q-OBS), and from ACRU (Q-ACRU) and SCS (Q-SCS-adj and SCS-II) simulations for Hastings 4403





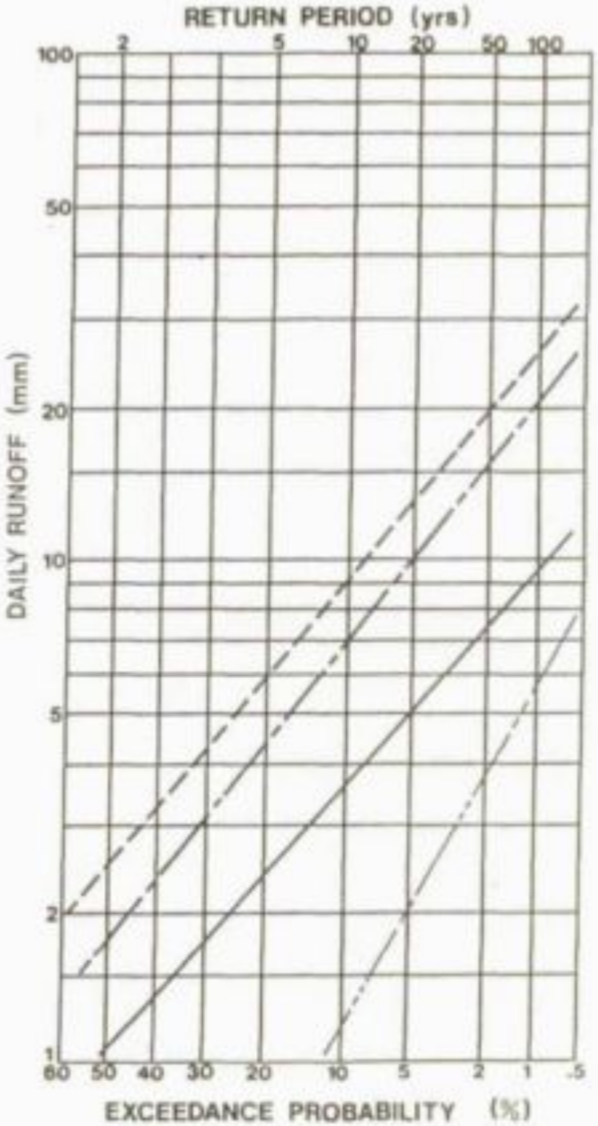


Figure 7.17 Log-Normal plots of maximum daily runoff series for observed data (Q-OBS), and from ACRU (Q-ACRU) and SCS (Q-SCS-adj and SCS-II) simulations for Safford 4501

Figure 7.18 Log-Normal plots of maximum daily runoff series for observed data (Q-OBS), and from ACRU (Q-ACRU) and SCS (Q-SCS-adj and SCS-II) simulations for Safford 4503 butions produced by both the SCS-adj and SCS-II methods (Figures 7.13 to 7.18) do not feature as favourably. However, on all catchments except 4503 the SCS-II method produces the better distribution of the two. Improved estimates could be obtained by adjusting the value of CN-II, but as mentioned previously, in design situations this is not normally possible.

7.4 Summary and discussion

It would appear from the above results that the N-th ranked daily rainfall depth will not necessarily produce the N-th ranked daily runoff depth, with the result that there is not necessarily a direct association between the T-year rainfall amount and the T-year runoff depth. The results indicate that the T-year runoff depth may in fact be produced by a rainfall depth with a return period either greater than or less than T-years. Hence, although no better alternative presently exists, the assumption inherent in current flood design methods of simulating the T-year return period flood from the T-year return period rainfall depth does not provide the engineer with a sound basis for risk analysis in small catchments.

An alternative which has become apparent in this study involves the generation of a runoff series from a series of rainfall events using a conceptually sound daily rainfall-runoff model such as ACRU. The frequency distribution of the rainfall series is then ignored and an extreme value distribution can then be fitted to the generated daily runoff series and an estimate of the T-year return period runoff depth can consequently be obtained. The generated runoff series will depend on the rainfall data available. This study is based on the annual maximum runoff series which requires more than the annual maximum rainfall series to generate.

A further point of note to be made from this research is the relative success of the ACRU model when compared with the SCS model. This implies that the role played by the antecedent soil moisture component is an important part of design flood estimation. To obtain a more quantitative perspective of the importance of ASM in design hydrology, the statistical significance of this component will now be investigated.

8. SIGNIFICANCE OF ANTECEDENT SOIL MOISTURE IN DESIGN DAILY RUNOFF

It has been postulated that considering mean values of catchment variables in a design method the return period of the design runoff depth would be equal to that of the design rainfall depth (Cordery, 1970; Cordery and Webb, 1974). It has, however, been shown that to assume similar return periods even for observed rainfall and runoff events is unsound; nevertheless the accurate simulation of runoff events is essential in the production of a representative maximum flow series. The literature as reviewed in Chapters 2 and 3 considers that, next to the adequate representation of the storm event, the moisture status of the catchment at the beginning of the event is one of the most important factors affecting both the rate and the volume of the storm runoff.

Hjelmfelt (1983) considers the SCS model as presented by the NEH-4 (1972) to be adequate as a frequency transformer, ie. it is adequate in generating a frequency curve for runoff from a maximum rainfall series. However, he states that the variability of the Curve Number leads to difficulty in application of the model, since it varies from event to event. Hjelmfelt maintains that antecedent precipitation explains only a portion of the Curve Number variability, stating that while high antecedent rainfall is associated with high values of CN, dry antecedent conditions are associated with a wide spectrum of Curve Numbers.

It is felt that much of this variability can be overcome by applying a soil moisture budgeting technique, such as that of the ACRU model, as a representation of the S component in the SCS model. As shown in Chapter 6, the ACRU model generally performs better than both the SCS-adj and the SCS-II methods, thereby implying that a more sophisticated representation of antecedent soil moisture causes this component to become significant in the role of design runoff. This chapter sets out to test the statistical significance of ASM, as represented by an antecedent soil moisture deficit (SMD), as a variable in explaining the differences in runoff amounts generated by similar rainfall depths.

8.1 Procedure and significance criteria

To test the statistical significance of SMD, those events selected for the model performance tests on each catchment, as shown in Tables 6.4 to 6.6, were selected and represented in terms of month of the year, rainfall depth, antecedent soil moisture deficit and observed runoff depth. These data were then run through the GENSTAT statistical package.

Each data set was then fitted to the following regression model:

$$Qo = b_0 + b_1(RAIN) + b_2(SMD) + e \qquad \ldots 8.1$$

where Qo is the observed runoff depth, RAIN is the observed storm rainfall depth, SMD is the estimated soil moisture deficit in the A-horizon as simulated by the ACRU model, and b_0, b_1 and b_2 are the regression coefficients with e the error term. In the ACRU model SMD is defined as a soil moisture deficit with respect to field capacity. Hence, negative values of SMD will occur when the soil moisture content is above field capacity.

Criteria for determining the significance of SMD in the regression model were based on the "students" T-value (Rayner, 1967), the adjusted coefficient of multiple determination R_a^2 and the extra sum of squares principle (Neter, Wasserman and Kutner, 1983).

8.2 Results of statistical analysis

Table 8.1 summarises the results, for each catchment, of the regression analysis with the regression model as shown in Equation 8.1. As an indication of model performance the regression equation of the observed flows on the simulated flows as presented in Tables 6.4 to 6.6 are given along with the value of R_a^2. In addition Table 8.1 gives the regression coefficients, the T-values and the values of R_a^2 for both the full model (Equation 8.1) and the reduced model, where the SMD term is dropped from Equation 8.1.

The values of R_a^2 for the regression of Qo on Qe again shows that the ACRU model performs well on the humid and sub-humid catchments. On all four of these catchments the role of SMD is significant with marked improvements in the R_a^2 values, and with T-values which are significant at the 5% level on the Hastings catchments and at the 1% level on the Coshocton catchments. The F* values are all much greater than the F values at the 1% level. Hence it can be concluded that, on these catchments and for daily rainfall amounts greater than 20mm, there is a significant relationship between antecedent moisture deficit, daily rainfall and daily runoff depth.

In the case of the Safford catchments, the lower value of the R_a^2 at 55% for 4501 shows an acceptable performance of the model in estimating flow from rainfall events greater than 10mm in depth. Here the T-value of SMD is small and not significant at the 5% level and the R_a^2 value actually decreases. Similarly F* is not significant at the 5% level. Hence it would seem appropriate to ignore the SMD term from the model. On catchment 4503, however, although the T-value of SMD is not significant and the value of R_a^2 increases only slightly, the extra sum of squares value of F* shows SMD to be significant at the 5% level.

Table 8.1 Results of the regression analysis of rainfall (RAIN) and soil moisture deficit (SMD) on observed flow (Qo) for rainfall amounts above a threshold level (Threshold levels of 20 mm for Coshocton and Hastings, and 10 mm for Safford. * and ** denote significance at the 5% and 1% levels respectively)

Coshocton 2630 : Qe = 2.62 + 0.79 Qo ; R_a^2 = 77.9%
(months 4-11)

Y variate	X variables	Regression Coefficients	T-value	R_a^2 (%)
Qo	CONSTANT	-8.49	-8.21	49.0
	RAIN	0.43	14.77*	
Qo	CONSTANT	-4.87	-5.72*	69.6
	RAIN	0.43	19.01**	
	SMD	-0.27	-12.36**	

Significance of SMD (using extra SS principle)
F* = 152.90** F(1,224) = 6.64 at 1% level

Coshocton 2635 : Qe = 2.34 + 0.74 Qo ; R_a^2 = 79.0%
(months 4-11)

Y variate	X variables	Regression Coefficients	T-value	R_a^2 (%)
Qo	CONSTANT	-8.07	-10.04	52.4
	RAIN	0.39	16.37*	
Qo	CONSTANT	-5.32	-7.61*	68.4
	RAIN	0.40	20.45**	
	SMD	-0.22	-11.55**	

Significance of SMD (using extra SS principle)
F* = 124.30** F(1,241) = 6.64 at 1% level

Hastings 4401 : Qe = 0.81 + 0.86 Qo ; R_a^2 = 81.8%
(months 1-12)

Y variate	X variables	Regression Coefficients	T-value	R_a^2 (%)
Qo	CONSTANT	-12.95	-12.87*	71.7
	RAIN	0.63	23.64*	
Qo	CONSTANT	-9.02	-8.97*	78.2
	RAIN	0.61	26.21**	
	SMD	-0.21	-8.15*	

Significance of SMD (using extra SS principle)
F* = 66.36** F(1,218) = 6.64 at 1% level

Table 8.1 continued

Hastings 4403 : $Qe = 1.46 + 0.90\ Qo$; $R_a^2 = 73.4\%$
(months 1-12)

Y variate	X variables	Regression Coefficients	T-value	R_a^2 (%)
Qo	CONSTANT	-8.17	-8.02	53.3
	RAIN	0.40	15.23*	
Qo	CONSTANT	-5.45	-6.11*	67.8
	RAIN	0.39	18.12**	
	SMD	-0.21	-9.56*	

Significance of SMD (using extra SS principle)
$F^* = 91.26^{**}$ $F(1,200) = 6.64$ at 1% level

Safford 4501 : $Qe = 0.60 + 0.65\ Qo$; $R_a^2 = 59.9\%$
(months 7-10)

Y variate	X variables	Regression Coefficients	T-value	R_a^2 (%)
Qo	CONSTANT	-4.64	-8.02	55.0
	RAIN	0.38	12.61	
Qo	CONSTANT	-4.48	-7.35*	54.9
	RAIN	0.39	12.62**	
	SMD	-0.04	-0.82	

Significance of SMD (using extra SS principle)
$F^* = 0.66$ N.S. $F(1,127) = 3.92$ at 5% level

Safford 4503 : $Qe = 0.40 + 1.05\ Qo$; $R_a^2 = 22.1\%$
(months 6-9)

Y variate	X variables	Regression Coefficients	T-value	R_a^2 (%)
Qo	CONSTANT	-0.68	-3.11	26.6
	RAIN	0.07	6.62	
Qo	CONSTANT	-0.51	-2.25	28.9
	RAIN	0.07	6.85*	
	SMD	-0.04	-2.17	

Significance of SMD (using extra SS principle)
$F^* = 4.69^*$ $F(1,116) = 3.92$ at 5% level
$= 6.85$ at 1% level

Only those events for which the rainfall depth was greater than the magnitude of the two year event, as listed in Table 7.4, were considered next. The same procedure was followed and the results are presented in Table 8.2. Again, introduction of the SMD term determined by the ACRU model generally improves performance on the humid and sub-humid catchments with high values of R_a^2. On the Coshocton catchments the SMD term is still significant at the 1% level, with relatively high values of F*. However, the situation changes somewhat on the Hastings catchments with SMD not significant at the 5% level on catchment 4401, and only just significant at the 5% level on catchment 4403. On both the Safford catchments SMD is not significant at the 5% level.

On catchments 4401, 4403 and 4501 there is little increase in the value of R_a^2 between the reduced regression model and the full model. In comparison with the other catchments, there is a relatively large difference between the T-values of the RAIN term and the SMD term. It would appear, therefore, that it is the rainfall which is the dominant component on these catchments for the so-called "extreme" events. On catchment 4503 the ACRU model gives a poor representation of the extreme events and neither RAIN nor SMD play a statistically significant role in the production of runoff.

As indicated in section 6.2 the soils data for catchment 4503 were deemed inadequate, which probably influenced the runoff simulations using the ACRU Model. In addition the daily data which was obtained from printouts received from the USA could not be verified when anomalies were suspected and thus errors in the data sets could have influenced the results.

Table 8.2 Results of the regression analysis of rainfall (RAIN) and soil moisture deficit (SMD) on observed flow (Qo) for rainfall amounts above the 2-year return period magnitude (* and ** denote significance at the 5% and 1% levels respectively)

Coshocton 2630 : Qe = 12.41 + 0.62 Qo ; R^2_a = 75.5%
(months 4-11)

Y variate	X variables	Regression Coefficients	T-value	R^2_a (%)
Qo	CONSTANT	-28.90	-2.32	53.3
	RAIN	0.75	4.39*	
Qo	CONSTANT	-16.20	-1.64	74.2
	RAIN	0.67	5.17*	
	SMD	-0.60	-3.62	

Significance of SMD (using extra SS principle)
F* = 13.12** F(1,14) = 8.86 at 1% level

Coshocton 2635 : Qe = 7.55 + 0.69 Qo ; R^2_a = 81.7%
(months 4-11)

Y variate	X variables	Regression Coefficients	T-value	R^2_a (%)
Qo	CONSTANT	-16.20	-1.97	61.9
	RAIN	0.53	4.70	
Qo	CONSTANT	-11.97	-2.20	83.7
	RAIN	0.60	7.91*	
	SMD	-0.65	-4.14	

Significance of SMD (using extra SS principle)
F* = 17.14** F(1,11) = 6.64 at 1% level

Hastings 4401 : Qe = 7.41 + 0.78 Qo ; R^2_a = 65.8%
(months 1-12)

Y variate	X variables	Regression Coefficients	T-value	R^2_a (%)
Qo	CONSTANT	-34.90	-2.84	67.8
	RAIN	0.92	6.07	
Qo	CONSTANT	-27.90	-1.58	66.4
	RAIN	0.86	4.65*	
	SMD	-0.16	-0.57	

Significance of SMD (using extra SS principle)
F* = 0.32 N.S. F(1,15) = 4.54 at 5% level

Table 8.2 continued

Hastings 4403 : $Qe = 6.88 + 0.91\ Qo$; $R_a^2 = 80.7\%$
(months 1-12)

Y variate	X variables	Regression Coefficients	T-value	R_a^2 (%)
Qo	CONSTANT	-29.36	-3.71	74.6
	RAIN	0.65	6.92	
Qo	CONSTANT	-16.33	-1.76	79.6
	RAIN	0.55	5.64*	
	SMD	-0.34	-2.17	

Significance of SMD (using extra SS principle)
F* = 4.73* F(1,14) = 4.60 at 5% level

Safford 4501 : $Qe = 4.67 + 0.48\ Qo$; $R_a^2 = 48.8\%$
(months 7-10)

Y variate	X variables	Regression Coefficients	T-value	R_a^2 (%)
Qo	CONSTANT	-14.54	-3.11	54.0
	RAIN	0.68	4.83	
Qo	CONSTANT	-14.47	-3.02	51.7
	RAIN	0.69	4.70*	
	SMD	-0.08	-0.36	

Significance of SMD (using extra SS principle)
F* = 0.13 N.S. F(1,17) = 4.45 at 5% level

Safford 4503 : $Qe = 4.46 + 0.49\ Qo$; $R_a^2 = 0.2\%$
(months 6-9)

Y variate	X variables	Regression Coefficients	T-value	R_a^2 (%)
Qo	CONSTANT	0.54	0.30	-
	RAIN	0.04	0.81	
Qo	CONSTANT	0.15	0.09	7.1
	RAIN	0.07	1.40	
	SMD	-0.16	-1.66	

Significance of SMD (using extra SS principle)
F* = 2.73 N.S. F(1,17) = 4.45 at 5% level

8.3 Regional trends in antecedent soil moisture and daily runoff

In order to obtain a better understanding of the relationship between antecedent soil moisture and storm runoff, the values of Qo and RAIN were plotted against SMD for a representative catchment of each region. The catchments selected were Coshocton 2630, Hastings 4401 and Safford 4501 representative of humid, sub-humid and semi-arid regions respectively. The plots considered both events selected above a threshold rainfall (20 mm for catchments 2630 and 4401, and 10 mm for catchment 4501), denoted by an "o", and events with magnitudes above those of the two-year return period rainfall amount (Table 7.4),denoted by an "*". These plots are shown in Figures 8.1 to 8.3.

From Figures 8.1a and 8.2a it appears that the spread of rainfall events over the soil moisture deficit range is relatively uniform for events above 20 mm in depth. Figures 8.1b and 8.2b show a trend that is representative of the humid and sub-humid catchments selected in this study. Here the range of runoff events magnitudes under wet conditions (ie. ASM above field capacity) is much greater than that under drier conditions, with a distinct decrease in the range as the conditions become drier. It would seem therefore, that the influence of SMD on storm runoff decreases as the initial conditions become wetter, as would have been expected. Conversely, the storm rainfall characteristics become more important under wet conditions. The only outlier from this general trend in the humid and sub-humid regions appeared on catchment 4401 as shown in Figure 8.2b. During this event 97 mm of rainfall produced 77 mm of runoff under what appeared to be dry catchment conditions. Cross checking rainfall data references did not show any contradiction and an observed hyetograph did not reveal any extreme intensities for any length of time over the ten hour duration of this particular event. The event in question again suggests errors in the data sets which could not be verified.

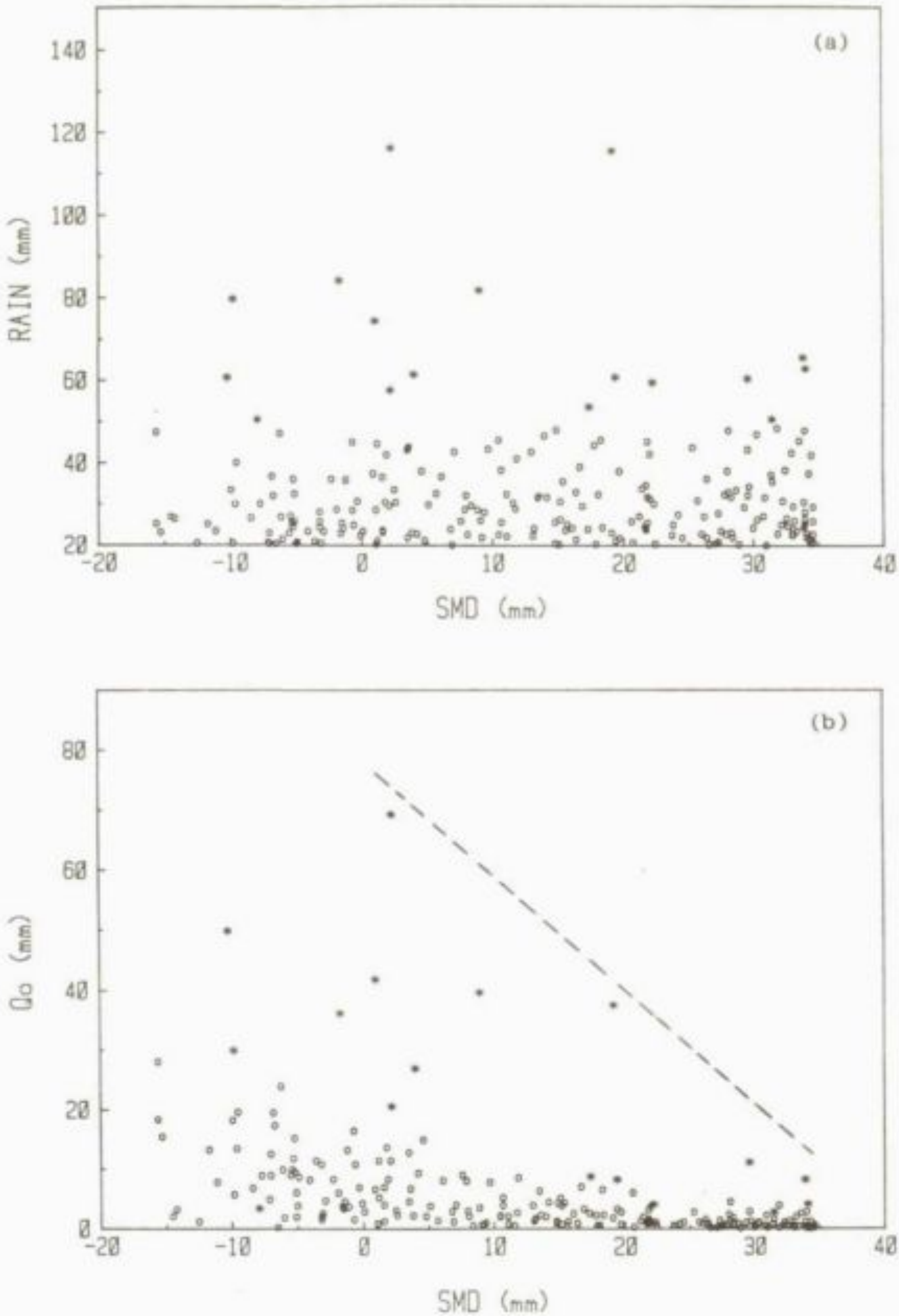


Figure 8.1 Storm rainfall (RAIN) and corresponding daily runoff amounts (Qo) plotted against antecedent soil moisture deficit (SMD) for events of daily rainfall at Coshocton 2630 exceeding amounts of 20 mm (* denotes events with rainfall amounts greater than the predicted 2-year return period amount)

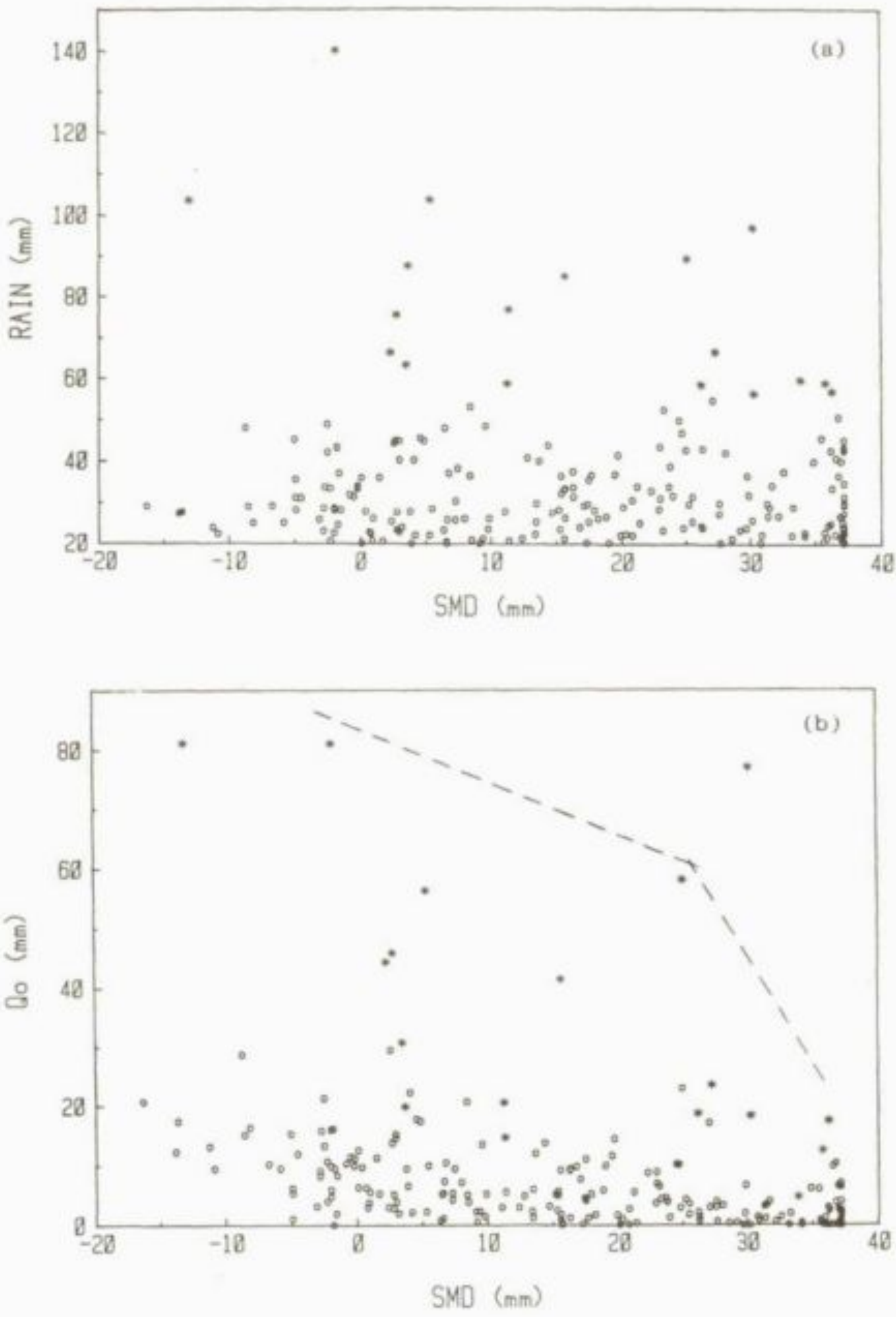


Figure 8.2 Storm rainfall (RAIN) and corresponding daily runoff amounts (Qo) plotted against antecedent soil moisture deficit (SMD) for events of daily rainfall at Hastings 4401 exceeding amounts of 20 mm (* denotes events with rainfall amounts greater than the predicted 2-year return period amount)

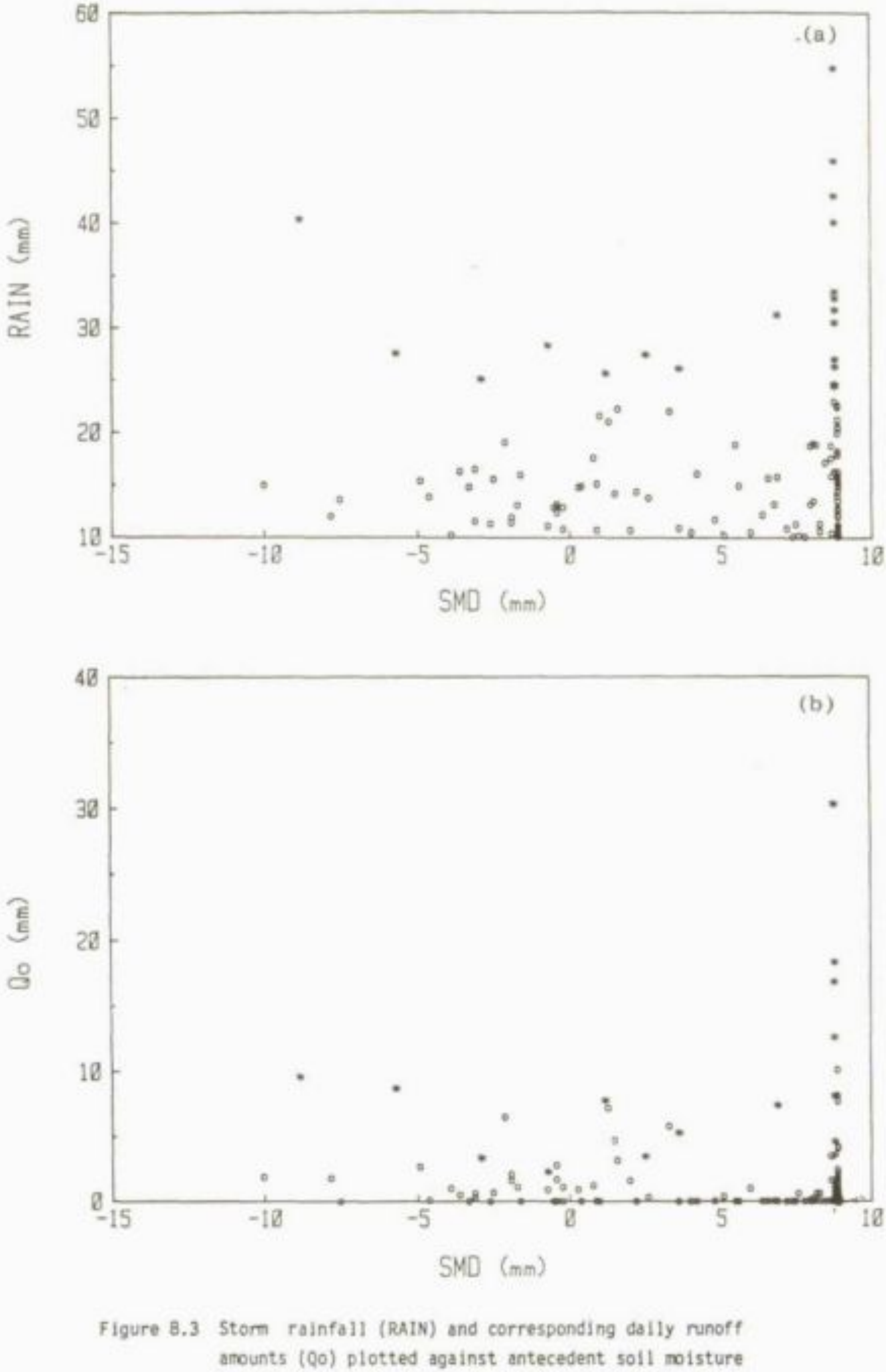


Figure 8.3 Storm rainfall (RAIN) and corresponding daily runoff amounts (Qo) plotted against antecedent soil moisture deficit (SMD) for events of daily rainfall at Safford 4501 exceeding amounts of 10 mm (* denotes events with rainfall amounts greater than the predicted 2-year return period amount)

For events with magnitudes exceeding those of the two-year return rainfall, the general trend is as shown by the events marked with an "*" in Figures 8.1b and 8.2b, with the exception, once more, of the outlier on 4401. Again, the range of runoff event magnitudes is reduced under drier conditions. Therefore, even under the extreme or design events the influence of SMD is greater under drier conditions.

The relationship between SMD and daily runoff on the arid catchments studied is well illustrated by catchment 4501 in Figure 8.3. The reason for the non-significance shown in Table 8.1 becomes obvious when one considers that 50 % of the events above 10 mm rainfall occur under a soil moisture condition less than half the plant available water (represented in catchment 4501 by an SMD value of 4.4 mm) In addition, 29 % of all the events fall on a soil at wilting point (ie. SMD = 8.8 mm in Figure 8.3a), while 60 % of the events with a return period greater than two years occur under this condition. Events occurring on wetter catchments do not appear to produce runoff depths which are any greater than those occurring on the drier catchments, and it is therefore assumed that temporal rainfall distributions play a far more important role in runoff generation on these arid catchments.

8.4 Summary and Discussion

The plots in Figures 8.1 to 8.3 have shown that on humid and sub-humid catchments the influence of the storm characteristics appear to be greater than that of the antecedent soil moisture deficit under wet catchment conditions. Conversely, under relatively drier conditions SMD appears to play a more important role than storm rainfall characteristics. This trend appears to hold for events with a relatively high return period as well as for those events with greater than 20 mm of rainfall certainly in the catchments tested. As mentioned previously this threshold level of rainfall was selected arbitrarily, and in all cases in the test catchments it is less than half the rainfall depth estimated for a two-year return period. It is important to consider these events of relatively little rainfall since the higher runoff amounts generated by some of these events will have a direct effect on the slope of the extreme value plots as shown in Figures 7.13 to 7.18.

On the arid catchments studied it appears that a large proportion of the events occur on a dry catchment, and even those runoff events occurring on wet catchments seem to be affected more by the storm rainfall than the SMD.

In terms of statistical significance, Table 8.1 indicates that SMD is an important term in a regression model of storm runoff of the type given in Equation 8.1 on the humid and sub-humid catchments, while on the arid catchments this term is much weaker. For rainfall events exceeding that of the two-year magnitude the SMD term still remains significant at the 1% level on both the Coshocton catchments tested (Table 8.2). For similar events on the Hastings catchments SMD proved to be significant at only the 5% level on catchment 4403 and not significant on catchment 4401. On both the Safford test catchments the SMD term proved not to be statistically significant. It appeares therefore, that as the climates became drier so the dependence of storm runoff on soil moisture deficit decreases for the more "extreme" events.

For purposes of design, the estimation of a flood volume from a storm rainfall depth, say the 20-year event, may therefore be more sensitive to the storm characteristics than to conditions of antecedent soil moisture. Such characteristics could include rainfall depth, storm duration and the storm profile. If, however, the design engineer wishes to determine the 20-year flood, the extent to which his model can simulate antecedent soil moisture deficits will determine to a large extent the accuracy of the events in the maximum flood series. Since this method of determining the X-year flood appears to be more reliable than the methods in present practice, the role of SMD can be considered to be a significant one in design.

9. DISCUSSION AND CONCLUSIONS

The main aim of this research was to study the daily rainfall-runoff frequency relationship and to investigate the importance of the role of antecedent soil moisture in the estimation of daily design runoff depths on small catchments under varying climatic conditions. This involved the comparison of the outputs of two daily runoff estimation models, the ACRU and SCS models, with the observed daily flows of six selected catchments at Coshocton (2630, 2635), Hastings (4401, 4403) and Safford (4501, 4503) with humid, sub-humid and arid climates, respectively. A brief discussion of the results and conclusions obtained is given below.

In simulating daily streamflows the ACRU model performed well on all but one of the six catchments selected for the study. The relatively poor results obtained for catchment 4503 were attributed in part to the difficulty in simulating low and infrequent flows on arid catchments, in part to the relatively scant information available on the soil types and characteristics for the catchment and in part on possible erroneous data sets. In addition, the Coshocton catchments exhibited periods of snowmelt, a process which ACRU cannot simulate, with the result that these periods (months December to March) were excluded from further analyses as the simulations of ASM could not be relied upon during this period. On the Safford catchments it was noticed that streamflow generally only occurred in certain summer months. Hence only these months were considered for further analyses. The overall conclusion from streamflow simulations was that the ACRU model provided representative indices of ASM for the selected months on all but the catchment 4503.

The use of the SCS model was confined to the procedures as recommended in current design manuals (eg. NPA, 1981; NTC,1983), namely that presented in NEH-4 (1972). In addition to applying the method of Curve Number adjustment according to antecedent rainfall, it was decided to apply the SCS method without the

Curve Number adjustment. This was based on the premise that antecedent rainfall amounts are frequently not available in practice and the designer would then merely apply the CN-II to the SCS method. The performances of the ACRU model and the two SCS methods (SCS-adj and SCS-II) were compared at two levels. Firstly their statistics of performance were compared for daily simulations from rainfall amounts greater than a threshold value of 20 mm on the Coshocton and Hastings catchments and 10 mm on the Safford catchments (Chapter 6). Secondly, maximum flow series were derived through each method and log-Normal frequency distribution was fitted to each series. The distributions were then plotted for comparison (Chapter 7).

In all the cases, with the exception of the comparisons on catchment 4503, the ACRU model showed a better level of performance than either of the SCS methods. However, the SCS-II method compared well with the ACRU model, especially on the relatively larger catchments in the humid and sub-humid regions. On the other hand, the SCS-adj method did not compare well with either of the other two methods on any of the catchments. Figures 8.1 and 8.2 show that rainfall events in the humid and subhumid regions occur over the full range of antecedent moisture deficits. One would therefore assume that the SCS-adj method should provide the better estimates, with the SCS-II method overestimating and underestimating the dry and wet conditions respectively. Similarly, on arid catchments such as the Safford catchments a large proportion of the events occur under dry conditions (Figure 8.3) with the result that the SCS-II method should overestimate the runoff amounts. Noting Hawkins' (1978) criticisms of "quantum jumps", it would appear that the number of AMC groupings need to be increased with smaller jumps between each group, or the group limits must vary from catchment to catchment under different climatic and soil moisture conditions. The fact that the ACRU model provides consistently better performance statistics implies that the soil moisture budgeting technique provides a much better representative of ASM, and that this component appears to have a marked effect on the simulated stormflow amounts.

In testing the significance of the ASM component in design rainfall-runoff processes the component was represented as a soil moisture deficit (SMD) in the ACRU model. With the exception of the arid catchments, the SMD term appeared to be more significant in generating stormflow from storms of relatively low rainfall amounts (but nevertheless greater than 20 mm) than in the more extreme storm rainfall amounts (amounts greater than the 2-year return period amount). Under so-called extreme events it would appear that characteristics such as rainfall depth, duration and the profile of the storm hyetograph may prove to be as important as, and in cases even dominant over, the influence of SMD in the generation of a flood event. It was noticed, however, that there was a tendency for the large flood events to occur under wetter conditions on the humid and sub-humid catchments.

On the arid Safford catchments the SMD term was found not to be statistically significant, especially for the larger events. This is due to the fact that a large proportion of the events fall on a dry catchment, with the result that the SMD term is relatively constant for most events. On catchment 4503, however, it was noted that for rainfall amounts exceeding 10 mm the SMD term was significant at the 5% level when non-significance was expected. Although this may be a good reflection of the catchments rainfall-SMD-runoff relationship, it must be borne in mind that the performance of the ACRU model on this catchment was comparatively poor. Therefore, considering the relatively poor soils information available for the catchment it is uncertain whether the model simulations of ASM can be relied upon.

Regional trends of the influence of ASM were noted as follows : The effect of antecedent SMD on daily runoff was stronger on drier catchments in the humid and sub-humid regions of the study. As the catchments became wetter so the effect of SMD became overshadowed by other influences which may include the storm characteristics of depth and duration of rainfall and the shape of the storm hyetograph. On the arid catchments it appeared that a large proportion of the events fell on dry catchment conditions, rendering the effect of SMD on daily runoff generation non-significant.

With respect to current design practice it appears that the assumption of equal return periods for a design storm rainfall and its resulting flood volume does not provide a sound basis for risk analysis on small catchments. It is the opinion of many researchers in this field that the probability of occurrence of a flood event will be an integration of the probabilities of occurrence of rainfall depth, duration and intensity as well as that for an antecedent condition (eg. Hiemstra, 1969; Cordery, 1970; Hughes, 1977; Hughes, 1985). In addition, it is likely that there are a large number of combinations of the above conditions that may produce the same flood volume (Hughes, 1985).

Therefore, it appears that there is no immediate solution to the problem of incorporating the above theory of joint probabilities into current design procedures, especially when one considers the amount of data that will be required to generate probability distributions of each of the above quantities. Some improvement must, however, be made to the existing design procedures.

A method of estimating the magnitude of the T-year return period flood event has been shown from this research to generally provide good estimates. The method involves the application of the design model, such as the ACRU model, to representative daily rainfall data for a catchment and to generate a daily runoff series. A frequency distribution may then be fitted to the runoff series and an estimate of the T-year flood volume can then be obtained. The nature of the generated runoff series will depend on the available rainfall data. This study considered the annual maximum daily runoff series which requires more than the annual maximum rainfall series to generate, and hence a larger number of recorded storm events within a year. Intuitively and statistically, the longer the period of record, the more representative the runoff series will be. The reliability of the method will also depend on the choice of the design model. In this research the ACRU model was selected because of its ability to represent and incorporate the antecedent soil moisture conditions in the simulation of flood volumes. However, this study has shown that, with carefull determination of the Curve Number, the SCS-II may be used with reasonable success.

Proposals for further research would include the testing for significance of antecedent soil moisture in design stormflow estimation on many more catchments under as wide a range of climatic conditions as possible. If this could be done in South Africa, specific regional trends may become apparent which will further assist design flood procedures in certain areas. In addition, the application of a distributed model may reveal areas of significance which cannot be identified through the use of a lumped model as was used in this research. If the distributed model can identify areas of a catchment which conform to the variable source area or partial area concepts of runoff generation, then the importance of antecedent soil moisture in design flood generation may be more fully understood.

Further research into flood frequency analysis should include the generation of a partial duration flood series instead of only an annual maximum flood series. This would require the same rainfall data, and may well provide a better estimate of the T-year flood volume particularly for the low recurrence intervals used frequently in the design of smaller structures in agricultural engineering. It is felt that with the current availability of powerful computer systems, the introduction of methods requiring computer facilities is not beyond the general practitioner in hydrological design. Hence, it is believed that the method described in this study, namely determining the magnitude of a flood volume of specific return period, has a place in design practice.

10. SUMMARY

The high annual costs of building hydraulic structures on small catchments in South Africa has induced the need for more accurate and reliable design flood estimation procedures. A review of the current design flood estimation techniques identified the assumption of equal return periods for a design storm depth and the resulting flood as being a possible area for improvement. A belief among researchers is that a component of the rainfall-runoff relationship which has been paid little attention in design techniques is the antecedent soil moisture component. An attempt was made in this study to determine the effect of antecedent soil moisture on runoff generation, and to investigate the problem of estimating the daily runoff volume for a given recurrence interval.

The ACRU and SCS models were employed to simulate daily runoff volumes from selected rainfall amounts and to compare these simulations to the observed floods. The ACRU model incorporates the SCS stormflow equation in its simulation of flood volumes, but in place of the Curve Number method it applies a soil moisture balance procedure to estimate antecedent soil moisture deficits. Comparison with the SCS estimates and the observed flows show that the ACRU model gives a better account of daily runoff depths, thereby implying that the inclusion of a representative index of ASM into stormflow estimation method is important.

Further statistical analysis of observed rainfall and runoff data with ACRU model estimates of ASM for each event indicate the importance of the ASM component in runoff generation in humid and sub-humid regions, especially for the smaller storm events. In arid regions the ASM component was found to be non-significant due to the high proportion of events occurring on dry catchments.

An investigation into the frequency of occurrence of a storm event and its corresponding runoff showed the current assumption, in design practice, of equal return periods for a design storm and the generated stormflow to be unreliable. An alternative procedure has been proposed whereby use is made of available rainfall data to generate an annual maximum flood series for he catchment. The fitting of some frequency distribution to the flood series will then enable an estimation of the flood volume for a desired return period to be made. It is believed that the use of this method in design practice will provide more reliable estimates for risk analysis.

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