Simulation of Stormflow Volumes From Small Catchments

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PREFACE

In May 1979 the Water Research Commission entered into a second five year contract with the University of Zululand. The Project had as one of its aims the testing of stormflow simulation models giving particular attention to the antecedent moisture component of these models. Studies presented in this interim report deal with research which was conducted essentially during the first three years of this Project. While the staff of the Hydrological Research Unit have been engaged in a variety of hydrological investigations, stormflow modelling has been the major research thrust during this initial period.

Research pertaining to two simple stormflow models is presented in two major sections. Each of these major sections is intended to be a separate entity although a general aim pertains to both investigations. This aim may be stated briefly as being to test these methods of calculating storm= flows under South African conditions and to improve or develop suitable antecedent moisture procedures for inclusion in the models. The research chapters of this report are preceded by a review of stormflow theories, the role of catchment moisture status in the production of stormflow and procedures for estimating antecedent moisture conditions.

Much of the research pertaining to the SCS model (Section A) was presented as an M Sc Eng thesis in the Department of Agricultural Engineering at the University of Natal with Professor R E Schulze as supervisor. The helpful suggestions and guidance by Professor Schulze is gratefully acknowledged. Most of the research for this Report was conducted in the Department of Agricultural Engineering at the University of Natal and a particular word of thanks is due to the Head of the Department, Professor P Meiring, for placing the facilities of the Department at my disposal. I would also like to express my appreciation to the staff of this Department for their kind assistance and particularly to Mrs K M Temple for typing the draft document.

Thanks are also due to the following persons and Departments of the University of Natal:

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Chapter 1
INTRODUCTION

The estimation of stormflow volumes from small agricultural catchments is important for the design of structures such as farm dams and culverts. This information is also of value in fields such as forest management and planning. Generally, stormflow volumes are used to derive peak discharge rates and inaccuracies in the calculated volumes are transferred to the estimated peak values. According to Orgosky and Mockus (1964) stormflow peaks are controlled primarily by stormflow volumes.

The moisture status of a catchment prior to a stormflow event may have a marked effect on the proportion of storm rainfall which leaves the catchment as stormflow. In this Report the role of catchment moisture status in the production of stormflow is given primary attention. Two stormflow models are tested on selected catchments and their suitability for estimating stormflow volumes using data generally available for small catchments in South Africa is assessed. The first model tested, the SCS model, is a procedure which has gained international acceptance for the estimation of stormflow volumes. This model has been found, however, to be unsuitable for use in forested and wildland catchments in the eastern United States of America (Hewlett, 1980). An alternative model, The R-index method, was developed for use in this region and is the second model dealt with in this study.

Conceptually, the two selected models differ markedly and in attempting to develop suitable procedures to represent catchment moisture status different techniques and approaches have had to be adopted for each model. Although the two investigations are dealt with as separate entities, general conclusions pertaining to stormflow modelling and the estimation of antecedent moisture conditions are presented. Because the research has been conducted over a number of years the data, catchments and techniques were not identical for both studies.

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1 Stormflow is synonymous with "quickflow" or "storm runoff".

Most of the catchments used in this investigation are located in Natal. Evaluation of the two models in terms of their suitability for simulating stormflow volumes may thus be regarded as a preliminary study having particular relevance to this province. The difficulty in obtaining satis= factory samples of stormflow and stormflow rainfall information for small catchments resulted in many of the analyses being conducted using only a few observations in some catchments. However, rather than exclude these catch= ments it was decided to include them for the analyses so that an indication of model performance under different environmental conditions could be obtained.

Throughout this investigation the research procedures adopted have been guided by a modelling philosophy which embraces the following:

(a) Through computational and technological advances it is possible to develop more sophisticated models. However, complex models are no always better and simple models will often suffice. Both the SCS model and the R-index method were intended to be simple models requi= ring limited data inputs.
(b) Equations and parameter estimation can be refined to improve estimates of observed stormflows but this does not necessarily result in improved estimates in other regions or outside of the limits of the data used for calibration.
(c) All hydrological models make certain assumptions and according to James and Burgess (1982) these assumptions limit the issues which a model can address.

Finally, James and Burgess (1982) draw attention to the pitfalls of vertical as opposed to lateral thinking in attempts to build and refine models. These authors present their case using the following quote from De Bono (1967):

> Logic is the tool that is used to dig holes deeper and bigger, to make them altogether better holes. But if the hole is in the wrong place, then no amount of improvement is going to put it in the right place.

> No matter how obvious this may seem to every digger, it is still easier to go on digging in the same place than to star all over again in a new place. Vertical thinking is digging the same hole deeper; lateral thinking is trying again elsewhere.

The research presented in this Report has been directed at improving aspects of the SCS and R-index models, efforts which could lead to digging the same hole deeper where a new hole may have been required. However, a conscious attempt has been made throughout the investigation to avoid this danger.

Chapter 2
STORMFLOW AND CATCHMENT MOISTURE STATUS

The production of stormflow from storm rainfall is a complex process and numerous theories have been proposed to describe this process. The varia= ble nature of catchment moisture status is a major determinant of the stormflow potential of a catchment. Data which are usually available to the engineer on ungauged catchments prohibit the use of complex procedures for determining catchment moisture status (CMS), indices generally being relied on to estimate this variable. It is the purpose of this chapter to review the major stormflow theories and the role attributed to CMS in the production of stormflow, to examine the variability of CMS in a catchment and further to discuss selected procedures for estimating this complex variable.

2.1 Stormflow Theories

In 1684 Edmé-Mariotte provided the first experimental proof that rainfall is responsible for river flow (Freeze, 1972a). It may be argued that almost 300 years later very little more is known about the rainfall-runoff process (Freeze, 1972a). It is only in recent years that hydrological research has "... begun to shift away from the total involvement in the needs of engineering hydrology toward the more academic goal of understan= ding the basic mechanisms of runoff generation. Possibly these same engi= neering needs, now in the form of a demand for improved hydrologic response models, are responsible for the recent revival of interest in the generic question" (Freeze, 1972b:1272).

Since the mid 1930's stormflow simulation models have been characterised by relationships based on infiltration theory and the allied principles of widespread overland flow - a concept first expounded by Horton in 1933. In recent years these traditional theories have been challenged seriously following field observations and experiments which failed to confirm the existence of overland flow as originally perceived. Numerous theories emphasising different components of the hydrological system have emanated from these observations. However, no single theory has as yet found accep= tance as a basis for stormflow simulation models having widespread applica= bility. It is possible to classify stormflow theories into two broad categories, viz:

(a) those based on the infiltration theory of runoff described by Horton in 1933, and
(b) unit source area theories.

The various stormflow theories proposed to date have different implications with respect to CMS and stormflow models. In reviewing the more prominent stormflow theories it is intended to highlight these implications.

2.1.1 The Horton Stormflow Theory

The Horton theory of stormflow production assumes stormflow to be generated by rainfall excess, this being defined as water failing to infiltrate the soil surface (Horton, 1933). Thus, stormflow is envisaged as a really wide= spread overland flow and the theory infers that most rainfall events exceed the infiltration capacity of the soils (Freeze, 1972a).

Horton recognised a maximum and minimum infiltration rate, the maximum rate occurring at the start of a rainfall event and decreasing exponentially, gradually approaching a somewhat stable minimum rate. If the infiltration rate fell below the rainfall intensity, overland flow and subsequently stormflow would occur.

The complex process of infiltration is, according to Betson (1964), princi= pally a function of soil moisture with the decay in infiltration rate resulting inter alia from changes in the surface soil moisture. Research conducted by Mulder and Hope (1981) on infiltration rates of the soils of the Ntuze catchment in Zululand have confirmed this observation. Thus, according to Horton's theory, high levels of antecedent soil moisture prior to rainfall results in an infiltration rate close to the minimum, facilita= ting the production of rainfall excess and overland flow.

The Horton theory asserts that rainfall excess is the sole source of stormflow and it may thus be concluded that this model is clearly most applicable in areas having a low capacity for infiltration where only a limited length of rainstorm is necessary to saturate the entire catchment surface and to initiate overland flow on all the slopes (Ward, 1975).

The traditional Hortonian theory of stormflow production has been criticised severely, particularly in the past two decades. This criticism has generally dealt with the contribution of sub-surface movement of water to the stormflow hydrograph. Hills (1971) has stated that soils in the United Kingdom are capable of absorbing and storing the majority of rainfalls and tests have revealed that less than 10 percent of rainfall events are capable of producing overland flow. Hills concludes that "overland flow can be demonstrated on small plots over short distances, but one cannot conclude, especially in rural areas with no artificial drainage, that this becomes a contribution to streamflow" (Hills, 1971:178). A similar view pertaining to conditions in the U S A is held by Freeze (1972a) who states that the Hortonian concept is only acceptable in the semi-arid western U S A.

The persistent application of the Hortonian theory in stormflow models may be ascribed to the simplicity of this theory, particularly with respect to procedures for separating and interpreting the storm hydrograph (Ward, 1975). However, increasing attention is being directed at unit source area theories of stormflow despite their relative complexity.

2.1.2 Unit source area theories

Unit source area theories of stormflow may be defined as those stormflow theories embodying one or more of the following principles:

(a) The production of stormflow in a catchment is non-uniform.
(b) Stormflow is not synonymous with rainfall excess or surface flow but may be subsurface flow or a combination of subsurface flow and surface flow.
(c) Certain areas of a catchment may seldom, if ever, contribute directly to the production of stormflow.

As early as 1935, Musgrave had concluded from field infiltration tests that surprisingly little rainfall failed to infiltrate the soil surface. In 1936 Hursh described subsurface stormflow and in 1943 Hoover and Hursh concluded from their studies of the stormflow process in the mountains of western North Carolina that subsurface stormflow may be found in the higher elevations of a catchment.

Since these early descriptions of subsurface flow, numerous researchers have claimed that this type of flow makes an important contribution to the storm hydrograph. The observations made by Hawkins in 1961 are typical. Following a study of 14 storm hydrographs in the Missouri Gulch Watershed of Colorado, Hawkins reported that there was no surface runoff and rainfall intensities were not greater than the infiltration capacity of the catch= ment soils. Following this observation, Hawkins concluded that there must have been subsurface stormflow as well as direct channel interception. Similar findings were described by Whipkey (1965) who reported subsurface stormflow during the actual storm period, this reaching the stream channel without entering the general groundwater zone.

Despite the large body of support for subsurface stormflow production, this concept has been questioned seriously by authors such as Betson (1964), Dunne and Black (1970a, 1970b) and Freeze (1972a, 1972b). The following questions posed by Freeze (1972a) regarding the relationship between sub= surface flow and the storm hydrograph are typical of these misgivings, viz:

(a) Is subsurface stormflow quantitatively important?
(b) Is subsurface stormflow a controlling mechanism on the development of wetland areas?
(c) Is subsurface stormflow unimportant in either context?

On the basis of the role ascribed to subsurface flow in the production of stormflow, unit source area theories may be categorised into:

(a) variable source area theories, and
(b) partial area theories.

It is in examining the fundamental components of these theories that the role of antecedent moisture conditions in the production of stormflow becomes apparent.

Variable source area theories are based on the principle of subsurface stormflow. The first formalised runoff theory embodying the variable source area concept was presented by Hewlett (1961). According to Hewlett and Hibbert "...when the subsurface flow of water from upslope exceeds the capacity of the soil profile to transmit it, the water will come to the surface and channel length will grow. This in essence is the variable source area concept" (Hewlett and Hibbert, p 279). Perennial channels expand into zones of low storage capacity, this process being facilitated by high antecedent moisture condition. Furthermore, it is postulated in this theory that the expanding channel network 'reaches out' to 'tap' the subsurface flow systems (Hewlett and Hibbert, 1967). It may thus be deduced that the amount of subsurface flow and hence water which may be tapped to become stormflow is largely a function of the antecedent moisture conditions. Furthermore, translatory flow (subsurface flow by displacement) is only important when high soil moisture conditions prevail (Ward, 1975). Tischendorf (1969) also refers to a 'critical' soil moisture value of the topsoil which increases the 'conductivity' of this horizon, thus permitting translatory flow. A variety of mechanisms are therefore described in the variable source area concept as contributing to stormflow volumes. However, as Ward (1975) states, the relative importance of these mechanisms depends on the rainfall characteristics and antecedent moisture conditions.

Partial area stormflow theories are based on the premise that fixed areas of the catchment are effective stormflow producing areas. Referring to these partial areas, Dunne and Black observed that "... the water table rose to the surface of the ground over small areas. When this occurred, water emerged from the soil surface and ran quickly to the channel as over= land flow" (Dunne and Black, 1970b:1208). Subsurface flow of water is not attributed to the prominent role as it is in variable source area theories. According to Freeze (1972a) the stormflow producing mechanism most fully supported by field evidence is that embodied in the partial area theory.

It is stated by Betson (1964) that partial areas are often 'wetlands' whose location is controlled by the topographical and hydrological configuration of the catchment. These wetlands are commonly adjacent to the river chan= nels. Hope and Mulder (1979) describe the existence of such wetlands adjacent to the river channels of the Zululand research catchments.

Antecedent moisture conditions thus have a two-fold effect on stormflow volumes. First, the higher the CMS the lower the storage capacity of con= tributing areas, less rain therefore being required to bring the water-table to the surface in order to provide for the production of stormflow. Secondly, the sizes of the contributing areas may be governed by CMS since these areas are fed by soil moisture draining from areas of higher eleva= tion.

2.2 The Variability of Catchment Moisture Status

From the preceding review of stormflow theories and the relevance of CMS in the production of stormflow it has been established that the potential for stormflow production varies both temporally and spatially. The following review deals with the variability of CMS in these two dimensions. Since the major dynamic storage component of a catchment is the soil matrix, much of the following discussion relates to the variability of soil moisture.

Temporal changes in CMS are governed by the sequence of inputs (rainfall) and outputs (runoff, drainage and evapotranspiration) into and from the catchment. Soil moisture recharge is an irregular process depending prin= cipally upon the sequence of rainfall amounts (Nixon, Lawless and McCormick, 1972). Losses of soil moisture are affected mainly by evapo= transpiration with drainage playing a secondary role (Saxton, Johnson and Shaw, 1974). In regions of high rainfall which is evenly distributed throughout the years, variations in soil moisture follow the load of solar energy available for evapotranspiration, this energy being a function prin= cipally of season (Helvey and Hewlett, 1962).

The temporal variations of soil moisture at different depths in the soil horizon are controlled by different mechanisms. Tischendorf (1969) con= cluded that the deeper soil moisture changes were related to season rather than to individual events, this having being confirmed by authors such as Henninger, Petersen and Engman (1976) and Hope and Schulze (1979). The depth to which daily fluctuations of evapotranspiration affect soil moisture is determined by the rooting patterns of the vegetation (Grindley, 1967; Jones, 1976).

Every phase of the hydrological cycle may give rise to spatial variations in CMS. It is, however, possible to identify the major components governing this variability within the catchment system. On small catchments this is frequently achieved by assuming the rainfall distribution to be uniform. Research findings, particularly in the U S A, generally attribute spatial differences in CMS to variations in one or more of the following: soils, vegetation, slope and topographical position in the landscape (for example, Wild and Scholz, 1930; Platt, 1955; Kovner, 1955; Stoeckeler and Curtis, 1960; Whipkey, 1965; Tischendorf, 1969; Helvey, 1971).

Variations of texture and pore size distribution within a soil are considered by many researchers to be the major determinants of the moisture characteristics of a soil (for example, Carlson, Reinhart and Horton, 1956; Jones, 1976 and Rivers and Ship, 1978). Tischendorf (1969) and Henninger et al (1976) also consider texture and to a lesser extent organic matter to have an important effect on soil moisture. Since the properties of soils may vary considerably within a catchment, associated variations in soil moisture may be expected.

The distribution of CMS may be affected by variations in the interception, infiltration and evapotranspiration characteristics of various types of vegetation. Interception is particularly important in regions of low rainfall intensity and/or events of short duration. However, interception is generally of less importance than the effect vegetation has on infiltration and evapotranspiration rates. Infiltration rates are commonly reported to be higher where the surface supports vegetation (for example, Vorster, 1959; Chow, 1964; Whipkey, 1965 and Rodda, Downing and Law, 1976).

Authors such as Cottle (1932), Homes and Robertson (1959), Stoeckeler and Curtis (1960), Jackson (1967) and Rouse and Wilson (1969) have illustrated the effect aspect has on soil moisture, drier slopes generally being those which intercept more solar radiation. Topographic position is also a major determinant of soil moisture. Research conducted by Tischendorf (1969) in the south Appalachians revealed that at depths greater than 2,4 metre more than 50 percent of the variance in soil moisture could be 'explained' by the height above and distance to the nearest channel. Similar findings have been reported by Helvey (1971) and Henninger et al (1976).

In this section the factors affecting the temporal and spatial variations in CMS have been reviewed briefly on an intra-catchment basis. However, the regional variability of the above factors, along with geological and climatological differences are also responsible for inter-catchment varia= tions in CMS. Ideally, procedures for estimating CMS should therefore incorporate the major factors responsible for the variability of CMS and they should be adaptable to catchments of different environmental condi= tions.

2.3 The Estimation of Catchment Moisture Status

The preceding discussion has illustrated the large number of variables which may control CMS and the complex nature of CMS. However, in most catchments limited information is available for estimating CMS and the estimates are generally made using simple procedures or indices. These indices usually calculate a single value representative of an entire catch= ment and are mainly concerned with monitoring the change in CMS through time. The major factors controlling this temporal variability are rain= fall, evapotranspiration, drainage and the topographic redistribution of soil moisture (cf Section 2.2). Since the latter two variables are not easily measurable, most indices are based on measured antecedent rainfall and an estimate of the moisture losses over time.

Amongst the most widely used antecedent precipitation indices (API) for estimating CMS is that described by Linsley, Kohler and Paulhus (1949). The API is calculated on the basis of logarithmic recession during periods of no rainfall, thus:

$$I_t = I_o K^t \qquad \text{..........} \qquad (2.1)$$

where

I_o = the initial moisture index,

I_t = the index after t days have elapsed, and

K = a recession constant, ranging between 0,85 and 0,98.

The index for any day is, therefore, equal to a constant K multiplied by the index of the day before. If rain is recorded on any day this is added to the index value. The value of K should be a function of season and should vary from one region to another (Linsley et al 1949). However, as

Cordery (1970) and Ward (1975) suggest, the choice of the value of K is not usually critical since the calculation is used as an index of soil moisture.

Hopkins and Hackett (1961) found stormflow predictions which included the API of Linsley et al (1949) could be improved if antecedent temperatures were also taken into account. An index of antecedent temperature (ATI) was calculated and used in conjunction with API.

An alternative API described by Linsley et al (1949) is the reciprocal API which is of the form:

$$APIR = P_1 + 1/2P_2 + 1/3P_3 \ldots 1/tP_t \qquad \ldots\ldots\ldots\ldots \qquad (2.2)$$

where

APIR = the reciprocal API, and

P_t = the amount of rainfall which occurred t days prior to the storm event under consideration.

This index has no physical basis and was developed entirely on the premise that the impact of antecedent rainfall on stormflow amounts decreased over time. Linsley et al (1949) suggest that the logarithmic recession is pre= ferable to this approach if day-by-day values of the index are required.

In developing a method for estimating stormflow volumes, Reich (1971) divided the independent variables in his investigation into three classes, viz, storm parameters, physiographic catchment parameters and state variables. The state variables were defined by Reich as "... indices of the hydrologic state of the watershed prior to the runoff event" (Reich, 1971: 26). Four state variables were tested in this study:

(a) API5 - This is the amount of rain that fell during the five day period prior to the stormflow event.

(b) API7 - This antecedent precipitation index takes into account potential evapotranspiration. The index is calculated by subtracting potential evapotranspiration from the rainfall of the seven antecedent days and using the residual values in a reciprocal API as defined in Equation 2.2. Potential evapotranspiration values were obtained from tables published by Thornthwaite and Mather (1957).

(c) QINIT - QINIT represents the stream discharge immediately prior to the rise of the hydrograph.

(d) TEMP - TEMP is the average maximum temperature for five days prior to the runoff event.

The variables QINIT and API7 were found to yield the strongest relationship with stormflow volumes. However, Reich concludes that "Antecedent conditions are expressed almost equally well by all four state variables, QINIT being slightly better than the indices based on antecedent precipitation. However, the overwhelming simplicity of the mere five-day precipitation gives that parameter which has been used nationally by the SCS for 20 years overall superiority" (Reich, 1971:40).

The British Meteorological Office produce fortnightly maps of soil moisture deficits (SMD) in the U K (Natural Environment Research Council, 1975). The British Flood Studies Team have incorporated SMD data in a procedure to calculate stormflow volumes along with a short term API which is defined as:

$$APIS_d = 0{,}5^{\frac{1}{2}}/P_{d-1} + 0{,}5\ P_{d-2} + (0{,}5)^2 P_{d-3} + (0{,}5)^3 P_{d-4}\ 1$$

$$(0{,}5)^4 P_{d-5} \qquad \ldots\ldots\ldots\ (2.3)$$

where

APIS = the antecedent precipitation index,

P = the antecedent rainfall, and

d = the day for which the API is calculated.

The antecedent precipitation indices discussed to this point have all included more than one days' antecedent rainfall. In a study of stormflow prediction from catchment characteristics and CMS conducted by Hawkins (1961) it was concluded that one day antecedent rainfall showed greater association with stormflow than either the two day, five day or seven day antecedent rainfalls.

An explanation of Hawkins' results may be found in examining the nature of the soils and topography of the area where the research was conducted, the Missouri Gulch Watershed, Colorado. Hawkins described the soils as "extremely porous" while the slope gradients range up to 60 percent. Both these characteristics are conducive to rapid drainage of water out of the catchment, which suggests that the longer period antecedent rainfall indices would have little meaning, since little of this rainfall would be retained by the catchment storages.

2.4 Summary and Conclusions

The preceding review of stormflow theories, the variability of CMS and selected procedures for estimating CMS has highlighted a number of conclusions relevant to the SCS and R-index models for calculating stormflow volumes, viz:

(a) There is strong evidence supporting theories of non-uniform stormflow production in a catchment, the mechanisms varying from catchment to catchment and possibly from storm to storm depending on CMS and the storm rainfall characteristics.

(b) Antecedent moisture conditions are shown in all the stormflow theories discussed to be a major determinant of stormflow volumes.

(c) Catchment and climatic factors give rise to spatial and temporal variation in CMS, the former variability within a catchment generally being ignored by procedures for estimating antecedent moisture conditions.

(d) Procedures for estimating CMS generally take the form of indices which have little physical relationship with actual values of soil moisture.

(e) Evapotranspiration and drainage components of these indices are gene= rally neglected or estimated by arbitrary procedures.

(f) The findings of Hawkins (1961) reveal that regional differrences in catchment and environmental conditions may be important to the approach adopted for estimating CMS.

The variability of CMS and its effect on stormflow is a highly complex process which may vary from catchment to catchment or event to event. In both the SCS and R-index models there are two major areas of concern in estimating CMS, namely, the procedure by which CMS is estimated and the number of antecedent days required in this calculation.

A

AN IMPROVED ANTECEDENT MOISTURE

PROCEDURE FOR THE SCS MODEL

Chapter 3
THE SCS STORMFLOW SIMULATION MODEL

Since the development of the rational formula in the nineteenth century, numerous techniques for predicting stormflow volumes and peak flow rates from a given amount of storm rainfall have been developed. In an attempt to simplify and standardise stormflow prediction, the Soil Conservation Service (SCS) of the United States Department of Agriculture developed a stormflow prediction model (NEH-4, 1972). In this chapter the SCS storm=flow simulation model will be outlined with particular attention being given to the antecedent moisture component.

3.1 The SCS Stormflow Equation

The SCS model for calculating stormflow is based on a relationship between accumulated storm rainfall and accumulated stormflow. This relationship was derived from plot and small catchment experiments set on different soils and with varying vegetation cover and land-use practices. The rela=tionship between storm rainfall and stormflow is expressed in terms of initial abstraction (Ia) and potential maximum retention (S) of storm rain=fall by the catchment. The initial abstraction is that rainfall removed to satisfy catchment storages prior to any stormflow occurring, such abstrac=tions being interception. The variable S is a catchment storage factor which theoretically can vary from infinity to zero. The relationship between the curves of accumulated storm rainfall, stormflow and infiltra=tion plus initial abstraction through time are shown in Figure 3.1.

It is assumed in the SCS Model that $\frac{F}{S} \rightarrow 1$ and $\frac{Q}{Pe} \rightarrow 1$ as $T \rightarrow \infty$

Thus

$$\frac{F}{E} = \frac{Q}{Pe} \qquad \text{..........} \quad (3.1)$$

where

F = actual accumulated infiltration, excluding Ia (mm)

Q = accumulated stormflow at time T (mm)

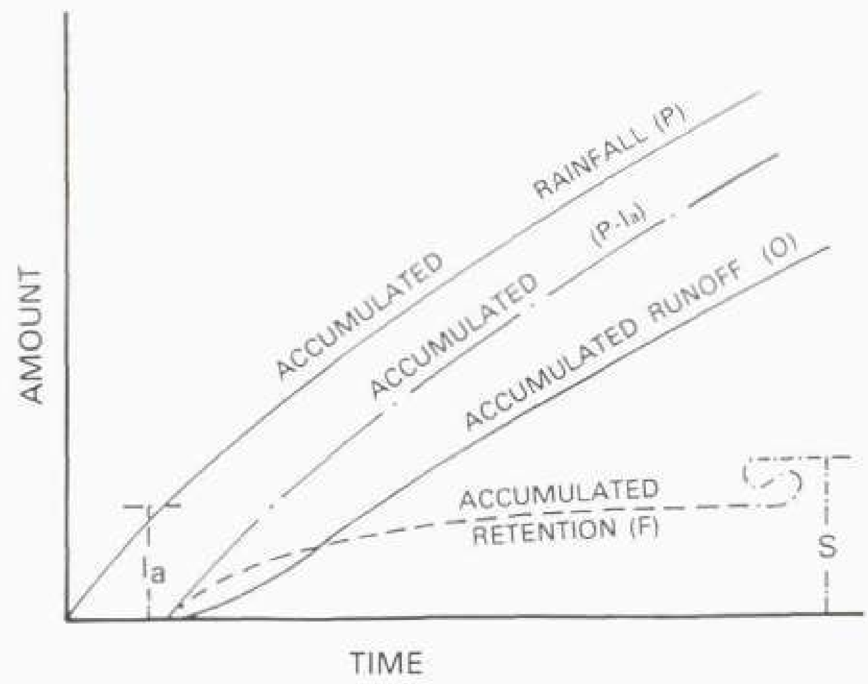
S = potential maximum retention (mm), ie, $F + Ia \to S$ as $T \to \infty$ and

Pe = potential stormflow or effective rainfall (mm)

With F = Pe - Q, Equation 3.1 can be written as

$$Q = \frac{Pe^2}{Pe + S} \qquad \text{..........} \quad (3.2)$$

Figure 3.1 Schematic curves of accumulated storm rainfall (P), accumulated stormflow (Q) and infiltration (F), plus initial abstration (Ia) showing the relationships used in the derivation of the SCS stormflow equation (USDA, 1980)



A relationship between Ia and S was established from the previously mentioned experimental catchment data and it was expressed as:

$$Ia = 0{,}2S \qquad \text{.......... (3.3)}$$

Thus

$$Pe = P - Ia = P - 0{,}2S \qquad \text{.......... (3.4)}$$

where

P = total storm rainfall (mm)

By substituting Equation 3.4 in Equation 3.2

$$Q = \frac{(P - 0{,}2S)^2}{P + 0{,}8S} \qquad \text{.......... (3.5)}$$

when

$P \geq 0{,}2S$

Equation 3.5 is the rainfall-stormflow relation used in the SCS model.

Since the value of S can vary from zero to infinity a transformation was introduced to scale the runoff curve number variability from 100 to zero, the transformation being of the form:

$$CN = \frac{1000}{\frac{S}{25{,}4} + 10} \qquad \text{.......... (3.6)}$$

where

CN = runoff curve number or the hydrological soil-cover complex number

From equation 3.6 it may be deduced that the runoff curve numbers (CN) are functionally related to S and have no intrinsic meaning, being only a con= venient transformation of S to establish a 0 to 100 scale (Hawkins, 1978). The potential maximum retention (S) of a catchment is, in this model, considered to be dependent on the land-use or vegetation cover, its treat= ment or practice, its hydrological condition and hydrological soil group of the catchment assuming average antecedent moisture conditions.

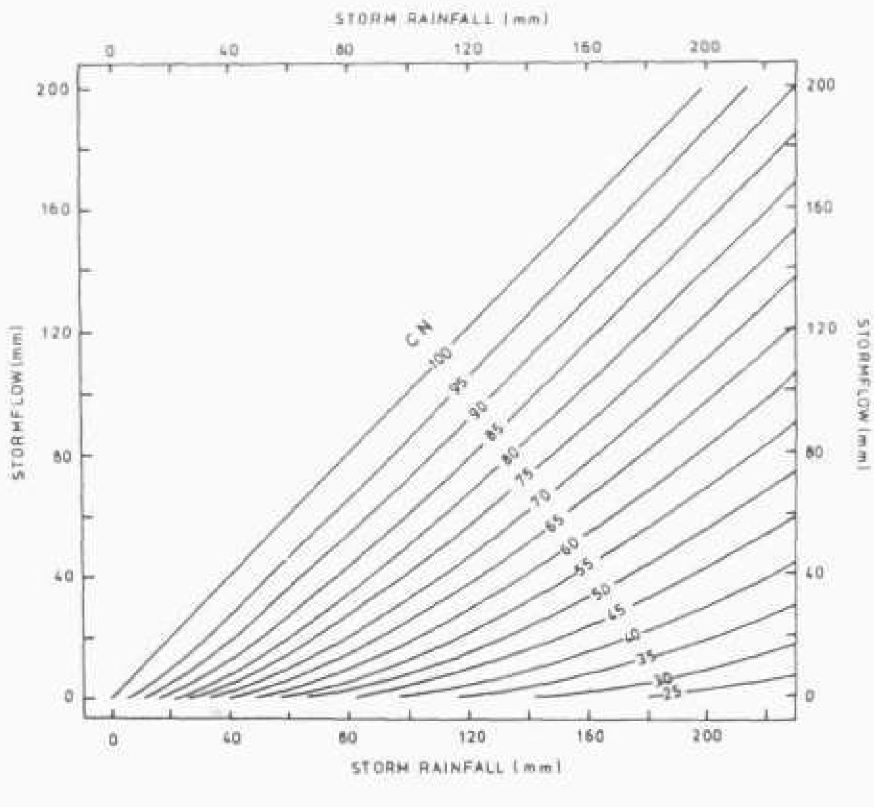
The soils of the USA have been classified into four hydrological groups A to D for application in the SCS model. These groupings were based on the runoff potential or infiltration characteristics of the soils with soils in group A having the lowest runoff potential while soils in group D have the highest runoff potential. A similar classification has been undertaken for South African soils and is described by Schulze and Arnold (1979). Based on experimental data CN values have been tabulated for catchment land-use or vegetation cover, treatment or practice, hydrological condition and hydro= logical soil groups (Table 3.1). The CN values in Table 3.1 are for average antecedent moisture conditions. These values are adjusted for the catch= ment moisture status before stormflow is derived from CN and storm rainfall.

Table 3.1 Curve numbers (CN) for hydrological soil-cover complexes for average antecedent moisture conditions (NEH-4, 1972)

Land use or cover	Treatment or practice	Hydrologic condition	Hydrologic soil group			
			A	B	C	D
Fallow	Straight row	Poor	77	86	91	94
Row crops	Straight row	Poor	72	81	88	91
	Straight row	Good	67	78	85	89
	Contoured	Poor	70	79	84	88
	Contoured	Good	65	75	82	86
	Contoured and terraced	Poor	66	74	80	82
	Contoured and terraced	Good	62	71	78	81
Small grain	Straight row	Poor	65	76	84	88
	Straight row	Good	63	75	83	87
	Contoured	Poor	63	74	82	85
	Contoured	Good	61	73	81	84
	Contoured and terraced	Poor	61	72	79	82
	Contoured and terraced	Good	59	70	78	81
Close-seeded legumes or rotation meadow	Straight row	Poor	66	77	85	89
	Straight row	Good	58	72	81	85
	Contoured	Poor	64	75	83	85
	Contoured	Good	55	69	78	83
	Contoured and terraced	Poor	63	73	80	83
	Contoured and terraced	Good	51	67	76	80
Pasture or range		Poor	68	79	86	89
		Fair	49	69	79	84
		Good	39	61	74	80
	Contoured	Poor	47	67	81	88
	Contoured	Fair	25	59	75	83
	Contoured	Good	6	35	70	79
Meadow (permanent)		Good	30	58	71	78
Woodlands (farm wood-lots)		Poor	45	66	77	83
		Fair	36	60	73	79
		Good	25	55	70	77
Farmsteads		....	59	74	82	86
Roads, dirt		....	72	82	87	89
Roads, hard-surface		....	74	84	90	92

By eliminating S between Equation 3.5 and Equation 3.6, the relationship between Q, P and CN may be represented by a family of curves (Figure 3.2).

Figure 3.2 Graphic solution to the SCS storm rainfall-flow equation (Adapted from: NEH-4, 1972)



3.2 Catchment Antecedent Moisture Conditions

Curve number adjustments for variations in the moisture status of a catchment are made in the SCS model on the basis of three classes of antecedent moisture conditions (AMC), described in NEH-4 (1972) in terms of stormflow potential. These three classes are given, descriptively, as:

AMC-I. Lowest runoff potential. The catchment soils are dry enough for satisfactory ploughing or cultivation to take place.

AMC-II The average condition.

AMC-III Highest runoff potential. The catchment is practically saturated from antecedent rains.

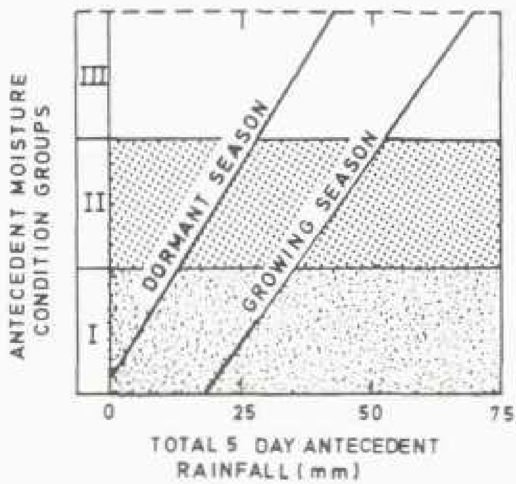
Catchment antecedent moisture conditions are estimated from the five day antecedent rainfall, this being the total depth of rainfall over the five days preceding the stormflow event under consideration. According to Miller the use of five day antecedent rainfall"... is based on subjective judgement of rainfall-runoff data scatter at various antecedent rainfall time periods" (Miller, 1979; Personal Communication). In the three classes of antecedent rainfall, adapted for the SCS model from material developed by the Fort Worth EWP Unit, different class limits are given for the growing and the dormant seasons (NEH-4, 1972). These antecedent rain= fall classes are presented in Table 3.2 The assumed relationship between the antecedent moisture condition groups and the five day antecedent rain= fall index is linear (Figure 3.3).

Table 3.2 Antecedent rainfall limits for estimating antecedent moisture conditions (Adapted from NEH-4, 1972)

AMC group	Total 5-day antecedent rainfall (mm)	
	Dormant season	Growing season
I	Less than 12	Less than 36
II	12 to 28	36 to 53
III	Over 28	Over 53

On the basis of the five day antecedent rainfall (Table 3.2) curve numbers derived from the soil-cover complex are adjusted before stormflow is calcu= lated (Table 3.3). The relationship between AMC and CN was determined empirically from rainfall-stormflow data from a number of catchments in the eastern USA. Catchments with single soil-cover complexes were chosen and depth of stormflow was plotted against depth of rainfall for the annual floods (NEH-4, 1972). The curves of Figure 3.2 were superimposed over the scatter of points and the curve dividing the scatter equally (median CN) was taken to be the CN for AMC-II (Figure 3.4).

Figure 3.3 The linear relationship between the total five day antecedent rainfall and the antecedent moisture condition groups (Adapted from: NEH-4, 1972)



The determination of curve numbers for AMC-I and AMC-III followed a similar procedure, with the curves which "...best fit the highest (AMC-III) and lowest (AMC-I) thirds of the plotting" taken as representative of these moisture classes (NEH-4, 1972:10.6). The procedure described in NEH-4 (1972) is not completely clear regarding the "best fit" for the highest and lowest thirds of the plotting. An explanation of this procedure is given by Miller (1979) of the United States Department of Agriculture, Soil Conservation Service (USDA-SCS): "To explain the variation on either side of the average RCN (Runoff Curve Number) curve, enveloping RCN lines were determined. The lower enveloping RCN curve represents AMC-I while the upper enveloping RCN curve represents AMC-III. Plotting and smoothing these data with straight lines on normal-normal probability paper produces the AMC I, II, III relationship except at the extreme RCN limits (Figure 3.5). The development of these AMC I and III curve numbers is not dependent on any particular antecedent time period" (Miller 1979; Personal Communication). The enveloping curves I and III in Figure 3.4 define error envelopes, the "cause" being attributed to variations in AMC. The plots of AMC-I, AMC-II and AMC-III on normal-normal probability paper are illustrated in Figure 3.5.

Table 3.3 Example of curve number adjustments for AMC-I and AMC-III (Adapted from: NEH-4, 1972)

CN for condition II	CN for AMC	
	I	III
100	100	100
98	94	99
96	89	99
94	85	98
92	81	97
90	78	96
88	75	95
86	72	94
84	68	93
82	66	92
80	63	91
78	60	90
76	58	89
74	55	88
72	53	86
70	51	85
68	48	84
66	46	82
64	44	81
62	42	79
60	40	78

Figure 3.4 Determination of AMC-I, AMC-II and AMC-III from storm rainfall and stormflow records (Adapted from: NEH-4, 1972)

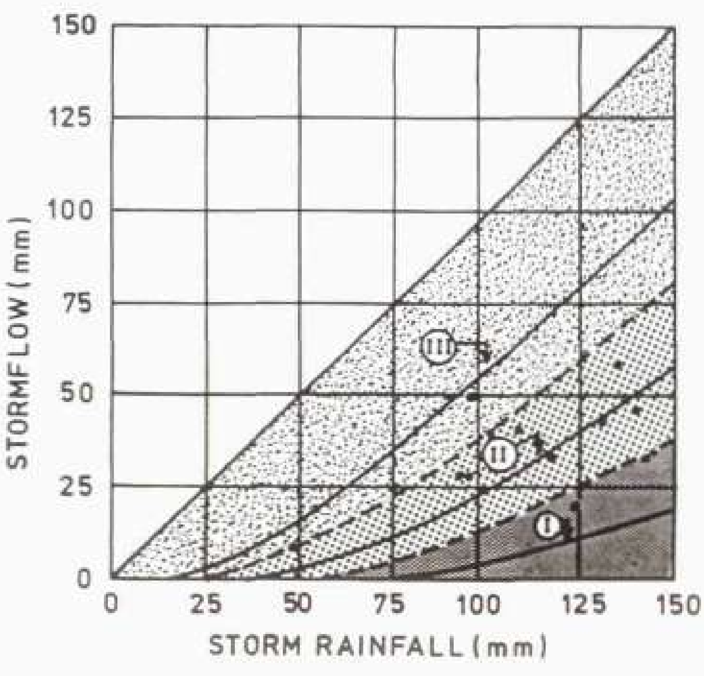
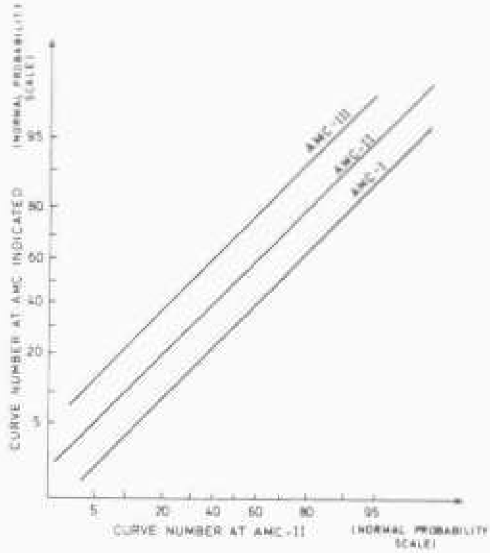


Figure 3.5 Relationship between AMC-I, AMC-II and AMC-II plotted on normal-normal probability paper (Adapted from: Miller, 1979)



The plotting of accumulated stormflow against accumulated storm rainfall (Figure 3.4) results in a scatter of plotted points representing changes in the value of S in Equation (3.5) and hence a corresponding change in the CN from one storm to the next (Kent, 1973). Most of this difference in the CN is attributable to the variations in soil moisture preceding each storm (Kent, 1973). The three levels of AMC are therefore directly related to S. AMC-I is the lower limit of soil moisture or the upper limit of S, AMC-II is the average for which the CNs of Table 3.1 apply, and AMC-III is the upper limit of soil moisture or the lower limit of S (NEH-4, 1972). Thus, on a single catchment with an unchanging soil-cover complex the stormflow poten= tial is considered to be entirely a function of antecedent moisture conditions.

3.3 Weakness of the AMC Component of the SCS Model and Alternative Procedures

Two major weaknesses in the AMC procedure of the SCS model are pertinently described by Hawkins (1978:391): "First, the relationships are shown as discrete, and not continuous, thus implying sudden shifts in CN, with corresponding quantum jumps possible in calculated runoff. Secondly, NEH-4 con= tains no background development or statement of assumptions, leaving only appeals to agency authority as a foundation for professional beliefs, and not faith based on physical reasoning or reconciliation with reality". The latter criticism is of particular relevance to researchers working in this field, and is illustrated in the following extract taken from correspon= dence with Miller of the USDA-SCS: "The National Engineering Handbook, Section 4, Hydrology, Table 4.2 Seasonal Rainfall limits for AMC was developed from empirical relationships based on experience. No documentation as to the exact table figures can be found in either our files or the files at the Fort Worth office... The use of five day antece- dent rainfall is based on subjective judgement of rainfall-runoff data scatter at various antecedent rainfall time periods" (Miller, 1979; Personal Communication).

In the preceding chapter evapotranspiration was shown to be a major factor affecting CMS. The SCS model does not allow for temporal or spatial variations in this variable, recognition only being given to gross seasonal differences. Furthermore, the same antecedent moisture procedure holds for all soils and vegetation types regardless of the variable influence which these catchment characteristics may have on evapotranspiration.

Despite the weaknesses of the antecedent moisture component of the SCS model, little attention has, until recently, been given to improving the AMC procedure. In an application of the SCS model by Simanton, Renard and Sutter (1973) in semi-arid conditions, the lowest antecedent moisture class was divided into four sub-classes. This research was, however, not speci= fically concerned with improving the SCS model. As early as 1954 four antecedent moisture classes had been described in "Hydrology Guide for Use in Watershed Planning" but did not contain any antecedent rainfall values associated with these classes (Miller, 1979: Personal Communication).

In research aimed at optimising CN and AMC, Dickey, Mitchell and Scarborough (1979) concluded that for the two selected catchments in Illinois, the five days' antecedent rainfall was not necessarily an appropriate adjusment of CN. These authors developed a multiple regression model to estimate CN correction for antecedent moisture conditions, this equation being given as:

$$CNC = -3,411 + 30,144\ (R_2) - 3,627\ (M) \qquad \ldots\ldots\ldots\ldots \quad (3.7)$$

where

CNC = curve number correction

M = month and

R_2 = 2 day cumulative rainfall prior to the event.

A most significant and directed attempt at developing an improved procedure for estimating CMS for application in the SCS model was made recently by Hawkins. The procedure providing the foundation for the approach presented by Hawkins (1978) was a water yield model based on SCS curve numbers developed by Williams and La Seur (1976). For their model, Williams and La Seur introduced a soil moisture index, SM, which was related to the potential maximum retention, S, by:

$$SM = V - S \qquad \ldots\ldots\ldots\ldots \quad (3.8)$$

where

V = the maximum value of potential moisture storage of the site (mm)

According to these authors a value of 508 mm was assigned to V "... because it provides ample storage to allow a wide range in curve numbers and yet is small enough to allow daily rainfall to influence SM properly" (Williams and La Seur, 1976:1243).

According to Hawkins (1978) the concept of moisture status proposed by Williams and La Seur (1976) is "... further developed on a conservation-of-mass basis to provide a logic-based alternate to the NEH-4 approach... It is also offered as an approximation of what may have been the original reasoning leading to NEH-4 relationships now apparently lost" (Hawkins, 1978:392). The following description of the procedure and rationale of this "logic-based alternate" is described by Hawkins (1978) as follows:

Taking the SCS stormflow equation

$$Q = \frac{(P - 0{,}2S)^2}{P + 0{,}8S} \qquad P \geq 0{,}2\,S \qquad .... \quad (3.9)$$

where

Q = stormflow (mm)

P = storm rainfall (mm)

S = potential maximum retention (mm) and

expanding the numerator, and applying polynomial division yields

$$Q = P - S\,(1{,}2 - \frac{S}{P + 0{,}8S}) \;, \quad P \geq 0{,}2\,S \; .... \quad (3.10)$$

Hawkins states: "It can easily be seen that the ultimate possible diffe= rence ($P \to \infty$) between rainfall P and direct runoff Q is not S, but 1,2 S, denoted $\forall$ here..." (Hawkins, 1978:392). Thus with:

$$\forall = 1{,}2\,S \qquad .... \quad (3.11)$$

Hawkins continued: "This may be envisioned as the total water storage available on site, for a given condition of soil, vegetation, and moisture status. This makes no statement concerning the total soil water storage under such an 'oven dry' condition but only as defined by the current state of soil moisture. The NEH-4 also makes no such distinction" (Hawkins, 1978: 392).

For a given curve number, the storage available at time 1 is therefore:

$$\forall_1 = 1.2S_1 = 1{,}2\,(\frac{1000}{CN_1} - 10)\,25{,}4 \qquad .... \quad (3.12)$$

the value 25.4 being introduced to express $\forall$ in millimetres. Hawkins furthermore states that any change in $\forall$ will be the difference between interim rainfall inputs (P) and losses due to evapotranspiration (ET) and runoff and drainage (Q_1), so that at time 2:

$$\forall_2 = \forall_1 + ET - (P - Q_1) = 1{,}2S_2 \qquad .... \quad (3.13)$$

Therefore, from Equations 3.12 and 3.13:

$$\psi = 1{,}2\left(\frac{1000}{CN_1} - 10\right) 25{,}4 + ET - (P - Q_1) = 1{,}2S_2 \qquad \text{..........} \quad (3.14)$$

Since by definition

$$CN_2 = \frac{100}{10 + S_2/25{,}4}$$

substituting and simplification leads to

$$CN_2 = \frac{1200}{\frac{1200}{CN_1} + \frac{ET - (P - Q_1)}{25{,}4}} \qquad \text{..........} \quad (3.15)$$

By adopting the above procedure to adjust CN for CMS, there are a number of advantages over the NEH-4 procedure. These are listed below:

(a) Evapotranspiration and drainage are implied in the NEH-4 classification for AMC and CN adjustment without conscious recognition of their roles (Hawkins, 1978). These losses are directly incorporated in the above procedure.

(b) Determination of CMS is not limited to a five day period.

(c) Curve numbers may be adjusted as continuous rather than discrete variables.

(d) The Hawkins procedure allows for regional variations in evapotranspiration and drainage as well as for temporal variability of CMS, which in Chapter 2 was shown to be important, is well accounted for this modified procedure.

In the preceding chapter a number of procedures for estimating CMS were reviewed and it was concluded that generally these procedures were indices of CMS which neglected evapotranspiration and drainage, thus being limited in their applicability from region to region. While the Hawkins procedure overcomes these weaknesses, this technique requires inputs which are not readily available on ungauged catchments, namely evapotranspiration, drainage and the initial value of CN. The research presented in the ensuing chapters therefore includes, inter alia, proposed techniques for estimating these variables on ungauged catchments.

Chapter 4
AIMS, DATA AND PROCEDURAL BACKGROUND

The principal objective of this investigation is to improve the antecedent moisture component of the SCS model. In attempting to achieve this end three areas of research were identified and the aims of each of these investigations are given. The research catchments are described and data requirements for this study are given. Finally, the analytical procedures for evaluating the results are outlined.

4.1 Aims

The three specific aims of this study are:

(a) to determine whether, given accurate measures of antecedent rainfall, runoff, evapotranspiration and the initial CN, the procedure described by Hawkins (1978)[1] for adjusting catchment CN provides improved estimates of stormflow when compared with the standard SCS procedure.

(b) to develop techniques for estimating, on ungauged catchments, the starting CN, evapotranspiration and runoff for application in HAWK and finally

(c) to establish the optimum number of days which should be considered for the determination of antecedent moisture conditions for CN adjust= ments.

While the first of the above aims was of a more fundamental nature, the second aim was directed at the application of the SCS model in ungauged catchments. This latter aim therefore had to meet the following require= ments: First, procedures developed for estimating CMS have to be simple to use, the simplicity of the SCS model being one of its major advantages. Secondly, data requirements for these procedures should be readily available on ungauged catchments.

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1 This procedure is referred to a HAWK in the ensuing discussion.

4.2 The Research Catchments

While a number of small agricultural research catchments have been monitored over the years in Natal, the availability of suitable data for hydrological research remains scarce. With the establishment, in the mid 1970's, of research catchments at Cedara and Zululand and a reinstitution of hydrological observations at the De Hoek catchments (Figure 4.1), the availabiity and quality of hydrological data have improved, although the records only cover a short period of time. Stormflow events on which this research was based were thus restricted to medium-sized rather than the annual stormflow events.

Catchments at Cedara, Zululand and De Hoek were selected on the basis of availability and quality of data, as well as their predominantly grassland vegetation. This latter requirement was included since most of Natal and South African agricultural catchments are grassland and any significant findings may thus be applicable on a regional and national scale. Further= more, variability in hydrological processes caused by different types of vegetation were thereby largely eliminated. Background information relating to the three selected locations is summarised in Table 4.1.

Suitable hydrological data were available for detailed analyses on five selected catchments, the areas of these catchments being given in Table 4.2.

Table 4.1 Background information to the Zululand, Cedara and De Hoek Catchments

	Location—		
	Zululand	Cedara	De Hoek
Latitude	28° 50'S	20° 43'S	29° 01'S
Longitude	31° 46'E	30° 15'E	29° 10'E
Mean annual rainfall	1 450 mm	875 mm	850 mm
Range of mean monthly temperatures	16,9°C-24,9°C	11,3°C-19,8°C	6,8°C-18,6°C
Lithology	Biotite granite gneiss	Shales intruded by dolerite sills and dykes	Mudstone, shales and sandstones

Figure 4.1 General location of the selected research catchments

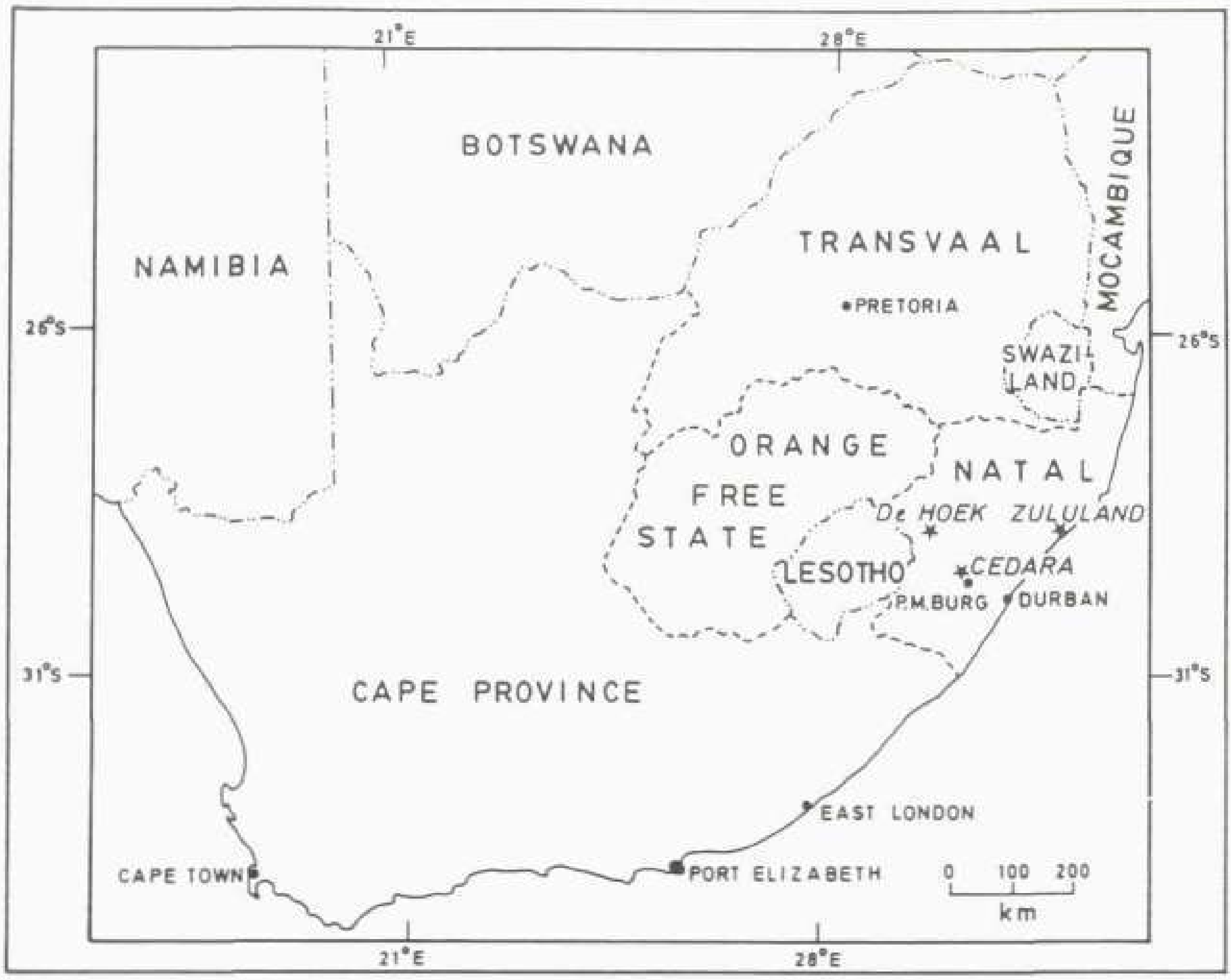


Table 4.2 Location and areas of the five selected catchments

Catchment	Location	Area (km)
U2M20	Cedara	0,25
V1M28	De Hoek	0,41
V7M03	De Hoek	0,45
W1M16	Zululand	3,22
W1M17	Zululand	0,67

The topography, instrumentation, vegetation/land-use and soils of the five selected catchments are presented in Figure 4.2 to Figure 4.6. Since catchments V1M28 and V7M03 consist entirely of short grassland, vegetation maps of these catchments are not included.

The information presented in Figure 4.2 to Figure 4.6 is based on field observations as well as on various surveys which have been documented by Hope and Mulder (1979) for the Zululand Catchments and Schulze (1979) for the Cedara Catchments. Information pertaining to the De Hoek Catchments was obtained from Cousens and Burney (1977) and De Villiers (1963).

Figure 4.2 Catchment U2M20 (a) topography and instrumentation
(b) vegetation/landuse and
(c) soils

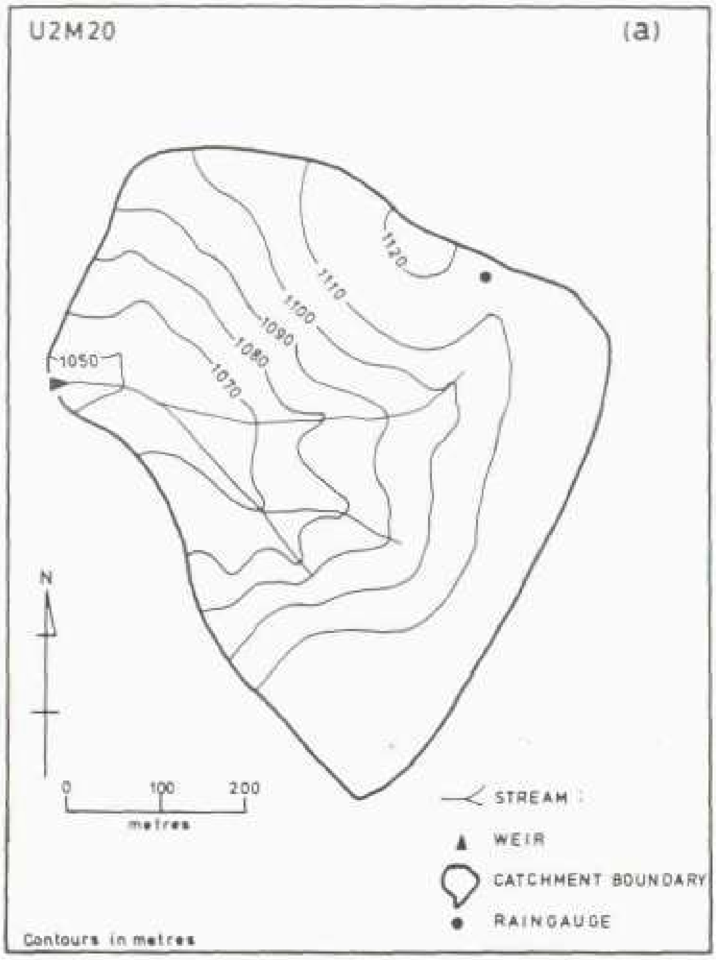
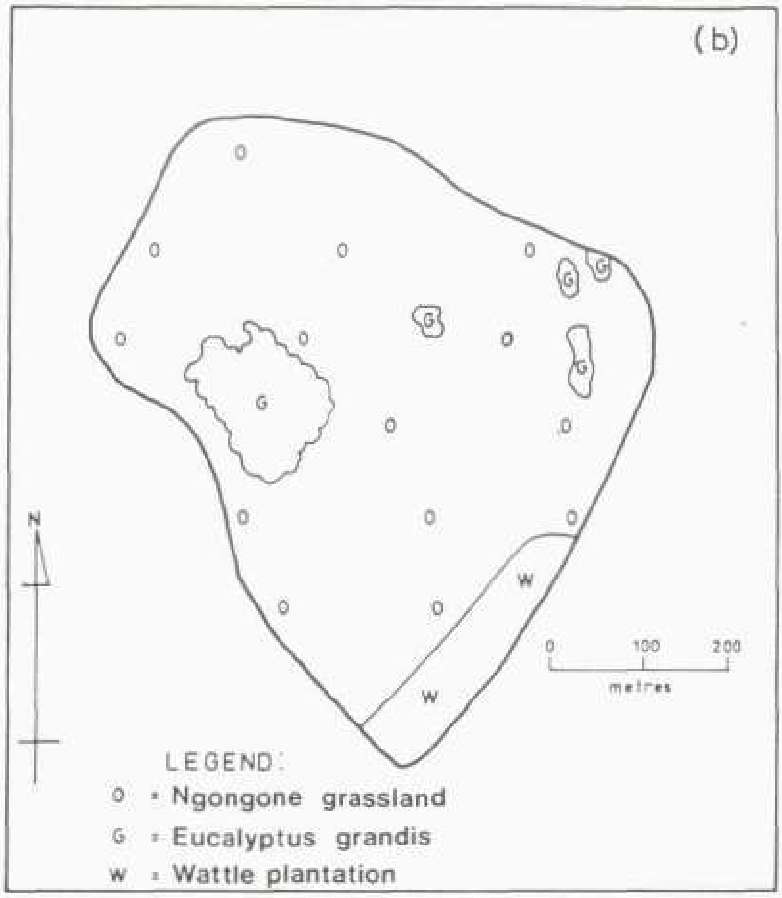


Figure 4.2 (Continued)



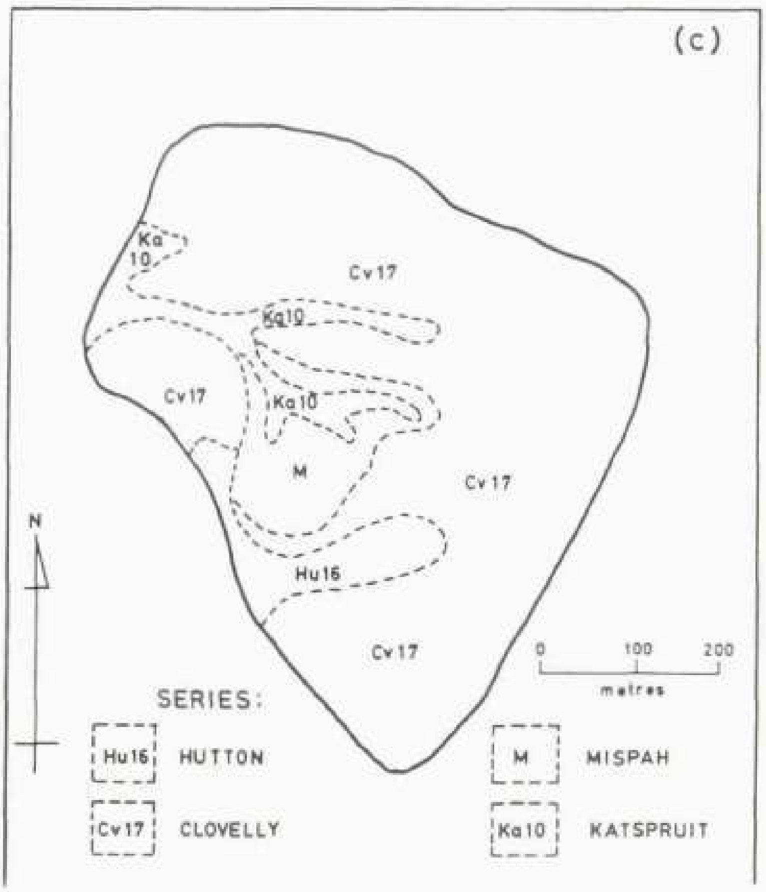
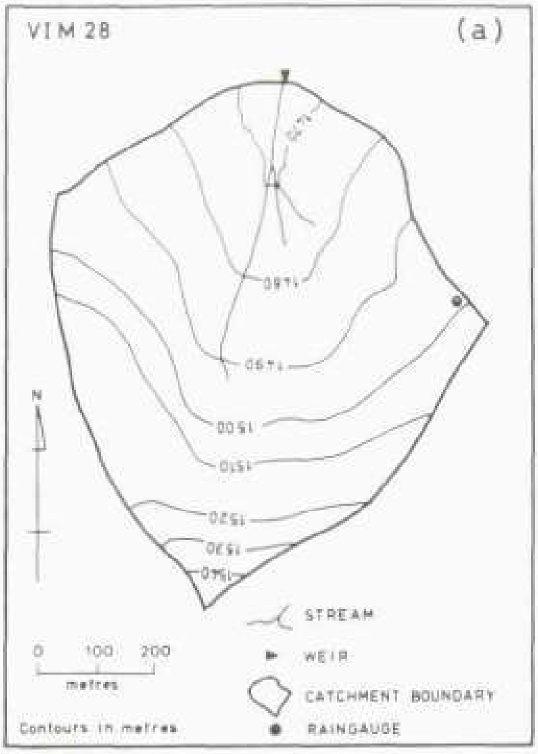


Figure 4.3 Catchment VIM28 (a) topography and instrumentation and (b) soils



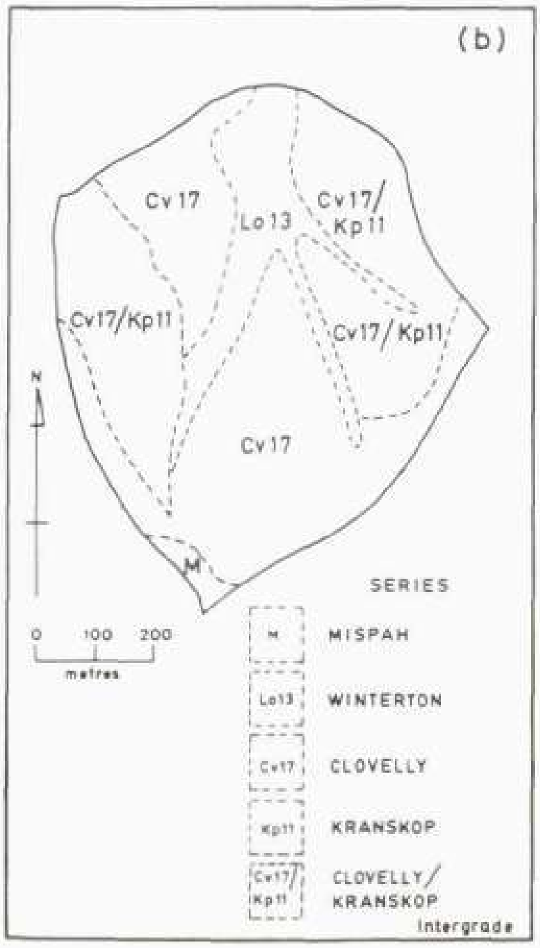
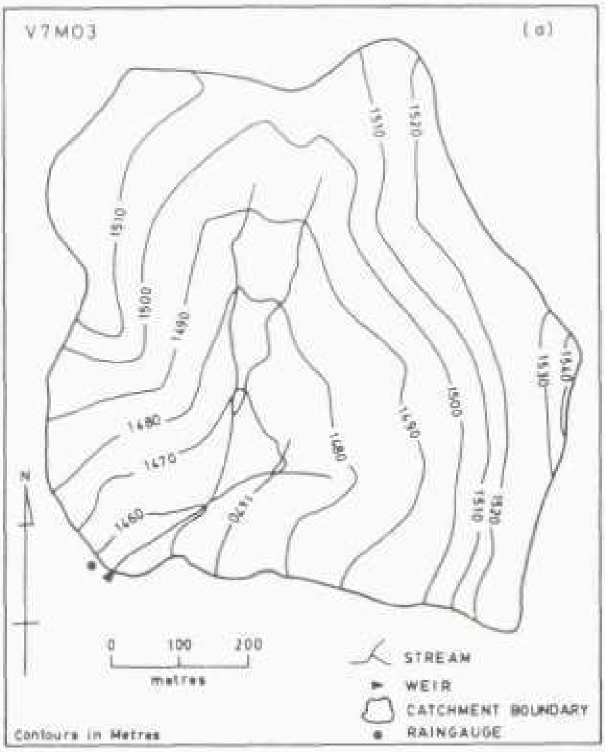


Figure 4.4 Catchment V7M03 (a) topography and instrumentation and (b) soils



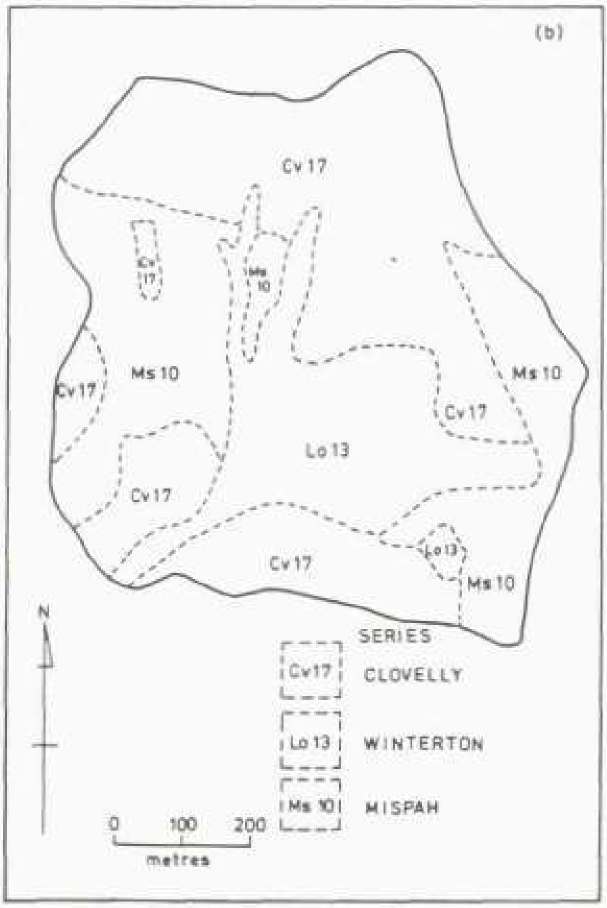
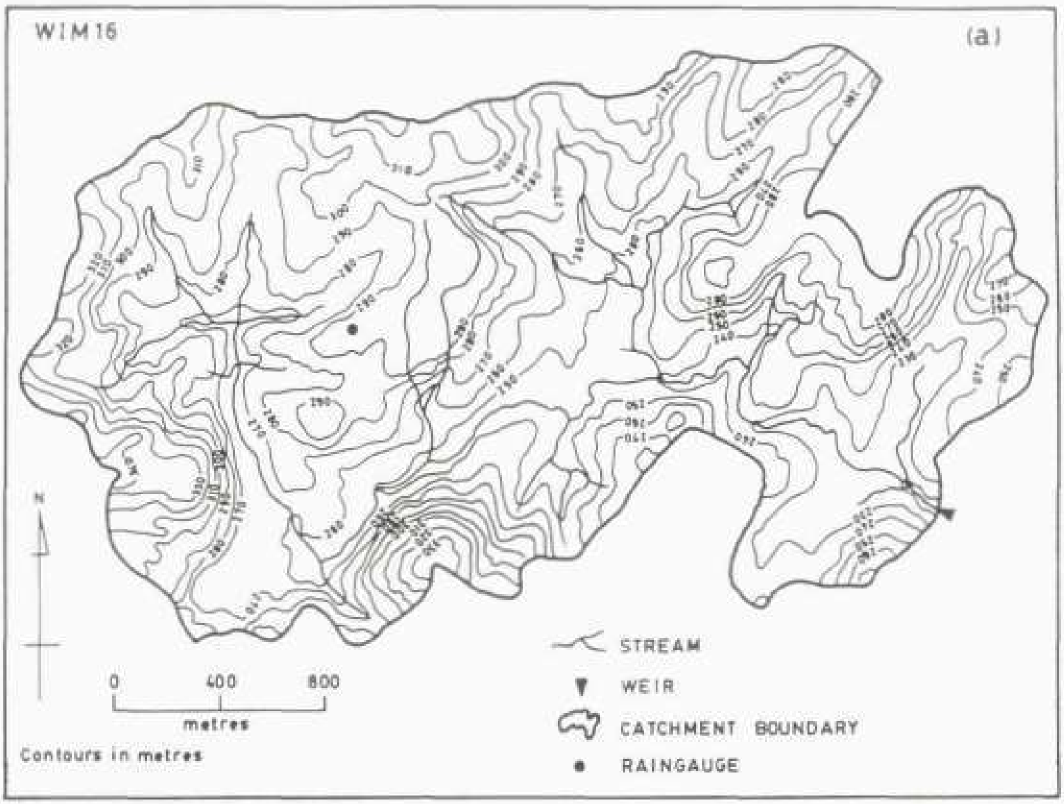


Figure 4.5 Catchment WIM16 (a) topography and instrumentation
(b) vegetation/landuse and
(c) soils



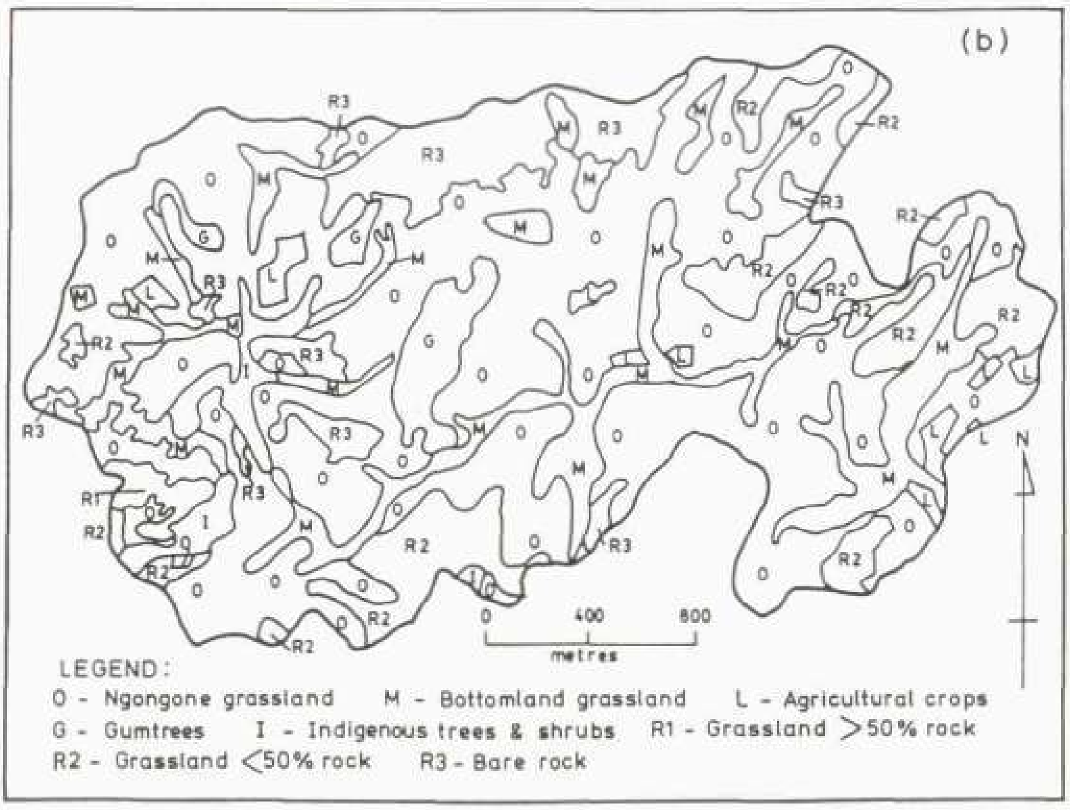


Figure 4.5 (continued)

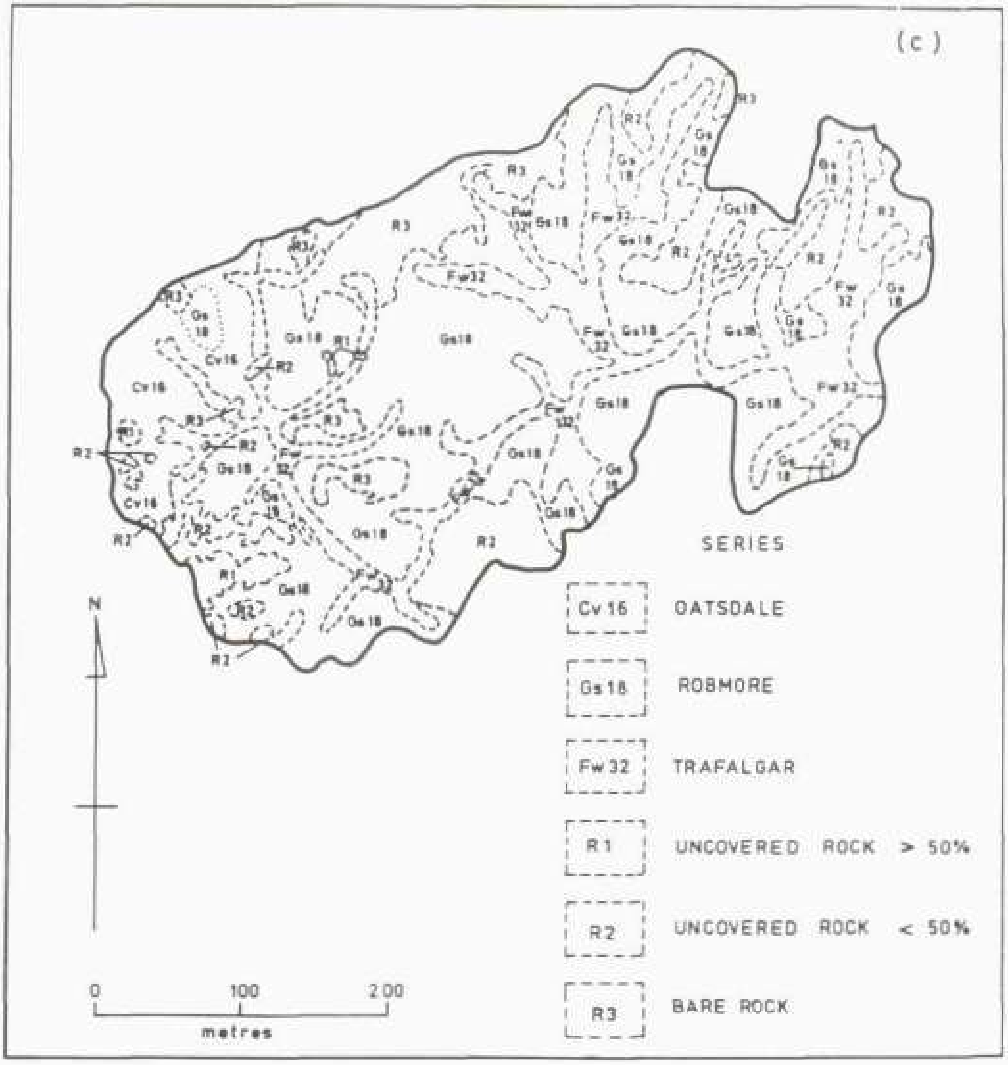
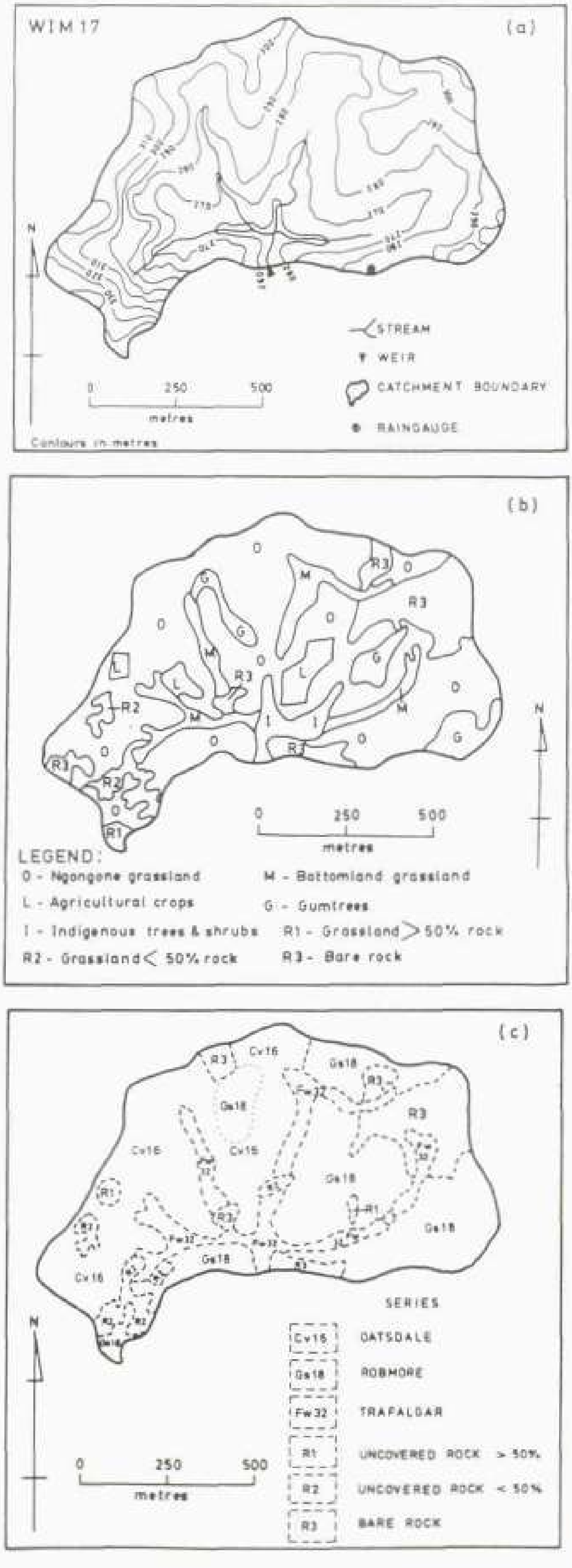


Figure 4.6 Catchment WIM17 (a) topography and instrumentation
(b) vegetation/land-use and
(c) soils



4.3 Hydrological and Meteorological Data

While each of the catchments under consideration is instrumented by a continuous flow recorder and at least one autographic raingauge, continuous processed data in digitised form for these continuous records are only available for catchments W1M16, W1M17 and U2M20. For the remaining catchments selected storm hydrographs have been digitised to provide the stormflow volumes and hydrograph characteristics for these events. The associated storm rainfall and 30 antecedent days' rainfall have also been recorded. The processing of runoff records and stormflow hydrographs followed the procedure described by Schulze and Arnold (1979).

The separation of stormflow from delayed flow was based on the Hewlett and Hibbert (1967) approach, whereby a line of constant slope of 1,13 mm. day^{-1}. day^{-1} is projected from the beginning of a stream rise to the point where it intersects the recession limb of the hydrograph (Arnold and Schulze, 1979). According to Arnold and Schulze, stormflow volumes "... estimated by the SCS model under control situations have shown very close agreement with results using the above method" (Arnold and Schulze, 1979:159). Furthermore, Hewlett, Cunningham and Troendle have stated that the classification of streamflow into stormflow and baseflow "... is an arbitrary decision of the analyst, whose main objective is, or should be, to maintain a consistent criterion for separation over all basins and all hydrographs" (Hewlett _et al_, 1979:232).

The selection of stormflow events for this study was restricted to those hydrographs produced by 15 mm or more rainfall. While this is not a particularly high threshold (SCS procedures were based on the annual storm) it allowed for the selection of a sample large enough for statistical analyses while the highly variable small events were largely excluded. Storm rainfall includes all rain falling between a point in time two hours before the hydrograph initiation and the termination of stormflow by the 1,13 mm.day^{-1}.day^{-1} separation slope. The two hour advance "allows for some clock error between water level and rainfall recorders and also for small aberrations in the computer-determined hydrograph rise" (Hewlett _et al_, 1977:234).

Additional meteorological data used in this study were American class A-pan evaporation depths and mean daily and monthly temperatures. These additional data were obtained from meteorological stations located adjacent to the catchments under consideration, the data for the Cedara and De Hoek Catchments having been provided by the Department of Agriculture and Fisheries and the data for the Zululand Catchments by the Department of Geography of the University of Zululand.

4.4 Catchment Curve Numbers

For the Determination of CN in the five catchments the procedures described in NEH-4 (1972) and Schulze and Arnold (1979) were followed. Having first identified homogeneous vegetation/soil units, curve numbers for average moisture conditions were assigned to those units and the proportion of the catchment covered by each unit determined. Details of the derivation of CN values for the five selected catchments are presented in Appendix 1.

Storm rainfall and stormflow data were used to determine the 'true' or optimum catchment CN value for each event. Solving for S in the stormflow equation:

$$Q = \frac{(P - 0{,}2S)^2}{P + 0{,}8S} \quad , \quad P \geq 0{,}2S \qquad \ldots\ldots\ldots\ldots \quad (4.1)$$

yields

$$S = 5(P + 2Q - (4Q^2 + 5PQ)^{0{,}5} \quad . \qquad \ldots\ldots\ldots\ldots \quad (4.2)$$

Making use of measured values of Q and P from actual storms and substituting in Equation 4.2 to obtain S, the 'actual' CN for these events could be calculated by using the previously described relationship.

$$CN = \frac{1000}{\frac{S}{25{,}4} + 10} \qquad \ldots\ldots\ldots\ldots \quad (4.3)$$

While the above procedure was used to determine a single lumped CN for the catchment, calculations of the optimum CN values for individual CN units within the catchment from storm rainfall and stormflow data necessitated a different approach, since stormflow amounts produced by each unit could not be determined individually. The adopted procedure was based on the equation developed by Hawkins (1978), which has been discussed previously (cf Section 3.3), viz:

$$CN_2 = \frac{1200}{\frac{1200}{CN_1} + \frac{\Delta V}{25,4}} \qquad \text{..........} \quad (4.4)$$

where

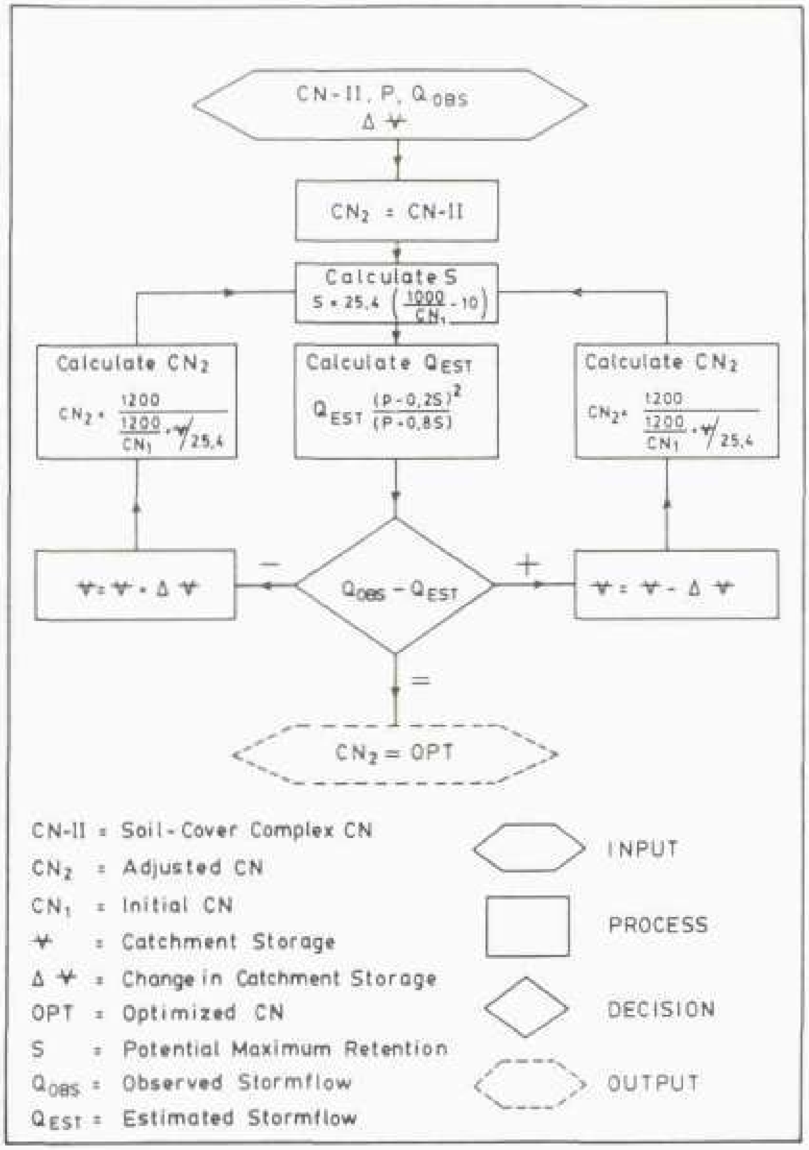
ΔV = $ET - (P - Q_1)$ or change in storage

CN_2 = calculated CN at end of interval and

CN_1 = initial CN at start of interval

Assuming CN values for each unit, based on the soil-cover complex, to be correct, stormflow (Q) is calculated for each unit (Equation 4.1). These proportional values of Q are added to yield the total calculated stormflow volume for the catchment. The calculated and observed volumes are then compared. If the observed value is less than the calculated value, V in Equation 4.4 is increased and the CN_2 values for each unit adjusted accordingly, and vice-versa. The procedure is repeated until observed and calculated stormflow volumes correspond. A flow chart of this procedure for optimising CN is presented in Figure 4.7.

Figure 4.7 Flow chart of the procedure for optimising CN



Regarding the above procedure, the following should be noted:

(a) The amount by which ¥ is adjusted in each step and the accuracy to which observed and calculated stormflow must correspond is pre-defined. In this study $\mathrm{¥}$ was adjusted by 0.2 mm and correspondence was to within one percent.

(b) The assumption is made that changes in $\mathrm{¥}$ are uniform throughout the catchment which, as has been shown in Chapter 2, is not entirely correct.

4.5 Statistical Tests and Error Functions

The accuracy of stormflow simulations using HAWK or the standard SCS model was assessed in terms of the coefficient of determination (D) and the coefficient of efficiency (E) of observed and calculated stormflow depths in which:

$$D = \frac{\Sigma(Q_o - \bar{Q}_o)^2 - \Sigma(Q_o - Q_{est})^2}{\Sigma(Q_o - \bar{Q}_o)^2} \qquad \text{..........} \quad (4.5)$$

and

$$E = \frac{\Sigma(Q_o - \bar{Q}_o)^2 - \Sigma(Q_o - Q_c)^2}{\Sigma(Q_o - Q_o)} \qquad \text{..........} \quad (4.6)$$

where

Q_o = observed stormflow
$\bar{Q}_o$ = mean of observed stormflows
Q_c = calculated stormflow and
Q_{est} = estimated stormflow obtained from the regression line of Q_o on Q_c.

Both D and E will always be less than unity, high values indicating accurate simulation of stormflow. However, these two statistics are not identical as may be seen by comparing Equation 4.5 with Equation 4.6. While D is a good measure of the degree of association between observed and estimated values it does not reveal systematic errors (Aitken, 1973). However, by considering D and E together it is possible to ascertain whether systematic error is present, the value of E being lower than D when this is so. The value of D can range from 0 to +1 while that of E can range from $-\infty$ to +1.

The error function F_1 may be used as an absolute measure of the efficiency of a model for comparison with other models (Roberts, 1979: Personal Communication). The error function F_1 is defined as the difference between D and E. Thus the closer F_1 is to zero, the less the systematic error occurs in simulated stormflow. In addition to the above procedures, observed versus calculated stormflow volumes using the various procedures have been plotted as scattergrams and may be compared with the line of perfect agreement (1:1).

The aims and hypotheses of this research have been outlined and the relevant data requirements and analytical procedures presented. Attention is now turned to the procedures by which these hypotheses were tested and the results thus obtained.

Chapter 5

THE APPLICATION OF THE HAWKINS PROCEDURE TO GAUGED CATCHMENTS

In order to gauge the efficiency of Hawkins technique (HAWK) for simulating stormflow volumes, it was necessary to eliminate as far as possible the inaccuracies caused by the limitations of the inputs into the model. The calculated stormflow volumes using these gauged or 'optimum' inputs were then compared with observed volumes. While rainfall and runoff data were gauged values, assumed to be correct, starting CN values (CN_1) and actual evapotranspiration (AET) depths used in HAWK had to be derived. HAWK was thus tested with optimum inputs using the lumped CN and distributed CN methods of calculating stormflow volumes (cf Section 3.1). This analysis was conducted on the two Zululand catchments, W1M16 and W1M17, since the required data, particularly with respect to the derivation of AET, were only available for these two catchments (Appendix 2).

5.1 Experimental Procedure

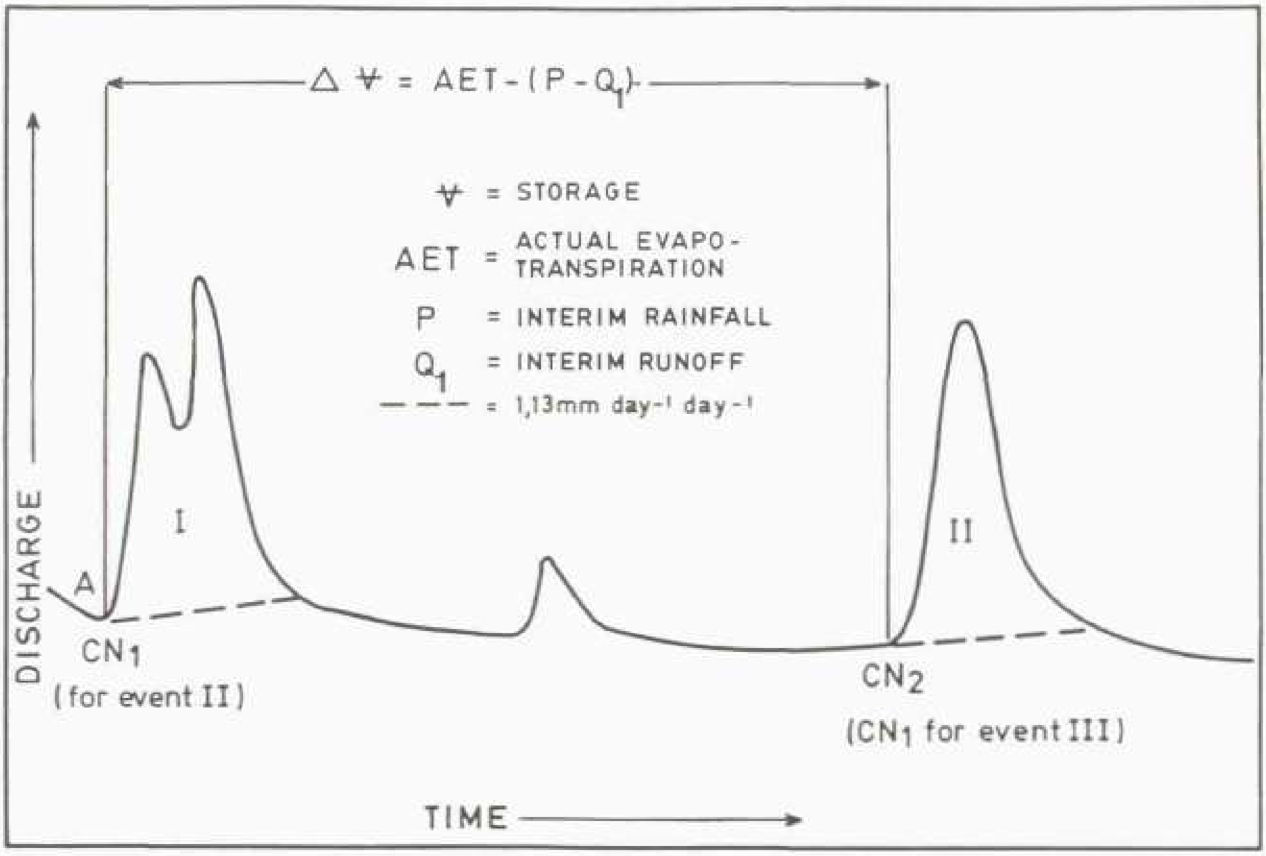
5.1.1 The optimum initial curve number

The value of CN_1 for a stormflow even was taken to be the optimum CN value of the previous stormflow event, this value having been determined by the procedure outlined in Section 4.4 Referring to Figure 5.1, the optimum CN for event I is the CN value of time A.. Since this is CN_1 for the event II, the rainfall, runoff and AET between the start of storm I and the start of storm II had to be determined in order to derive the change in storage, ¥ used to calculate the CN_2 for event II.

5.1.2 The derivation of actual evapotranspiration

The determination of AET posed a major problem in this research. Potential evapotranspiration (PET) may be estimated relatively easily by procedures such as those described by Penman (1948), Thornthwaite (1948), Blaney and Criddle (1950) or Van Bavel (1966). Actual evapotranspiration rates are, however, governed not only by potential evapotranspiration but

Figure 5.1 Schematic representation of the derivation of optimum CN_1, AET, P and Q_1 for use in HAWK



to a large extent by CMS, which is highly variable within a catchment (cf Chapter 2).

According to Dunne and Leopold (1978) the most popular method of computing

AET is by equation:

$$AET = PET \times f\left(\frac{AW}{AWC}\right) \qquad \text{..........} \quad (5.1)$$

where

AET = the actual rate of evapotranspiration

PET = the potential rate of evapotranspiration

AW = the available soil moisture and

AWC = the available water capacity of the soil

Since, however, information regarding AW and AWC was not available for the catchments under consideration an alternative procedure was considered more suitable for calculating AET.

A regression equation was developed whereby AET could be determined. The equation took the following form:

$$AET = \beta_0 + \beta_1 E + \beta_2 W \qquad \text{..........} \quad (5.2)$$

where

AET = actual evapotranspiration

E = a measure of the energy available for evapotranspiration

W = soil moisture available for evapotranspiration

β_0 = the unknown regression coefficient referred to as the constant term and

β_{1-2} = the unknown regression coefficients associated with the independent variables E and W.

For the derivation of AET the hydrological equation may be written as:

$$AET = P - Q_1 \pm \Delta S \qquad \text{.........} \quad (5.3)$$

where

P = rainfall inputs to the catchment

Q_1 = runoff from the catchment and

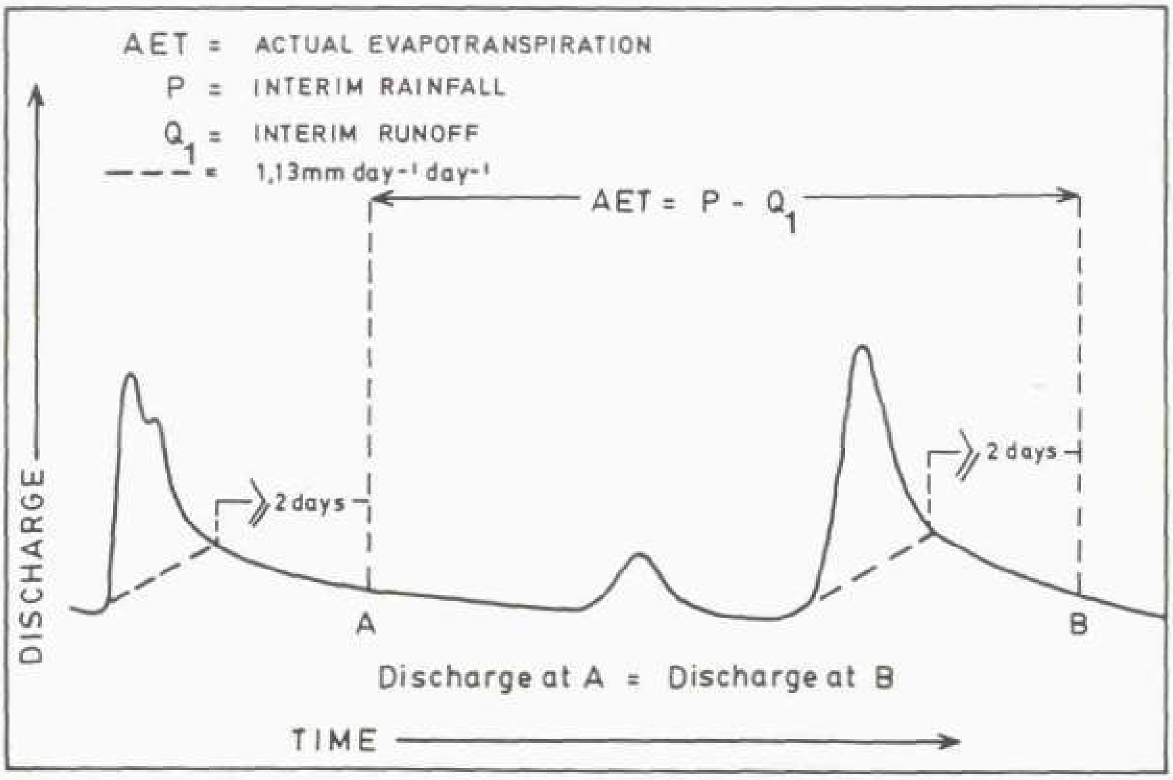
ΔS_t = changes in catchment storage

While P and Q_1 may be determined on a gauged catchment, changes in S_t are more difficult to assess, this only being possible when soil moisture and groundwater are being monitored adequately. By considering AET over a period of time where ΔS_t is assumed to be zero, Equation 5.3 becomes:

$$AET = P - Q_1 \qquad \text{............} \quad (5.4)$$

In this study it was assumed that the catchment storages were at the same level when the rate of streamflow discharges were equal, an approach described by Lambert (1969). Furthermore, the selection of equal storage levels had to be on the recession limb of the hydroraph and at least two days after the cessation of the last stormflow event, thus allowing temporary storages to be depleted (Figure 5.2).

Fire 5.2 Schematic representation of the derivation of AET using the water balance approach



In a situation such as that illustrated in Figure 5.2, AET would be calculated between points A and B and the measure of energy and soil water for evapotranspiration would be determined for the same period.

Two measures of the energy for evapotranspiration were tested, viz, mean temperature (°C) and A-Pan evaporation depths (mm). The total depth of rainfall for the period under consideration was assumed to be measure of the soil moisture available for evapotranspiration. Assuming temperature and A-Pan evaporation exhibit strong intercorrelation, one of these energy variables had to be excluded from the regression equation. The excluded variable was that variable contributing least to the coefficient of determination.

The above water balance procedure is an adaptation of the procedure generally used to make estimates of AET over long periods, usually in excess of a year (Dunne and Leopold, 1978). However, Schulze (1974) used this procedure over periods as short as one month in a study of catchment evapotranspiration. The average duration over which AET values were calculated for developing the regression equations was 12,7 days. For greater accuracy two regression equations were developed for each catchment under consideration, one for the summer months and one for the winter months allowing for seasonal differences in soil moisture and soil radiation.

5.2 Results and Discussion

5.2.1 Optimised curve numbers

The average optimised CN values for events tested in catchments W1M16 and W1M17 are presented in Table 5.1. The average optimised CN values for each soil-cover complex unit in W1M16 are lower than the associated average SCS values of CN for AMC-II (Table 5.1). This observation is also manifest in the comparison of lumped CN values. These lower optimised CN values may be the result of the prevalent moisture conditions on W1M16 being lower than those assumed to be associated with CN at AMC-II. Alternatively, CN values may, for some reason, have been overestimated from field data.

Table 5.1 Average optimised CN values (a) and soil-cover complex CN values (b) for catchments W1M16 and W1M17

Catchment		Homogeneous Soil Cover Complex Units						Lumped
		I	II	III	IV	V	VI	CN
W1M16	a	80,8	69,1	57,8	88,2	-	-	71,2
	b	88,5	74,3	61,5	98,0	-	-	77,2
W1M17	a	96,3	55,6	87,2	61,8	74,5	36,1	62,1
	b	98,0	55,0	87,2	61,0	74,1	39,8	63,2

5.2.2 Equations for actual evapotranspiration

The results of the analysis for the derivation of regression equations to calculate AET for catchments W1M16 and W1M17 are presented in Table 5.2 and Table 5.3, with both tables giving the individual coefficients of determination (D) between the three independent variables and AET as well as the coefficient of determination for each set of independent variables regressed against AET.

Table 5.2 Coefficients of determination (D) for the association of individual and combined independent variables (A-Pan evaporation, rainfall and mean temperature) with the dependent variable AET, for catchment W1M16 (n = number of observations)

	Summer		Winter	
Variable	D	D	D	D
A-Pan Evaporation	0,521		0,687	
		0,935		0,994
Rainfall	0,925		0,993	
		0,929		0,993
Mean Temperature	0,640		0,442	
	n = 28		n = 15	

Table 5.3 Coefficients of determination (D) for the association of individual and combined independent variables (A-Pan evaporation, rainfall and mean temperature) with the dependent variable, AET, for catchment W1M17 (n = number of observations)

	Summer		Winter	
Variable	D	D	D	D
A-pan Evaporation	0,640		0,568	
		0,936		0,959
Rainfall	0,925		0,958	
		0,926		0,968
Mean Temperature	0,677		0,404	
	n = 31		n = 15	

On the basis of the lowest coefficient of determination (D), either A-Pan evaporation or temperature was excluded from each of the regression equations, since these variables exhibited strong intercorrelation (ranging from 0,664 to 0,955). The following equations were finally accepted to calculate AET on catchments W1M16 and W1M17:

W1M16

$$AET = 1{,}923 + 0{,}121\ A + 0{,}540\ P \text{ (Summer)} \quad \ldots\ldots\ldots\ldots \quad (5.5)$$

$$AET = -4{,}698 + 0{,}019\ A + 0{,}833\ P \text{ (Winter)} \quad \ldots\ldots\ldots\ldots \quad (5.6)$$

W1M17

$$AET = 1{,}406 + 0{,}120\ A + 0{,}541\ P \text{ (Summer)} \quad \ldots\ldots\ldots\ldots \quad (5.7)$$

$$AET = -5{,}076 + 0{,}011\ T + 0{,}872\ P \text{ (Winter)} \quad \ldots\ldots\ldots\ldots \quad (5.8)$$

where

AET = actual evapotranspiration (mm)

A = A-Pan evaporation (mm)

Energy variables and

T = mean air temperature (°C)

P = rainfall (mm).

(All the values in the above equations are cumulative totals for the interim period for which AET is calculated.)

Examination of the above equations reveals that the relative importance of soil moisture and energy for evaporation are different for summer and winter in both catchments W1M16 and W1M17. In catchment W1M16 β_2 (associated with P) is greater in winter than in summer while the converse is true for β_1 (associated with A). Similarly in catchment W1M17 the rainfall variable has greater weight in winter than in summer. These trends are confirmed by comparing the coefficients of determination for the individual independent variables on a seasonal basis (Table 5.2 and 5.3).

The above findings could possibly be due to the rainfall regime of the Zululand region. In summer the number of rain days is greater than in winter and it may be expected that soil moisture is at or close to field capacity more often in summer than in winter. Evapotranspiration may consequently be assumed to be at the potential rate more frequently in summer than in winter. Therefore, the factors affecting potential evapotranspiration (PET), the energy variables, would play a greater role in summer than in winter.

It may be concluded from the results presented in this section that the regression equations explain much of the variation of AET. In the light of this finding and considering the large amount of variance accounted for by these equations (D>0,935), the four equations presented above were regarded as suitable for calculating AET for inclusion in this study where data of optimum accuracy was required.

5.2.3 The calculation of stormflow

Having excluded as well as possible the errors due to inaccuracies of the inputs into HAWK, namely, CN_1 (initial CN), rainfall, runoff/drainage and AET, it was possible to gauge the efficiency of HAWK for simulating stormflow depths on catchments W1M16 and W1M17. Comparison of the efficiency of HAWK with that of the standard SCS technique for CN adjustment was by way of the objective functions D, E and F_1 described in Section 4.5. Both techniques were tested using the lumped CN as well as the distributed CN approaches. The error functions for these tests are summarised in Table 5.4 for catchment W1M16 and in Table 5.5 for W1M17. Associated scattergrams of calculated versus observed stormflow depths are presented in Figure 5.3 and Figure 5.4 for these two catchments respectively.

Table 5.4 Error functions D, E and F_1 for the standard SCS model and HAWK tested on catchment W1M16 using the lumped CN (LCN) and distri= buted CN (DCN) methods with optimum data

Procedure	Error Function		
	D	E	F_1
SCS (LCN)	0,653	0,446	0,207
(DCN)	0,747	0,467	0,280
HAWK (LCN)	0,764	0,503	0,261
(DNC)	0,787	0,698	0,089

Table 5.5 Error functions D, E and F_1 for the standard SCS model and HAWK tested on catchment W1M17 using the lumped CN (LCN) and distri= buted CN (DCN) methods with optimum data

Procedure	Error Function		
	D	E	F_1
SCS(LCN)	0,227	-0,193	0,420
(DCN)	0,634	0,584	0,050
HAWK(LCN)	0,719	-0,053	0,772
(DCN)	0,840	0,833	0,007

A number of observations may be made in comparing the HAWK procedures with the standard SCS model:

(a) For both catchments W1M16 and W1M17, stormflow simulations were more accurate using HAWK (Table 5.4 and Table 5.5).

(b) Overestimation was common to all the procedures tested in catchment W1M16. This overestimation is illustrated in the scattergrams (Figure 5.3). It may be noted that this overestimation is associated primarily with observed stormflow depths of between five and 25 mm.

Figure 5.3 Scattergrams of calculated versus observed stormflow depths in catchment W1M16 using optimum data inputs and optimised CN_1

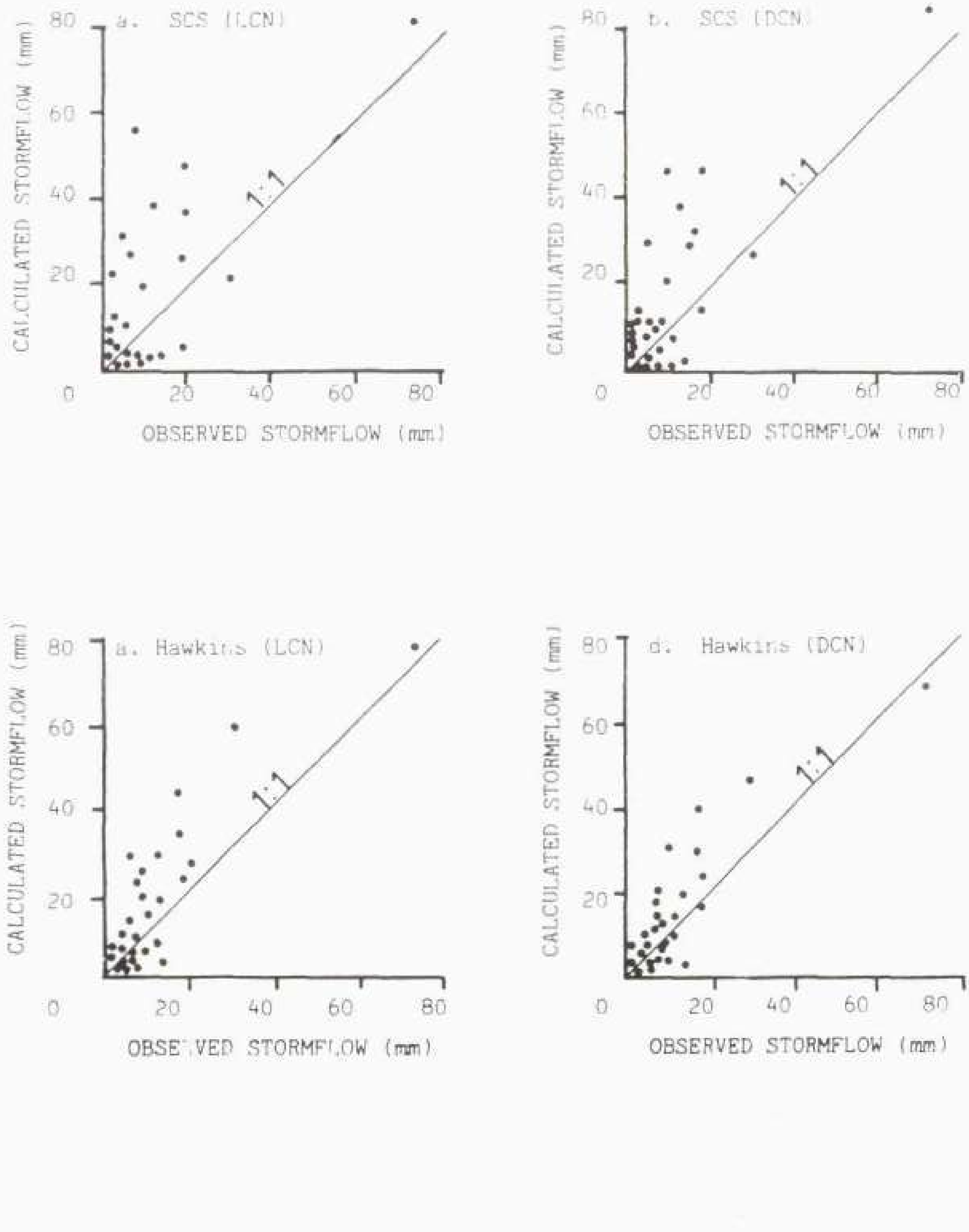
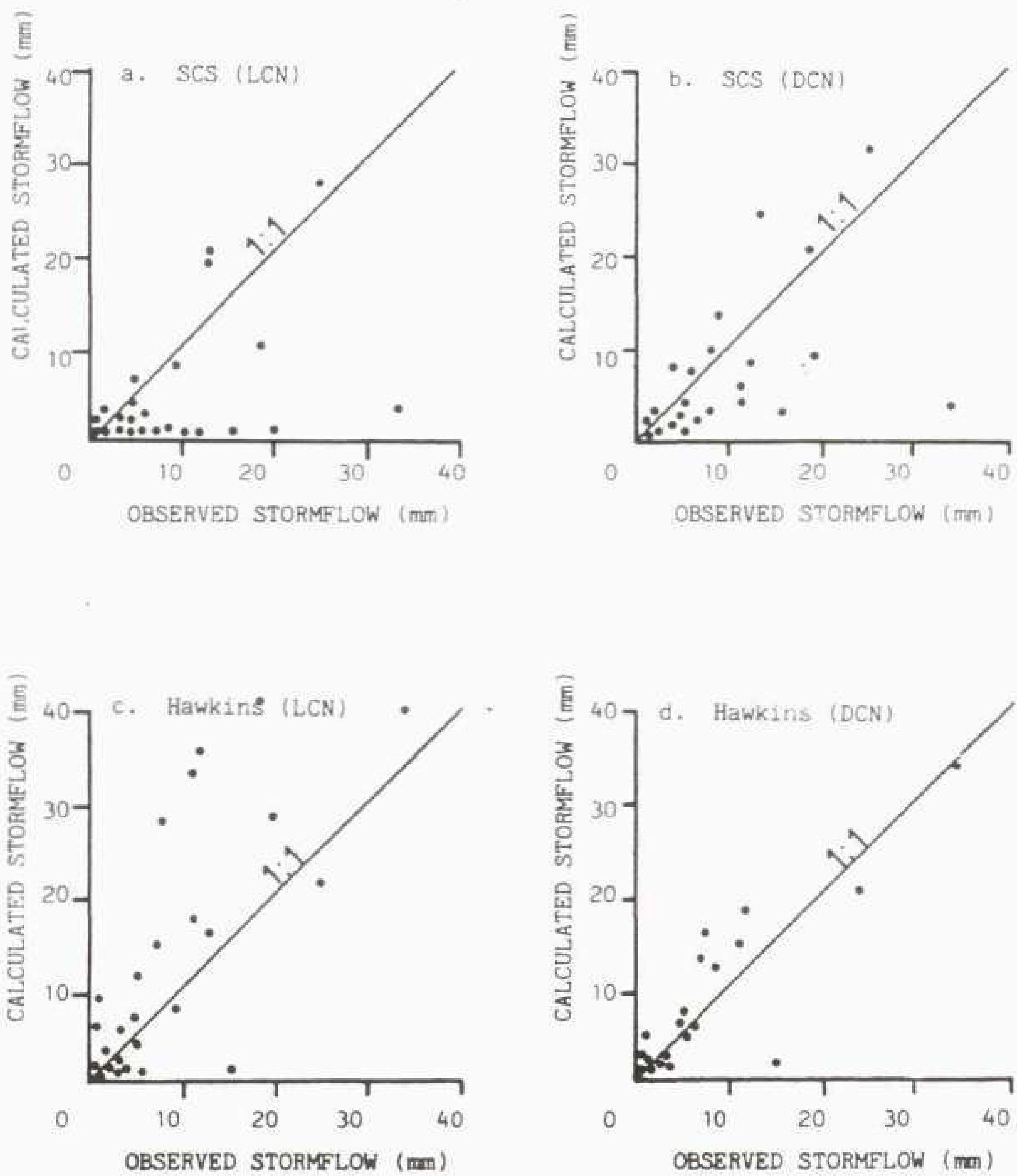


Figure 5.4 Scattergrams of calculated versus observed stormflow depths in catchment W1M17 using optimum data inputs and optimised CN_1



Furthermore, overestimation or underestimation was less on catchment W1M17, particularly when using the HAWK technique with distributed CN.

(c) The influence of the three-fold classification of antecedent moisture conditions for use in the standard SCS model is particularly evident in Figure 5.4 for catchment W1M17, where many of the stormflow events were associated with AMC-I, giving rise to little or no simulated stormflow for the associated storm rainfall.

(d) Adopting the distributed CN approach in favour of the lumped CN approach improved the accuracy of stormflow simulation using both the SCS and HAWK techniques on catchments W1M16 and W1M17, this being particularly discernible when comparing the error function E for these procedures.

According to NEH-4 (1972) the distributed CN approach will simulate storm= flow more accurately than the lumped CN approach. The results of this analysis support this assertion. The distributed CN approach falls within the framework of the unit source area theories described in Section 2.1.2.

5.3 Conclusions

To conclude this analysis, it may be stated that given accurate data inputs, the Hawkins technique for CN adjustment has been shown to be a marked improvement on the standard SCS curve number adjustment procedure in simulating stormflow depths for the two selected catchments (Tables 5.4 and 5.5). However, it is necessary to establish whether this finding holds true for the more limited data usually available on ungauged catchments and also for catchments in different regions.

Chapter 6
THE ADAPTATION OF THE HAWKINS PROCEDURE TO UNGAUGED CATCHMENTS

The four basic inputs required to adjust curve numbers for antecedent moisture conditions using the Hawkins procedure have been outlined in Chapter 5 as being:

(a) the initial curve number (CN_1)
(b) the interim actual evapotranspiration (AET)
(c) the interim drainage or runoff (Q) and
(d) the interim rainfall (P)

Assuming antecedent daily rainfall values to be available on ungauged catchments, the remaining three inputs need to be estimated. Procedures for estimating these inputs are proposed in this chapter followed by an examination of the results using these procedures and HAWK to adjust CN for catchment moisture status and thence calculate stormflow by the SCS model.

6.1 Experimental Procedure

6.1.1 The estimation of initial curve number

The accuracy of CN_1 is of utmost importance in deriving CN_2 (the CN prior to the stormflow event) because inaccuracies in the original estimate of CN_1, assuming an accurate measure of changes in storage (¥), are carried through to CN_2 and are not 'averaged out' over time. However, if CN_1 could be determined accurately by one means or another, it would obviate the need to determine CN_2 using CN_1. Initially two procedures for estimating CN_1 on ungauged catchments were developed and tested, both procedures using avera= ging techniques. These procedures were based on the 20 antecedent days' rainfall prior to each stormflow event, these 20 days being divided into four pentads. The following analyses were all conducted using the distri= buted CN approach since, according NEH-4 (1972), this method yields better results than the lumped CN method, this having been substantiatated in Chapter 5.

The first procedure developed for calculating CN_1 involved the determination of CN values for each of the four antecedent pentads and the calculation of an average CN value (CNA1) using the following methods:

(a) Calculate the CN for each pentad (PCN). The CN at the start of the pentad was assumed to be the soil-cover complex CN for the AMC-II condition and the CN at the end of the pentad, PCN, was determined using the Hawkins technique (Equation 3.15).

(b) Calculate the average CN for the four pentads (CNA1).

$$CNA = \frac{\sum_{i=1}^{4} PCN_i}{4} \qquad \text{..........} \quad (6.1)$$

where

CNA1 = CN_1 in HAWK and

PCN_i = the calculated pentad CN for each pentad

(c) Re-adjust CNA1 for changes in storage (¥) over the final pentad. This was the final CN used to calculate stormflow volumes (CN_2) and thus gave additional weight to changes in ¥ during the pentad closest to the stormflow event.

The second procedure for calculating CN_1, referred to as CNS2, was based on the moving average principle. Starting with the pentad furthest from the event (pentad 1) the pentad CN $(PCN)_1$ was calculated by HAWK assuming the soil-cover complex CN for the AMC-II condition to be the initial CN (CN_1). The average of the soil-cover complex CN and the calculated PCN for this pentad became the new starting CN, viz, CN_1, for the next pentad. This procedure was repeated for the second to third and finally third to fourth pentads, with the adjusted CN in each pentad being averaged with the soil-cover complex CN to constitute the initial CN of the next pentad.

Four additional procedures for estimating the initial CNs required in adjusting CN by HAWK were tested. Each of these procedures assumed the soil-cover complex CN at AMC-II to represent CN_1. The first procedure calculated changes in ¥ over five antecedent days, the second procedure was based on 10, the third on 15 and the fourth on 20 antecedent days. These four procedures are referred to as CN5, CN10, CN15 and CN20 respectively.

The testing of the six CN procedures described above was performed on two sets of data:

(a) First, the data of 'optimum' accuracy, derived from gauged catchments, were used. Thus, measured rainfall, measured runoff and AET calculated by a regression equation were used to determine changes in catchment storage, ¥. Since both continuous flow records and the information for the regression equations to calculate AET were available only for catchments W1M16 and W1M17, these were the only two catchments where 'optimum' data were used in these analyses.
(b) Secondly, measured rainfall with estimated values of runoff and of AET were used, viz, 'test' data.

6.1.2 The estimation of actual evapotranspiration

For the calculation of AET on ungauged catchments, estimates of the following variables had to be made:

(a) the rate of potential evapotranspiration (PET) and
(b) the soil moisture available for evapotraspiration.

The estimation of PET was made by the Blaney and Criddle (1950) equation, this method being chosen because:

(a) the equation is based on average air temperatures, which are available for most regions of Natal and
(b) crop type and day length are considered in this equation, thereby providing for regional and catchment differences in PET.

According to the Blaney and Criddle equation:

$$PET = (0,142\ T_a + 1,095)(T_a + 17,8)kd \quad .... \quad (6.2)$$

where

PET = potential evapotranspiration (mm x 10)

T_a = average air temperature (°C)

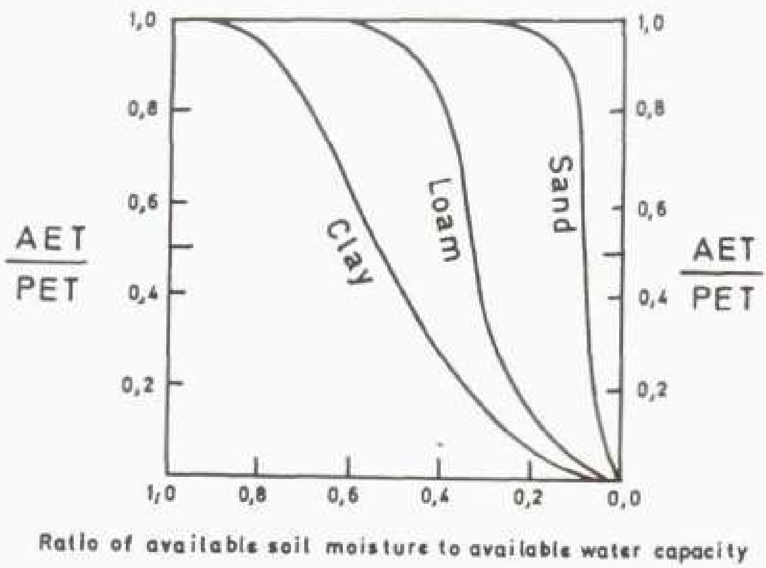
k = empirical crop factor which varies with crop type and stage of growth and

d = the monthly fraction of annual hours of daylight (Blaney and Criddle, 1950)

Values of k and d as tabulated in Dunne and Leopold (78) were used in the above equation.

Information pertaining to the moisture characteristics of many soil series in Natal are not readily available. To overcome the problem of limited information for application in calculations of actual evapotranspiration, a procedure was developed to adjust PET rates for restrictions in the availa= bility of soil moisture based on Holmes' (1961) relationship between available soil moisture and the rate of AET:PET for different textured soils (Figure 6.1).

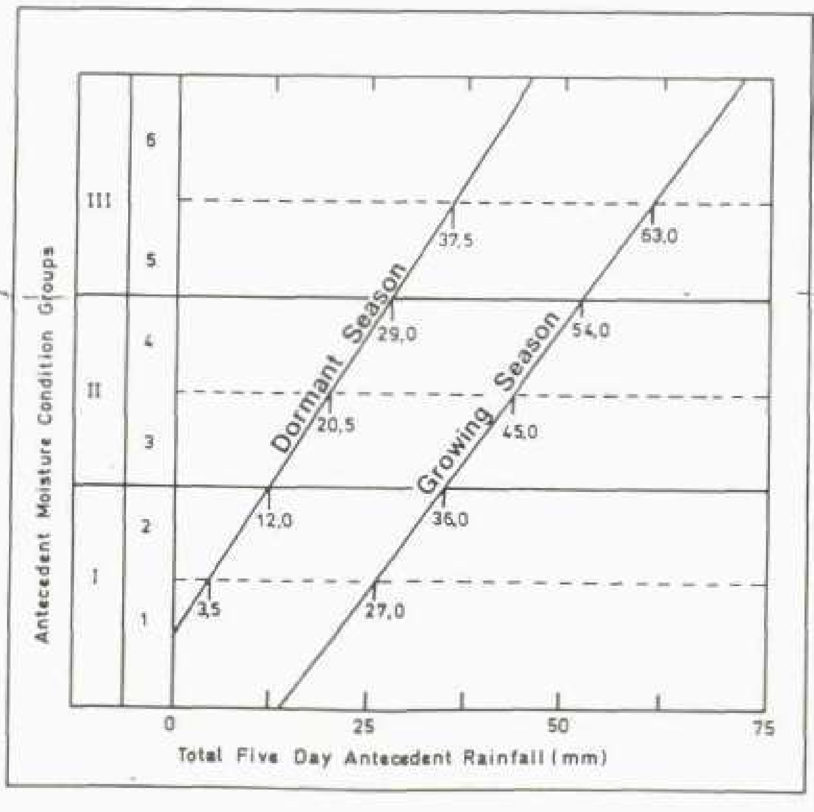
Figure 6.1 Ratio of actual evapotranspiration (AET) to potential evapo= transpiration (PET) as a function of soil moisture for three soil textures (Adapted from: Holmes, 1961)



Since it was not practicable to determine, by direct means, the available soil moisture on a catchment, it was necessary to define classes of antecedent rainfall which may be equated with soil moisture available for evapotranspiration. The antecedent rainfall classes defined in NEH-4 (1972) for application in the SCS stormflow model were adapted for this purpose, and since most stormflow events in Natal occur during the growing season, the rainfall class limits associated with that season were assumed (cf Section 3.2). The SCS antecedent moisture classes were used since these classes imply the upper and lower boundaries of soil moisture, namely, field capacity and wilting point, which correspond with the soil moisture limits in Figure 6.1.

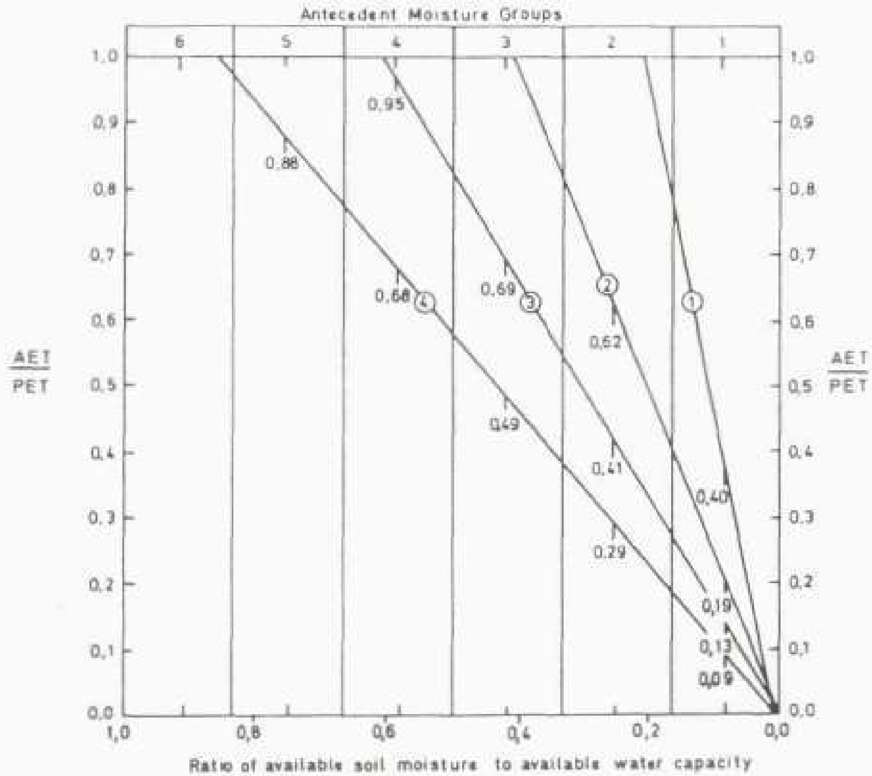
In order to provide a finer resolution for the determination of AET, the three moisture classes were each divided into two sub-classes to produce six classes. Since the relationship between the five day antecedent rainfall and the antecedent moisture classes (AMC) is linear (NEH-4, 1972), AMC-II could be divided into two equal sub-classes and classes of equivalent 'width', shown in Figure 6.2, were created in the AMC-I and AMC-III classes.

Figure 6.2 The derivation of class limits for six antecedent moisture classes from the three original SCS classes



By superimposing the six antecedent moisture classes on the abscissa in Figure 6.2 and assuming the centre of the class to be representative of that class, the ratio AET:PET for the major soil types could thus be estimated for each antecedent rainfall class (Figure 6.3).

Figure 6.3 The assumed relationship between antecedent moisture condi= tions, soil texture and the ratio of actual to potential evapotranspiration



AET Actual Evapotranspiration
PET Potential Evapotranspiration
(1) Sand (2) Sandy-Loam (3) Loam (4) Clay

The curves presented in Figure 6.1 were simplified in Figure 6.3, being represented as straight lines. An additional line for sandy-loams was introduced half way between curves for sand and loam since many of the soils in Natal fall into this category. The conversion factors for calcu= lating AET from PET based on soil texture and moisture conditions are contained in Figure 6.3

While the procedure outlined above includes a number of assumptions, the major factors governing AET rates are accounted for thereby providing a conceptually sound estimate of AET. Furthermore, the data requirements for this method, viz, daily rainfall and the major soil types, are generally available for ungauged catchments. Textural descriptions of the soils of Natal are given, inter alia, by Van der Eyk, MacVicar and De Villiers (1969). A further advantage of this method is that AET may be weighted for each soil type within a catchment.

For the stormflow events considered in this research, PET was calculated for the respective month and reduced to a depth per pentad. On the basis of the rainfall in each pentad these values of PET were adjusted for the assumed available soil moisture (Figure 6.3), with AET being weighted according to the area of each major soil texture type in the catchments.

6.1.3 The estimation of runoff

The estimation of runoff or drainage from a catchment is a fundamental problem in hydrology with models for this variable generally being of a complex nature. For the purpose of this study an estimate of runoff from ungauged catchments over a minimum period of five days was required. With the view to applying HAWK on ungauged catchments it was necessary to develop a procedure whereby relative measures of the runoff response from catchments in different regions could be estimated. However, no such procedure exists for application in South Africa over such short periods, namely, a pentad.

The method proposed in this study for estimating runoff for each pentad is based on a procedure described by Midgley and Pitman (1969) for calculating the mean annual runoff from ungauged catchments. According to the above authors the relationship between mean annual rainfall (P_m) and the mean annual runoff (R) is non-linear and varies geographically within South Africa.

The relationship between P_m and R was expressed by Midgley and Pitman (1969) as a power curve:

$$R = \beta P_m^{\gamma} \quad \text{..........} \quad (6.3)$$

where

R = mean annual runoff (mm)

P_m = mean annual rainfall (mm) and

β and γ = coefficient and exponent respectively of the power function

The above relationship holds up to a critical value of mean annual rainfall, P_m, after which the slope of the power curve is unity. Beyond this critical value mean annual runoff is calculated according to the following equation:

$$R = P_m - L \qquad \text{.......... (6.4)}$$

where

L = a constant loss (mm), applicable where $P_m > P$

The value of P_c and hence L may be determined by differentiating Equation 6.3 and equating dR/dP_m to unity, thus establishing the point at which the slope of the power curve is unity (Midgley and Pitman, 1969).

Regional values for β and γ were determined by Midgley and Pitman (1969) for South Africa. Thus for a given location and given mean annual rainfall, the runoff response of a catchment may be determined, this response being expressed as:

$$R_e = \frac{R}{P_m} \qquad \text{.......... (6.5)}$$

where

R_e = the mean annual runoff response.

The values of β, γ, P_c and R_e for the catchments included in this study are summarised in Table 6.1.

Table 6.1 Values of the coefficient (β), exponent (γ), critical mean annual rainfall (P_c) and response ratio (R_e) for calculating runoff in the six selected research catchments

Location	β	γ	P_c (mm)	R_e
Zululand	6.414×10^{-9}	3,433	1403	0,310
Cedara	$6,414 \times 10^{-9}$	3,433	1403	0,093
De Hoek	$5,033 \times 10^{-9}$	3,554	1080	0,153

For calculations of runoff for each pentad the assumption was made that the response of the catchment to the rainfall during the respective pentad was the same as R_e. For example, if a pentad's rainfall at Cedara (R_e = 0,093) was 30,0 mm, the pentad's runoff was estimated at 30,0 x 0,093 = 2,79 mm. While it is accepted that there are fundamental weaknesses in this approach, particularly with respect to delayed drainage, no alternatives were researched for estimating runoff over short periods. Furthermore, this procedure provides a relative measure of drainage losses from region to region.

6.2 Results and Discussion

The simulation of stormflow depths on ungauged catchments by the SCS model using HAWK necessitates the derivation of CN_1, AET and interim runoff/drainage. Procedures for estimating these model inputs have been proposed in Section 6.1. Two catchments, W1M16 and W1M17, have accurate data available for HAWK (optimum data) thus making it possible to evaluate the effects of the various procedures for estimating CN_1 on simulated stormflow depths, largely independent of variations caused by data inaccuracies. The results of the analyses conducted on these two Zululand catchments are dealt with first followed by a presentation and discussion of the results from catchments U2M20, V1M28 and V7M03 for which only calculated runoff and AET were available (test data).

6.2.1 Stormflow simulation on catchments W1M16 and W1M17

The results for the stormflow simulation analyses conducted on catchments W1M16 and W1M17 are summarised in Table 6.2 and Table 6.3 respectively. The associated scattergrams of observed versus calculated stormflow depths for these two catchments are presented in Appendices 3 and 4 respectively.

By the first examining the error functions D, E and F_1 associated with the tests conducted using optimum data, the following observations may be made regarding the six CN procedures tested on catchment W1M16 (Table 6.2):

(a) Although procedure CN5 results in the highest value of D (0,918), this procedure gives rise to large systematic over-estimation in calculated stormflow depths. The values of E and F_1 are -1,207 and 2,118 respectively, these being the greatest error values of the six CN procedures.

(b) The three procedures CN10, CN15 and CN 20 simulate stormflow depths almost equally in terms of the error functions, D, E and F_1.

(c) The averaging procedures, CNA1 and CNS2, are associated with high values of D, viz, 0,840 and 0,884 respectively. However, the systematic over/underestimation reflected in the values of E and F_1 negate the usefulness of these procedures for adjusting CN and subsequently calculating stormflow by the SCS model.

Table 6.2 Error functions D, E and F_1 for the standard SCS model and six HAWK curve number procedures tested on catchment W1M16 based on optimum data (OPT) and test data (TES)

Procedure	Error Function		
	D	E	F_1
SCS	0,747	0,467	0,280
CNA1(OPT)	0,840	-0,458	1,298
(TES)	0,866	-0,693	2,266
CNS2(OPT)	0,884	-1,022	2,106
(TES)	0,884	0,750	0,134
CN5 (OPT)	0,918	-1,207	2,118
(TES)	0,891	-0,370	1,261
CN10(OPT)	0,701	0,305	0,396
(TES)	0,933	-2,597	3,530
CN15(OPT)	0,692	0,387	0,305
(TES)	0,941	-2,712	3,653
CN20(OPT))	0,735	0,443	0,292
(TES)	0,932	-3,085	4,107

(d) The systematic error, as indicated by F_1, was found on examining the scattergrams in Appendix 3 to be overestimation of stormflow depths for all the procedures tested.

(e) While procedure CN20 results in a value of D of only 0,735 (the fourth highest), the better results reflected in functions E and F_1 make this the most suitable CN procedure for calculating stormflow on this particular catchment given optimum data inputs.

Assuming the optimum data for the analysis on catchment W1M16 to be accurate, the consistent overestimation of stormflow depths associated with each of the procedures tested may be attributed to the very nature of these procedures. Each procedure requires the soil-cover complex CN at AMC-II as a basic input, thus any error in the derivation of this CN would be carried through to the final adjusted CN used to calculate the stormflow depths. The value of the average soil-cover complex CN and AMC-II was shown in Section 5.1.1 to b higher than the average optimised CN values. This earlier finding may thus account for the overestimation of stormflow depths reflected in the results of this analysis. Since by using optimised start= ing CN values in the preceding analysis (cf Section 5.2.3) did not give rise to overestimation of this magnitude on catchment W1M16, the explanation presented above is given added weight. Furthermore, the procedures CNA1 and CNS2 are particularly sensitive to errors in the estimation of the CN at AMC-II because of the greater emphasis these procedures give to this CN in the derivation of CN_1.

The simulation of stormflow depths on catchment W1M17 using optimum data inputs reveals very little systematic over/underestimation regardless of which of the six CN procedures are used, with values of F_1 ranging between 0,002 and 0,028 (Table 6.3). This lack of systematic error would be expected if the argument given above explaining the systematic errors on catchment W1M16 holds true, since the average optimised and average soil-cover complex CN values were found to be similar for catchment W1M17 (cf Section 6.2.1).

Table 6.3 Error functions D, E and F_1 for the standard SCS model and six HAWK curve number procedures tested on catchment W1M17 based on optimum data (OPT) and test data (TES)

Procedure	Error Function		
	D	E	F_1
SCS	0,634	0,584	0,050
CNA1(OPT)	0,821	0,807	0,014
(TES)	0,652	0,526	0,126
CNS2(OPT)	0,826	0,798	0,028
(TES)	0,637	0,414	0,223
CN5 (OPT)	0,853	0,849	0,004
(TES)	0,890	0,875	0,015
CN10(OPT)	0,821	0,818	0,003
(TES)	0,883	0,845	0,038
CN15(OPT)	0,782	0,780	0,002
(TES)	0,881	0,816	0,065
CN20(OPT)	0,779	0,776	0,003
(TES)	0,890	0,741	0,149

Further examination of the error functions D and E associated with the CN procedures using optimum data on catchment W1M17 show little variation (Table 6.3). The values of D range between 0,853 for procedure CN5 and 0,779 for procedure CN20 while the values of E range from 0,849 for procedure CN5 and 0,741 for procedure CN20. However, since procedure CN5 is associated with the highest value of D and E and its F_1 value is closest to zero, it may be concluded that this procedure is the most suitable procedure for stormflow simulation on catchment W1M17, given optimum data inputs for HAWK.

A comparison of the accuracy of HAWK using the CN5 procedure with optimum data inputs and HAWK based on optimised initial CN values reveals very little difference in the error functions for catchment W1M17 (Table 6.4). Each of the error functions improved slightly using procedure CN5, sugges= ting that for catchment W1M17 the assumption that soil-cover complex CN for AMC-II may be used as the value of CN_1 is valid. This situation may be expected to arise in regions having a high frequency of rainfall events and soil moisture contents which are consistently close to those values associated with AMC-II.

Table 6.4 Error functions D, E and F_1 for the curve number procedure CN5 based on optimum data (OPT) and the HAWK procedure based on optimised initial CN values (CN_1) and the optimum data

Procedure	Error Function		
	D	E	F_1
CN5 (OPT)	0,853	0,849	0,004
CN_1 (OPT)	0,840	0,833	0,007

While the accuracy of stormflow simulations on catchments W1M16 and W1M17 is not affected markedly by using any one of the selected CN procedures and HAWK with optimum data, attention is now directed at assessing the influence of using test data (estimated runoff and AET values) in conjunc= tion with these procedures. For this purpose, the error functions for optimum and test data in Table 6.2 and Table 6.3 associated with the SCS model and the six CN procedures are compared. In examining the changes in the error functions when test data rather than optimum data are used for catchment W1M16 (Table 6.2), the following observations may be made:

(a) The values of D for procedures CNA1, CNS2 and CN5 using test data are similar to the corresponding values using optimum data. However, the values of D increase markedly using test data for procedures CN10, CN15 and CN20.

(b) The error function E generally reflects greater error associated with the CN procedures when test data are used. However, using test data in procedures CNS2 and CN5 improved the value of E substantially, from -1,022 to 0,750 and -1,207 to -0,370 respectively.

(c) Systematic overestimation of stormflow depths resulting from the use of test data probably accounts for the less favourable values of E as described in (b) above. This may be deduced by examining the increases of F_1 values for test data in place of optimum data when D values are generally comparable. This finding is confirmed by exami= ning the scattergrams in Appendix 3. The improved simulation results using procedures CNS2 and CN5 with test data are also confirmed in Appendix 3 with the points of observed and calculated stormflow plotting evenly about the 1:1 line.

(d) On the basis of the three error functions, procedure CNS2 is the most effective procedure for use with test data while procedure CN5 is the most accurate of the less complex procedures (CN5 to CN20).

In comparing the values of F_1 for procedures CN5 through to CN20 for test data on catchment W1M16 (Table 6.2), it may be noted that the systematic overestimation of stormflow increases with the number of antecedent days considered. This is also confirmed by examining the associated scatter= grams in Appendix 3. Since the systematic error associated with these procedures did not reveal this trend when using optimum data, it may be concluded that the test data gave rise to this progressive increase in the overestimation of stormflow. Thus the true AET and runoff/drainage would appear to be greater than those values estimated, these differences being cumulative and thus greater the longer the antecedent period considered.

A comparison of the error functions for the six CN procedures using optimum data with those using test data on catchment W1M17 (Table 6.3), leads to observations somewhat different to those discussed above:

(a) In considering procedures CNA1 and CNS2, values for both D and E decreased with the use of test data, indicating that the use of test data in these procedures reduced the accuracy of stormflow estimation.

(b) As was reported for catchment W1M16, the values of D as well as E improve when using test data rather than optimum data with procedures CN5, CN10, CN15 and CN20, an exception being the value of E which decreased for procedure CN20. The explanation given previously for catchment W1M16 may be assumed to hold for catchment W1M17.

(c) The very small systematic over/underestimation associated with simulated results using optimum data is not increased markedly by using the test data (F_1 in Table 6.3).
(d) On the basis of the three error functions, procedure CN5 is the most suited procedure for simulating stormflow on this catchment given test data. This is a conclusive observation since this procedure produces the highest value of D (0,890), has the highest value of E (0,875) and is associated with the least systematic error (F_1 = 0,004).

The use of test data instead of optimum data on catchment W1M17 resulted in minimal decreased in the accuracy of stormflow simulation except when included with the averaging procedures CNA1 and CNS2. In contrast to the results obtained on catchment W1M16, slight underestimation of stormflow depths for observed values greater than 12,5 mm was revealed for the two averaging procedures CNA1 and CNS2 (Appendix 3).

Having examined the results of the six CN procedures using both optimum and test data on catchments W1M16 and W1M17, a number of general conclusions may be reached:

(a) The methods proposed for estimating AET and runoff on ungauged catch= ments are successful for inclusion in HAWK and thence simulating stormflow depths on these two catchments. However, there is evidence suggesting systematic underestimation of either runoff or AET (or both) in catchment W1M16, thought this is not conclusive.
(b) The two averaging procedures, CNA1 and CNS2, hold no discernible advantage over the less complex CN procedures, CN5, CN10, CN15 and CN20.
(c) The accurate determination of CN values from the soil-cover complex is critical to the accuracy of predicting stormflow depths, a view sub= stantiated by Hawkins (1975). Inaccuracies in estimating the soil-cover complex CN and AMC-II may account for systematic over or under= estimation of stormflow depths.

The final step in this analysis is to determine whether the six CN procedures dealt with above would simulate stormflow depths, on ungauged catchments, more accurately than the standard SCS procedure. For catchment W1M16 the error functions associated with the standard SCS procedure (distributed CN) are given in Table 6.2. Comparing the error functions for the standard SCS procedure with those of the modified procedures using test data indicates that the error expressed by D is greater for the standard SCS than for any of the six CN procedures tested on catchment W1M16. However, the value of E associated with the standard SCS procedure indicates a higher efficiency of simulation than for the remaining procedures, except procedure CNS2. Furthermore, systematic overestimation is not as apparent for the standard SCS procedure as it is for the modified HAWK procedures, only procedure CNS2 having a value of F_1 closer to zero than the standard SCS procedure. From the above observations it may thus be concluded that for catchment W1M16 simulation of stormflow depths, assuming this to be an ungauged catchment, would be best achieved by using procedure CNS2, with the standard SCS procedure being the alternative choice.

The error functions for the standard SCS procedure and modified CN procedures for catchment W1M17 are given in Table 6.3. In terms of error functions D, E and F_1, the standard SCS procedure simulates stormflow depths reasonably well on catchment W1M17. However, besides the two averaging procedures, CNA1 and CNS2, the modified CN procedures based on test data have substantially higher values of D and E while the values of F_1 are smaller than, or similar to, the value of the standard SCS procedure. These results lead to the conclusion that the CN procedures CN5 through to CN20 are superior to the standard SCS procedure for adjusting CN values on catchment W1M17. Furthermore, the procedure CN5 is associated with the least random and systematic error of all the procedures tested on catchment W1M17 and may thus be regarded as the most suitable procedure for adjusting CNs on the catchment.

Evidence has been presented in this section that the use of HAWK on ungauged catchments such as W1M16 and W1M17 is likely to simulate stormflow depths more accurately than the standard SCS model. However, at this stage it cannot be assumed that this finding will hold for catchments in other regions. Furthermore, the selection of the most suitable CN procedure for HAWK for general application requires further investigation. Attention is thus turned to testing these procedures on three more catchments in Natal, assuming ungauged conditions.

6.2.2 Stormflow simulations on Catchments U2M20, V1M28 and V7M03

Catchments U2M20, V1M28 and V7M03 are representative of large parts of Natal. The following results thus have particular relevance to the application of HAWK for stormflow simulations in this Province. All the analyses relating to these three catchments were based on calculated AET and calculated runoff (test data), summarised in Appendix 2.

U2M20:

The error functions associated with each of the selected CN procedures for catchment U2M20 are presented in Table 6.5 and the associated scattergrams in Appendix 5. From an examination of Table 6,5 it may be concluded that the simulated stormflow depths are generally inaccurate regardless of the procedure used, since the values of D are all less than 0,495, of E less than 0,105 and F_1 greater than 0,244. These results indicate that both random and systematic errors are associated with the simulated stormflow depths on this catchment. It should, however, be noted that all the events considered for this catchment were of the order of four millimetres or less of stormflow, these small events being particularly difficult to simulate.

Table 6.5 Error functions D, E and F_1 for the standard SCS model and six HAWK curve number procedures for catchment U2M20

Procedure	Error Function		
	D	E	F_1
SCS	0,001	-1,762	1,873
CNA1	0,307	-0,645	0,952
CNS2	0,144	-1,286	1,430
CN5	0,349	0,104	0,245
CN10	0,366	0,014	0,322
CN15	0,409	-0,171	0,580
CN20	0,494	-5,407	5,901

The standard SCS model performs particularly poorly on catchment U2M20 (Table 6.5). An examination of the scattergram of estimated versus observed stormflow depths reveals a localisation of points corresponding to, or close to, zero estimated stormflow (Appendix 5). This finding may be attributed to the nature of the three-fold classification of antecedent moisture conditions in the SCS model. All but one of the stormflow events of U2M20 was associated with AMC-I and the corresponding CN adjustments were clearly excessive.

The use of averaging CN procedures, CNA1 and CNS2, gave better results than the SCS model, CNA1 simulating stormflow depths more accurately than CNS2 in terms of D, E and F_1 (Table 6.5). However, both these averaging proce= dures are associated with marked systematic underestimation of stormflow depths as reflected in the values of F_1 (CNA1:F_1 = 0,952; CNS2:F_1 = 1,340) and the scattergrams presented in Appendix 5.

Of the remaining CN procedures, the trend is for the systematic error to change from underestimation in CN5 through to progressively large overesti= mation in CN10, CN15 and CN20. From the above observation, it may be deduced that the underestimation associated with procedure CN5 is not caused by the test data but more likely to be a function of the initial CN (CN_1 = soil-cover complex CN). The shift for underestimation to progressively greater overestimation may, however, be attributed to the estimates of AET and drainage/runoff being too low. The above hypothesis is substantiated since the longer the antecedent period considered, the greater the absolute discrepancies in 'true' and calculated water losses from the catchment would be, giving rise to greater overestimation of stormflow because of lower values of ¥:

Selecting the most efficient CN procedure for simulating stormflow depths on catchment U2M20 is not conclusive in favour of one or other procedure. However, on the basis of the error functions D, E and F_1, two procedures may be regarded as yielding more accurate results than the remaining procedures, namely, CN5 and CN10. While CN5 is associated with the higher value of D, slightly greater systematic error is reflected in the values of E and F_1 in this procedure than in procedure CN10. Since procedure CN5 underestimates and procedure CN10 overestimates stormflow depths, procedure CN10 is proposed as a suitable procedure for estimating stormflow depths on this catchment, since for design purposes, this procedure incorporates an inherent safety factor. It should be reiterated, however, that the latter were performed only on storms with low stormflow.

V1M28:

An examination of Table 6.6 shows that the error function D for all procedures tested on catchment V1M28 is high, with the lowest value being 0,943 (CN15). However, the corresponding values of E exhibit a substantial range, the lowest being -0,123 and the highest 0,966. Similarly, F_1 values range between 1,086 and 0,006. It may thus be concluded that the major type of error which differentiates the accuracy of these procedures for simulating stormflow is systematic error.

Table 6.6 Error functions D, E and F_1 for the standard SCS model and six HAWK curve number procedures for catchment V1M28

Procedure	Error Function		
	D	E	F_1
SCS	0,963	-0,123	1,086
CNA1	0,944	0,607	0,337
CNS2	0,945	0,449	0,496
CN5	0,956	0,750	0,206
CN10	0,953	0,846	0,107
CN15	0,943	0,903	0,040
CN20	0,972	0,966	0,006

Although the coefficient of determination is 0,963 for the standard SCS procedure, the associated value E(-0,123) is the lowest of all the procedures tested. Furthermore, on examining the scattergram of estimated versus observed stormflow depths for the SCS procedure in Appendix 6, it is once again clear that the adjustment of CN values for antecedent moisture conditions has been excessive since most simulated stormflow depths are zero or close to zero.

The two averaging procedures, CNA1 and CNS2, give rise to very similar values of D, being 0,944 and 0,945 respectively. However, greater under= estimation of stormflow is associated with the procedure CNS2 than that associated with procedure CNA1, this being reflected in the values of E and F_1 in Table 6.6 and the corresponding scattergrams in Appendix 6.

The error function F_1 in Table 6 improves consistently from procedure CN5 through CN20, as does the error function E. This observation together with an examination of the corresponding scattergrams in Appendix 6 indicates that the systematic underestimation of stormflow decreases with the number of days used to determine antecedent moisture conditions. This finding suggests that moisture losses from the catchment are being underestimated, as was the case for catchment U2M20. Furthermore, the value of the soil-cover comlex CN at AMC-II on catchment V1M28 is a low estimator of CN_1. Either the soil-cover complex CN has been underestimated or catchment moisture conditions are generally higher than those assumed to correspond to AMC-II.

The procedure CN20 simulates stormflow depths very accurately on catchment V1M28, both random and systematic error being negligible (D = 0,972; E = 0,966 and F_1 = 0,006). The error functions for this procedure are not bettered by any of the other five procedures, indicating that this is clearly the most suitable procedure for simulating stormflow depths on catchment V1M28.

V7M03:

The error function for the seven procedures tested on catchment V7M03 are summarised in Table 6.7 and corresponding scattergrams are presented in Appendix 7. An examination of these results yields findings very similar to those described for catchment V1M28.

Table 6.7 Error functions D, E and F_1 for the standard SCS model and six HAWK curve number procedures for catchment V7M03

Procedure	Error Function		
	D	E	F_1
SCS	0,299	-1,062	1,361
CNA1	0,078	-0,857	0,935
CNS2	0,231	-0,859	1,090
CN5	0,413	0,110	0,303
CN10	0,681	0,612	0,069
CN15	0,734	0,701	0,033
CN20	0,857	0,620	0,237

The standard SCS procedure simulates stormflow equally as poorly on catchment V7M03 as it did on catchment V1M28, severe underestimation being apparent in the scattergram of estimated versus observed stormflow depths (Appendix 7). Furthermore, there is evidence that the soil-cover complex CN is a lower estimator of CN_I while the calculated AET and runoff underestimate moisture losses from catchment V7M03. Initial underestimation of stormflow by procedure CN5 is consistently reduced with the procedures based on the progressively longer antecedent periods, CN10 and CN15, while procedure CN20 overestimates stormflow depths slightly.

The procedure most suited to simulating stormflow on catchment V7M03 is CN15, having both relatively high D and E values. The two averaging procedures, CNA1 and CNS2, are associated with large random and systematic errors, with the value of D and E in Table 6.7 being very low for both these procedures (D = 0, 232 and E = -0,856).

6.3 Conclusions

A number of procedures for adjusting CN for antecedent moisture conditions, each based on HAWK, have been tested on five catchments in Natal utilising data which may be assumed to be generally available on ungauged catchments. The procedures which were found to be most suitable for each of these catchments are summarised below:

Catchment	Procedure
W1M16	CNS2
W1M17	CN5
U2M20	CN10
V1M28	CN20
V7M03	CN15

While no single procedure was most suited to all the catchments selected in this study, the following should be noted:

(a) The standard SCS procedure simulated stormflow less accurately than the HAWK procedures tested.

(b) The two procedures using averaging techniques, viz, CNA1 and CNS2, did not result in more accurate estimates of stormflow than the less complex procedures except on catchment W1M16 where CNS2 was the most accurate procedure.

(c) Two sources of systematic error were identified. First, the use of the soil-cover complex CN as a starting CN underestimated the initial CN (CN_1) on the two De Hoek and the Cedara catchments, while overestimation of stormflow depths on catchment W1M16 may be partially attributed to the overestimation of CN_1 by the soil-cover complex CN. Secondly, the methods for calculating AET and runoff underestimated the interim moisture losses from the catchments. All other things being considered equal, the second source of error resulted in overestimates of stormflow.

On the basis of the above findings it may be concluded that no single CN procedure may be conclusively proposed for general application on ungauged catchments in Natal. However, this research has revealed that even with errors inherent in some of these procedures, particularly systematic error, the simulation of stormflow using the Hawkins technique of CN adjustment is more accurate than that by the standard SCS model. Furthermore, areas where further research is required have been highlighted and these are discussed in more detail in the following chapter.

Chapter 7

AN IMPROVED ANTECEDENT MOISTURE PROCEDURE FOR THE SCS MODEL - CONCLUSIONS

In an attempt to improve the antecedent moisture component of the SCS model, three analyses were undertaken. The first analysis was aimed at establishing whether a specific number of antecedent days' rainfall was associated with changes in the potential maximum retention of the selected catchments. The second analysis examined the efficiency of the Hawkins technique of adjusting curve numbers for antecedent moisture conditions given gauged data inputs while the final analysis was concerned with adapting the Hawkins procedure to ungauged catchments.

The salient features of the conclusions reached after each of the three analyses may be summarised as follows:

(a) No single antecedent period of rainfall is found to more highly associated with S (potential maximum retention) on all the catchments tested than any other antecedent period. However, on individual catchments there is evidence that a specific number of days' antecedent rainfall has a greater association with S, the number of days possibly being a function of the climate, soils and topography of the catchment. Thus the five days' antecedent rainfall, as used in the SCS model, is not necessarily the most suitable antecedent period for estimating catchment moisture status (CMS) on all catchments. Ten to 15 days appears to be a more suitable antecedent period.

(b) Given gauged data inputs, the Hawkins procedure (HAWK) is shown on two selected catchments to be an effective procedure for adjusting CN values for CMS, thus providing for accurate estimates of stormflow depths. The accuracy of stormflow simulations using HAWK based on gauged data inputs and the optimised initial CN values (CN_i) is vastly superior to that of the standard SCS model on the storms tested.

(c) The HAWK procedure is successfully adapted for use on ungauged catchments. However, there is evidence that the techniques for estimating actual evapotranspiration and runoff/drainage underestimate moisture losses from the catchments considered. Furthermore, accepting a catchment's soil-cover complex CN as the value for CN_1 introduces systematic errors, particularly when calculating stormflow where the true CN_1 value differs substantially from the soil-cover complex CN. Despite these weaknesses, there is conclusive evidence that in ungauged catchments the simulation of stormflow using the Hawkins procedures is far more accurate than the standard SCS procedure.

In view of the above findings it is clear that future research based on the Hawkins procedure of CN adjustment is warranted. However, more testing is needed on events of a magnitude used in hydrologic designs. More specifically, improved procedures for estimating actual evapotranspiration and runoff/drainage over short periods on ungauged catchments are called for. Furthermore, the determination of a 'most probable' initial CN value requires further attention. While adopting the soil-cover complex CN as the initial CN may be satisfactory in regions where soil moisture is close to that assumed for AMC-II, this practice is likely to be unsuitable at times where soil moisture contents are generally higher or generally lower than this assumed value. Consequently, the regionalisation of 'average' soil moisture conditions may provide a means of adjusting the soil-cover complex CN to be a more representative value of the expected initial CN.

A major strength of the SCS model is that it is a simple method, not requiring a high level of expertise nor sophisticated computing facilities for its application. The modified techniques proposed in this study have attempted to retain this feature of the model. Finally, while the research presented in this Report may be regarded as a pilot study, particularly in the South African context, it has further helped towards focussing attention on the complexity of catchment moisture status and on the importance of incorporating hydrologic processes into simple models such as the SCS model.

B

SIMULATION OF STORMFLOW VOLUMES USING THE R-INDEX METHOD

Chapter 8

SIMULATION OF STORMFLOW VOLUMES USING THE R-INDEX METHOD: INTRODUCTION

The R-index method in the form as used in this report was published by Hewlett, Cunningham and Troendle (1977) for estimating stormflow volumes and peak stormflow rates from small forested and wildland catchments in the eastern United States of America (USA). According to the definitions of Jackson and Aron (1971) this is a parametric, deterministic, non-linear model. Hewlett and Moore (1976) state that the variable source area theory of stormflow production provides the basis for this model (cf Section 2.1.1). Conventional procedures for estimating stormflow volumes, such as the SCS model, emphasise the role of soil type, vegetation and land-use on infiltration capacities in a catchment. Hewlett et al (1977), however, contend that the impact of these variables is dependent on how far from the channel they occur and that the responsiveness of a catchment cannot be simply an interpretation of the weighted infiltration capacities. Rather, catchment response is an expression of the nature of the channel network and the dynamic subsurface storage capacities of these parts of the catchment having an immediate influence on stormflow (Hewlett et al, 1977).

Stormflow simulation techniques which assume stormflow to be solely a result of overland flow are invalid for small rainstorms and in areas where overland flow is negligible (ie, forests and other well vegetated lands). No method for predicting stormflow and peak discharge from easily obtainable data is very accurate and errors in excess of 100 percent are not unusual (Hewlett and Moore, 1976). The R-index method was intended as an intermediate tool in the range of methods that begins with the most basic (rational formula, Talbot's formula and ends with the complex simulation methods that require much input data. This method is considered suitable for making stormflow estimates from first, second and third order streams using the classification of Horton (1945).

Selection of the R-index method for this investigation was based on a number of considerations. The major reasons were:

(a) The R-index method is simple to use making it a viable procedure for stormflow estimates from small catchments in South Africa.

(b) Most stormflow and runoff models in current use emphasise the infiltration process. This model is based on the variable source area concept which emphasises different characteristics of the catchment.

(c) The R-index method is a non-linear model and it is widely accepted that stormflow processes are non-linear.

(d) A central concern of this study is to assess the importance of antecedent moisture conditions in the modelling of stormflow volumes. The structure of the R-index model permits such an evaluation to be made.

(e) Although the adaptation of this method for use in South Africa is focussed on throughout the investigation, particular attention is given to the suitability of this method for catchments of the coastal belt of Natal and Zululand. The R-index model was developed in the humid eastern USA and may thus be expected to be suitable for these humid regions of South Africa.

(f) The authors of the model claim that stormflow estimates in well vegetated catchments of the eastern USA are more accurate using this method than the SCS curve number method (Hewlett et al, 1977).

An important consideration emphasised by Hewlett et al (1977) is that the R-index method was not intended to replace other procedures for estimating stormflow volumes. The method was intended to supplement these procedures where they were found to be inadequate. In working towards the adaptation of this procedure for South African conditions, this study embraces the same philosophy as that adopted by Hewlett et al (1977).

The research procedures used in this investigation were influenced by the availability of suitable data and in many instances were modified in successive studies according the findings of the initial analyses. For example, calibration of the model was initially conducted using parameter values including two decimal places. This was later changed to three decimal places when greater efficiency was achieved in the iterative routines of the optimising procedure.

Following a description of the R-index method and the background to this method, attention is given to the specific objectives of the study. The results and analyses are not intended to be conclusive for South Africa or any region of the country but rather to be a step in this direction, particularly in developing procedures which may be adopted for testing the method elsewhere in South Africa.

Chapter 9
THE R-INDEX METHOD

This description of the R-index method is intended to provide an insight into the rationale and objectives behind the development of the procedure. A detailed description of the model is given and finally attention is drawn to the research requirements for testing and adapting this method for stormflow estimates in South Africa.

9.1 Model Development

The R-index method was developed using 468 stormflow events from 11 catch= ments in the eastern USA, the areas of these catchments ranging from $0{,}23^2$ km to 46 km^2. Stormflow volume was assumed to be dependent on three factors, namely:

(a) storm rainfall or input
(b) antecedent storage or moisture conditions on the catchment at the time of the event and
(c) the inherent or dynamic storage capacity of the catchment.

Eight independent variables were selected to represent the three factors outlined above and the following general model was investigated:

$$Q = f(P, P_{60}, D, I, S, A, G, R)$$

where

Q = stormflow depth (mm)

P = storm rainfall depth (mm)

P_{60} = storm rainfall depth during the most intense hour of the storm ($mm\ h^{-1}$),

D = duration of the storm (h),

I = initial flow rate immediately prior to the rise in the stormflow hydrograph ($l.s^{-1}.km^{-2}$)

S = seasonal factor based on the time of the year (-)

A = catchment area (km^2)

G = gradient from the measuring station to a point on the catch= ment divide directly above the origin of the main channel ($m\ km^{-1}$) and

R = mean hydrological response of the catchment (-) calculated from:

$$R = \frac{1}{n} \sum_{1}^{n} \left(\frac{Q}{P}\right) \qquad \text{..........} \quad (9.1)$$

where

P = storm rainfall ≥25,4 mm and

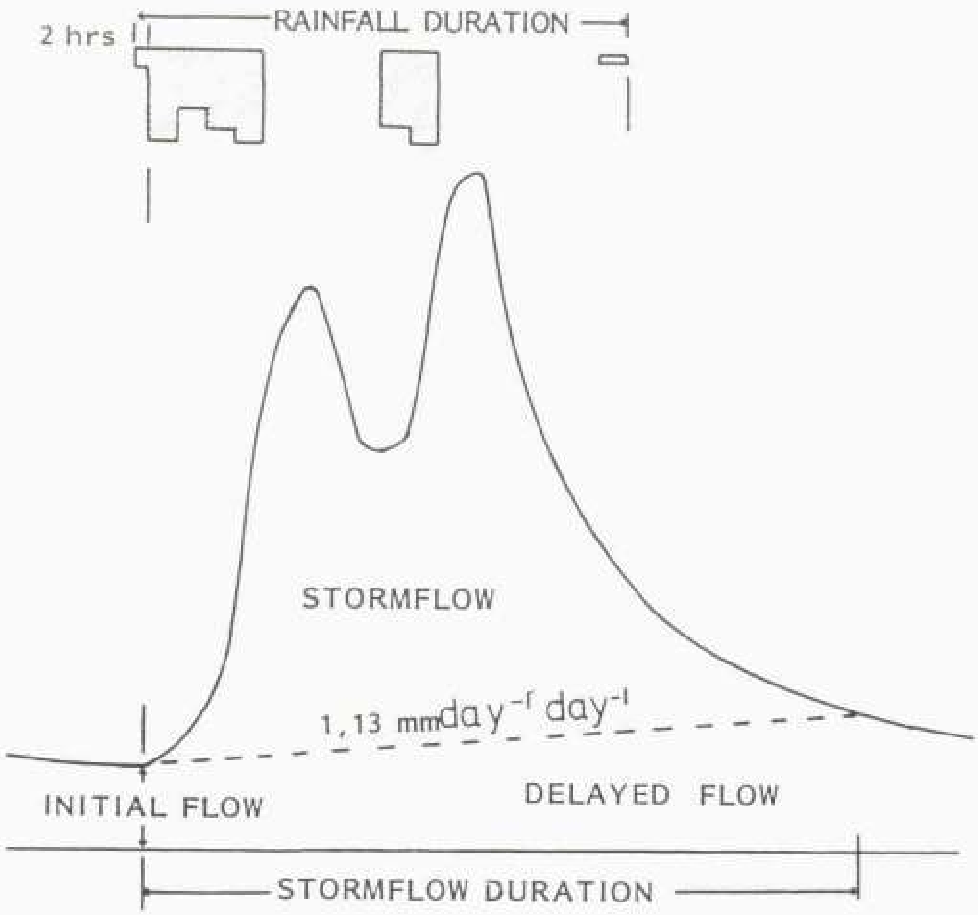
n = number of observations.

A definition diagram showing the relationship between input and output variables is presented in Figure 9.1.

Stormflow (Q) was separated from delayed flow by projecting a line of constant slope of 1,13 mm.day^{-1}.day^{-1}; from the beginning of a stream rise to the point where it intersects the recession limb of the hydrograph (Hewlett and Hibbert, 1967). The classification of streamflow into stormflow and delayed flow is an arbitrary decision of the analyst, whose main objective is, or should be, to maintain a consistent criterion for separation over all catchments and hydrographs (Hewlett et al, 1977). In developing the R-index model three additional rules of separation were tested by Hewlett et al (1977) which yielded a vector of four successively smaller values for stormflow delivered by each event. These four quantities correlated highly and had similar associations with the independent variables investigated. According to Hewlett et al (1977) it seems to matter very little what fixed rule of hydrograph separation is used for catchments smaller than 50 km^2.

Storm rainfall (P) was taken to include all rain falling up to two hours before the initiation of the storm hydrograph and until the termination of stormflow by the delayed flow separation line. The two-hour advance allows for some clock error between water level and rainfall recorders and also for small aberrations in the computer-determined hydrograph rise (Hewlett, et al, 1977).

Figure 9.1 Definition diagram showing the relationship between input and output variables (After: Hewlett *et al*, 1977)



Factor analysis of the eight independent variables and one dependent variable defined in the general model revealed four factor complexes in the data, namely, input variables (P, P_{60}, D), existing storage condition (I, S), dynamic storage capacity and output (R, Q) and physiography (A,G). Following numerous trials and transformations of the data, Hewlett *et al* (1977) fitted an equation to the observed stormflows using a Marquardt (1963) non-linear least-squares method. When metricated this equation gives:

$$Q \quad = \quad B_1\ R\left(\frac{P}{25,4}\right)^{B2} \left[1,0 + (0,0136\ I)^{B3}\right] 25,4 \ldots\ldots\ldots \quad (9.2)$$

where

Q = stormflow volume (mm)

R = R-index (-)

P = storm rainfall (mm)

I = initial flow rate ($\ell.s^{-1}$ km^{-2}) and

β_{1-3} = regression parameters.

The addition of 1,0 in the term between square brackets prevents an indeterminate Q when I approaches zero. Inclusion of other variables contributed very little to the improvement of the model.

Since increments of predicted stormflow cannot exceed increments of causative rainfall, the constant that $\frac{\delta Q}{\delta P}$ must not exceed 1,0 is placed in Equation 9.2. The equation which best predicted stormflows in the eastern USA is given by Hewlett et al (1977) as:

$$Q = 0,4\ R\ (\frac{P}{25,4})^{1,5}\ [1,0 + (0,0136\ I)^{0,25}] \quad ..... \quad (9.3)$$

In this equation, for large values of P, the first derivative of Q with respect to P must not exceed 1,0, that is:

$$\frac{\delta Q}{\delta P} < 1,0 = 0,6\ R(\frac{P}{25,4})^{0,5}\ [1 + (0,0136\ I)^{0,25}]\ 25,4 \quad ...... \quad (9.4)$$

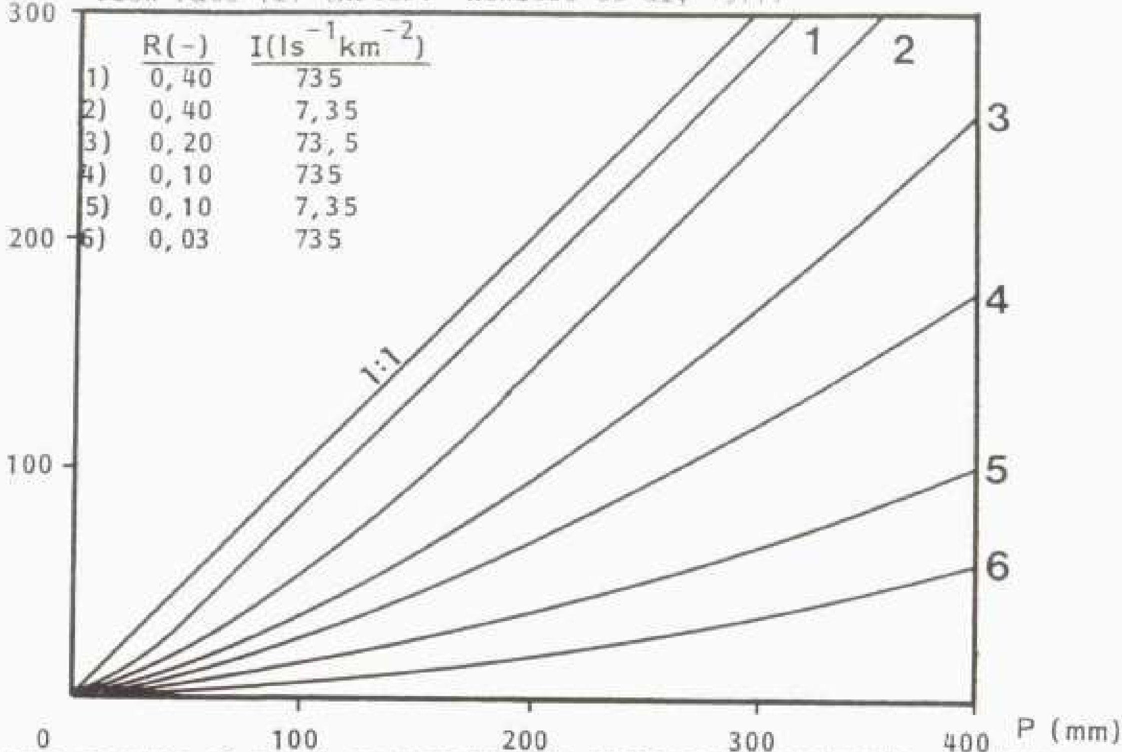
Solving the derivative under this constraint, the value of P above which any further storm rainfall produces an equal amount of stormflow becomes:

$$P = \frac{25,4}{(0,6\ R\ [1 + (0,0136)^{0,25}\ ]\ )^2} \quad .... \quad (9.5)$$

Generally, the constraint operates beyond the data range normally experienced (Hewlett et al, 1977).

The relationship between storm rainfall (P), the R-index (R), initial flow rate (I) and stormflow in Equation 9.2 (constrained by Equation 9.4) is illustrated by a family of curves in Figure 9.2.

Figure 9.2 The relationship between storm rainfall and stormflow in the R-index model (β_1=0,4; β_2=1,5; β_3=0,25) for four assumed values of the R-index (R) and three values of the initial flow rate (I) (After: Hewlett et al, 1977)



Comparing the results of model calibration in different catchments, Hewlett <u>et al</u> (1977) concluded that catchments with high R-indices gave larger absolute errors than the others. Furthermore, these authors found the parameter β_3 to be relatively unstable while β_1 and β_2 were similar for 10 of the 11 catchments studied.

9.2 The Sine-Day Factor

The authors of the R-index method recognised that for the practical appli= cation of this method an alternative for the initial flow rate in Equation 9.2 would have to be introduced. Thus Hewlett <u>et al</u> (1977) substituted a seasonal variable S for (1 + 0,0136 I) with S being defined as:

$$S = \sin\left(360\left(\frac{D}{365}\right)\right) + 2 \qquad \text{..........} \quad (9.6)$$

where

S = sine-day factor and

D = the number of the day counted from November 21 = zero.

The numeral 2 is added to the sine to avoid negative numbers or zeros. Twelve sine functions beginning in sequence on the 21st of each month were tested. November 21 was selected using stepwise linear regression since this index minimised the standard error of Q and P and S (Hewlett *et al*, 1977). Sine of day values for use in the R-index method in the eastern USA are given in Table 9.1.

Table 9.1 Sine of day values for the eastern USA (Hewlett *et al*, 1977)

Day	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct
1	1,66	2,17	2,65	2,94	2,99	2,77	2,36	1,84	1,37	1,06	1,01	1,23
7	1,76	2,27	2,72	2,98	2,97	2,70	2,26	1,74	1,29	1,03	1,04	1,30
14	1,88	2,39	2,80	2,99	2,93	2,61	2,15	1,62	1,21	1,01	1,08	1,39
21	2,00	2,49	2,87	3,00	2,88	2,52	2,03	1,51	1,14	1,00	1,13	1,49
28	2,12	2,59	2,92	2,99	2,82	2,41	1,90	1,43	1,08	1,01	1,20	1,60

The rationale for using the sine-day factor as an antecedent moisture index was, according to Hewlett *et al* (1977), based on the findings of Helvey and Hewlett (1962) who showed that the annual march of both average soil mois= ture and monthly streamflow in the southern Appalachian Mountains generally follows a sine wave. The variable S may thus be regarded as a seasonal correction for R.

9.3 Estimation of the R-index

In recognising that the inherent simplicity of the R-index method is one of its most desirable characteristics, Hewlett *et al* (1977) drew attention to the desirability of mapping the R-index (R) or deriving the index from easily measurable catchment characteristics. A map of the average annual hydrological response for the eastern USA, presented in Figure 9.3, was produced by Woodruff and Hewlett (1970). This annual response index was calculated by expressing the annual stormflow depth as a fraction of the total annual rainfall and then calculating the average response for the number of years of record. The map was based on records from 201 catch= ments ranging in size from 5,0km^2 to 500 km^2.

Some variation in stormflow response is a function of catchment area (Woodruff and Hewlett, 1970). Stormflows from headland catchments are attenuated downstream and the localisation of rainfall in large catchments also affects the calculated response. Consequently, Woodruff and Hewlett (1970) regressed the annual response ratios (R_A) against catchment areas (A) and established the following equation for area corrected annual response (R_{AC}):

$$R_{AC} = R_A + 0{,}00017\ A \quad \text{.......... (9.7)}$$

Although the regression coefficient was found to be significant, area accounted for only one percent of the total variation in R_A.

An attempt was made by Woodruff and Hewlett (1970) to relate the average annual response ($\bar{R}_{AC}$) to physiographical and land-use characteristics of the study catchments. No relationship could be established but these authors noted that variations in $\bar{R}_{AC}$ were closely associated with the geo= logical regions of the eastern USA. Furthermore, no information regarding the soils was considered in this study and since $\bar{R}_{AC}$ is a measure of the inherent storage capacity of a catchment, this would appear to be a serious omission. Hewlett et al (1977) found that $\bar{R}_{AC}$ values were approximately half the magnitude of the R-index as calculated for the stormflow model (Equation 9.1).

A hydrological response map of eastern Kentucky was developed by Bryan (1980). This author proposed a corrected response ratio which brought the yearly values (R_A) in line with the catchment's mean annual precipitation as well as correcting for stormflow attenuation caused by larger catch= ments. The corrected response ratio (R_C) was of the form:

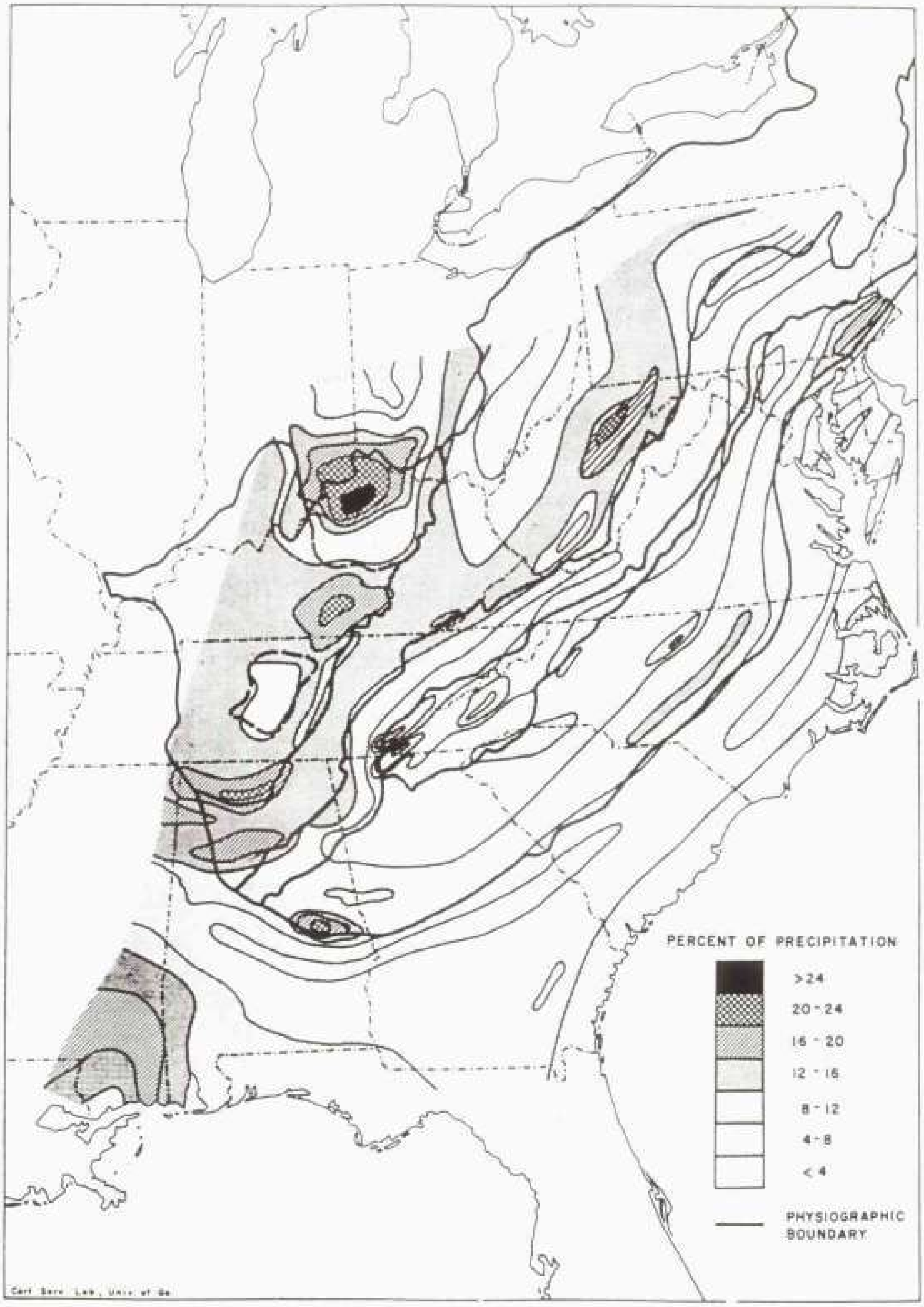
$$R_C = R_A + 0{,}00027\ (A) - 0{,}00241\ (P_Y - MAP) \quad \text{..... (9.8)}$$

where

P_Y = total precipitation for the year and

MAP = mean annual precipitation.

Figure 9.3 Average annual response map of the eastern USA (Based on: Woodruff and Hewlett, 1970)



The distribution of stormflow responses $\frac{Q}{P}$ for a catchment is generally characterised by a positive skew which, according to Olszewski (1978), makes it difficult to get a good estimate of the average response (R). Generally, in excess of 100 observations is required for an estimate of R to be within five percent of the 'true' value while 15 to 20 sequential observations would suffice if the data could be normalised (Olszewski, 1978). For catchments in north-eastern Georgia, Olszewski (1978) found that the distribution of stormflow responses could be normalised by substi= tuting $(\frac{Q}{P})^{0,5}$ in place of $\frac{Q}{P}$. Hewlett et al (1977) used an exponent of 0,667 to normalise the ratio for the catchments they studied in the eastern USA.

While normalising the distribution of the response ratio allowed for an unbiased estimate of the average response, the variable R could no longer be interpreted linearly and directly in terms of response as before. However, Olszewski (1978) concluded that this was unimportant since R was intended as an index and normalised index did not affect the predictive accuracy of the stormflow model.

Mapping the R-index is not possible in many states of the USA let alone in developing and underdeveloped countries. Researchers such as Woodruff and Hewlett (1970), Olszweski (1978) and Bryan (1980) failed to establish any relationship between this index and readily measurable catchment charac= teristics. However, none of these were exhaustive or detailed studies and did not give sufficient attention to catchment soils. Hewlett and Moore (1976) succeeded in relating variations in the R-index to the soil, geomor= phological and land-use conditions of catchments in the Redlands district of Georgia (Table 9.2).

Table 9.2 R-index values for given land characteristics in the Redlands district of Georgia (Hewlett and Moore, 1976)

R-Index	Land Characteristics
0,10	Old forest bluffs and slopes with virgin forest soils
0,12	Forested coves near the river; with entrenched channels
0,14	Forested uplands near the river; relatively narrow ridges
0,16	Forested upland interfluves, wide flat ridges
0,18	Average agricultural land; pastures, crops, old fields
0,20	Bottomlands, swamplands and beaver pond area
0,22	Actively cultivated or badly abused and gullied land

The R-indices given in Table 9.2 are for first order catchments, the basic land unit for stormflow prediction in the R-index method. This contrasts with the SCS model where responses values are determined for individual soil-cover complex units regardless of their position in the catchment.

The concept of average hydrological response is central to the R-index method. From the preceding review the following conclusions may be drawn:

(a) The R-index can be mapped successfully provided sufficient rainfall and stormflow records (spatial and temporal) are available for the study area.
(b) Suitable exponential transformations of the hydrological response $\frac{Q}{P}$ may reduce the number of events required to make an unbiased estimate of the average response (R-index). The use of temporary gauging structures may be viable for determining this index.
(c) First order catchments have R-indices which generally responded conservatively to large changes in land-use but are quite sensitive to the inherent geological differences in catchments.
(d) R-indices may be defined according to the soils, geomorphological and land-use conditions of catchments.
(e) Area adjustments to R-indices are only necessary for catchments with areas greater than 50 km^2.

9.4 Adapting the R-index Method for South African Conditions

Preliminary studies conducted by Hewlett et al (1977) revealed that when field information normally available to planners and managers was used stormflow predictions using the R-index method were considerably more accurate than those using the SCS curve number technique (NEH-4, 1972). However, the authors of the R-index method state that these results could not be interpreted as conclusive superiority of the R-index method for all uses or all regions.

The possibility of using a model such as the R-index method for stormflow simulations in South Africa is attractive because of the relative simplicity of this method and the promising results obtained in the eastern USA. In testing the R-index method on catchments in South Africa attention needs to be given to establishing:

(a) the accuracy of the model for stormflow estimates

(b) the model parameters for different environmental conditions

(c) a suitable catchment wetness index for use in ungauged catchments

(d) a procedure for estimating the R-index or a similar index using information usually available to engineers or hydrologists in South Africa and

(e) the sensitivity of the model to errors in the estimation of parameters or input variables.

The analyses presented in the ensuing chapters are intended to address each of these needs. Availability and suitability of data did, however, influence the scope of each study.

Chapter 10
SIMULATION OF STORMFLOW VOLUMES FROM SMALL CATCHMENTS IN NATAL

The R-index method was developed for application in humid catchments of the eastern USA (Hewlett et al, 1977). This model may be expected to be suitable for stormflow estimates in humid and possibly sub-humid catchments of South Africa. Both humid and sub-humid catchments with readily available rainfall and stormflow data were chosen for this initial study of the R-index method. The investigation is aimed at evaluating the model for possible use in small catchments (<50 km^2) of Natal. By selecting catchments with readily available data greater attention could be given to the adaptation of the method and to the analytical procedures.

10.1 The Problem

Although parts of Natal may be regarded as climatically humid, there are marked differences between the climates of these areas and that of the eastern USA. Rainfall in Natal is distinctly seasonal (summer maximum) compared with the generally uniform distribution throughout the year in the eastern USA (Helvey and Hewlett, 1962). Furthermore, mean annual rainfall in Natal ranges from 600 mm to 1400 mm while the range in the eastern USA is from 900 mm to 1500 m. In order to make this initial evaluation of the R-index method, two specific aims were defined, namely, to:

(a) calibrate the model, as defined in Equation 9.2, using suitable data inputs from catchments in Natal and
(b) determine whether a simple substitute could replace the initial flow rate as a measure of antecedent moisture conditions since this variable is not available in ungauged catchments.

From the first aim the accuracy of this method may then be assessed and the model parameters compared with those reported by Hewlett et al (1977) for the eastern United States (Equation 9.3). The R-index as defined in Equation 9.1 needs to be estimated for ungauged catchments and thus the determination of this variable for catchments in Natal warrants investigation. However, this aspect of the model is dealt with in Chapter

12 and unless stated otherwise the R-indices used in these analyses were calculated from observed data (Equation 9.1).

10.2 Study Catchments and Data

Six research catchments in Natal which had readily available data were selected for this study, namely, three from Zululand (W1M15, W1M16, W1M17), one from Cedara (U2M20) and two from De Hoek (V1M28, V7M03). Background information relating to these catchments is given in Table 4.1 while their location in South Africa is indicated in Figure 4.1

Rainfall estimates in five of the six catchments were made from single autographic raingauges within or in close proximity to the catchment limits. Rainfall estimates for catchments W1M15 in Zululand were made from three autographic raingauges. The Hewlett et al (1977) criteria for hydrograph separation and definition of storm rainfall were adhered to, though the threshold for storm rainfall was reduced from 25,4 mm to 15,0 mm (cf Section 9.1). A lowering of the storm rainfall threshold prevented the exclusion from this study of catchments U2M20, V1M28 and V7M03 due to insufficient stormflow events.

Data for the three Zululand catchments were obtained from Barnes and Hope (1980) while data for the Cedara and De Hoek catchments were drawn from Hope (1979) and from records of the Department of Agricultural Engineering at the University of Natal. The number of events and some characteristics of the stormflow depths for each catchment are contained in Table 10.1, while the raw data are presented in Appendix 8.

Table 10.1: Stormflow characteristics for the study catchments

Region	Catchment Codes	Number of events	Mean storm= flow depth (mm)	Standard devia= tion of storm= flow depths (mm)	Mean storm= flow response*[1]
Zululand	W1M15	43	5,104	5,5850	0,122
	W1M16	43	14,267	36,374	0,157
	W1M17	43	16,195	35,747	0,187
Cedara	U2M20	11	1,652	1,234	0,053
De Hoek	V1M28	12	4,256	8,896	0,088
	V7M03	12	2,655	2,691	0,103

*[1] Calculated from Equation 9.1 for events with storm rainfall ≥ 15,0 mm

The lack of readily available stormflow data for small catchments in Natal is reflected in Table 10.1 with only a limited number of events being available for the Cedara and De Hoek catchments. In order to undertake this investigation for different hydrological regions it was necessary to include these catchments and thus in examining the results of this study the size of these sample constitutes an important consideration.

10.3 Procedures

10.3.1 Testing the original R-index method

The original R-index method (Equation 9.2) includes initial flow rate as a measure of antecedent moisture conditions. Since the samples of stormflow events in catchments U2M20, V1M28 and V7M03 were small (Table 10.1) and most of the events occurred when the initial flow rate was zero, Equation 9.2 could not be fitted satisfactorily to these individual sets of storm= flow data. In addition to the three Zululand catchments an additional set of data was compiled by combining 11 stormflow events from catchments W1M16, V7M03 and U2M20. Events were selected randomly where a catchment's data set exceeded 11 observations. This data set referred to as TOTAL, was used to derive parameters for a generalised R-index model representing the

Zululand, De Hoek and Cedara regions. TOTAL contained sufficient events with an initial flow rate for the use of Equation 9.2. Furthermore, the generalised model could be tested independently on catchments W1M15, W1M16 and V1M28 which were not included in TOTAL.

A computer programme, INDEX, was developed to calculate stormflow volumes for a given number of events using the R-index method. This programme has two major routines referred to as the 'print' and 'optimisation' routines. The routine was intended to calculate stormflow volumes for a set of events from the required input data and selected parameter values. This routine allows for either initial flow rate or a selection of antecedent precipitation indices (API) to be used as the catchment wetness index and calculates the following statistics:

(a) The coefficient of determination, D (cf Section 4.5, Equation 4.5).
(b) The coefficient of efficiency, E (cf Section 4.5, Equation 4.6).
(c) The difference between D and E (F).
(d) Means of the observed and calculated stormflow.
(e) Standard deviation and coefficients of variation of the observed and calculated stormflows.
(f) Standard error of estimate of the regression equation (SE).
(g) Base constant ($\underline{a}$) and regression coefficient ($\underline{b}$) from the regression of observed stormflow depths on calculated stormflow depths.

A simplified flow diagram outlining the operation of the print routine is presented in Figure 10.1. Although stormflow volumes are dealt with in this study, the programme INDEX provides for either stormflow peaks or volumes. This programme can be used interactively from a computer terminal allowing alterations to be made to the model parameters without re-execution of the entire programme (Figure 10.1).

The optimisation routine includes all the features of the print routine but also provides for the optimisation of the model parameters according to a specified objective function (D, E or SE). Optimisation is based on an iterative procedure whereby each combination of parameter values is tested with the chosen objective function being compared with the highest value of the preceding trials. Upper and lower limits for each parameter need to be

Figure 10.1 Simplified flow diagram of the print routine in INDEX

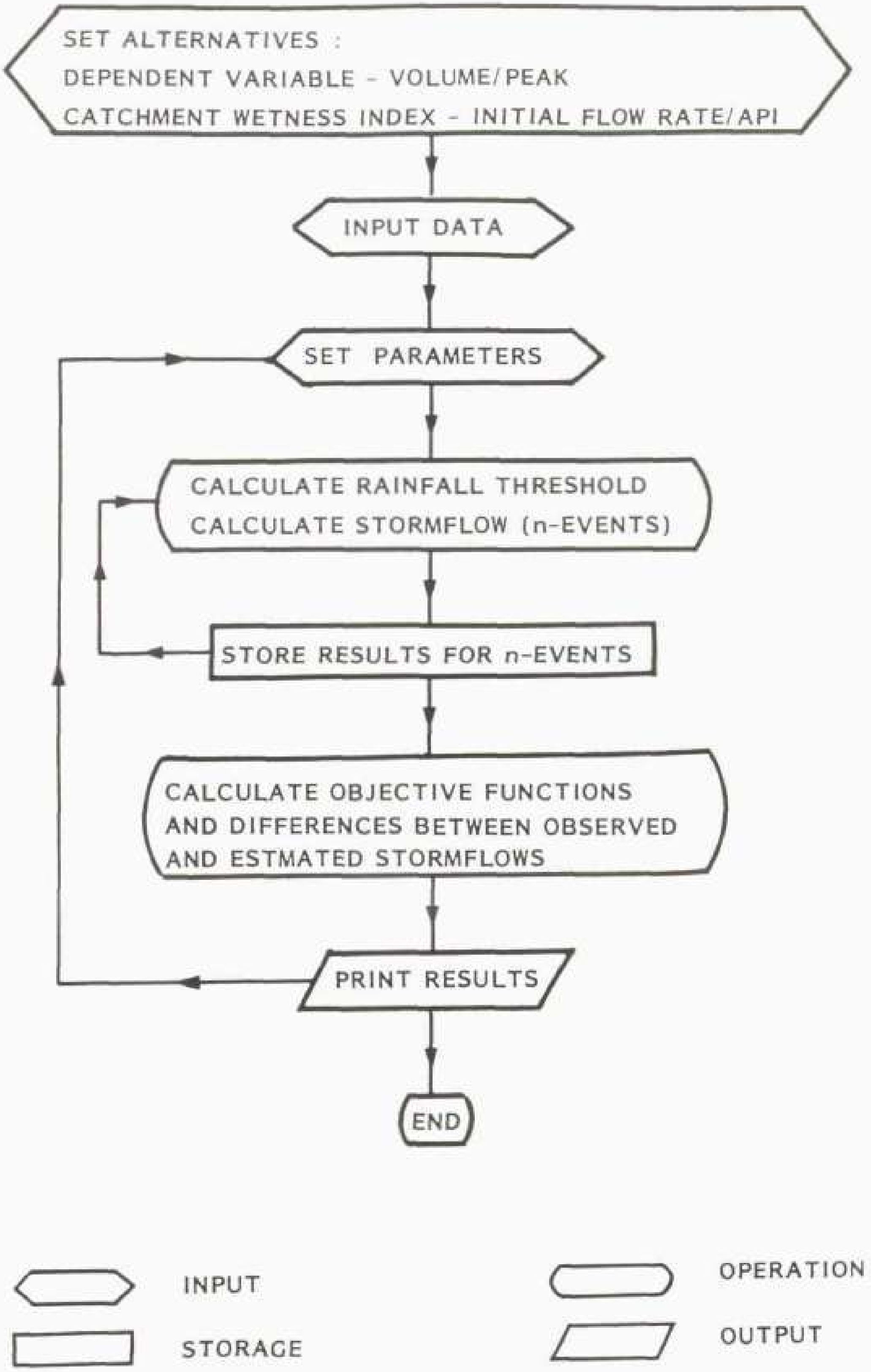
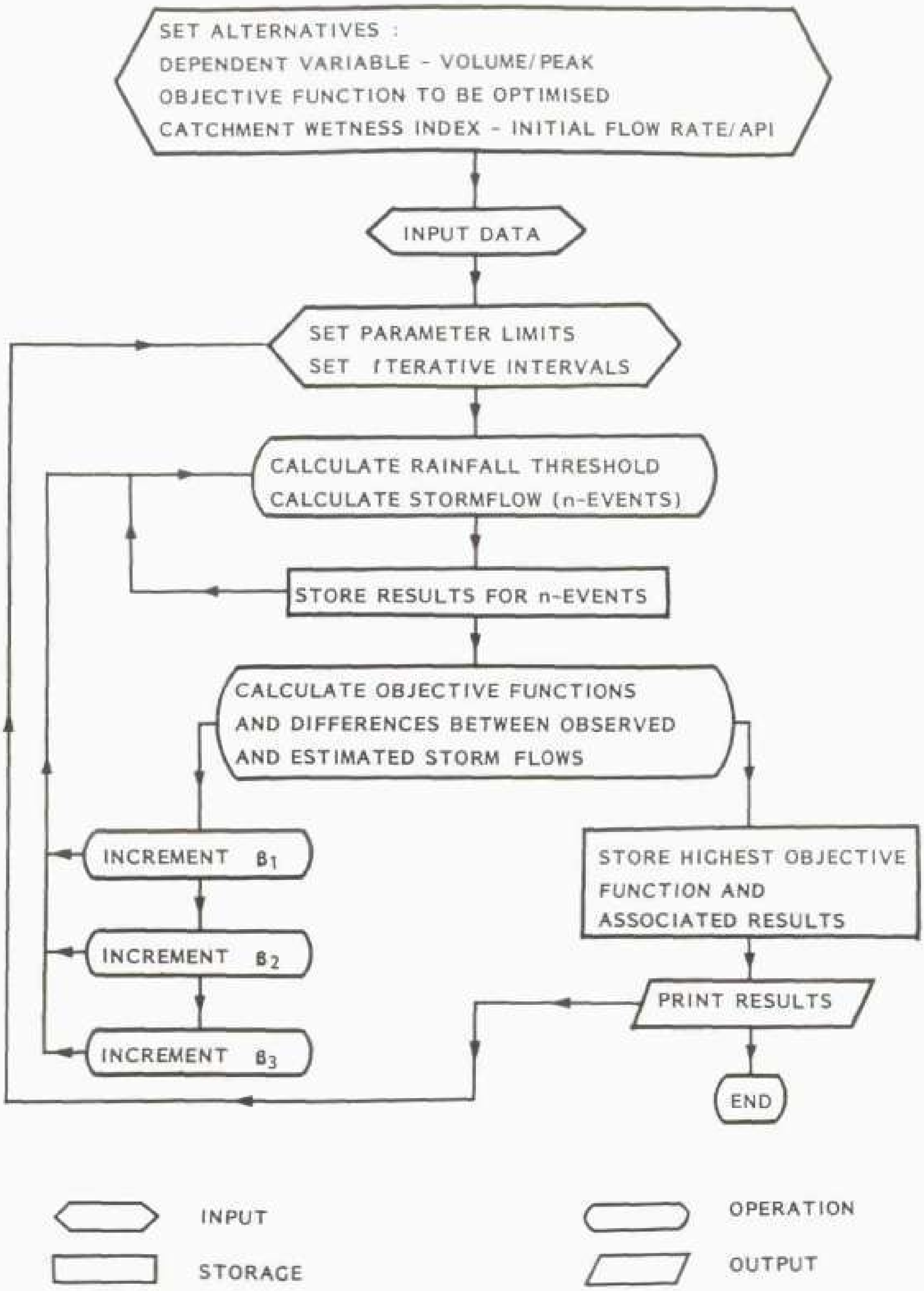


Figure 10.2 Simplified flow diagram of the optimisation routine in INDEX



set as well as the associated iterative intervals. A schematic presentation of the optimisation routine is given in Figure 10.2. A more detailed flow diagram of the structure of INDEX is given in Appendix 9 along with the computer programme, an explanation of how to use the programme and an example of the output.

In order to test the original R-index method (which included initial flow rate as the catchment wetness index) the parameters of the model were optimised using the programme INDEX and data from the three Zululand catchments and TOTAL. For comparative purposes stormflow were also simulated using the model with parameters reported by Hewlett et al (1977) for the eastern USA (cf Section 9.1, Equation 9.3). All optimisation were based on the objective function E since high values of E were generally associated with high values of D although the reverse was not true.

10.3.2 An alternative index for antecedent moisture conditions

The authors of the R-index method recognised that for the practical application of this method an alternative for the initial flow rate in Equation 9.2 would have to be introduced. Thus, Hewlett et al (1977) substituted a seasonal variable S (sine-day factor) for (1 + 0,0136 I) in Equation 9.2 (cf Section 9.1). The rationale for using the sine-day factor as an antecedent moisture index was based on the observation that the annual march of both average soil moisture and monthly streamflow in the southern Appalachian mountains generally follow a sine wave (Helvey and Hewlett, 1962). However, in Natal the distribution of rainfall throughout the year is not as uniform as it is in the southern Appalachians and the changes in soil moisture are more likely to be associated with the sequence of rainfall events than with the annual flux of solar radiation which follows a sine wave. Such expectations have been substantiated by Hope and Schulze (1979) in a study of soil moisture changes within a catchment at Cedara.

In view of the considerations outlined above antecedent rainfall was selected as a possible surrogate for the initial flow rate in the R-index method. Hawkins (1961) reported that for the Missouri Gulch Watershed the one day antecedent rainfall showed the greatest association with stormflow volumes when compared with antecedent rainfall totals for other periods. The five day total antecedent rainfall was found by Reich (1971) to be a suitable index of catchment moisture status for calculating stormflow volumes from small catchments in Pennsylvania. Following these observations and the results of the analyses for the SCS model presented in Chapters 5 and 6 it was concluded that the number of days antecedent rainfall optimally associated with stormflow volumes is likely to vary from region to region along with variations in catchment characteristics and climate.

Thus, in this study of the R-index method three periods of total antecedent rainfall were tested, namely, the total five day antecedent rainfall (AP5), total 10 day antecedent rainfall (AP10) and total 15 day antecedent rainfall (AP15). Antecedent rainfall is expressed as a total for the period under consideration, the units of measurement being 10^{-2}m. This total was substituted for 0,0136 I in Equation 9.1 which becomes:

$$Q = \beta_1 R\left(\frac{P}{25,4}\right)^{\beta_2} \; 1,0 + (APn)^{\beta_3} \; 25,4 \qquad \ldots\ldots \quad (10.1)$$

where

APn = the total depth of rainfall for the antecedent period of n days (10^{-2}m)

For each of the selected catchments the parameters for the R-index model were optimised using the three antecedent moisture indices in place of the initial flow rate and the index providing the most accurate stormflow estimates could thus be identified. Furthermore, for the three Zululand catchments and TOTAL the accuracy of the R-index model using antecedent rainfall could be compared with the accuracy of the original model in which initial flow rate was used as the antecedent moisture variable.

10.4 Results and Discussion

10.4.1 Testing the original R-index method

The results of analyses carried out using the R-index method with initial flow rate as the antecedent moisture variable are summarised in Table 10.2.

Table 10.2 Results of stormflow simulations using the original R-index method *

Analysis	Catchment or Data Set	Parameters β_1	β_2	β_3	Objective Functions D	E	<u>a</u>	<u>b</u>
(a) Optimised parameters	W1M15	0,38	1,54	0,75	0,789	0,783	-0,224	1,101
	W1M16	0,32	1,63	0,63	0,971	0,971	-0,349	1,045
	W1M17	0,34	1,62	0,42	0,994	0,994	-1,653	1,074
	TOTAL	0,47	1,40	0,30	0,988	0,987	-1,047	1,074
(b) Independent tests using parameters optimised for TOTAL	W1M15	0,47	1,40	0,30	0,757	0,665	0,223	0,843
	W1M17	0,47	1,40	0,30	0,985	0,954	1,230	0,926
	V1M28	0,47	1,40	0,30	0,867	0,438	0,889	0,389
(c) Tests using parameters for the eastern United States	W1M15	0,40	1,50	0,25	0,747	0,631	0,132	0,783
	W1M16	0,40	1,50	0,25	0,945	0,870	1,702	0,760
	W1M17	0,40	1,50	0,25	0,988	0,984	0,292	0,971
	TOTAL	0,40	1,50	0,25	0,988	0,984	-1,439	1,123

* Initial flow rate used to represent antecedent moisture conditions

Except for the data set TOTAL, inter-catchment variability in optimised model parameters is limited (Table 10.2a). The parameters β_1 and β_2 for the three Zululand catchments are similar to the values reported by Hewlett <u>et al</u> (1977) for the eastern United States (β_1 = 0,4 and β_2 = 1,5). However, β_3 values for Zululand catchments were markedly higher than the corresponding parameter value for the eastern United States (β_3 = 0,25). Hewlett <u>et al</u> (1977) do, however, point out that β_3 is the least stable model parameter. It is of interest to note that β_1 and β_2 are similar for the eastern United States and Zululand. It was also observed that storm=flows may be simulated accurately by the model in the three Zululand catch=ments, the values of D and E all being greater than 0,783 (Table 10.2a). Furthermore, systematic inaccuracies are limited with the values of D and E being very similar for each data set while <u>a</u> and <u>b</u> do not deviate substantially from zero and one respectively.

The simulation of stormflows for catchments W1M15, W1M17 and V1M28 using the R-index method calibrated for the data set TOTAL resulted in systematic inaccuracies for each catchment with the values of E being lower than the associated values of D in Table 10.2b. While losses in accuracy for catch= ments W1M15 and W1M17 were minimal when compared with the objective functions for the optimised model parameters (Table 10.2a), stormflow simulations for catchment V1M28 exhibited substantial systematic inaccuracies with D = 0,867 and E = 0,438. Although not presented, an examination of the scattergram of observed versus calculated stormflows revealed that observed values less than 2,0 mm were severely underestimated. This syste= matic error was confirmed by the regression of observed stormflow on calculated stormflow which produced a regression coefficient of 0,389 and base constant of 0,889.

Since most of the stormflow events in catchment V1M28 were not preceded by an initial flow rate (I), this variable made very little contribution to the model simulations of stormflow, storm rainfall (P) being the major source of variability of stormflow estimates under these conditions. Thus, it may be expected that errors in simulating stormflows for catchment V1M28 could be reduced by increasing the value of β_2 associated with P while retaining the values of β_1 and β_3. By increasing β_2 from 1,40 and 2,48 the values of D and E rose from 0,867 to 0,960 and from 0,438 to 0,957 respec= tively, thus confirming the hypothesis that the variability of stormflow simulations in catchment V1M28 were little affected by the initial flow rate component of the model.

The use of parameters derived from the eastern USA in place of optimised parameters gave rise to increased random and systematic errors for stormflow simulations in the three Zululand catchments and for the data set TOTAL (Table 10.2c). A comparison of D, E, a and b values in Table 10.2c with those of Table 10.2a reveals that there were greater increases in systematic errors than random errors. However, considering the regional differences between Natal and the eastern USA these results are considered to be understandable.

Considering the data set TOTAL in Table 10.2c, the loss in model accuracy resulting from the use of parameters reported by Hewlett et al (1977) was minimal, the value of E being reduced from 0,987 to 0,984 and the value of D being unchanged. This finding may be attributed to the overall similarity in optimised parameters for TOTAL and the parameters used by Hewlett et al (1977). While the optimised parameters β_1 and β_2 for catchment W1M15 (β_1 = 0,38; β_2 = 1,54) were very close to those given by Hewlett et al (1977), the β_3 values associated with the initial flow rate differed substantially (β_3 = 0,75) which accounts for the greater loss in accuracy for this catchment (Table 10.2c). It would thus appear that general similarity in parameter values may result in more accurate stormflow simulations than exact estimates of two parameters and a substantial deviation in the third. The sensitivity of the model to changes in the parameter values is given detailed attention in Chapter 14.

The R-indices used for stormflow calculations in these analyses were based on measured stormflow and storm rainfall data (Equation 9.1). However, only 43 events with storm rainfalls as low as 15,0 mm were included compared with the limit of 25,4 mm adopted by Hewlett et al (1977). These calculated values for the three Zululand catchments may therefore not have been completely compatible with model parameters developed for eastern USA. By using estimates of the R-index from catchment characteristics as described by Hewlett and Moore (1976) this problem could be avoided (cf Section 9.3). According to the method of Hewlett and Moore (1976) the - index value for the three Zululand catchments would be 0,18. Substituting this value of the calculated R-index resulted in better stormflow estimates for two of the three catchments (Table 10.3).

By substituting R-indices tabulated by Hewlett and Moore (1976) for calculated values in the R-index model (parameters for eastern USA) the values of E in Table 10.3 reflected improved stormflow simulations in catchment W1M15 and W1M16 while in catchment W1M17 the model was less accurate with the value of E decreasing from 0,971 to 0,961. The reduction in model accuracy for catchment W1M17 was not marked, using either approach the systematic errors as reflected in the value a and b were not substantial (Table 10.3).

Table 10.3 Results of stormflow simulations using the original R-index method and parameters for the eastern USA based on
(a) the Hewlett and Moore (1976) R-index values and
(b) calculated R-index values

Catchment or Data Set	Parameters β_1	β_2	β_3	Objective Functions D	E	a	b
W1M15(a)	0,40	1,50	0,25	0,747	0,718	0,194	1,155
(b)	0,40	1,50	0,25	0,747	0,631	0,132	0,783
W1M16(a)	0,40	1,50	0,25	0,945	0,917	1,945	0,872
(b)	0,40	1,50	0,25	0,945	0,870	1,702	0,760
W1M17(a)	0,40	1,50	0,25	0,987	0,961	0,262	0,935
(b)	0,40	1,50	0,25	0,987	0,971	0,272	0,971

Based on the findings of these analyses, it may be concluded that the original R-index method is suitable for stormflow simulations in Zululand. Stormflow producing mechanisms in this region and the eastern USA appear to be similar. It is therefore not surprising that the optimised model parameters for the three Zululand catchments are similar to those for the eastern USA. Furthermore, adopting the values reported by Hewlett et al (1977) did not give rise to substantial errors in stormflow simulations in the Zululand catchments.

10.4.2 An alternative for initial flow rate

The optimisation of the R-index model using antecedent rainfall totals over five days (AP5), 10 days (AP10) and 15 days (AP15) in place of the initial flow rate resulted in markedly different parameter values for the different antecedent periods and between different data sets for the same antecedent period (Table 10.4). An examination of the objective functions in Table 10.4 reveals a range in values from D = 0,995 and E = 0,995 for catchment W1M16 (AP5) to D = 0,324 and E = 0,322 for catchment V7M03 (AP5). Using the total antecedent rainfall over five days (AP5) resulted in the most accurate stormflow simulations on four catchments, namely, W1M15, W1M16, U2M20 and V1M28. The procedure AP10 gave the best results in catchment

V7M03 while AP15 was the most accurate procedure in catchment W1M17 and for the data set TOTAL.

Table 10.4 Results of model calibrations using selected periods of antecedent rainfall in the R-index method

Catchment or Data Set	Period of Antecedent Rainfall	Parameters			Objective Functions			
		β_1	β_2	β_3	D	E	a	b
W1M15	AP5	0,62	1,90	0,99	0,752	0,752	-0,416	1,071
	AP10	0,39	2,01	0,34	00,719	0,714	-4,555	1,037
	AP15	0,41	1,89	0,33	0,718	0,717	-0,281	1,025
W1M16	AP5	0,39	1,72	0,36	0,995	0,995	-0,939	1,065
	AP10	0,20	2,00	0,01	0,989	0,988	-2,065	1,077
	AP15	0,10	2,13	0,35	0,978	0,973	-3,240	1,050
W1M17	AP5	0,40	1,62	0,01	0,974	0,0974	-0,590	1,070
	AP10	0,32	1,71	0,01	0,976	0,976	-1,161	1,069
	AP15	0,27	1,58	0,23	0,990	0,990	-1,099	1,079
U2M20	AP5	0,18	3,08	1,54	0,738	0,738	-0,612	1,371
	AP10	0,20	1,65	0,98	0,512	0,512	-0,133	1,086
	AP15	0,08	1,97	1,30	0,614	0,599	-0,281	1,212
V1M28	AP5	0,31	2,76	1,19	0,983	0,982	-0,587	1,080
	AP10	0,15	3,52	0,42	0,975	0,974	-0,529	1,054
	AP15	0,16	3,76	0,08	0,978	0,976	-0,294	0,983
V7M03	AP5	0,72	2,44	0,15	0,324	0,322	0,858	0,647
	AP10	0,31	1,46	1,08	0,663	0,661	-0,040	1,043
	AP15	0,15	1,64	1,31	0,650	0,650	-0,096	1,031
TOTAL	AP5	0,21	2,02	0,68	0,987	0,984	-1,515	1,081
	AP10	0,13	2,17	0,01	0,963	0,951	-2,128	1,040
	AP15	0,34	1,45	0,18	0,988	0,987	-0,999	1,081

A comparison of the objective function values for the best antecedent rainfall procedure (Table 10.4) with those values obtained using initial flow rate (Table 10.2a) for the three Zululand catchments and the data set TOTAL suggests that very little accuracy, if any, would be lost in using these antecedent rainfall procedures, the accuracy of stormflow simulations actually improved by using AP5 for catchment W1M16 and did not change by using AP15 for the data set TOTAL. However, an important consideration is the loss of accuracy which may occur if the wrong ante= cedent rainfall period were to be used for a catchment. In two catchments there are substantial inaccuracies associated with the least suitable procedure, namely, catchment U2M20 and AP10 and catchment V7M03 with AP5.

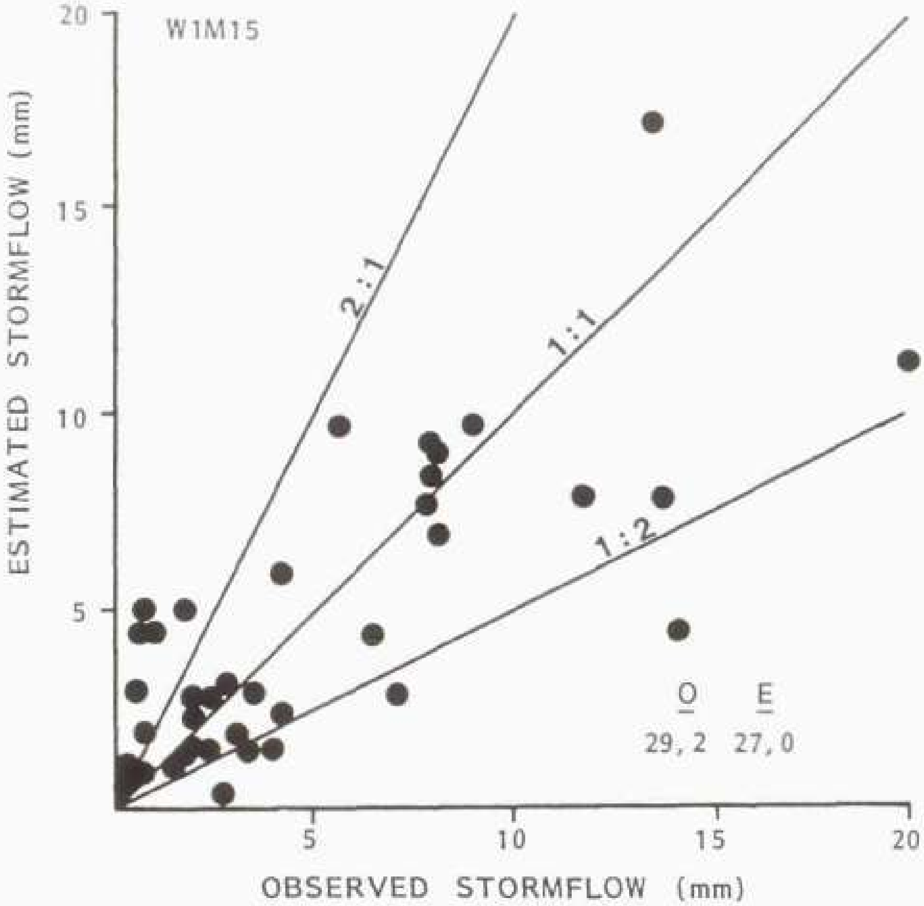
A suitable substitute for the initial flow rate should ideally not give rise to substantial inaccuracies in stormflow simulations in any particular region or catchment. In examining the results presented in Table 10.4 it may be concluded that the antecedent rainfall totalled over 15 days (AP15) was the most suitable overall antecedent moisture procedure for producing good calibrations. A notable finding was that in no single catchment did the use of AP15 result in large random or systematic errors, the lowest values for D and E being 0,614 and 0,599 respectively for catchment U2M20 while the highest values for D and E in this catchment were both 0,738 (AP5). The AP15 was therefore applied in ungauged catchments of Natal, and scattergrams of observed and estimated stormflows for the six catchments and TOTAL are presented in Figure 10.3

In examining the scattergrams presented in Figure 10.3 the following general observations may be made:

(a) The R-index method simulated large stormflows accurately in all the catchments and for TOTAL. Large data values affect the coefficient of efficiency (E) disproportionately and the use of logarithmic values in the calculation of E may have given different results. However, the accurate estimation of large events is considered to be desirable since it is these events which are generally of concern to engineers and planners.

(b) In the three Zululand catchments (W1M15, W1M16, W1M17) the increase in random errors follows the increase in catchment size, successively more points being outside of the 1:2 and 2:1 lines for catchments W1M15, W1M16 and W1M17 (areas: $13,65^2$; $3,22\ km^2$; $0,67^2 km$).

Figure 10.3 Scattergrams of observed and estimated stormflows for catchments W1M15, W1M16, W1M17, U2M20, V1M28, V7M03 and the data set TOTAL



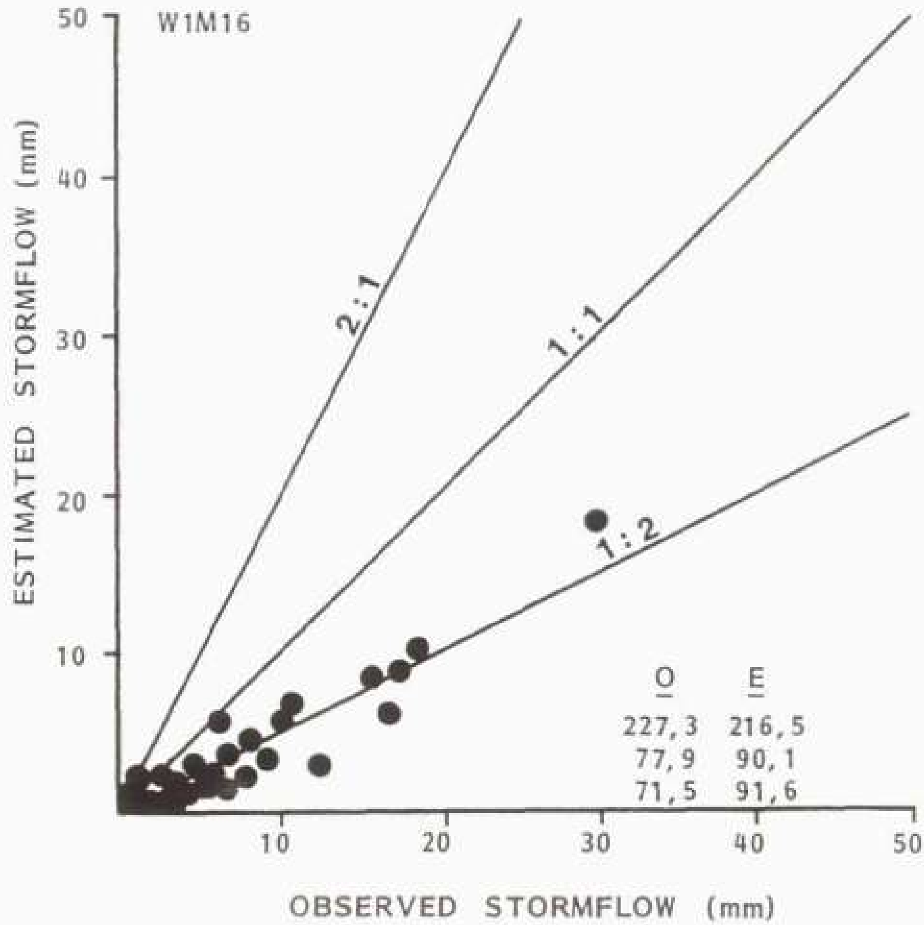


Figure 10.3 (continued)

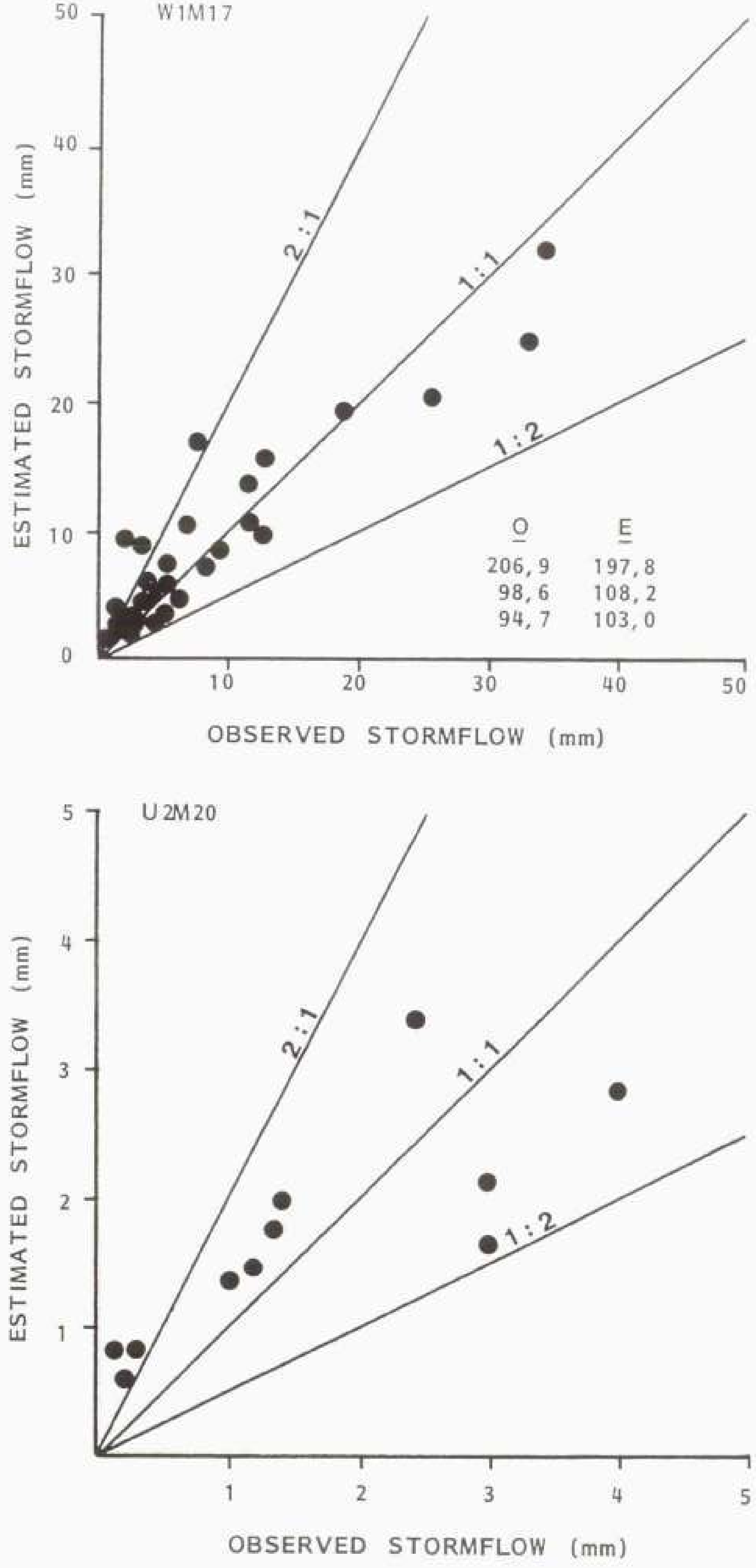
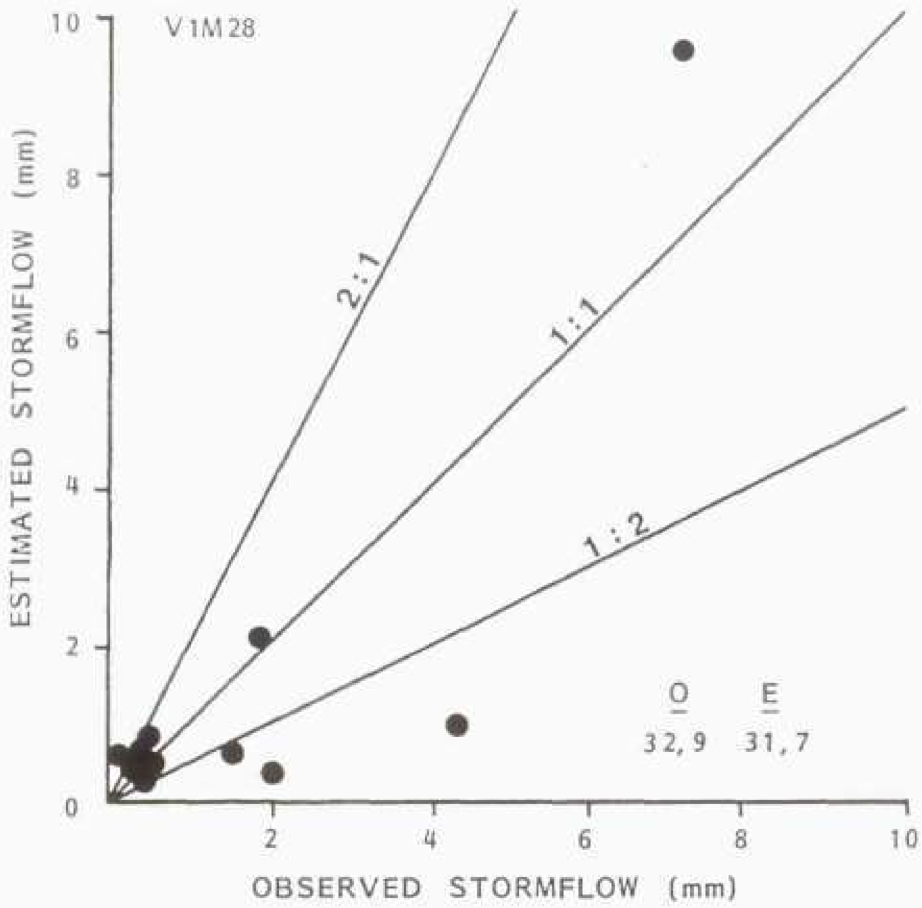


Figure 10.3 (continued)



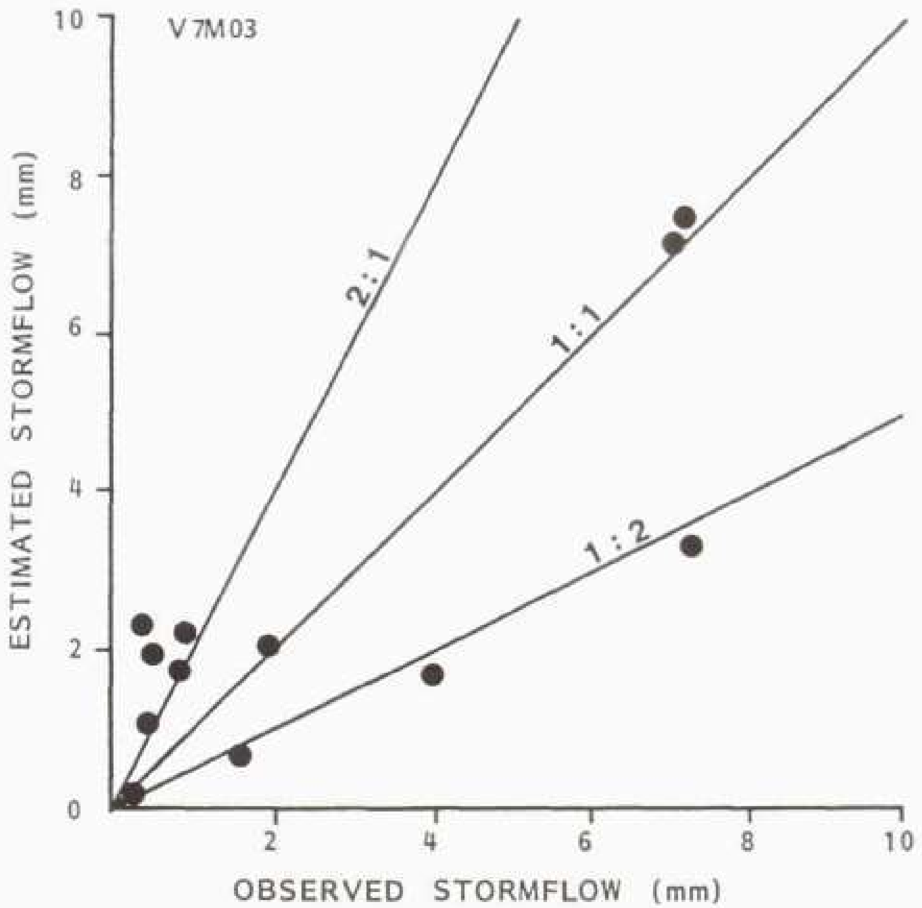
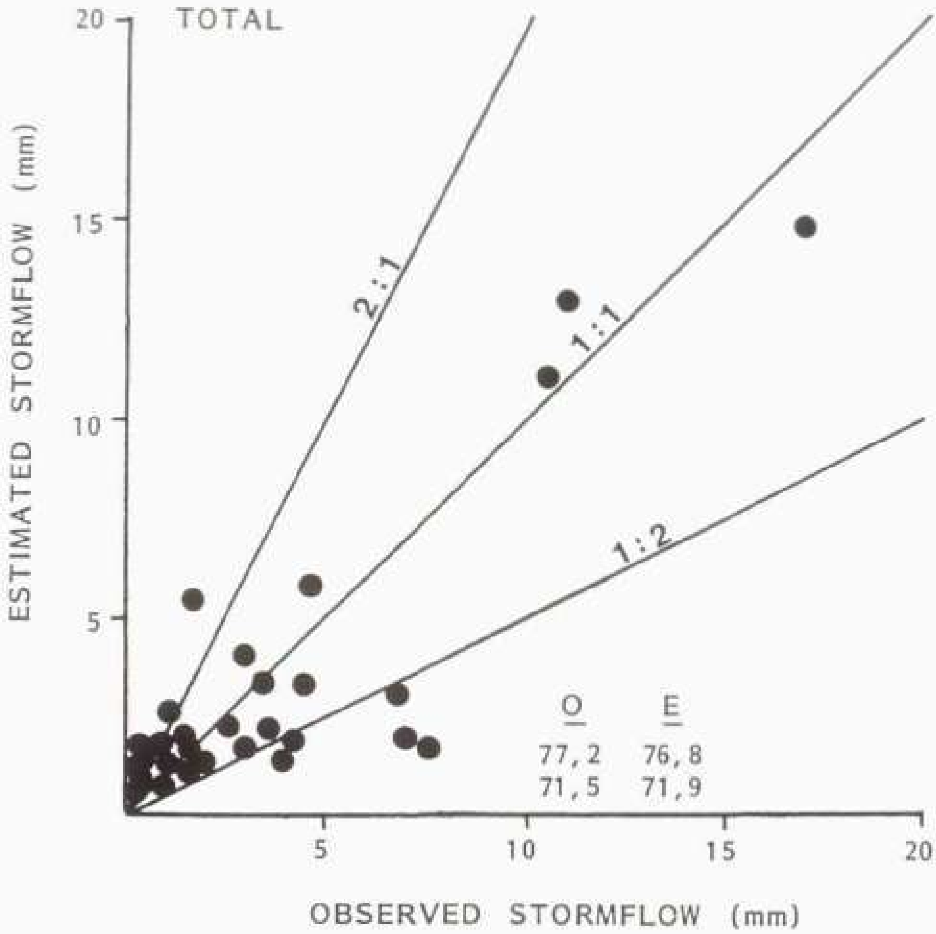


Figure 10.3 (continued)



(c) For events up to 20 mm of observed stormflow there is consistent underestimation in calculated stormflows for catchment W1M16 with most of the points scattering around the 1:2 lines.

(d) The R-index method was particularly successful in stormflow simula= tions in catchment W1M17, with most of the points clustering around the line of perfect agreement.

(e) Stormflow simulations in the three sub-humid catchments (U2M20, V1M28 and V7M03) do not exhibit consistent over or underestimation in calculated stormflow depths. Errors are generally random with points falling close to or outside of the 1:2 and 2:1 lines in the scatter= grams for each catchment.

(f) Most of the points in the scattergram for TOTAL are contained within the 1:2 and 2:1 lines. For events in excess of 8 mm of observed stormflow all the points in the scattergram were within these two lines.

Summated antecedent rainfall has been shown to be a suitable catchment wetness index for stormflow estimates in selected catchments of Natal using the R-index method. This index does not, however, take evapotranspira= tional losses into account. In some areas of Natal pan evaporation data is readily available and may be incorporated into catchment wetness indices. An adjusted antecedent rainfall index was calculated for stormflow events in the three Zululand catchments by subtracting daily A-pan evaporation depths (10^{-2} m) from the cumulative antecedent rainfall totals. The residual value had a lower limit of zero. Indices were calculated for the three antecedent periods, namely, five, 10 and 15 days. The R-index method was recalibrated using these indices in place of the antecedent rainfall totals and the results are given in Table 10.5 along with the results using summated antecedent rainfall (from Table 10.4).

The inclusion of A-pan evaporation in the catchment wetness index did not improve stormflow calculations in any of the catchments regardless of the antecedent period used (Table 10.5). Parameter values and the values of D and E were similar for both sets of stormflow simulations. The nature of the systematic inaccuracies did alter by including A-pan evaporation losses in the catchment wetness index as may be gleaned by comparing the values of a and b for each pair of simulation results in Table 10.5. On the basis of these results it may be concluded that the inclusion of A-pan evaporation in the catchment wetness index for this model is not justified. However, this conclusion needs further testing.

Table 10.5 Results of stormflow simulations using A-pan adjusted catchment wetness indices (a) and summated antecedent rain= fall (b) for selected periods in the R-index method

Catchment or Data Set	Antecedent Period (Days)	Parameters			Objective Functions			
		β_1	β_2	β_3	D	E	a	b
W1M15(a)	5	0,60	1,93	1,14	0,746	0,745	0,751	0,709
	10	0,40	1,93	0,33	0,714	0,712	-0,040	0,700
	15	0,40	1,92	0,34	0,708	0,707	0,953	0,681
W1M15(b)	5	0,62	1,90	0,99	0,752	0,752	-0,416	1,071
	10	0,39	2,01	0,34	0,719	0,714	-0,455	1,037
	15	0,41	1,89	0,33	0,718	0,717	-0,281	1,025
W1M16(a)	5	0,40	1,71	0,37	0,995	0,995	1,447	0,930
	10	0,20	2,00	0,01	0,990	0,988	0,099	0,921
	15	0,10	2,14	0,33	0,979	0,974	-1,440	0,927
W1M16(b)	5	0,39	1,72	0,36	0,995	0,995	-0,939	1,065
	10	0,20	2,00	0,01	0,989	0,988	-2,065	1,077
	15	0,10	2,13	0,35	0,978	0,973	-3,240	1,050
W1M17(a)	5	0,40	1,60	0,04	0,972	0,971	1,097	0,934
	10	0,30	1,74	0,01	0,976	0,976	1,000	0,909
	15	0,20	1,70	0,24	0,991	0,991	0,547	0,914
W1M17(b)	5	0,40	1,62	0,01	0,974	0,974	-0,590	1,070
	10	0,32	1,71	0,01	0,976	0,976	-1,161	1,069
	15	0,27	1,58	0,23	0,990	0,990	-1,099	1,079

10.5 Conclusions

Conclusions from the discussion of results may be summarised as follows:

(a) The R-index method, using initial flow rate as an input for antecedent moisture conditions, was able to be accurately calibrated for the selected catchments in Natal.

(b) General similarity in parameter values may result in more accurate stormflow simulations than exact estimates of two parameters and a substantial deviation in the third.
(c) The possibility of similarity stormflow producing mechanisms operating in the eastern United States and Zululand may be a reason for similar model parameters having been generated for the two regions.
(d) In catchments where the streams are non-perennial or intermittent, the initial flow rate is an unsuitable variable for representing antecedent moisture conditions since many stormflow events are preceded by zero flow.
(e) Antecedent rainfall is a good substitute for the initial flow rate as a measure of catchment moisture status and in some cases is as good or better than the initial flow rate for stormflow prediction.
(f) The total antecedent rainfall over fifteen days appears to be the most suitable index of catchment moisture status for incorporating in the R-index method for stormflow estimates in Natal.
(g) Including A-pan evaporation in the catchment wetness index index requires additional calculations without improving the accuracy of the R-index method on calibration.
(h) Proper verification simulation need still to be undertaken with this method.

A major requirement for all stormflow modelling in Natal is the testing of models under the variety of environmental conditions which are found in this region. However, only a limited number of small catchments are suitable for such studies. Thus, future research may well be oriented towards the use of temporary gauging structures to regionalise the para= meters of the R-index method.

The results presented in this study have indicated that with further research the R-index method could be a viable and accurate procedure for calculating stormflow volumes from small catchments in Natal. Attention needs, however, to be given to testing the method under semi-arid condi= tions since much of South Africa may be regarded as semi-arid. Further= more, the model was not intended for use in semi-arid catchments and such a study could help to establish whether the model has environmental limita= tions. The problem of testing the R-index method in semi-arid catchments is addressed in the following chapter.

Chapter 11

SIMULATION OF STORMFLOW VOLUMES IN SMALL SEMI-ARID CATCHMENTS

Three small semi-arid catchments which are monitored for research purposes were selected for this investigation. The principle objective of this study is to calibrate the R-index model using observed stormflow data from these catchments and to assess the accuracy of the method under physical and environmental conditions which are markedly different to those where the model has been shown to be a good simulator of stormflow volumes (eg, eastern USA and Natal).

The nature of the data obtained for this study necessitated the adoption of different analytical and research procedures to those used for evaluating the model in catchments of Natal.

11.1 Study Catchments and Data

In an analysis of the hydrograph characteristics from three semi-arid research catchments near Grahamstown, South Africa, Murray and Görgens (1981) presented data for a total of 68 stormflow events which included <u>inter alia</u>, stormflow depths, storm rainfall depths, antecedent baseflow and antecedent rainfall totals. This study of the R-index method is based on the information tabulated by Murray and Görgens (1981). The three catchments are referred to as I, II and III and have areas of 76 km^2, 10 km^2 and 24 km^2 respectively (Figure 11.1). The major physical characteris= tics of the region are summarised in Table 11.1.

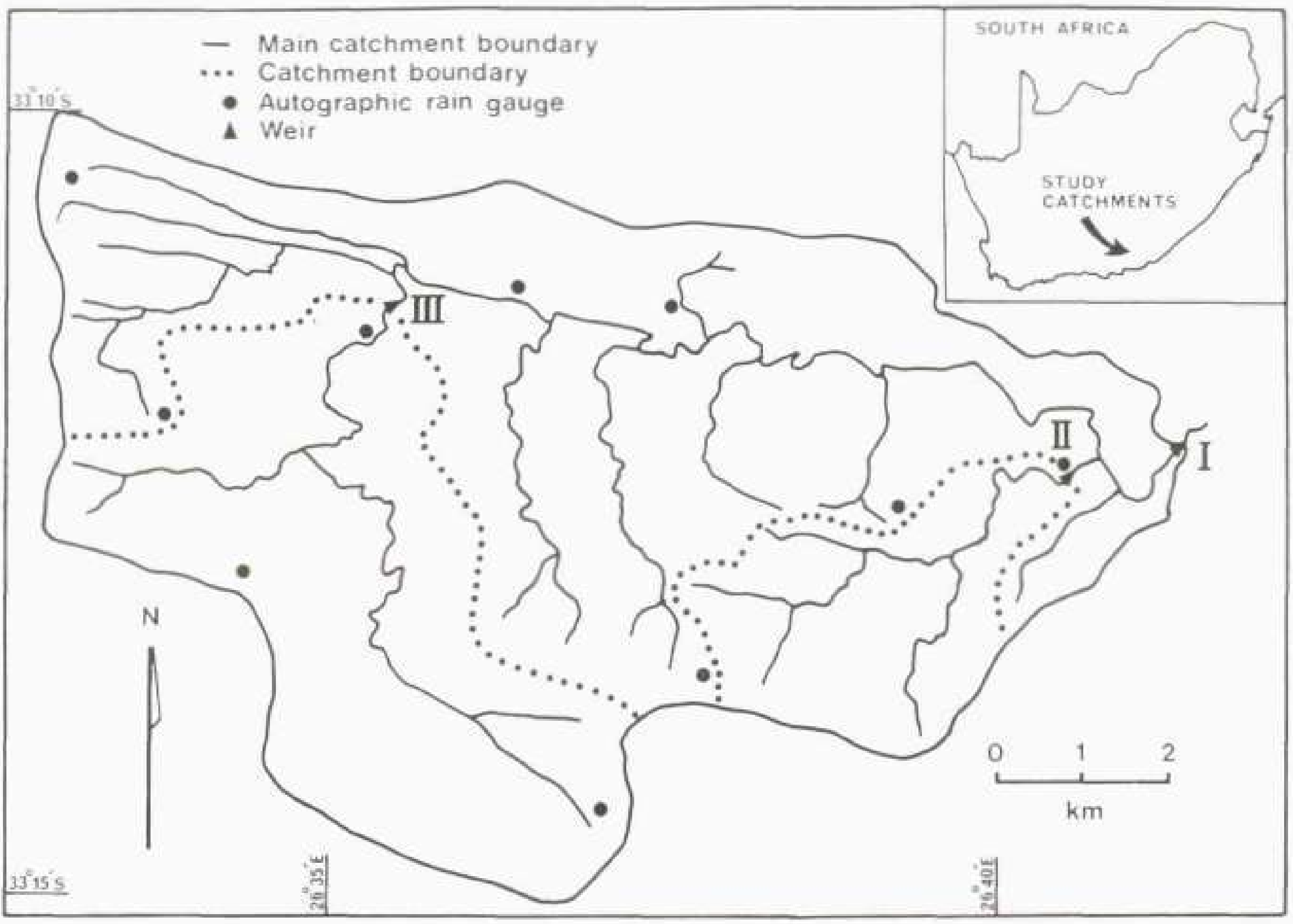
Murray and Görgens (1981) adopted the same technique for separating storm= flow from baseflow as that described by Hewlett <u>et al</u> (1977) while antecedent baseflow was taken as the stream discharge at the onset of the rising limb of the storm hydrograph. Storm rainfall was distinguished from antecedent rainfall according to the procedure outlined by Hewlett, Fortson and Cunningham (1977), whereby the modal value of time between peak rain= fall intensity and peak runoff rate for all events in each catchment is subtracted from the time when stormflow begins. Storm rainfall is taken to

Table 11.1 Background information to the Grahamstown study catchments

<table>
<tr><th>Characteristic</th><th>Description</th><th>Source</th></tr>
<tr><td>Mean Annual Precipitation</td><td>± 420 mm</td><td>Midgley and Pitman (1969)</td></tr>
<tr><td>Mean Annual Runoff</td><td>± 7,5 % of Mean Annual Precipitation</td><td>Murray and Görgens (1981)</td></tr>
<tr><td>Mean Annual Pan Evapora= tion (American A Class)</td><td>1 430 mm</td><td>Roberts (1978)</td></tr>
<tr><td>Vegetation</td><td>Tall sub-succulent woodland thinning to low succulent scrub on the flatter areas. Uniform in type and density underlain by shale, tillite, sandstone and occasional quartzites</td><td>Roberts (1978)</td></tr>
<tr><td>Soils</td><td>Shallow and stoney on ridge= tops and valley side slopes, with deeper coluvial deposits in the valley bottoms</td><td>Jolly (1980)</td></tr>
<tr><td>Slopes (percent of catchment area)</td><td><table>
<tr><th rowspan="2">Catch= ment</th><th colspan="3">Slope (%)</th></tr>
<tr><th>0-20</th><th>20-40</th><th>40</th></tr>
<tr><td>I</td><td>69</td><td>19</td><td>12</td></tr>
<tr><td>II</td><td>52</td><td>29</td><td>19</td></tr>
<tr><td>III</td><td>79</td><td>13</td><td>8</td></tr>
</table></td><td>Adapted from Roberts (1978)</td></tr>
</table>

be the accumulated rainfall depth between this time and the termination of the storm hydrograph by the stormflow separation line. According to Murray and Görgens (1981) this procedure allows for the effects of both the response lag phenomena in a catchment and possible clock errors in the raw data.

Figure 11.1 The three selected semi-arid catchments (After: Murray and Görgens, 1981.)



Antecedent rainfall totals for one, seven and 10 day periods were tabulated by Murray and Görgens (1981) for each stormflow event. Daily rainfall records were used for the seven and 10 day totals while the one day antecedent rainfall was taken to be the rainfall occurring in the 24 hour period preceding the onset of the storm rainfall. The 68 stormflow events were collected over a period of four years, 1976 to 1979. This record is dominated by two events of extreme magnitude in July and August 1979 as may be seen by comparing the stormflow depths of these two events with the next highest and median stormflow depths in each catchment (Table 11.2).

Table 11.2 Stormflow depths for the two extreme events of July and August 1979 and the next highest and median stormflow depths for each catchment

Catchment	Stormflow Depth (mm)			
	July 1979	August 1979	Next Highest	Median
I	24,615	36,054	5,819	0,051
II	23,610	21,287	1,458	0,068
III	14,774	14,650	1,650	0,007

In attempting to model stormflow volumes in a catchment small events pose a particular problem. Inaccuracies in the measurement process are more pronounced for such events as are perturbations in the stormflow producing mechanisms particular individual events. To ensure that the major mechanisms controlling stormflow production in a catchment were represented in the R-index method, Hewlett et al (1977) excluded events where storm rainfall was less than 25,4 mm while in testing this model in catchments of Natal a threshold of 15,0 mm was imposed on the selection of stormflow events. The data presented by Murray and Görgens (1981) for the three semi-arid catchments included all events since the exclusion of any events would have resulted in too few observations in each catchment for meaningful analyses. In order to evaluate the effects of the two extremely large events of July and August 1979 and very small events ($P < 15,0$ mm) on the calibration and accuracy of the R-index method, the data were arranged into seven individual sets for this study, viz:

(a) Three individual data sets were established, one for each catchment, containing all the events tabulated by Murray and Görgens (1981).
(b) All the events from each catchment were pooled to constitute a single data set, POOL 1.
(c) The two extreme events of July and August 1979 were removed from POOL 1 (six observations), this data set being referred to as POOL 2.
(d) Stormflow events associated with less than 15,0 mm of storm rainfall were removed from POOL 1 to constitute the data set POOL 3.
(e) The final pooled data set, POOL 4, excluded both the two extreme events and the small events ($P < 15,0$ mm).

Some characteristics of the storm rainfalls and stormflow depths of each data set are presented in Table 11.3 and data for each catchment are given in Appendix 10.

Table 11.3 Mean ($\bar{x}$), standard deviation (s), coefficient of variation (CV) and the number of events (N) for each data set

Catchment/	Storm Rainfall			Stormflow			N
Data Set	$\bar{x}$(mm)	S(mm)	CV(%)	$\bar{x}$(mm)	s(mm)	CV(%)	
I	29,980	31,17	104,0	3,631	9,440	26,0	20
II	23,545	23,774	101,0	1,68	5,410	324,3	33
III	25,680	32,382	126,1	2,456	5,169	210,5	15
POOL 1	25,909	27,789	107,3	2,419	6,699	276,9	68
POOL 2	18,061	10,586	58,6	0,476	1,181	248,1	62
POOL 3	37,823	31,025	82,0	4,070	8,346	205,1	40
POOL 4	25,615	8,030	31,3	0,843	1,521	180,4	34

11.2 Aims and Procedures

11.2.1 Aims

While the broad aim of this study is to calibrate the R-index method on data from three semi-arid catchments and to assess the performance of this technique for stormflow simulations under these conditions, three specific aims may be identified, namely, to:

(a) Calibrate the R-index method on the three catchments using antecedent baseflow, the one, seven and 10 day antecedent rainfalls as alterna= tive catchment wetness indices in Equation 9.2 and Equation 10.1 and to determine which of these indices provides the best estimates of stormflow volumes.

(b) Establish general model parameters for the region by repeating the analysis outlined in (a) above using pooled data from the three catch= ments. The effects of the two extreme events of July and August 1979 and very small events the model versatility are also investigated.

(c) Assess the relative contributions of storm rainfall and the catchment wetness index in accounting for variations in stormflow volumes using the R-index method.

Table 11.4 Results of stormflow simulations for the three study catchments using selected catchment wetness indices in the R-index method

Catchment	Catchment Wetness Index	Parameters			Objective Functions			
		β_1	β_2	β_3	D	E	a	b
I	BF	1,136	1,833	0,154	0,891	0,885	0,695	0,925
	AP1	1,300	1,881	0,000	0,845	0,843	0,337	0,927
	AP7	0,760	1,780	0,001	0,849	0,844	0,559	0,923
	AP10	0,760	1,780	0,001	0,849	0,844	0,560	0,923
II	BF	1,207	2,144	0,001	0,976	0,972	0,372	0,955
	AP1	1,176	1,763	0,001	0,862	0,855	0,367	0,951
	AP7	1,138	1,780	0,001	0,857	0,848	0,399	0,952
	AP10	1,083	1,814	0,001	0,855	0,848	0,362	0,951
III	BF	1,908	1,646	0,001	0,966	0,962	0,515	0,896
	AP1	1,451	1,469	0,000	0,949	0,946	0,432	0894
	AP7	1,011	1,573	0,225	0,973	0,972	0,404	0,896
	AP10	0,837	1,628	0,336	0,974	0,972	0,403	0,896

11.2.2 Procedures

Optimisation of model parameters was based on the coefficient of efficiency (E) using the programme INDEX (cf Section 10.3.1). The assessment of random and systematic errors in simulated stormflows was based on this objective function as well as the coefficient of determination (D), base constant (a) and regression coefficient (b) which are described in chapter 10 (Section 10.3.1).

In order to assess the relative importance of storm rainfall and the catch= ment wetness index on the simulation of stormflow volumes in each catchment, the model parameters β_1 and β_2 in Equation 9.2 and Equation 10.1

were optimised with B_3 being set at zero. Thus, event to event variability in calculated stormflow volumes could only be affected by changes in storm rainfall.

11. Results and Discussion

11.3.1 Calibration of the R-index method

The results of calibrating the R-index method on catchments I, II and III using alternate catchment wetness indices viz, antecedent baseflow (BF), antecedent rainfall totalled over one day (AP1), seven days (AP7) and 10 days (AP10), are presented in Table 11.4. The high coefficients of efficiency in Table 11.4 ($E > 0,843$) indicate that goodness of fit using the R-index method were accurate in each of the three catchments regardless of the antecedent wetness index used. Furthermore, the values of D are similar to those of E, reflecting minimal systematic inaccuracies (Table 11.4). The lack of over or underestimation may be gleaned from the values of a and b in Table 11.4, the minimum deviation of a from zero being 0,695 while the maximum deviation of b from unit is 0,106.

The catchment wetness index which provided the most accurate simulations of stormflow volumes, based on E, was BF in catchments I and II and AP10 in catchment III. Although the values of E associated with AP7 and AP10 in catchment III were the same, the use of AP7 resulted in a marginally lower value of D (Table 11.4). An examination of intra-catchment differences in the objective functions presented in Table 11.4 reveals that the use of different catchment wetness indices did not generally result in substantial variations in model accuracy except in catchment II where BF gives notably higher values of D and E compared with the other indices.

Antecedent baseflow has been shown by authors such as Reich (1971) and Hewlett et al (1977) to be a valuable index of the catchment wetness status for stormflow calculations in humid areas. However, Murray and Görgens (1981) concluded that this variable was of little use in increasing the explained variance of stormflow volumes using regression analysis in catchments I, II and III. The results presented in Table 11.4 do not, however, coincide with these findings of Murray and Görgens (1981). The simulated stormflows in catchments I and II were most accurate using BF while simulations in catchment III using this index were also found to be accurate. The most suitable catchment wetness index for catchment III was AP7 with the value of E being 0,967, only slightly higher than the value associated with BF (E = 0,962).

Considering stormflow estimates in catchments where BF is assumed not to be available, the antecedent rainfall indices AP7 and AP10 are, on the basis of the objective function E in Table 11.4, equally as good for calculating stormflows in each of the test catchments. This finding may be explained by examining the seven and 10-day antecedent rainfall totals tabulated by Murray and Görgens (1981), totals for these two periods are identical for many events and correlate very highly ($r = 0,884$; $n = 68$).

The parameters β_1, β_2 and β_3 were given by Hewlett et al (1977) for the humid eastern United States as 0,4, 1,5 and 0,25 respectively when BF was included in the R-index method (Equation 9.2). Stormflow estimates in humid catchments of Natal were found to be accurate when these parameters values were used in Equation 9.2 and it was suggested that similar stormflow producing mechanisms may have accounted for this finding (cf Chapter 10). However, the optimised parameter values for each catchment presented in Table 11.4 using BF in Equation 10.2 differ considerably to those reported by Hewlett et al (1977). The β_1 values for the semi-arid catchments are greater than 1,135, β_2 values range between 1,646 and 1,833 while β_3 values do not exceed 0,154 (Table 11.4). These marked differences in parameter values for the humid and semi-arid catchments may be expected since there are bound to be regional differences in stormflow producing mechanisms. Furthermore, the results presented in Table 11.4 are based on all events recorded in the three semi-arid catchments while Hewlett et al (1977) and the study based on catchments in Natal dealt with events produced by storm rainfalls above given thresholds.

11.3.2 Pooled data

The objective functions and optimised model parameters for the pooled data sets are presented in Table 11.5. Calibrating the R-index method on all 68 observations (POOL 1) using the four catchment wetness indices reveals that only the index BF contributed towards explaining variability in stormflow volumes since β_3 values for the three antecedent rainfall indices were all zero. However, the exclusion of BF from the model did not affect model accuracy substantially since the value of E declined marginally from 0,864 to 0,833. Furthermore, systematic inaccuracies as reflected in the differences between D and E did not increase notably when β_3 assumed the value of zero (Table 11.5).

Calibrating the R-index method on the data set POOL 2, which excludes the extreme events of July and August 1979, results in notably different findings to those described for POOL 1. The most suitable antecedent moisture index for this data set is AP10 (E = 0,705) and not BF (E = 0,312) as was the case for POOL 1. Substituting AP7 for AP10 in the model gives rise to similar parameter and objective function values for POOL 2 while the least accurate stormflow simulations for this data set were associated with AP1, the value of E being 0,267.

The results for the data set POOL 3, which includes all events associated with 1,50 mm or more of storm rainfall, are similar to those for POOL 1 (Table 11.5). Antecedent moisture conditions are best represented by BF while antecedent rainfall did not contribute to explaining the variability in the stormflow volumes, β_3 being equal to zero for each of the antecedent rainfall indices. While the parameter values of β_2 for POOL 1 and POOL 3 are similar, β_1 values for POOL 3 are less than half the values for POOL 1. This finding may be accounted for by the difference in R-index values (Equation 9.1) for POOL 1 and POOL 3, the values for POOL 3 being between 1,4 and 3,0 times greater than the values for POOL 1. Thus for the product of β_1 and R in Equation 9.2 and Equation 10.1 to be of the same order for these two data sets, β_1 values need to be proportionally reduced for POOL 3.

Table 11.5 Results of stormflow simulations for the pooled data sets using selected catchment wetness indices in the R-index method

Data Set	Catchment Wetness Index	Parameters			Objective Functions			
		B_1	B_2	B_3	D	E	a	b
POOL 1	BF	1,158	1,778	0,230	0,866	0,863	0,289	0,933
	AP1	1,731	1,749	0,000	0,835	0,833	0,216	0,931
	AP7	1,731	1,749	0,000	0,835	0,833	0,216	0,931
	AP10	1,731	1,749	0,000	0,835	0,833	0,216	0,931
POOL 2	BF	1,240	2,414	0,150	0,312	0,312	-0,233	0,810
	AP1	0,824	2,317	0,001	0,268	0,267	-0,272	0,789
	AP7	0,022	5,309	1,915	0,703	0,697	-0,121	0,900
	AP10	0,020	5,206	1,953	0,709	0,705	-0,098	0,899
POOL 3	BF	0,717	1,797	0,074	0,821	0,819	-0,208	0,887
	AP1	0,753	1,887	0,000	0,714	0,714	-0,208	0,866
	AP7	0,753	1,887	0,000	0,714	0,714	-0,208	0,866
	AP10	0,753	1,887	0,000	0,714	0,714	-0,208	0,866
POOL 4	BF	0,836	2,442	0,107	0,488	0,459	0,048	0,797
	AP1	0,565	2,418	0,001	0,370	0,353	-0,072	0,748
	AP7	0,052	4,456	1,291	0,692	0,690	-0,042	0,829
	AP10	0,031	5,166	1,450	0,703	0,702	-0,012	0,826

While both the two extreme events and events associated with less than 15,0 mm of storm rainfall are excluded from the data set POOL 4, the results presented in Table 11.5 for this data set are discernibly closer to those of POOL 2 than they are to those of POOL 3. This finding suggests that the extreme events of July and August 1979 have a more substantial influence on parameter values and in determining which catchment wetness index is most suitable for stormflow simulations than the large number of small events ($P < 15,0$ mm) have. Furthermore, the data sets POOL 1 and POOL 3, both of which include the extremely large events, have been shown to have similar parameter and simulation results despite differences in the data sets.

The two extreme events of July and August 1979 appear to have a marked and possibly disproportionate influence on the calibration results based on the objective function E. However, adopting the R-index model which has been optimised on data which excludes these events (POOL 2) would restrict the applicability of the model to the range of this data. The calculation of stormflow volumes outside of the range of data on which the model was calibrated could lead to substantial inaccuracies in the simulated results. This may be illustrated by calculating stormflow volumes for the two extreme events in each catchment using the parameters and catchment wetness index which gave optimum results for the data set POOL 2. The over-estima= tion of stormflow volumes was in excess of 300 % for one events, 200 % for two events, 100 % for one event and 30 % for two events.

11.3.3 Estimation of stormflow in ungauged catchments

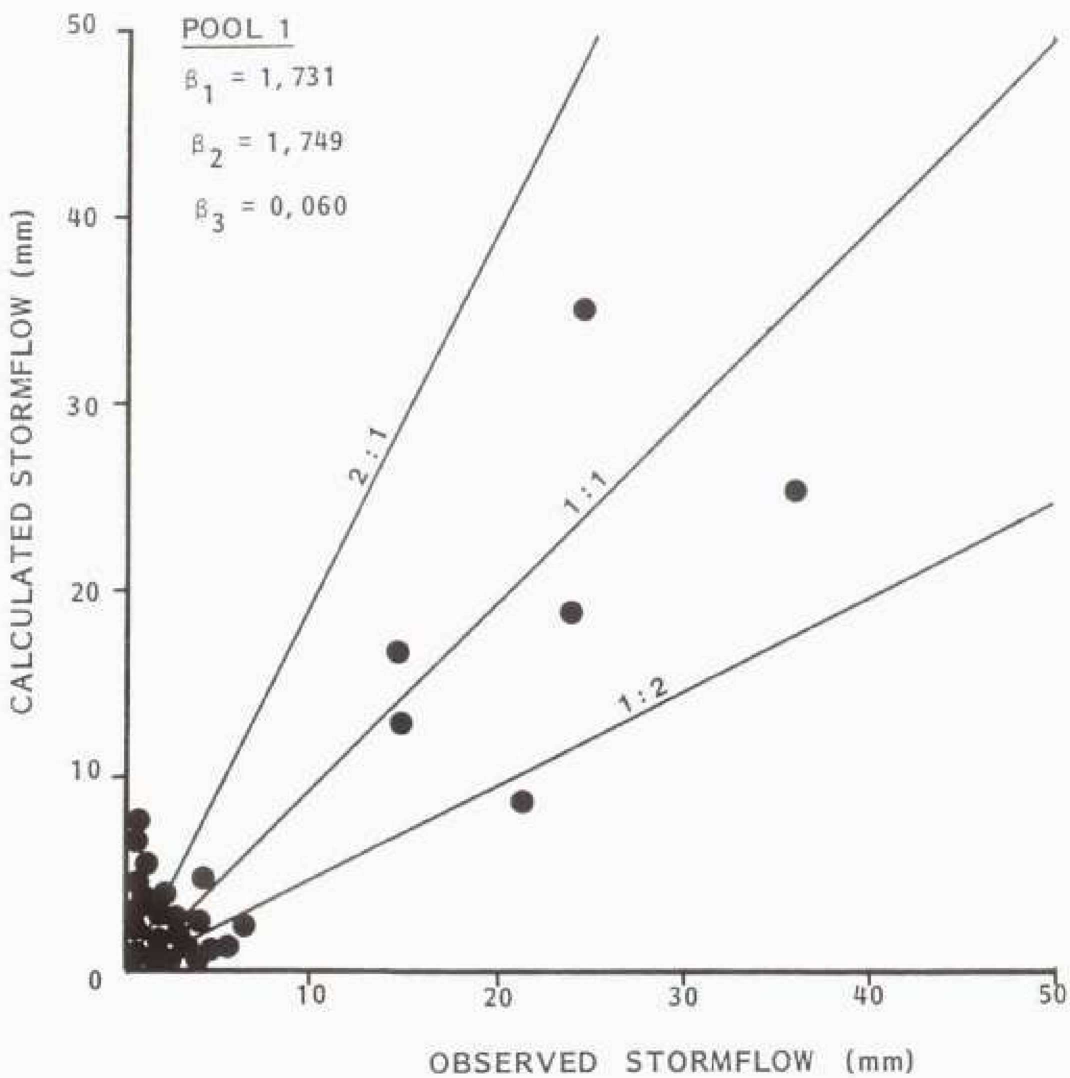
The catchment wetness indices AP7 and AP10 were found to be almost equally as good for calibrating stormflows in the individual catchments (cf Section 11.3.1). Murray and Görgens (1981) reported that AP7 was the most suitable index in their regression analysis of stormflows in these catchments. In view of this finding and the unnecessary inclusion of three additional days antecedent rainfall in the catchment wetness index, the optimised model including AP7 was selected as being most suitable for stormflow estimates assuming the catchments to be ungauged.

On the basis of the results obtained for the pooled data sets the generalised R-index model which appears potentially the most suitable for small catchments in this semi-arid region is the optimised model, excluding a catchment wetness index ($\beta_3 = 0$), for POOL 1 (all events). This version of the model covers the full range of recorded stormflow depths which avoids excessive errors in predicted stormflow for the larger events.

Different findings to those given above may have been reached if an alternative objective function had been used in place of E. Simulations which included BF were not considered in reaching the conclusion since this variable is not available in ungauged situations. The scattergram of observed and estimated stormflows using the R-index method recommended for general use in this region (optimised on POOL 1; $\beta_3 = 0{,}0$) is presented in Figure 11.2. The difficulty of modelling small stormflow events is illu=

strated in Figure 11.2. Events with observed stormflow depths less than 2,4 mm were generally overestimated, this systematic inaccuracy becoming

Figure 11.2 Scattergram of observed and calculated stormflow depths using the optimised R-index method for POOL 1



more severe for the smaller events. Larger events in the data set POOL 1 were modelled with reasonable accuracy, most points falling between the 1:2 and 2:1 lines in Figure 11.2. These results give a measure of the degree of caution which should be exercised if the R-index method were to be used on catchments similar to those included in this study.

11.3.4 The contribution of storm rainfall and the catchment wetness index

Intra-catchment variations in calculated stormflow volumes using the R-index method are determined by the variations in storm rainfall and the catchment wetness index, the response ratio providing for inter-catchment variability. Results presented thus far have indicated that for some data sets and catchment wetness indices storm rainfall alone accounts for differences in the calculated stormflow, the value of β_3 in Equation 9.2 and Equation 10.1 being zero in these instances. Restricting the parameter to zero and then recalibrating the model for each data set provides a means of assessing the relative contribution of storm rainfall to variations in calculated stormflow in each data set for the particular model structure. Table 11.6 contains the results or such stormflow simulations along with the results obtained for stormflow simulations using the most suitable catchment wetness index in the model (from Table 11.4 and Table 11.5).

In examining the results presented for the individual catchments (I, II and III) in Table 11.6 it is apparent that the exclusion of a catchment wetness index from the R-index method in catchments I and III had only a marginal effect on model accuracy with the values of E decreasing slightly (Table 11.6). Furthermore, systematic inaccuracies in these two catchments did not increase notably with the exclusion of the catchment wetness index, this being reflected in the values of a and b and the small differences between D and E in Table 11.6.

The exclusion of F from stormflow estimates in catchment II results in a notable decrease in the value of E from 0,976 to 0,835. However, the reduction in model accuracy for this catchment is not as marked when the objective functions associated with the most suitable antecedent rainfall index (AP7) are considered. The value of E when AP7 is used is 0,848 (Table 11.4) compared with 0,835 when no antecedent moisture index is used (Table 11.6). Thus, it may be concluded that for calibrations in catchment II the only catchment wetness index warranting inclusion in the R-index method would be BF while in catchments I and III catchment wetness indices could be excluded from the method without substantial losses in model accuracy. Further evidence for the greater effect of antecedent moisture

Table 11.6 Results comparing stormflow simulations using the R-index method without a catchment wetness with simulations including the most suitable index

Catch=ment/ Data Set	Catchment Wetness Index	Parameters			Objective Functions			
		β_1	β_2	β_3	D	E	<u>a</u>	<u>b</u>
I	-	1,300	1,881	0,000	0,845	0,843	0,337	0,927
	BF	1,136	1,833	0,154	0,891	0,995	0,695	0,925
II	-	1,368	2,120	0,000	0,835	0,835	0,007	0,946
	BF	1,207	2,144	0,001	0,976	0,972	0,372	0,955
III	-	2,541	1,469	0,000	0,949	0,972	0,432	0,984
	AP10	0,837	1,628	0,336	0,974	0,972	0,403	0,896
POOL 1	-	1,731	1,749	0,000	0,835	0,833	0,216	0,931
	BF	1,518	1,778	0,230	0,866	0,863	0,289	0,933
POOL 2	-	1,383	2,596	0,000	0,236	0,234	-0,322	0,771
	AP10	0,020	5,206	1,953	0,709	0,705	-0,098	0,899
POOL 3	-	0,753	1,887	0,000	0,714	0,714	-0,208	0,866
	BF	0,717	1,797	0,074	0,821	0,819	0,407	0,887
POOL 4	-	0,959	2,670	0,000	0,308	0,299	-0,148	0,713
	Ap10	0,031	5,166	1,450	0,703	0,702	-0,012	0,826

conditions on stormflow volumes in catchment II may be found by examining the differences in the coefficient of variation (CV) for storm rainfall and stormflow for each catchment (Table 11.3). The lowest CV for storm rain=fall and the highest CV for stormflow is in catchment II. This greater relative variability, it may be hypothesised, is attributable to the effect variations in antecedent moisture conditions have on stormflow volumes in this catchment.

Considering the results of stormflow simulations for pooled data where catchment wetness indices have been excluded (Table 11.6), reveals that the maximum reductions in E would be for the data sets POOL 2 and POOL 4. The exclusion of catchment wetness indices from both data sets also gives rise to an increase in systematic errors, with the values of a and b deviating more notably from zero and unit respectively than the values of simulations which include antecedent wetness indices (Table 11.6). Neither POOL 2 nor POOL 4 include the extremely large events of July and August 1979 which suggests that antecedent moisture conditions are important in determining the magnitude of stormflows for the smaller and intermediate events. Since the data sets for catchments I and III included these two extreme events, the finding that antecedent wetness indices had little effect on the accuracy of stormflow simulations in these catchments may have differed had the data been stratified according to the magnitudes of the stormflow events.

The importance of antecedent moisture conditions to small and intermediate events and the apparent irrelevance of these conditions to the large events may be explained in terms of the relative proportions of storm rainfall retained by catchment storages during an event. While, for a given antecedent moisture condition, the amount of storm rainfall required to satisfy catchment storages may be constant regardless of the size of the rainfall events, the proportion of storm rainfall abstracted from smaller events would exceed the proportion retained from larger events. Thus, as catchment storages deplete and approach zero capacity in the larger events stormflow production becomes primarily a function of storm rainfall. Since the soils of the study catchments are poorly defined and shallow, except in the valley bottoms, it may be expected that the storage capacity of these catchments is not substantial. thus the potential variability in total catchment moisture status would be limited and only of significance to the small and intermediate size events.

11.4 Conclusions

The major conclusions reached from this study of the R-index method in three small semi-arid catchments may be summarised as follows:

(a) The model may be calibrated successfully in catchments which are physically and environmentally dissimilar to the humid catchments for which the model was intended.

(b) Parameter values established for the model in these three catchments differed markedly to those of the eastern USA and humid catchments of Natal. This is not surprising as the stormflow producing mechanisms in the semi-arid catchments are probably different from those catchments tested from the USA and Natal.

(c) Antecedent baseflow was found to be the most suitable catchment wetness index in two of the three catchments and a very good index in the third catchment.

(d) Stormflow simulations using seven or 10 days antecedent rainfall were almost equally as accurate in the three catchments. This finding was attributed to the similarity in antecedent rainfall totals for these two periods.

(e) The general model which can be applied in this region was based on calibrations of the pooled data set which included all events. The calibrated model for this data set excluded the catchment wetness index since the associated parameter assumed a value of zero.

(f) Antecedent moisture conditions were found to be important for calculating stormflow volumes for small and intermediate size events and generally unimportant for the larger events.

This study has also indicated that in order for the R-index method to be used with any degree of reliability on ungauged catchments in South Africa, the factors affecting the parameter values and number of days antecedent rainfall most suitable for the model need to be understood and regional values established. The structure of the model lends itself to this approach while the satisfactory results obtained from diverse environmental regions suggests that the model components cater for the major variables affecting stormflow production.

Estimates of the R-index for this study and the evaluation of the R-index method in catchments of Natal have been based on measured stormflow and rainfall data. In ungauged situations this index would have to be estimated and attention is now turned to finding a possible surrogate for the measured R-index.

Chapter 12
ESTIMATION OF THE R-INDEX

The average stormflow response (R-index is described by Hewlett et al (1977) as a measure of the inherent storage capacity of a catchment. Assuming all other variables and parameters in the R-index model to be constant, inter-catchment variations in stormflow are then a function of different R-indices. Authors such as Woodruff and Hewlett (1970) and Bryan (1980) have shown that the R-index can be mapped successfully for the eastern USA (cf Section 9.3). There are, however, insufficient streamflow gauging stations in small catchments of South Africa for this index to be mapped. Widespread use of the R-index method for stormflow estimates in ungauged catchments of South Africa would thus require the inclusion of an alternative response index in the model.

The statistical nature of stormflow response in three catchments is examined in this chapter. Information obtained from these analyses is intended to assist in calculating unbiased stormflow response indices from relatively few observations. Attention is also given to the relationship between catchment R-indices and mean annual discharge response.

12.1 Aims and Procedures

Individual stormflow responses are used to calculate an average response (R-index) for a catchment (Equation 9.1). This sample value approximates the population mean and the accuracy of this approximation is a function of the sample size and degree of normality in the stormflow response data. Small samples and skewed distributions result in biased estimates of the average stormflow response. As Olszewski (1978) has shown, only 15 to 20 sequential observations are required for an unbiased estimate of R if the data are normalised. However, Hewlett et al (1977) concluded that in excess of 100 observations would be required to estimate R within five percent of the 'true' (population) value for data which exhibits marked skew in its distribution. By reducing the number of observations required for an unbiased estimate of R, the use of temporary gauging structures to determine this index in selected catchments becomes a viable undertaking.

The first aim of this study is to examine the frequency distributions of stormflow responses in three Zululand catchments (W1M15, W1M16 and W1M17) and make an attempt at improving the normality of the data by using two exponential transformations. This investigation is based on the three Zululand catchments because sufficient stormflow events were available for meaningful analyses to be conducted. The general applicability of the study is limited and may be regarded as a case study with the findings pertaining specifically to the Zululand region.

Forty-three stormflow responses were available for each of the three Zululand catchments, this data being the same as that used in the study described in Chapter 10 (Appendix 8). Three types of stormflow response were calculated for each catchment according to the following:

(a) $\frac{Q}{P}$

(b) $(\frac{Q}{P})^{0,5}$ and

(c) $(\frac{Q}{P})^{0,667}$

where Q and P are depths (mm) of stormflow and a storm rainfall respectively. The exponents 0,5 and 0,667 were selected because Hewlett et al (1977) and Olszewski (1978) found that these transformations normalised the response data from selected catchments in the eastern USA.

In order to evaluate the normality of each distribution the skew and kurtosis were calculated and a frequency histogram constructed for each set of data. According to Yevjevich (1972) the following expressions give unbiased estimates of skew and kurtosis for small samples:

$$\hat{g}_1 = \frac{n^2}{(n-1)(n-2)} \quad \frac{m_3}{m_2^{1,5}} \qquad \text{..........} \quad (12.1)$$

and

$$\hat{g}_2 = \frac{n^2}{(n-1)(n-2)(n-3)} \quad \frac{m_4}{m_2^2} \qquad \text{..........} \quad (12.2)$$

where

$\hat{g}_1$ = skew (-)

$\hat{g}_2$ = kurtosis (-)

n = number of observations

m_2 = sample second central moment

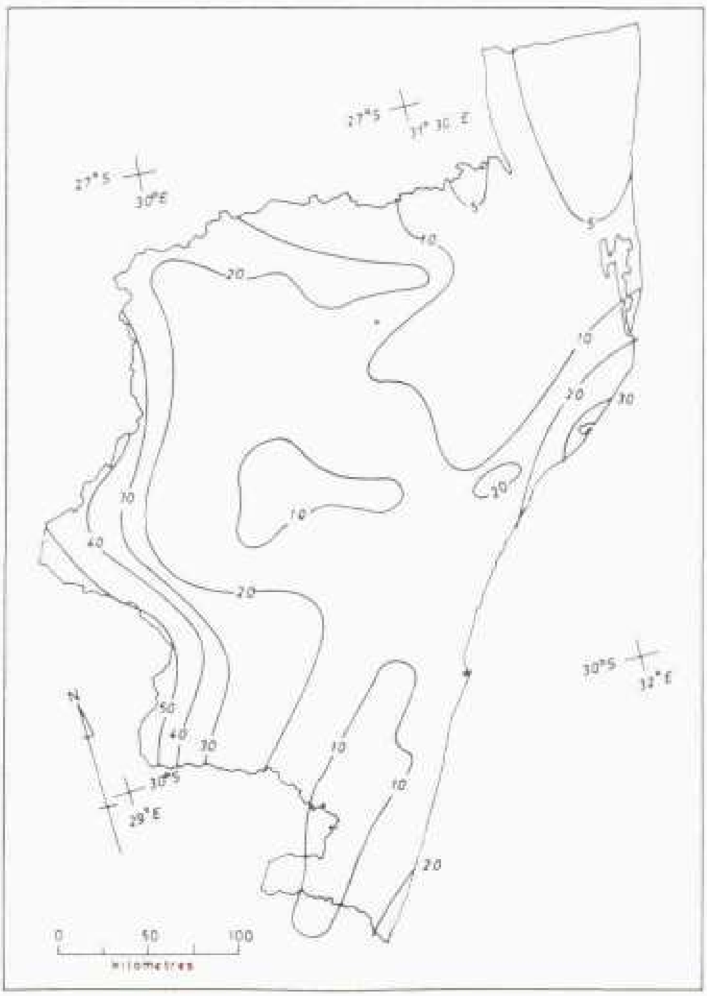
m_3 = sample third central moment and

m_4 = sample fourth central moment

As a distribution tends to normality $\hat{g}_1 \rightarrow 0$ and $\hat{g}_2 \rightarrow 3$.

The second aim of this study is to examine the relationship between mean annual discharge response and the R-index. Mean annual response may be calculated using a procedure such as that described by Midgley and Pitman (1969) (cf Section 6.1.3). Maps of mean annual response have been developed for Natal by Whitmore (1970) (Figure 12.1). If a relationship could be established between mean annual response and R-indices then the estimation of these indices for ungauged catchments would be simplified.

Figure 12.1 Mean annual discharge as a percentage of mean annual rainfall in Natal (After: Whitmore, 1970)



Data used in this second investigation were drawn from catchments W1M15, W1M16 and W1M17 at Zululand (Appendix 8), catchment U2M20 at Cedara (Appendix 8) and the three semi-arid catchments, I, II and III, near Grahamstown (Appendix 10) (cf Sections 10.2 and 11.1). Mean annual discharge response values for the four regions were determined according to the procedure described by Midgley and Pitman (1969). R-indices were calculated using linear data (Equation 9.1) as well as exponentially trans= formed response values using the exponents 0,500 and 0,677 in the following expressions:

$$R_{e0,500} = \frac{\sum_{i=1}^{n} (\frac{Q}{P})^{0,500}}{n} \qquad \text{.......... (12.3)}$$

$$R_{e0,677} = \frac{\sum_{i=1}^{n} (\frac{Q}{P})^{0,667}}{n} \qquad \text{.......... (12.4)}$$

where

R_{ea} = the exponentially transformed R-index for stormflow responses raised to power a.

Average regional response values were calculated by pooling data from each catchment of a region and then recalculating R, $R_{e0,500}$ and $R_{e,0677}$. It was not possible to evaluate statistically the results of this investiga= tion since data from only four regions were analysed. Mean annual response and the R-indices were compared graphically and the results were intended to indicate any possible trends or relationships.

12.2 Results and Discussion

12.2.1 Stormflow response in Zululand

Coefficients of skew ($\hat{g}_1$) and kurtosis ($\hat{g}_1$) for R-indices in the three Zululand catchments are summarised in Table 12.1.

Table 12.1 Coefficients of skew ($\hat{g}_1$) and kurtosis $\hat{g}_2$) for R-indices calculated using linear and transformed data

Catchment	R-index					
	Linear		e(0,500)		e(0,667)	
	$\hat{g}_1$	$\hat{g}_2$	$\hat{g}_1$	$\hat{g}_2$	$\hat{g}_1$	$\hat{g}_2$
W1M15	1,135	4,079	0,458	2,737	0,735	3,137
W1M16	2,347	10,668	0,706	4,169	1,072	6,037
W1M17	1,768	6,619	0,781	4,014	1,515	4,758

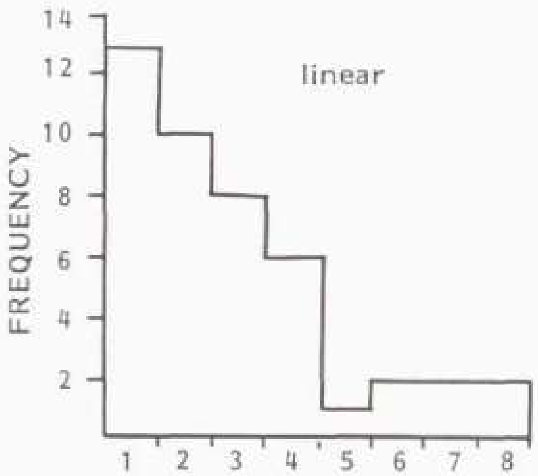
Since the symmetry of a distribution is the major factor affecting bias in estimated values of the mean, most of this discussion focuses on the measure of skew. Distributions of linear stormflow response data exhibit substantial skew in each of three catchments with the minimum value of $\hat{g}_1$ being 1,135 for catchment W1M15 (Table 12.1). Both exponential transforma= tions reduced the skew of data in each catchment with the exponent 0,500 resulting in notably lower value of $\hat{g}_1$ than those for the exponent 0,667. Linear and transformed data of each catchment were all skewed positively and the distributions generally exhibited mesokurtosis ($\hat{g}_2 \rightarrow 3,0$) or tended towards leptokurtosis ($\hat{g}_2 \rightarrow 3,0$).

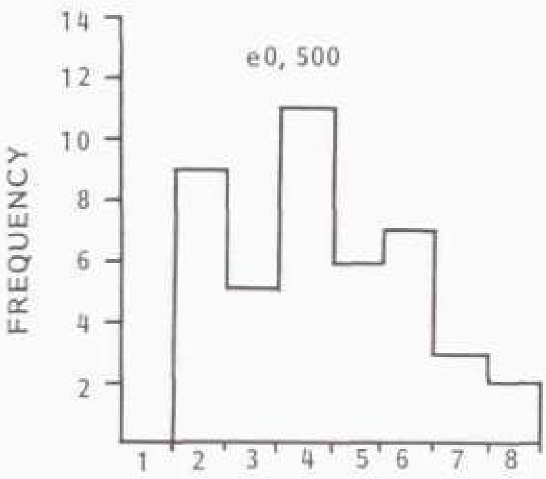
Frequency histograms depicting the distribution of linear and transformed stormflow responses for the three selected catchments are presented in Figure 12.2, 12.3 and 12,4. Three extremely large response values in catch= ments W1M16 and W1M17 were grouped together for convenience (group 9), this group being indicated by a broken line.

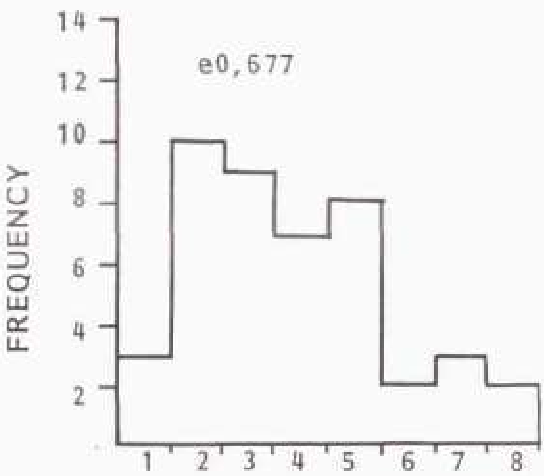
The histograms presented in Figures 12.2, 12.3 and 12.4 illustrate the substantial skew present in the distributions of stormflow response when linear data are used. This assymmetry is reduced notably when data in an exponential form are used, the exponent 0,500 clearly resulting greater normalisation of the data (Figures 12.2, 12.3 and 12.4). Frequency distri= butions for exponential data of catchment W1M16 (Figure 12.3) reflect a tendency towards bimodality but this feature may be a function of the small sample size (n = 43).

Figure 12.2 Frequency histograms based on linear and transformed stormflow response data for catchment W1M15

W1M15



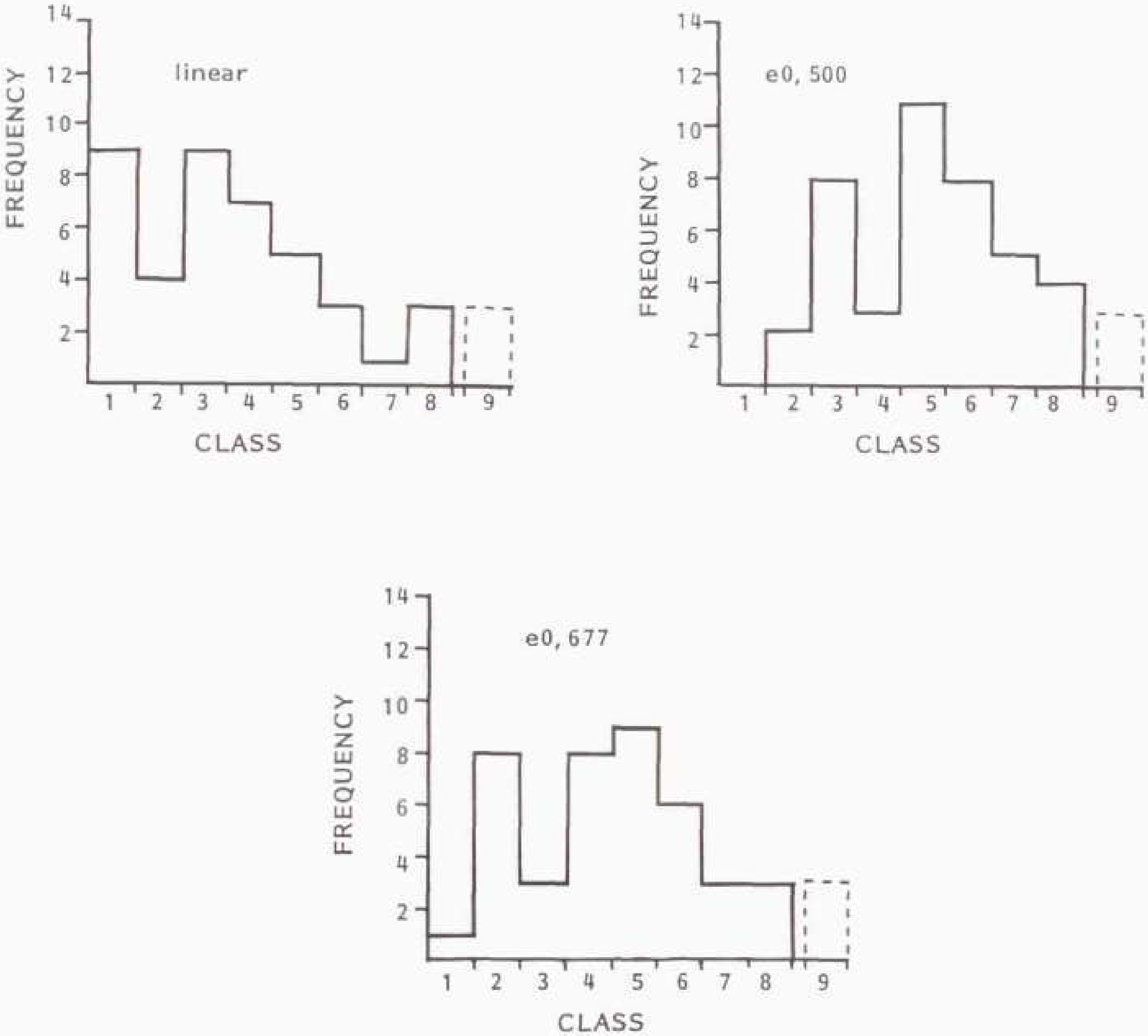




Data	Class								
	1	2	3	4	5	6	7	8	9
Linear	0,000-0,050	0,051-0,100	0,101-0,150	0,151-0,200	0,201-0,250	0,251-0,300	0,301-0,350	0,351-0,400	-
e 0,500	0,000-0,079	0,080-0,158	0,159-0,237	0,238-0,316	0,317-0,395	0,396-0,474	0,475-0,553	0,554-0,632	-
e 0,667	0,000-0,068	0,069-0,136	0,137-0,204	0,205-0,272	0,273-0,340	0,341-0,408	0,409-0,476	0,477-0,544	-

Figure 12.3 Frequency histograms based on linear and transformed storm-flow response data for catchment W1M16

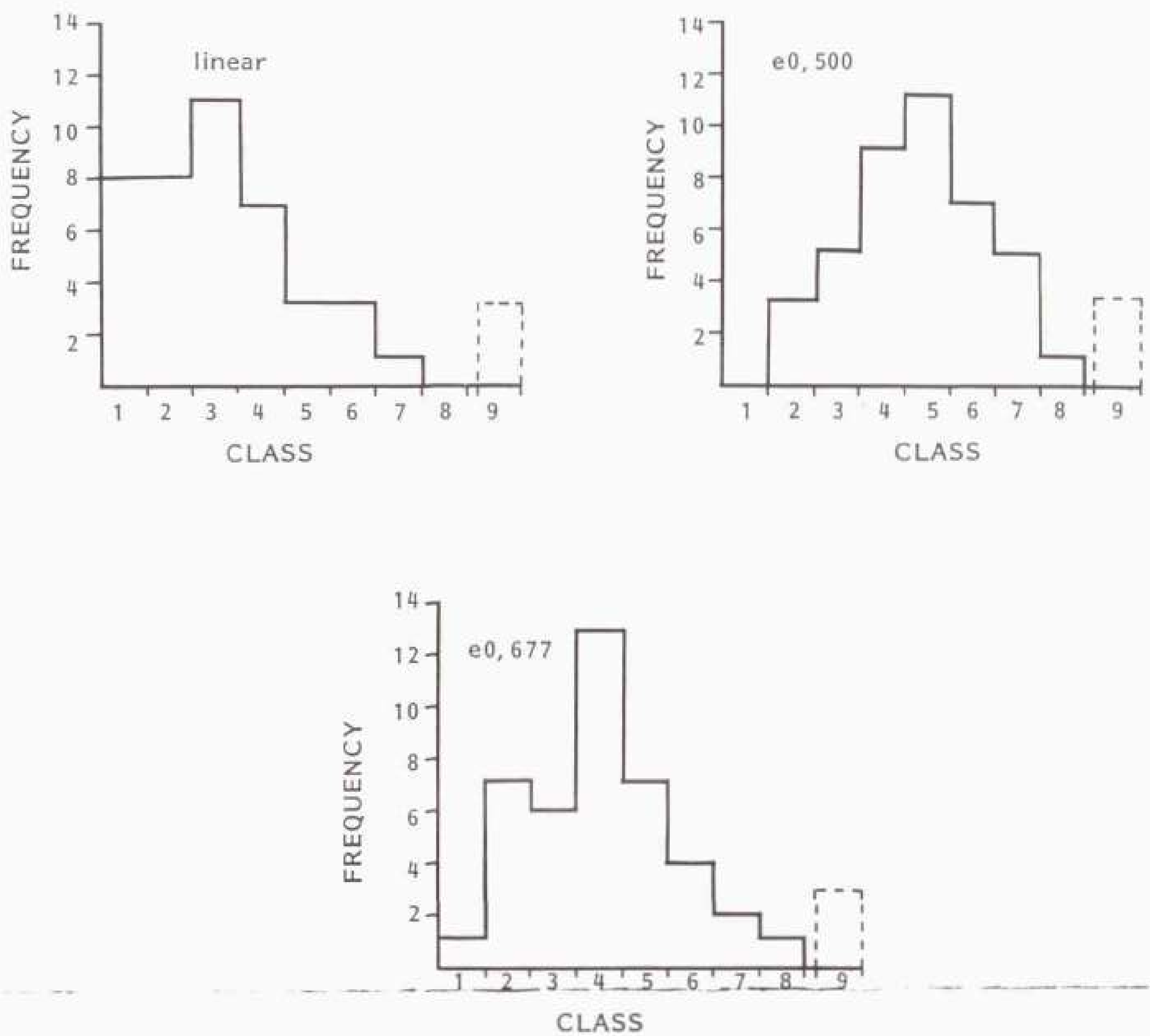
W1M16



Data	Class								
	1	2	3	4	5	6	7	8	9
Linear	0,000-0,041	0,042-0,082	0,083-0,123	0,124-0,164	0,165-0,205	0,206-0,246	0,247-0,287	0,288-0,328	>0,328
e 0,500	0,000-0,072	0,073-0,144	0,145-0,216	0,217-0,288	0,289-0,360	0,361-0,432	0,433-0,504	0,515-0,576	>0,576
e 0,667	0,000-0,060	0,061-0,120	0,121-0,180	0,181-0,240	0,241-0,300	0,301-0,360	0,361-0,420	0,421-0,480	>0,480

Figure 12.4 Frequency histograms based on linear and transformed storm= flow response data for catchment W1M17

W1M17



Data	Class								
	1	2	3	4	5	6	7	8	9
Linear	0,000-0,060	0,061-0,120	0,121-0,180	0,181-0,240	0,241-0,300	0,301-0,360	0,361-0,420	0,421-0,480	>0,480
e 0,500	0,000-0,087	0,088-0,173	0,174-0,260	0,261-0,347	0,348-0,434	0,435-0,521	0,522-0,608	0,609-0,695	>0,695
e 0,667	0,000-0,077	0,078-0,154	0,155-0,231	0,232-0,308	0,309-0,385	0,386-0,462	0,463-0,539	0,540-0,616	>0,616

The value of normalising a frequency distribution of response data may be illustrated by calculating the limits of the true mean response (R-index) with a given probability based on normalised and unaltered data. Limits of the true of population mean were calculated from the sample data (43 events) using the following expression:

$$\bar{X} = \bar{x} \pm t \left(\frac{s}{n-1}\right) \quad \text{.......... (12,5)}$$

where

$\bar{X}$ = the limits of the true mean

$\bar{x}$ = the sample mean

t = Students t value for a given confidence level with degrees of freedom being n-1

s = sample standard deviation and

n = number of observations

Limits of the true mean stormflow response were determined for each set of data in the three catchments (Equation 12.5) and are tabulated in Table 12.2.

Table 12.2 Upper ($\bar{X}_u$) and lower ($\bar{X}_l$) limits of the true mean stormflow response (95 % confidence) and percent deviation from the sample mean for the three Zululand catchments

Catchment	Data	$\bar{X}_1$	$\bar{X}_u$	Deviation (%)
W1M15	Linear	0,093	0,151	23,4
	e0,500	0,272	0,354	13,0
	e0,667	0,187	0,261	16,6
W1M16	Linear	0,117	0,197	25,8
	e0,500	0,318	0,358	12,4
	e0,667	0,225	0,317	17,0
W1M17	Linear	0,144	0,230	22,9
	e0,500	0,352	0,447	11,3
	e0,557	0,260	0,352	15,1

By improving the normality of stormflow response data the limits of the true mean response index are reduced substantially (Table 12.2). Limits of the true mean deviated from the sample mean in catchments W1M16 and W1M17 by 25,8 percent and 22,9 percent respectively when linear data were used. These limits were more than halved when the data were transformed using an exponent of 0,500 (Table 12.2). A similar result was obtained for catchment W1M15 but the deviation from the sample mean was reduced by slightly less than half from 23,4 percent to 13,0 percent. There is also a substantial improvement in estimating the population an when the alternative exponential transformation (e0,667) is used (Table 12.2).

The results of this study are in agreement with the findings of Hewlett _et al_ (1977) and Olszewski (1978) that exponential transformations normalise the distribution of stormflow responses from small catchments in the eastern USA. Hewlett _et al_ (1977) reported that the use of the exponent 0,500 resulted in the most normalised distribution, a finding substantiated in this study of the three Zululand catchments.

12.2.2 Estimation of the R-index from mean annual hydrological response

R-indices calculated using linear and exponentially transformed data from catchments in the Zululand, Cedara, De Hoek and Grahamstown regions are given in Table 12.3 along with the mean annual discharge response values for those regions. Diagrams illustrating the relationship between stormflow response indices and mean annual discharge response for each region are presented in Figure 12.5. From an examination of Table 12.3 and Figure 12.5 the following may be noted:

(a) R-indices calculated using linear data are close to half the magnitude of the mean annual response in each of the four regions. This relationship is particularly notable where average regional R-indices were plotted against mean annual response. The scatter of values about the 1:2 line for individual catchments may be attributed to individual catchment differences.

b) Normalising stormflow response data with an exponential transformation of e = 0,500 results in a greater scatter of points when individual catchments are considered. However, averaging the response indices results in a very convincing non-linear relationship between stormflow response ($R_{e0,500}$) and mean annual discharge response.

Table 12.3 Mean annual response and R-indices using linear and transformed data for selected catchments of the Zululand, Cedara, De Hoek and Grahamstown regions

Region	Catchment	R-index			Mean Annual
		Linear	e0,500	e0,667	Response
Zululand	W1M15	0,122	0,313	0,224	0,310
	W1M16	0,157	0,363	0,271	
	W1M17	0,187	0,402	0,306	
	Average	0,155	0,359	0,267	
Cedara	U2M20	0,053	0,214	0,133	0,094
De Hoek	V1M28	0,088	0,249	0,170	0,153
	V7M03	0,103	0,282	0,195	
	Average	0,096	0,266	0,183	
Grahams= town	I	0,068	0,178	0,124	0,075
	II	0,043	0,238	0,085	
	III	0,090	0,258	0,179	
	Average	0,058	0,169	0,112	

(c) Results obtained using e = 0,667 in the exponential transformation of stormflow response data are similar to those obtained using an exponent of 0,500 with the relationship between the R-index ($R_{e0,667}$) and mean annual response also being non-linear.

For each of the three R-indices (R, $R_{e0,500}$ and $R_{e0,667}$) used in this study the results have indicated that individual catchment response indices exhibit a less clearly defined relationship with mean annual response than the averaged R-indices do. Since catchment size may cause this variability, future studies of the R-index in South Africa should investigate the relationship between response indices and catchment size.

Figure 12.5 Relationship between mean annual discharge response and the R-index of (a) individual catchments and (b) the average for each region using linear and transformed (=0,500; =0,677) stormflow response data

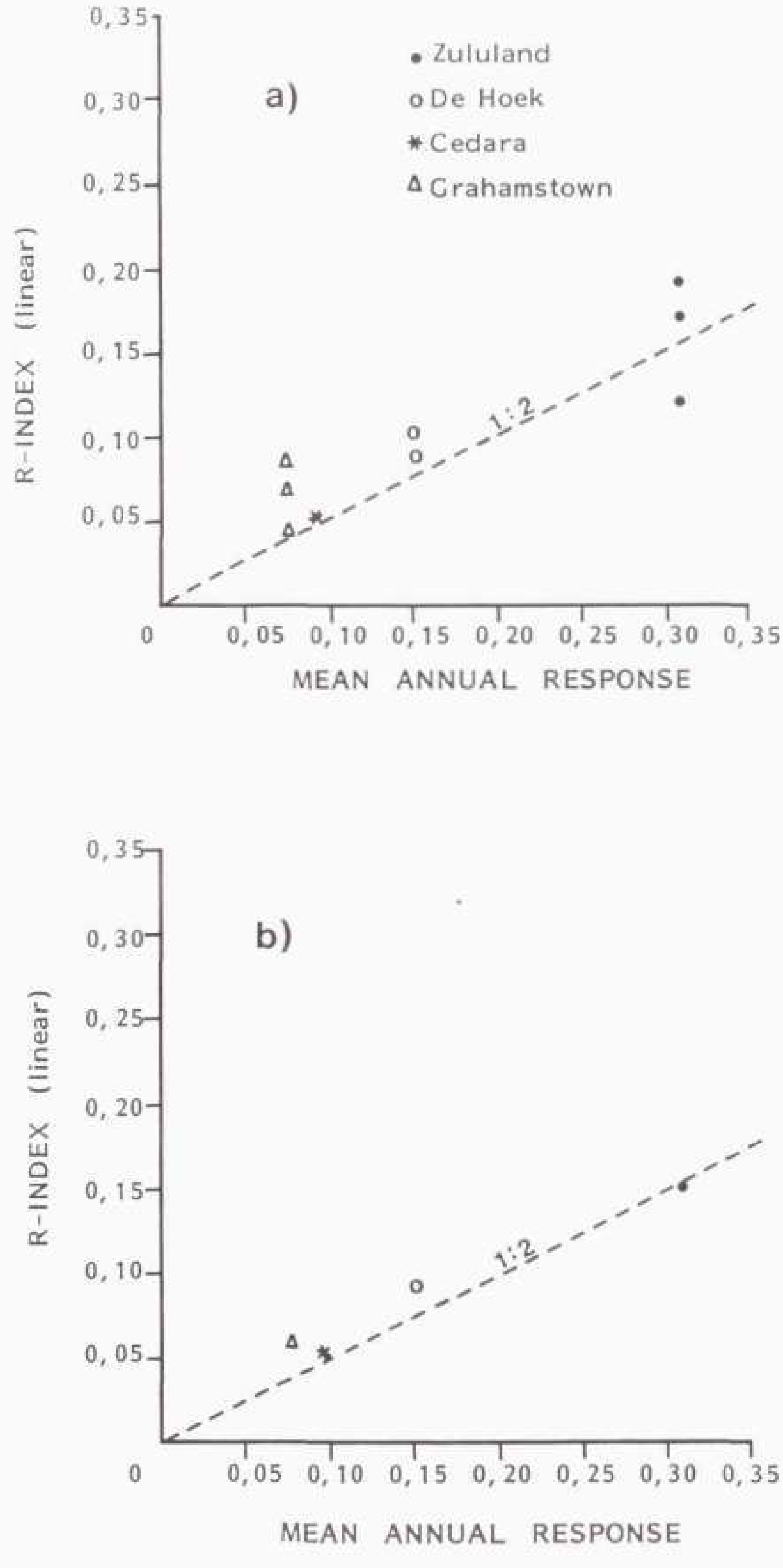


Figure 12.5 (continued)

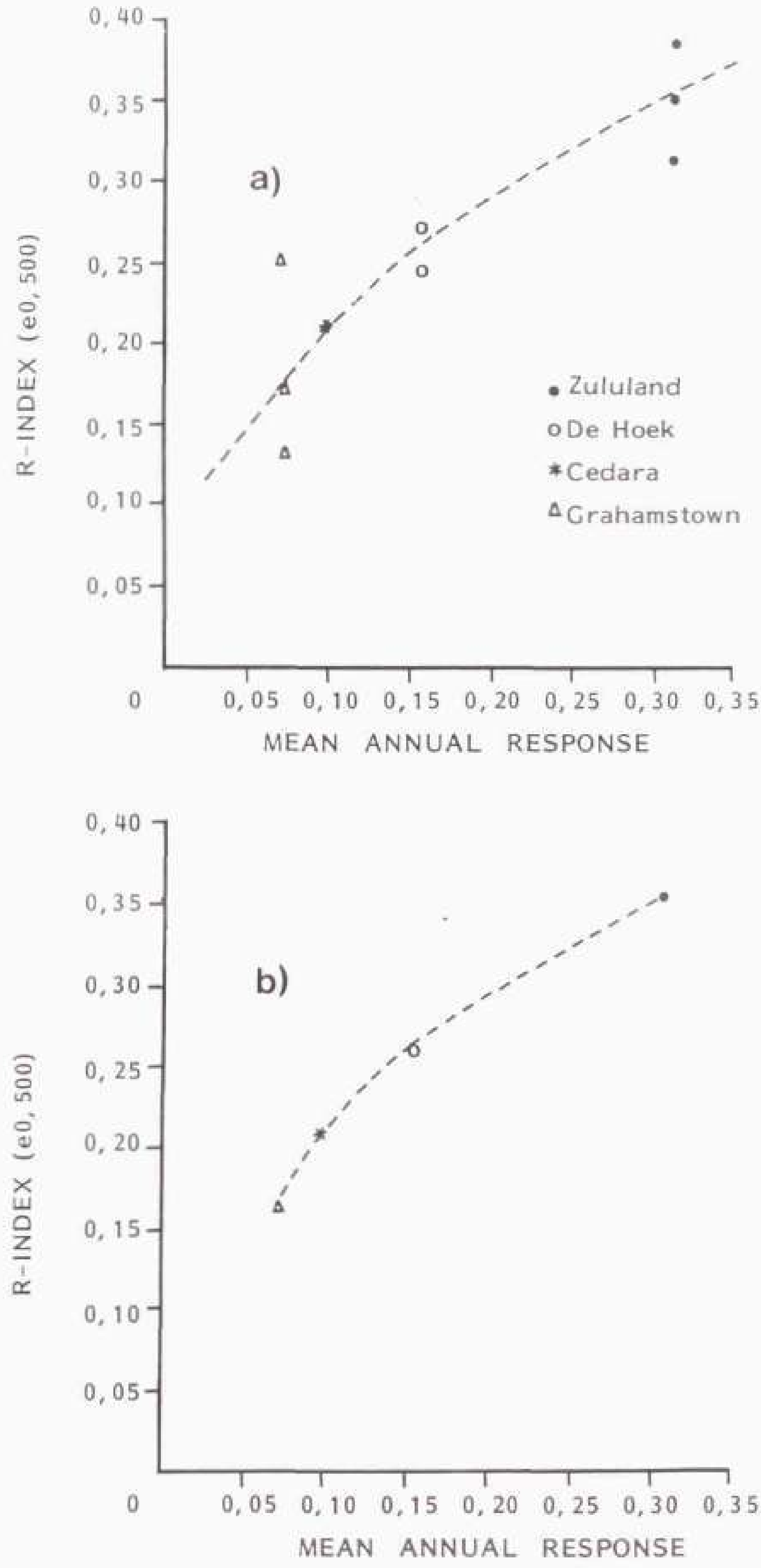
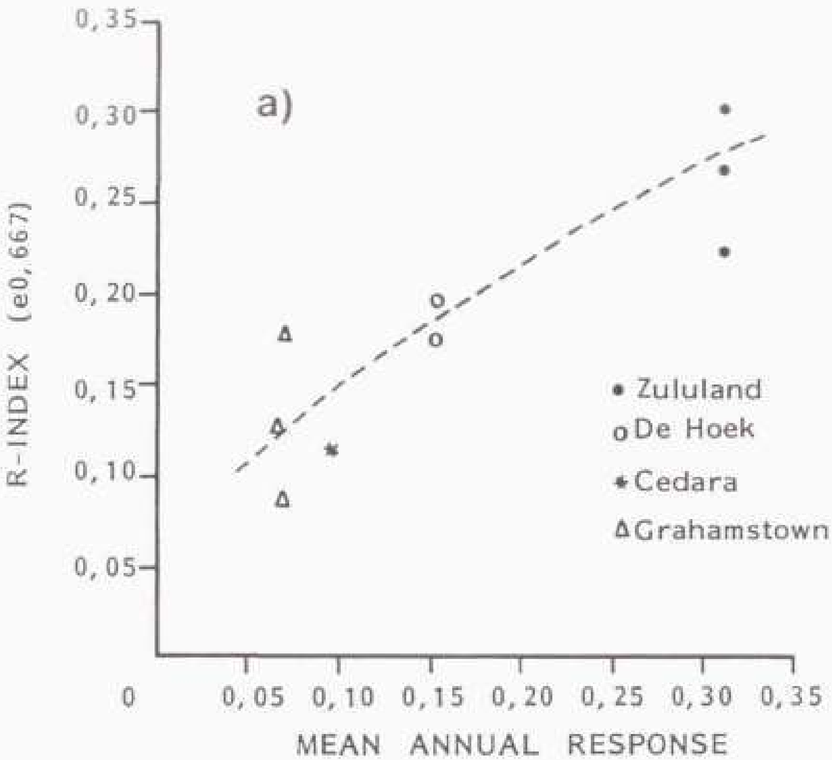
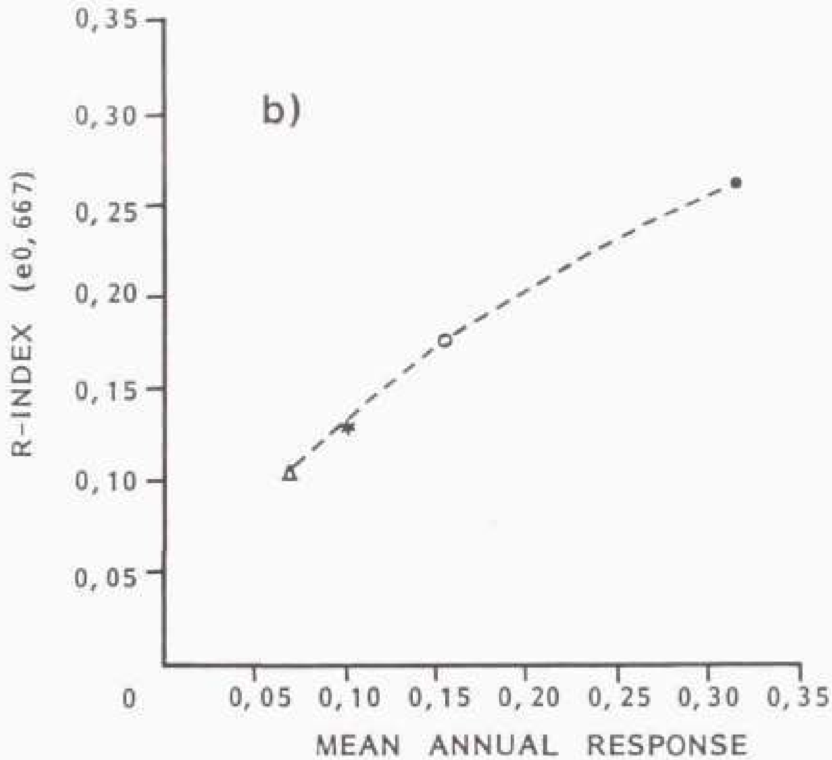


Figure 12.5 (continued)





12.3 Conclusions

A major limitation of this study has been the small sample of catchments included in the analyses. However, a number of notable conclusions were reached, namely:

(a) The use of exponential transformations, particularly the exponent 0,500, made the stormflow response data of three small catchments in Zululand more normal. This was the same exponential transformation which was found by Hewlett et al (1977) to normalise stormflow response data from catchments in the eastern USA. It was hypothesised that the existence of similar stormflow producing mechanisms in the two regions accounted for this finding. A similar conclusion was reached in testing the R-index model on data from these three Zululand catchments (cf Section 10.4.1).

(b) Normalising the frequency distributions of stormflow responses in the Zululand catchments resulted in substantially more accurate estimates of the true mean response index.

(c) Although catchments from only four regions of South Africa were included in the second aspect of this study, there was convincing evidence of a relationship between regional mean annual discharge response and the R-indices.

In view of the general availability of mean annual response information for most regions of South Africa this research warrants further investigation with a larger and more diverse sample of catchments being considered.

Although promising results have been obtained in this investigation of the R-index, these findings are either limited in their applicability or require further investigation. Immediate or near future use of the R-index model in South Africa requires a more readily available index of catchment response, such as a curve number. An examination of this problem is included in the following chapter.

Chapter 13
THE DISTRIBUTED R-INDEX METHOD

The original R-index model developed by Hewlett et al (1977) is a lumped model in which the basic unit of study is the first order catchment. A single response index is assigned to a catchments and no allowance is made for separate indices of sub-units in a catchment. Estimates of stormflow volumes using the SCS model have been shown to improve substantially when the distributed curve number method was adopted in favour of using the lumped curve number approach (cf Chapter 5). For a distributed R-index method to be developed, a surrogate would have to be found for the lumped catchment response index which would reflect the different stormflow potentials of sub-units in a catchment.

Attention is given in this chapter to developing and testing a distributed R-index model. Implicit in this objective is the establishment of a readily determinable substitute for the lumped response index in the model.

13.1 The problem and approach

Many hydrological investigations require estimates of stormflow volumes from sub-catchments or small areas in a catchment. The original form of the R-index method is not suited to this application because of the lumped nature of the response index (R). The concept of a curve number (CN) for assessing average stormflow response is particularly attractive since it defines potential response on the basis of the soil-cover complex of a catchment (cf Section 3.1). While the absolute relationship between these variables and stormflow may be challenged the strength of the N concept lies in its definition of relative stormflow potential. It is for this reason that CN's were selected to replace the lumped R-index in this model.

Furthermore, CN's may be determined from readily available soils, vegetation and land-use information (cf Section 3.1).

A large number of gauged small catchments covering a wide range of CN values is not available in South Africa for calibrating the R-index model for single CN units. However, an attempt was made to circumvent this problem by adopting the following approach:

(a) A computer programme, INDST, was developed to calculate stormflow from sub-units in a catchment using CN's in the R-index model.

(b) Optimisation of model parameters was based on the assumption that β_1, β_2 and β_3 (Equation 9.2) were consistent for each CN unit in a catchment and that the summation of stormflow volumes from sub-units could be compared with total stormflow volume at the outlet of the catchment. A further assumption was that errors from different sub-units did not compensate one another.

An attempt is made in the ensuing analyses and discussion to answer two questions, viz:

(a) Can catchment stormflow volumes be calculated accurately using a distributed R-index model and CN's as the response indices?

(b) Once the distributed model has been calibrated using observed stormflow data are the parameters of the model transferable up and/or down stream from the gauging station?

13.2 The model, catchments and data

The computer programme INDST was based on the programme INDEX which is described in Section 10.3.1. INDST allows for up to 10 R-indices to be entered for sub-units are also entered and stormflows are calculated for each sub-unit which are then summated and compared with observed values as in INDEX. An important aspect of calculating stormflow for individual sub-units is that each unit has a specific storm rainfall threshold above which any additional storm rainfall is added directly to stormflow (cf Section 9.1). Furthermore, only antecedent rainfall can be used as an index of catchment wetness since antecedent baseflow is not available for sub-units. A listing of the programme INDST along with operation instructions is given in Appendix 11.

An examination of the distributed R-index method was conducted using data from three Zululand catchments, W1M15, W1M16 and W1M17 (Appendix 8). These catchments were particularly useful for this study since:

(a) A large number of measured stormflow events (n=43) was available for each catchment, this data having been used to test the lumped R-index model (cf Chapter 10).

(b) Curve numbers had been determined for catchments W1M16 and W1M17 for testing the SCS model (cf Section 4.4). The derivation of CN units for catchment W1M15 is given in Appendix 12.

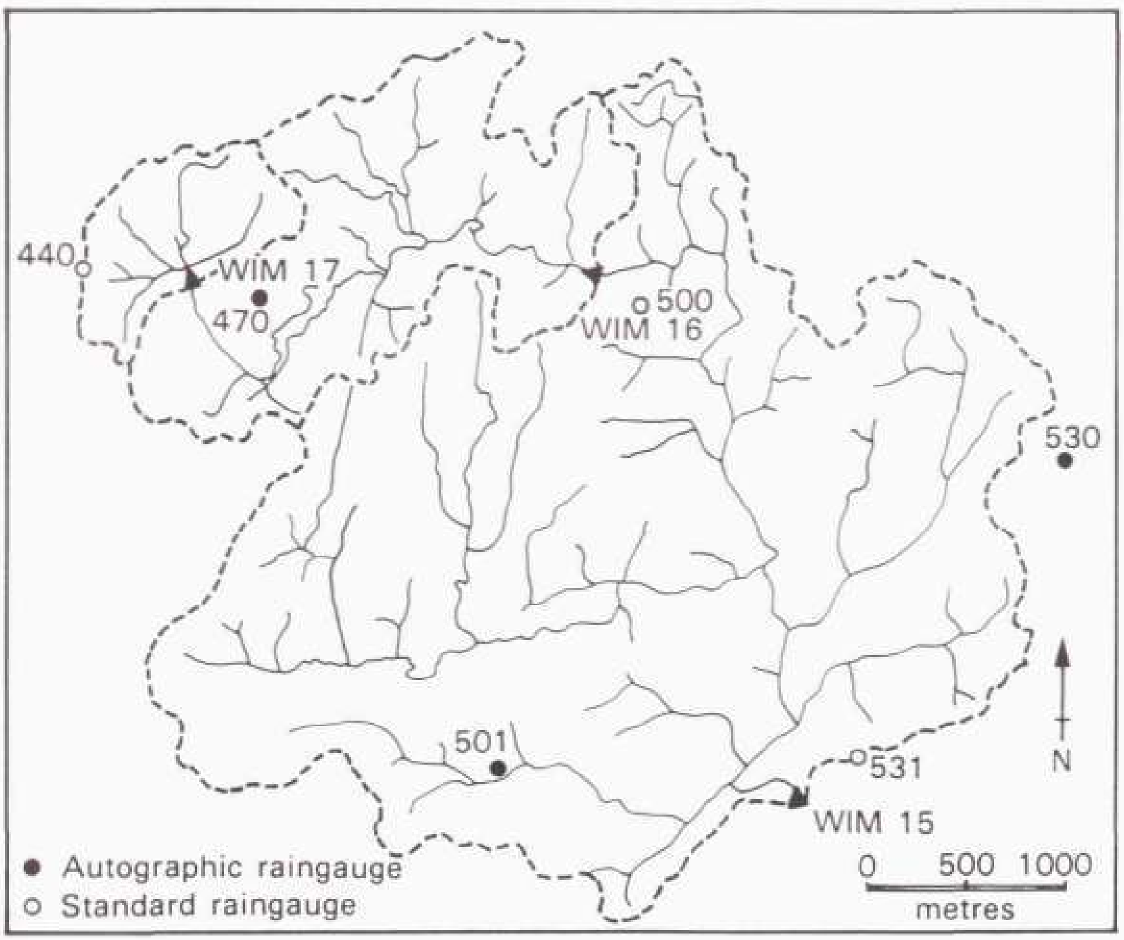
(c) The three catchments are nested allowing for the model to be tested against stormflows measured up or downstream for the gauging station where the model was calibrated (Figure 13.4).

13.3 Results and discussion

13.3.1 Calibrating the distributed model

Calibration of the distributed R-index method was undertaken by optimising the coefficient of efficiency (E) as was done for the lumped R-index method (cf Chapter 10). Since calibrations of the lumped model were restricted to

Figure 13.1 The three nested Zululand catchments W1M15, W1M16 and W1M17



using parameters accurate to two decimal places, this procedure was adopted for the distributed model allowing for unbiased comparisons to be made of the results of the two approaches. Model parameters were optimised using observed data from each of the catchments with antecedent rainfall totals for 5-days (AP5), 10-days (AP10) and 15-days (AP15). Results of these calibrations are presented in Table 13.1.

Table 13.1 Results of stormflow simulations using selected periods of antecedent rainfall in the distributed R-index method

Catchment	Catchment Wetness Index	Parameters β_1	β_2	β_3	Objective Functions D	E	a	b
W1M15	AP5	0,060	1,690	0,440	0,761	0,760	-0,568	0,988
	AP10	0,060	1,700	0,180	0,723	0,719	-0,595	1,010
	AP15	0,050	1,830	0,190	0,726	0,726	-0,696	0,986
W1M16	AP5	0,050	1,910	0,340	0,994	0,993	-0,292	0,996
	AP10	0,060	1,860	0,010	0,977	0,977	-0,021	1,021
	AP15	0,040	1,760	0,300	0,956	0,956	-1,055	1,017
W1M17	AP5	0,080	1,870	0,040	0,985	0,985	0,126	0,971
	AP10	0,070	1,930	0,010	0,988	0,987	0,041	0,976
	AP15	0,070	1,650	0,260	0,988	0,988	-0,630	1,009

Stormflow simulations using the distributed R-index method were generally accurate for all catchments regardless of the catchment wetness index used (Table 13.1). Values of D and E are similar indicating minimal systematic inaccuracies in the calculated stormflows. An examination of a and b values in Table 13.1 confirms this finding with these values approaching zero and one respectively. The most accurate stormflow calibrations, as defined by the objective function E, were associated with AP5 in catchments W1M15 and W1M16 and AP15 in catchment W1M17. However, the value of E for AP5 (E=0,985) in catchment W1M17 was only marginally lower than the value for AP15 (E=0,988).

By comparing the simulation results of the lumped model (cf Chapter 10) with those of the distributed model, the relative success of using CN's and a distributed procedure may be gauged. Selected objective functions (D and E) for stormflow simulations using both versions of the model in the three catchments are given in Table 13.2.

Table 13.2 Coefficients of determination (D) and efficiency (E) for stormflow simulations using the lumped and distributed R-index models

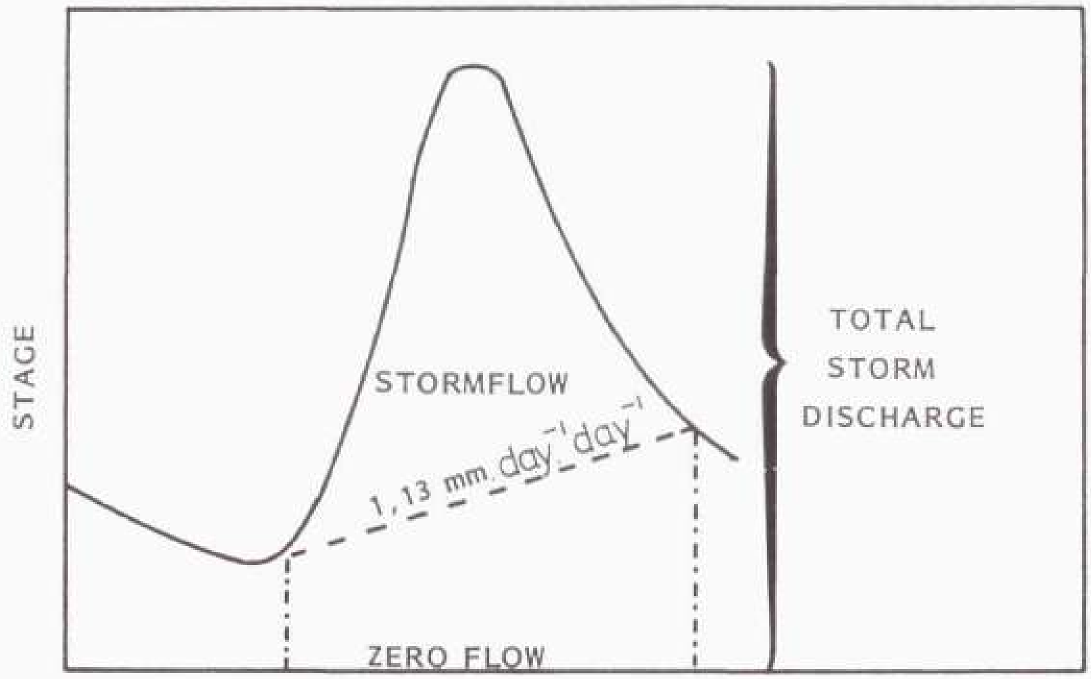
Catchment	Catchment Wetness Index	Objective Functions			
		D		E	
		Lumped	Distributed	Lumped	Distributed
W1M15	AP5	0,752	0,761	0,752*	0,760*
	AP10	0,719	0,723	0,714	0,719
	AP15	0,718	0,726	0,717	0,726
W1M16	AP5	0,995	0,994	0,995*	0,993*
	AP10	0,989	0,977	0,988	0,977
	AP15	0,978	0,956	0,973	0,956
W1M17	AP5	0,974	0,985	0,974	0,985
	AP10	0,976	0,988	0,976	0,987
	AP15	0,990	0,987	0,990*	0,988*

* Highest catchment value

Stormflow calibrations using the distributed R-index method were more accurate than calibrations using the lumped method in catchments W1M15 and W1M17 for all antecedent rainfall periods tested except AP15 in catchment W1M17 (Table 13.2). However, the values of D and E in Table 13.2 are generally similar for both versions of the model. The most suitable catch= ment wetness index for stormflow simulations in each catchment was found to be the same for both the lumped and distributed models (Table 13.2). In catchment W1M17 the value of E using the distributed model with AP5 (E=0,985) is marginally less than the value for AP15 (E=0,988). This was not the case for the lumped model with AP5 being associated with an E value of 0,974 compared to 0,988 for AP15.

Simulation of stormflow volumes in the three Zululand catchments using the distributed R-index method and CN's was generally successful. In view of this finding the distributed model was also tested using total storm discharge in place of stormflow volumes. The distinction between stormflow and total storm discharge is illustrated in Figure 13.2. Simulation

Figure 13.2 Definition diagram of stormflow and total storm discharge



results using the distributed R-index method to calculate total storm discharge for the three Zululand catchments are presented in Table 13.3. Estimation of total storm discharge using the distributed R-index model was successful in each of the three catchments (Table 13.3). In comparing these results with those obtained for stormflow simulations (Table 13.1) the following may be noted:

(a) The parameter β_1 increased for all simulations of total storm discharge while β_2 decreased for all simulations except those based on AP5 and AP10 in catchment W1M17. The parameter values for β_3 were similar for simulations of stormflow and total storm discharge. However, there was a tendency for β_3 to increase slightly when the model was optimised using total storm discharge.

Table 13.3 Results of total storm discharge simulations using selected periods of antecedent rainfall in the distributed R-index method

Catchment	Catchment Wetness Index	Parameters			Objective Functions			
		β_1	β_2	β_3	D	E	a	b
W1M15	AP5	0,080	1,560	0,470	0,719	0,718	-0,939	0,964
	AP10	0,070	1,690	0,210	0,658	0,656	-1,171	0,949
	AP15	0,060	1,780	0,220	0,661	0,655	-1,343	0,939
W1M16	AP5	0,070	1,840	0,340	0,990	0,990	-0,729	-0,996
	AP10	0,090	1,680	0,060	0,972	0,970	-1,399	1,056
	AP15	0,070	1,570	0,290	0,960	0,960	-1,030	1,021
W1M17	AP5	0,090	1,910	0,090	0,987	0,985	-0,658	0,963
	AP10	0,080	1,970	0,010	0,987	0,985	-0,686	0,967
	AP15	0,100	1,530	0,290	0,987	0,988	-0,608	1,004

(b) Model accuracy was reduced (lower E values) for most simulations using total storm discharge. This reduction in accuracy decreases with the reduction in catchment size and in catchment W1M17 two of the three values of E in Table 13.1 and Table 13.3 are equal, the third value only differing by 0,002 (AP10).

(c) The catchment wetness indices which gave the best stormflow simulations result in each catchment also gave the best total discharge simulation results.

The findings outlined in the preceding discussion have indicated that the distributed R-index method may be calibrated successfully to simulate both stormflow and total storm discharge. The model does, however, appear to be more suited to stormflow estimation (cf Tables 13.2 and 13.3). While the R-index method including CN's as response indices gives accurate estimates of the stormflows at the outlet of each catchment. This cannot be taken as conclusive evidence that the stormflow from sub-units in a catchment has been modelled successfully. The following analysis is, however, intended to provide a clearer indication of the value of the method for estimating stormflow from sub-catchments or areas in a catchment.

13.3.2 Transferability of model parameters

In developing the distributed R-index method it was assumed that parameters of the model optimised an observed stormflow data at the outlet of a catchment would be applicable to different sub-units in the catchment. Furthermore, it was assumed that CN's provide a relative measure of the stormflow potential from sub-units in a catchment. If these assumptions are valid it may be expected that calibrating the distributed R-index method on part of a catchment should provide suitable parameter values for stormflow estimates in other parts of the catchment.

Parameters for the distributed R-index method are optimised for the three Zululand catchments using the three selected catchment wetness indices (AP5, AP10 and AP15). Optimised parameters for any one catchment were used in the R-index method to calculate stormflow volumes in the other two catchments. The accuracy of these simulations was then compared with that of the optimised model for the catchment. Results of tests are presented in Table 13.4 for AP5, Table 13.5 for AP10 and Table 13.6 for AP15.

Table 13.4 Results of stormflow simulations using AP5 in the distributed R-index method with optimised and transferred parameters

Catchment	Catchment Parameters	Objective Functions D	E	a	b
W1M15	W1M16	0,715	0,691	-0,172	0,849
	W1M17	0,652	0,592	0,639	0,772
	OPT	0,761	0,760	-0,568	0,988
W1M16	W1M15	0,970	0,939	-6,666	1,190
	W1M17	0,974	0,971	1,294	0,951
	OPT	0,994	0,993	-0,292	0,996
W1M17	W1M15	0,926	0,879	-8,540	1,243
	W1M16	0,970	0,968	-1,579	0,993
	OPT	0,985	0,985	0,126	0,971

Table 13.5 Results of stormflow simulations using AP10 in the distributed R-index method with optimised and transferred parameters

Catchment	Catchment Parameters	Objective Functions D	E	a	b
W1M15	W1M16	0,639	0,591	0,672	0,829
	W1M17	0,643	0,607	0,036	0,809
	OPT	0,723	0,719	-0,575	1,010
W1M16	W1M15	0,959	0,954	-2,710	1,049
	W1M17	0,972	0,970	0,815	0,959
	OPT	0,977	0,977	-0,021	1,021
W1M17	W1M15	0,955	0,942	-4,434	1,106
	W1M16	0,975	0,963	-3,203	1,117
	OPT	0,988	0,987	0,041	0,976

Table 13.6 Results of stormflow simulations using AP15 in the distributed R-index method with optimised and transferred parameters

Catchment	Catchment Parameters	Objective Functions D	E	a	b
W1M15	W1M16	0,643	0,639	-0,787	0,936
	W1M17	0,652	0,639	-0,276	0,891
	OPT	0,726	0,726	-0,696	0,986
W1M16	W1M15	0,946	0,937	1,550	0,911
	W1M17	0,954	0,949	1,515	0,938
	OPT	0,956	0,956	-1,055	1,107
W1M17	W1M15	0,985	0,983	-0,175	0,969
	W1M16	0,987	0,976	-3,320	1,108
	OPT	0,987	0,988	-0,630	1,009

The transferability of model parameters from a sub-catchment to a larger catchment or vice versa may be affected by the relative size of the sub-catchment to the larger catchments. Areas of catchments W1M15, W1M16 and W1M17 are 13,65 km^2, 3,22 km^2 and 0,67 km^2 respectively. Thus, the smallest catchment (W1M17) is 4,0 percent of the area of W1M15 and W1M16 is 23,5 percent of this area. Catchment W1M17 is 20,8 percent of the area of catchment W1M16. However, if catchment area is unimportant and model parameters are consistent for all sub-units (CN's) in a catchment then these parameters should be transferable from one catchment to another without substantial losses in model accuracy.

From a comparison of the optimum objective functions of each catchment in Zululand with those obtained using the model with parameters obtained from calibrations up or downstream (Tables 13.4, 13,5 and 13,6), it is evident that goodness of fit of the model, based on E, is reduced when transferred parameters are used. This reduction in accuracy is generally not substan= tial with the greatest reduction in E being from 0,760 to 0,592 for catch= ment W1M15 using the parameters of catchment W1M17 and the catchment wetness index AP5 (Table 13.4). Examining the corresponding values of D, a and b for this catchment indicates that systematic errors increased more than random errors.

Whether the distributed R-index model is calibrated up or downstream from a test catchment does not appear to result in notably different decreased in model accuracy from the optimised model's accuracy. What is revealed as important in transferring model parameters is that the catchment wetness index most suitable for the test catchment does not change. A summary of parameters which were most successfully transferred to test catchments and the associated catchment wetness index is given in Table 13.7.

Table 13.7 Catchment's parameters most successfully transferred to a test catchment and the catchment wetness index used

Test Catchment	Most Suitable Parameters	Catchment Wetness Index
W1M15	W1M16	AP5
W1M16	W1M17	AP10
W1M17	W1M16	AP15

The three catchment wetness indices for each test catchment in Table 13.7 are the same as those found to give the best optimised results in these catchments (cf Section 13.3.1).

13.4 Conclusions

The distributed R-index method using CN's as response indices in the three Zululand catchments has been shown to be successful in terms of simulation accuracy and transferability of model parameters for stormflow estimates up or downstream from the point of calibration. Response indices other than CN's could be used in this model and where adequate data exists the storm rainfall and antecedent rainfall for each sub-unit may be determined and possibly improve model accuracy. Estimation of total storm discharge from these catchments was also accurate using this model.

Antecedent moisture conditions were, once again, shown to be important in determining the accuracy of the R-index model using either optimised or transferred parameters. Errors in model parameters values and inputs to the model gave rise to simulation inaccuracies. A better understanding of the magnitude of these inaccuracies in relation to the parameter and input errors is, however, required. This problem is addressed in the following chapter.

Chapter 14
ERROR ANALYSIS

The preceding calibrations and tests of the R-index model have been conducted assuming the inputs and model parameters to be accurate. According to Troutman (1982) input variables for hydrological models are never error free. Since the determination of model parameters is affected by inaccuracies in input data, the optimised values should also be regarded as estimates of the 'true' parameter values. Error analyses are described in this chapter which are intended to provide a preliminary guide to the type of errors which may be expected in using the R-index method.

14.1 Source of model errors

Errors in calculated stormflow volumes using the R-index method may be apportioned as follows:

$$E_T = f(R_E, P_E, CWI_E, \beta_E, U_E)$$

where

E_T = total error in calculated stormflow volume
R_E = error in estimated R-indices
P_E = error in estimated storm rainfall
CWI_E = error in estimated catchment wetness index
β_E = error in estimated model parameters and
U_E = variability in stormflow volumes unexplained by the model.

Errors in estimated model parameters based on observed input data may in turn be defined as:

$$\beta_E = f(R_E, P_E, CWI_E, Q_{OE}, U_E)$$

where

Q_{OE} = errors in observed stormflow volumes used to calibrate the model.

From an analysis of input errors in rainfall-runoff models, Troutman (1982) concluded that severe errors in estimated stormflow volumes from a non-linear regression model could result from inaccuracies in estimated storm rainfall. Furthermore, such inaccuracies may also give rise to substantial bias in the estimated parameter values. The errors in calculated stormflow volumes associated with inaccuracies in storm rainfall and model parameters are dealt with in the following analyses and discussion.

14.2 Aims and procedures

The distributed R-index method incorporating curve numbers has been shown to be a suitable technique for estimating stormflow volumes (cf Chapter 13). Using this version of the R-index model in the three Zululand catchments (W1M15, W1M16 and W1M17) the following investigations were undertaken:

(a) An assessment was made of the increase in model errors, based on the coefficient of efficiency, associated with inaccuracies in model parameters.

(b) The effect on calculated stormflow volumes of systematic inaccuracies in storm rainfall inputs were evaluated.

The initial investigation was conducted by increasing and decreasing individual model parameters by up to 20 percent of the optimised parameter value for the study catchment. The two remaining parameters were held at their optimised values while changes in the value of E were monitored. This procedure was repeated for each parameter and the change in E was plotted against the associated increase or decrease in parameter value. Optimised parameter values were taken to be those obtained using observed stormflow and input variables and the most suitable catchment wetness index for the catchment (cf Chapter 13).

A set of storm rainfall data was established covering the range of values observed in the three Zululand catchments. The computer programme INDST was adapted to permit increases or decreases in these values by a specified amount (percent). Similarly, the appropriate catchment wetness index could be neither increased or decreased. The optimised model parameters and associated wetness index for each catchment were used to calculate storm-flow volumes. Three amounts of antecedent rainfall were selected for each catchment, these amounts covering the range observed in the original data sets. For each level of antecedent rainfall the stormflow volumes were calculated using storm rainfalls systematically underestimated and over= estimated by specified amounts. The percent change in stormflow volumes for the various storm rainfalls and three selected antecedent moisture conditions could thus be assessed.

14.3 Results and discussions

Changes in the coefficient of efficiency (E) associated with changes in the three parameters of the R-index model optimised on data from catchments W1M15, W1M16 and W1M17 are illustrated in Figure 14.1. In each catchment the maximum reduction in E corresponding to errors in individual parameters was associated with β_2 the storm rainfall parameter (Figure 14.1). he parameter having the least effect on E in each catchment was β_3 (catchment wetness index parameter). Both β_1 and β_2 had a limited effect on E even for deviations of 20 percent above or below the optimised values.

The parameter changes given in Figure 14.1 are percentage values. Since the value of parameter β_2 is substantially greater than that of β_1 or β_3 in each catchment (cf Table 13.1), the larger absolute change in β_2 values may account for the greater reduction in the associated values of E. However, by adjusting each of the three parameters of the R-index model by fixed amounts the changes in E were similar to those presented in Figure 14.1. Underestimation of β_2 in catchments W1M16 and W1M17 (Figure 14.1 b and c) resulted in more substantial decreases in E than did overestimation of this parameter. In catchment W1M15 (Figure 14.1 a) the direction of the error in parameter estimation did not result in substantial differences in the reduction of E.

While errors in the parameter β_2 may result in substantial losses in model accuracy this does not necessarily warrant the use of additional decimal places in optimising this parameter. An inaccuracy of 0,01 in β_2 is an error of less than 0,62 percent of the optimised value in each of the three Zululand catchments and referring to Figure 14.1 it may be deduced that the associated reduction in E which may be expected would be minimal. Optimising model parameters to two decimal places does not appear to be justified particularly when the required computer time is considered.

Figure 14.1 Changes in the coefficient of efficiency (E) associated with changes in parameter values above and below optimised values for catchments (a) W1M15, (b) W1M16 and (c) W1M17

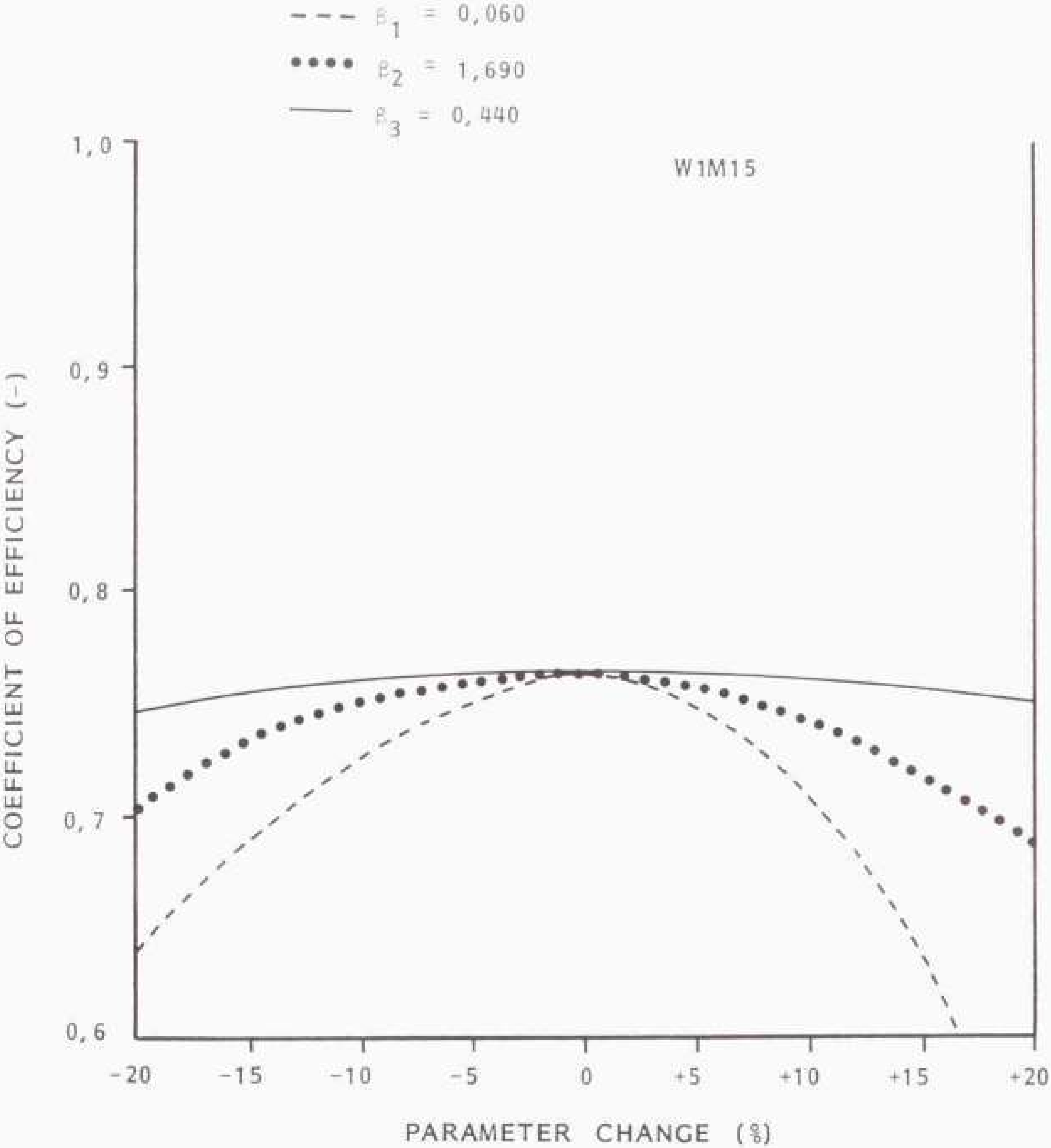


Figure 14.1 (continued)

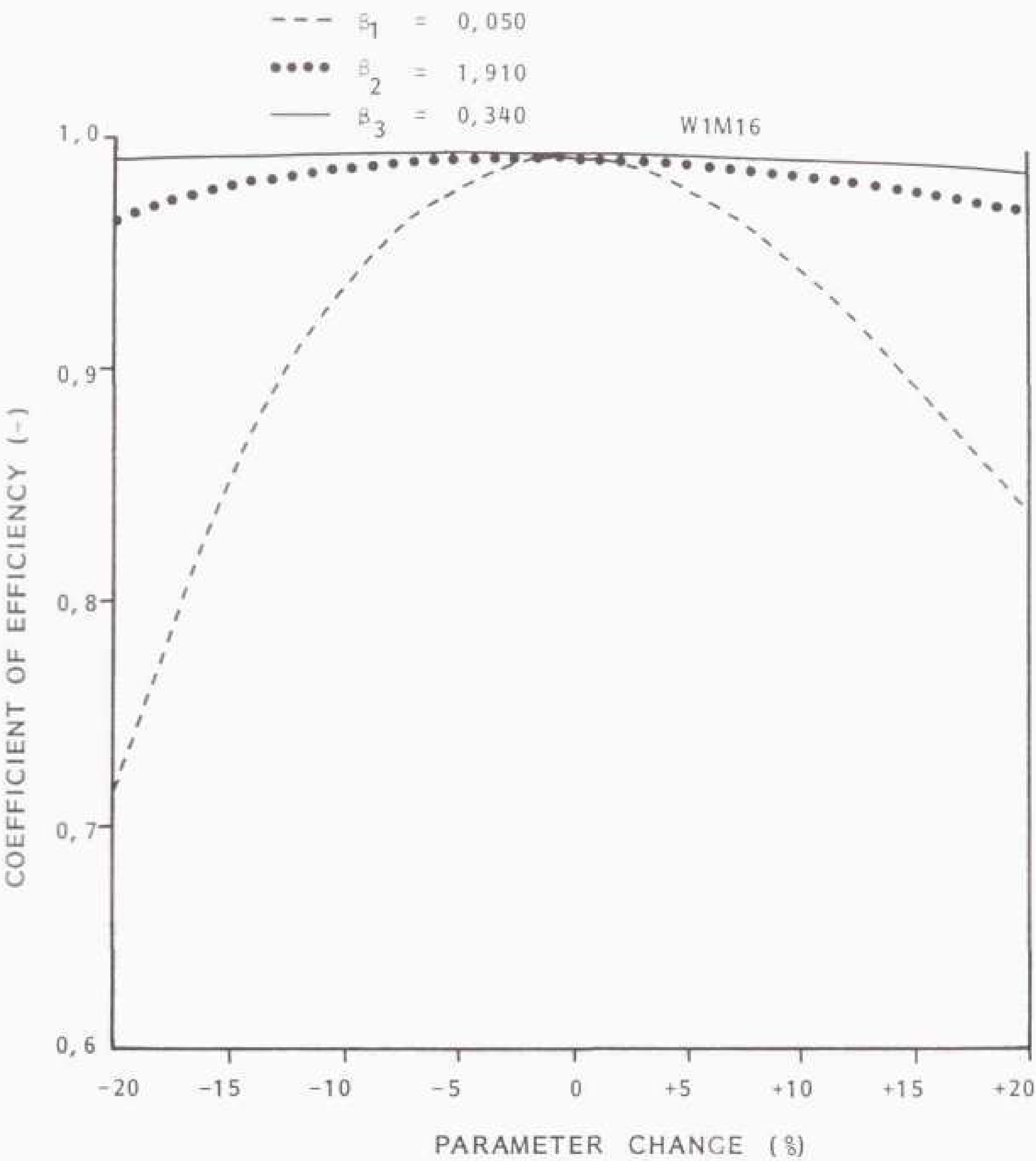
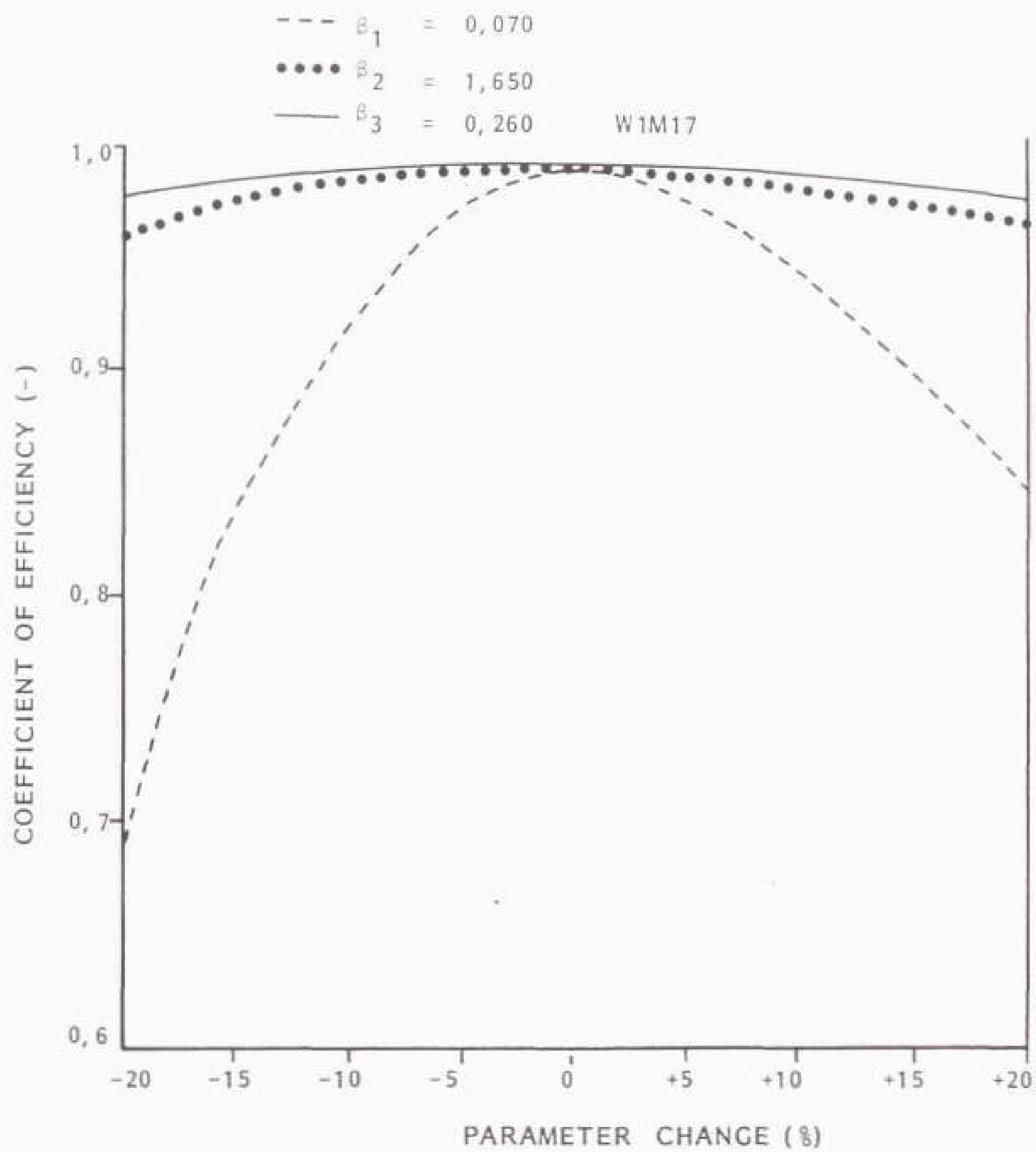
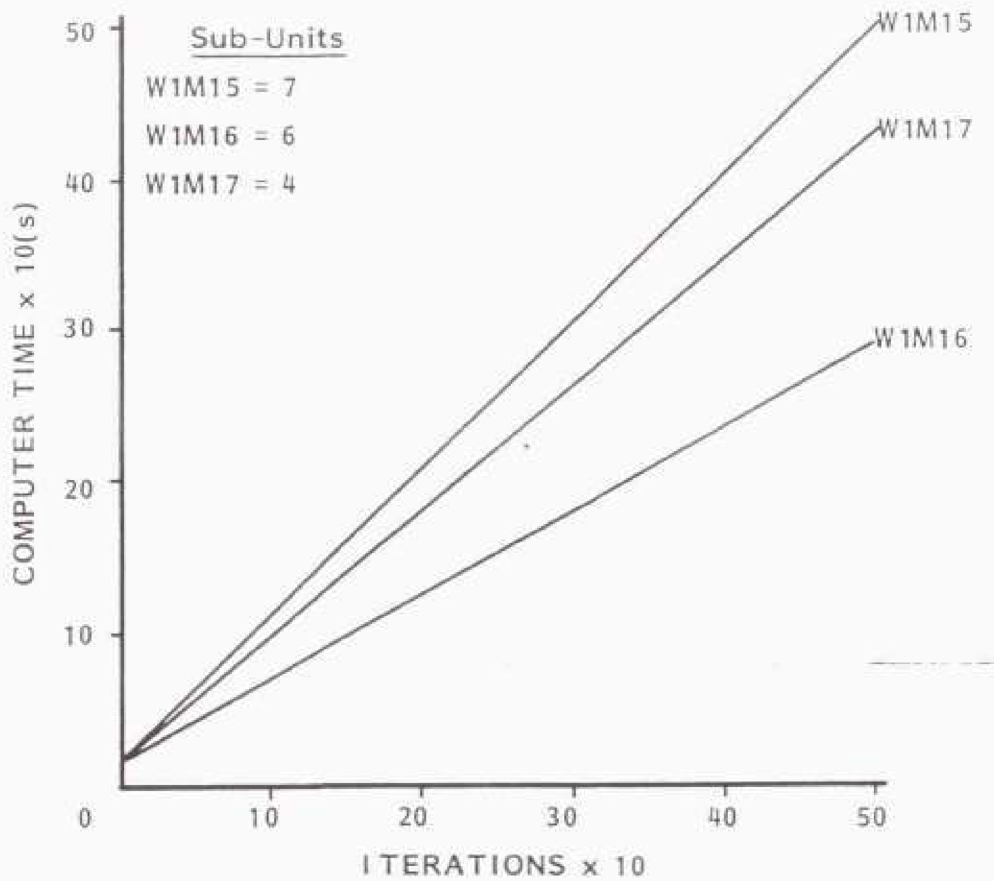


Figure 14.1 (continued)



The relationship between the number of iterations and computer time required to optimise model parameters using the programme INDST for 43 events in each of the Zululand catchments is illustrated in Figure 14.2. The relationships were developed for the Univac 1100 computer at the University of Natal.

Figure 14.2 Relationship between the number of iterative steps and computer time for the programme INDST using 43 stormflow events in the three Zululand catchments



A minimum of 15 seconds is required to run INDST while the relationship between the iterative steps and computer time is also a function of the number of sub-units in each catchment (W1M15=7, W1M16=4 and W1M17=6). This relationship may be described by the following expression:

$$T = 15{,}0 + \frac{C_n}{7{,}143} I \qquad \ldots\ldots\ldots\ldots \quad (14.1)$$

where

T = computer time (s)

C_n = number of R-index sub-units and

I = number of iterations.

The following example illustrates the importance of reducing to a minimum the number of iterations required for model calibration:

> The programme INDST is set to test parameters between the following limits for catchments W1M15:
>
> β_1 : 0,010 - 0,080
>
> β_2 : 1,400 - 1,800
>
> β_3 : 0,100 - 0,500
>
> The first test is conducted using parameters accurate to two decimal places (I = 20 000) and then repeated using β_2 accurate to three decimal places (I = 200 000). The first test would require 5,449 h of computer time compared to 54,448 hours for the second test.

It must, however, be pointed out that convergence to the final solution generally requires substantially less time by using larger iterative steps during the initial calibration runs and then re-defining narrower parameter limits for runs using finer iterative steps.

The parameter β_2 associated with storm rainfall in the distributed R-index model has been shown to be a critical model parameter affecting the accuracy of stormflow simulations. Errors in estimated storm rainfall may also give rise to substantial inaccuracies in calculated stormflow depths. The error in calculated stormflow depths associated with over-estimation and under-estimation of storm rainfall is illustrated for each of the three Zululand catchments in figure 14.3. These tests were conducted using three

Figure 14.3 Percent error in calculated stormflow depths associated with errors in storm rainfall for three levels of antecedent rainfall (AP) for catchments (a) W1M15, (b) W1M16 and (c) W1M17

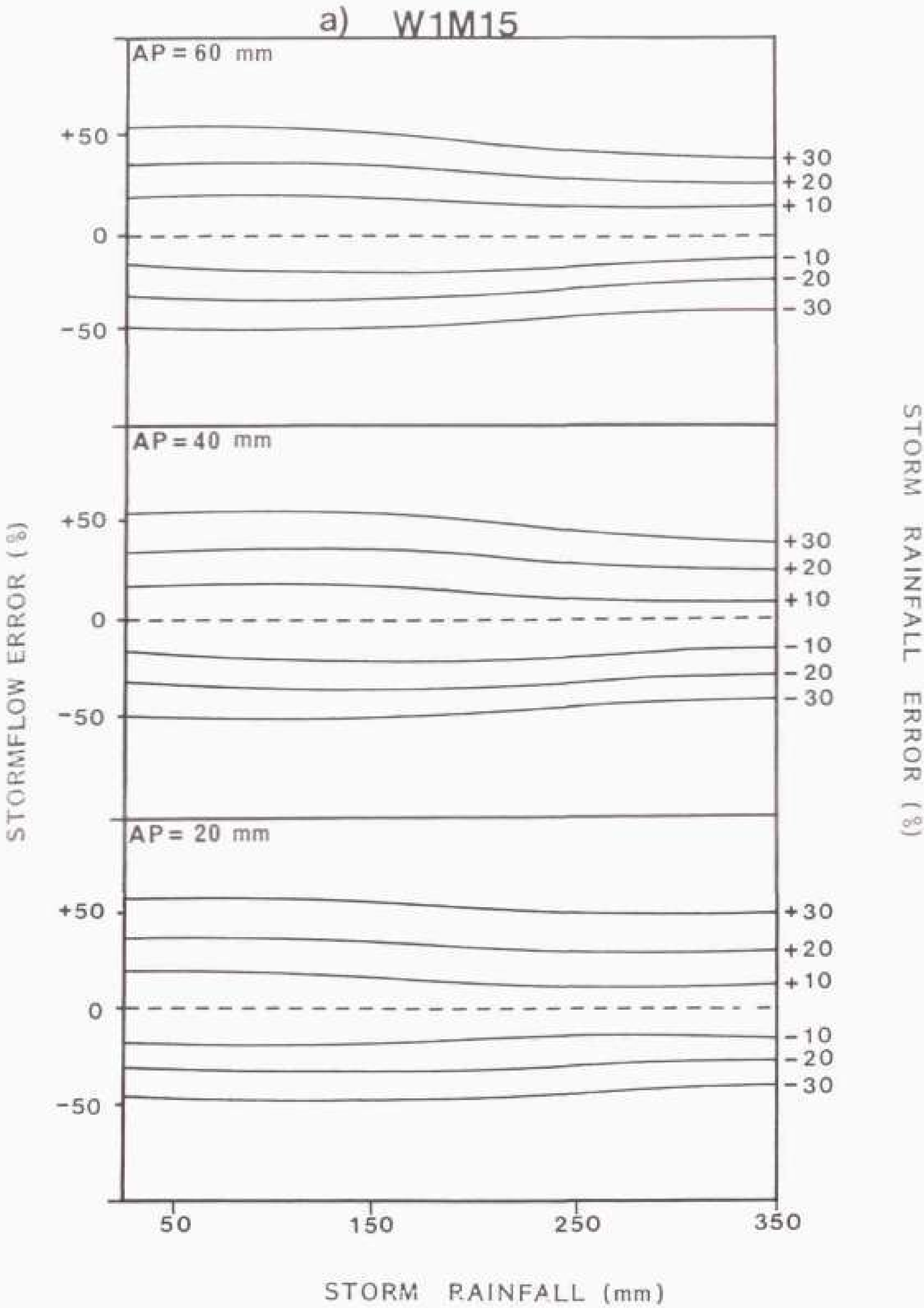


Figure 14.3 (continued)

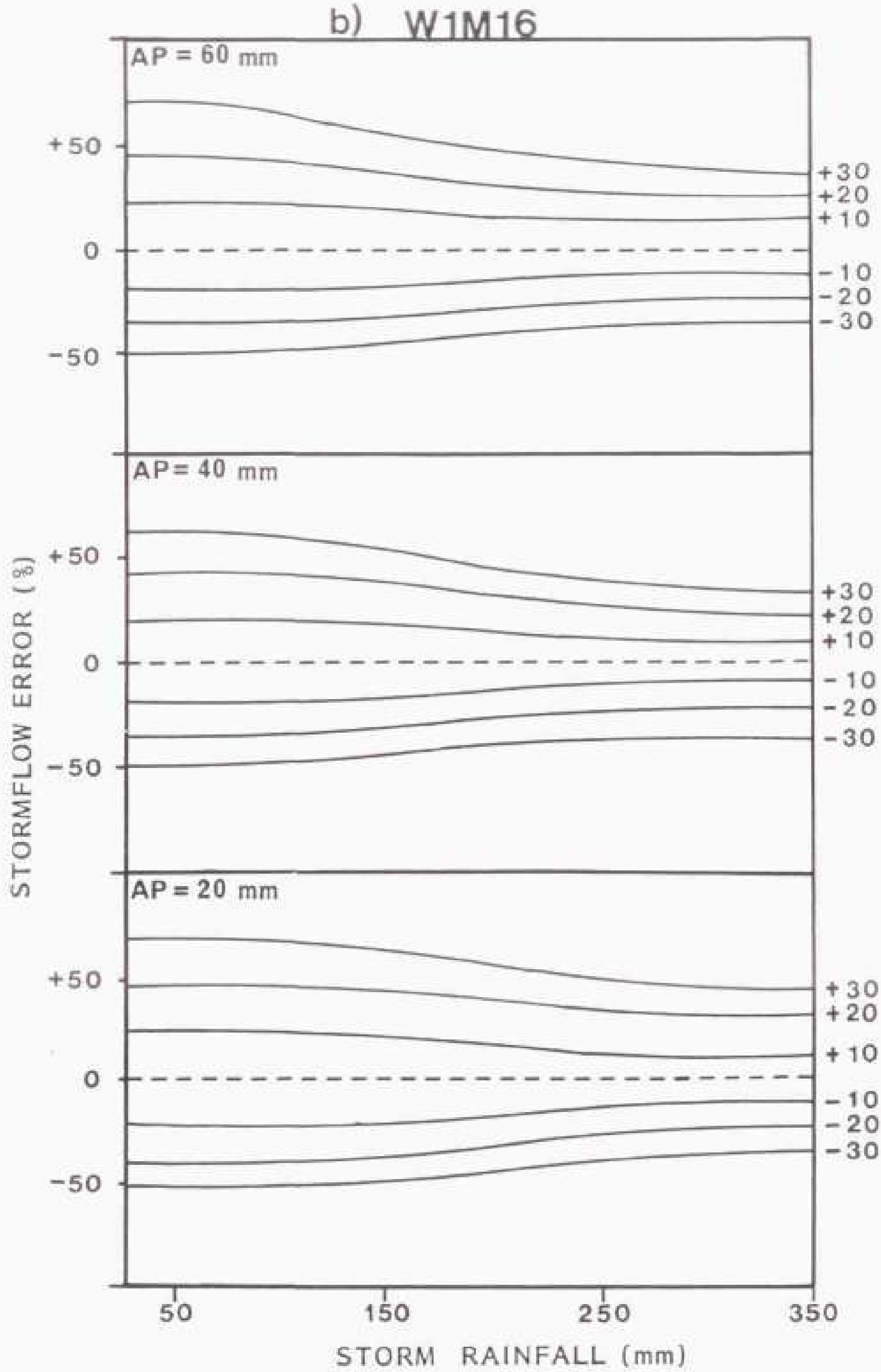
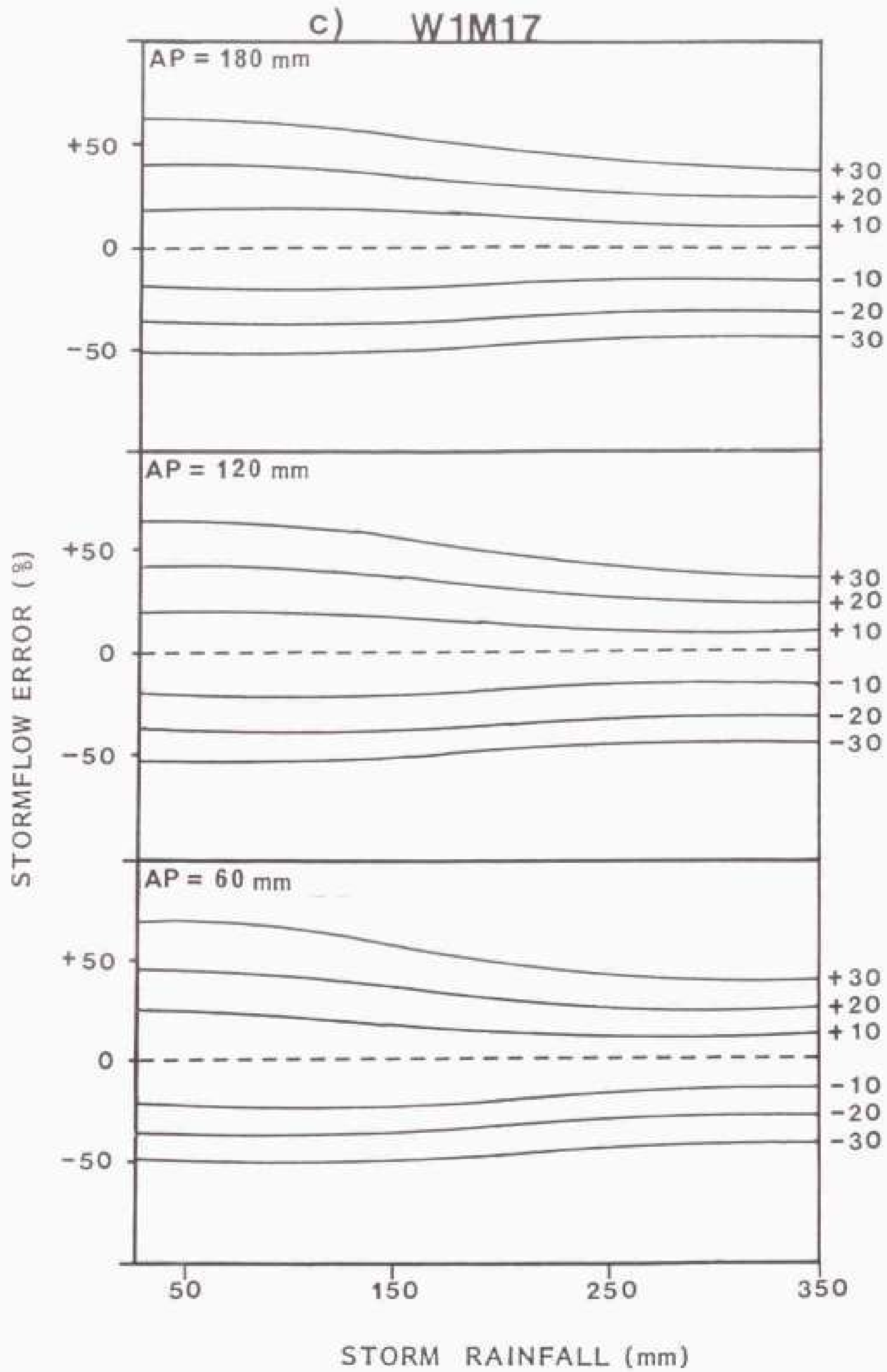


Figure 14.3 (continued)



levels of antecedent rainfall for each catchment to determine whether the nature of stormflow errors in each catchment would be influenced by the antecedent moisture conditions.

14.4 Conclusions

The sensitivity of the R-index model to errors in parameter values and storm rainfall input has been dealt with briefly in this chapter. These tests were intended to highlight the potential sources and magnitudes of errors in calculating stormflow volumes using this method. Although the results pertain specifically to the three Zululand catchments it may be expected that the parameter β_2 would be as important in other catchments. Furthermore, errors in calculated stormflows resulting from inaccuracies in storm rainfall input are likely to be of a similar magnitude to those found in this study since β_2 values do not vary considerably from catchment to catchment. However, future research in this area is required and attention needs to be given to the combined effect of inaccuracies in parameters and input variables.

Chapter 15

SIMULATION OF STORMFLOW VOLUME USING THE R-INDEX METHOD: CONCLUSIONS

The R-index method has been shown to be a relatively simple procedure for simulating stormflow volumes. Despite the simplicity of the model the results obtained in this study have indicated that the technique may be readily adapted for calculating stormflows in a variety of environmentally dissimilar regions of South Africa, but all the presented work requires extensive verification. The salient features of conclusions reached in this investigation may be summarised as follows:

(a) The model calibrates stormflows accurately in selected semi-arid, sub-humid catchments of South Africa. However, model parameters differ markedly from region to region.

(b) Initial flow rate is generally a good index of catchment moisture status for calculating stormflow volumes. Antecedent rainfall is a highly satisfactory surrogate for this variable in the R-index method resulting in more accurate simulations of stormflow volumes in some catchments. The use of A-pan evaporation in the catchment wetness index did not not improve the accuracy of stormflow calibrations.

(c) The number of days antecedent rainfall which is most suitable for stormflow calculations varies from region to region.

(d) Antecedent moisture conditions are more important in determining stormflow volumes in humid and sub-humid catchments than in semi-arid catchments. Also, this variable affects simulations of small and intermediate size stormflow events more than it influences the larger events.

(e) Exponential transformations of stormflow response result in more normalised frequency distributions of the variable. Substantially fewer observations are required to determine an unbiased estimate of the R-index when normalised rather than skewed data are used.

(f) Regional R-indices may be related to mean annual discharge response. Future research is, however, required to substantiate this observation and to determine the effect of catchment area on the R-index.

(g) Curve numbers may be used with some success in place of the R-index in a distributed R-index model. This distributed model is a viable procedure for simulating stormflow from sub-units in a catchment.

(h) The transferability of model parameters up or down stream of a gauging point is possible without incurring substantial errors in the calculated stormflows but attention needs to be given to the effect of catchment area on the parameter values.

(i) Calibrating the parameters of the R-index model to two decimal places appears to be justified. While the programmes INDEX and INDST were adequate for the purpose of this study, the use of more advanced procedures for parameter determination may reduce the required computer time.

(j) Errors in estimating storm rainfall or the associated model parameter (β_2) results in substantial errors in calculated stormflows.

Many of the conclusions reached in this study of the R-index method concur with findings reported for the investigation into the SCS model. In the concluding chapter attention is given to the common findings of the two studies as well as to future research needs.

Chapter 16

SIMULATION OF STORMFLOW VOLUMES FROM SMALL CATCHMENTS: CONCLUSIONS AND FUTURE RESEARCH

The simulation of stormflow volumes using two conceptually different procedures has been undertaken with particular attention being given to the catchment moisture status component of each model. Both models are intended to be simple procedures requiring limited information for storm= flow simulations, a constraint which has been adhered to in this reseach. Despite the notable differences in model structure, a number of findings were common to both the SCS and R-index models, viz:

(a) Stormflow could be simulated more accurately when distributed rather than lumped models were used.

(b) The simulation of small stormflow events is particularly difficult, large relative errors being common regardless of the procedure used. Since these smaller events are generally not of concern to engineers or planners this was not regarded as a major consideration in evalua= ting these models. However, calibrating the model on small events may give rise to substantial errors in estimated parameter values. Attempts to calibrate the R-index method on four small catchments (areas: 0,027 km^2 - 0,059km^2) near La Mercy on the coastal belt of Natal using small events substantiated this conclusion.

(c) The period of antecedent rainfall optimally associated with stormflow volumes varies from region to region. The results indicated that topographical and pedalogical characteristics of a catchment may be related to the number of days antecedent rainfall which should be considered for calculating stormflow volumes. Despite regional differences in the most suitable antecedent period, the use of 10 to 15 days antecedent rainfall is suited to most catchments for stormflow simulations since inaccuracies are not substantial when this period is used.

(d) The curve number concept is valuable for representing the stormflow potential of a catchment whether it is used as intended in the SCS model or as a response index in the R-index model.

While both the SCS and R-index models may be regarded as simple procedures for calculating stormflow volumes, the modified SCS model as used in this research required a more sophisticated antecedent moisture procedure and more input variables for improved stormflow simulations to be achieved. A major difficulty in using the R-index method is that parameters of this model are not fixed for all catchments and regional values would have to be estalbished for Southern Africa.

Further improvements to the SCS model are likely to be restricted by the structure and assumptions of the model. While individual components of the model may undergo improvements and more sophisticated procedures could be developed, attention should also be focussed on the central aspect of the model, the curve number. South African soils have been classified hydrolo= gically for curve number determinations by Schulze and Arnold (1979) this classification being based on a subjective assessment of the soils accor= ding to specified criteria. Experimental attention needs to be given to the stormflow potential of South African soils under various vegetation covers or land-use. The curve number concept is valuable for stormflow estimates using both the SCS and R-index methods.

The effect of catchment area on stormflow volumes in small catchments (< 50 km^2) is generally neglected. Results presented in this study have indicated that area may be an important variable to consider particularly when the average stormflow response is being examined. Although Hewlett et al (1977) found no relationship between stormflow response and catchment physiography, these variables may be important in sub-humid or semi-arid catchments. However, analyses of this type would require a large sample of small catchments with adequate rainfall and stormflow records. The lack of suitable data from small catchments in South Africa is a major difficulty which researchers in the field of stormflow modelling have to deal with.

Temporary gauging structures may offer a possible short-term solution to the problem of inadequate stormflow records for many regions of South Africa. While permanent structures are obviously desirable, temporary structures would permit the determination of R-indices, model parameters and could assist in determining which models are most suited to the region. The regionaliation of model parameters and the determination of suitable antecedent rainfall indices for stormflow models would also be possible.

In dealing with the modified SCS model and R-index method attention has been directed at the application of these procedures to ungauged catchments. While this is likely to be a principal objective of future research into the two selected stormflow models it is essential that such studies be accompanied by research of a more fundamental nature. Results presented in this study have indicated that there is a possible relationship between the soils and topography of a catchment and the number of days antecedent rainfall optimally associated with stormflow volumes. If the processes responsible for such a relationship could be understood and quantified then the task of selecting an antecedent rainfall index for use in stormflow calculations may have a more sound basis.

While the SCS and R-index models have many features in common the two procedures are based on different assumptions and are structurally distinct. No attempt was made in this study to compare model performance on controlled sets of data. An important phase in stormflow modelling in small catchments of South Africa will be a comparative study of model performance. However, due to the vast range of environmental conditions found in South Africa it is unlikely that a single model will be suitable for the entire country.

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APPENDICES

(A)

APPENDIX I

The derivation of CN units from catchments soils
and vegetation data for catchments:

(a) W1M16

(b) W1M17

(c) U2M20

(d) V2M28

(e) V7M03

Note: Curve numbers were combined generally on the basis of the soil series, similarity of CN values and where small areas of a CN were within larger units of another CN (areas of <3 % of the catchment area). Where deep and shallow soil phases were identified, these have been indicated by the symbols (D) and (S) respectively.

(a) W1M16

Soil		Vegetation/Land-use				CN
Series	Hyd Gp	Type	Condition	CN	Prop	Unit
Marsh	-	-	-	98	,144	1
Katspruit	D	Veld + 50 % Rock	Good	90	,149	
Katspruit	D	Veld + 35% Rock	Good	87	,080	2
Katspruit	D	Woods	Fair	79	,010	
Robmore (S)	C	Veld	Good	74	,303	
Robmore (S)	C	Woods	Good	70	,006	3
Robmore (S)	C	Woods	Fair	73	,001	
Robmore (S)	C	Straight row crop	Poor	85	,012	
Robmore (D)	B	Veld	Good	61	,256	
Robmore (D)	B	Woods	Good	55	,005	
Robmore (D)	B	Woods + 35 % Rock	Good	71	,012	4
Robmore (D)	B	Woods	Fair	60	,017	
Robmore (D)	B	Straight row crop	Poor	78	,004	

CN Unit	1	2	3	4
CN	98,0	88,5	74,3	61,5
Proportion	0,14	0,24	0,32	0,30

(b) W1M17

Soil		Vegetation/Land-use				CN
Series	Hyd Gp	Type	Condition	CN	Prop	Unit
Trafalgar (D)	B	Forest	Good	55	,016	1
Marsh	-	-	-	98	,078	2
Rock 100 %	-	-	-	100	,005	
Katspruit	D	Forest	Fair	79	,003	
Katspruit	D	Veld + 50 % Rock	Good	90	,019	3
Katspruit	D	Veld + 35 % Rock	Good	87	,120	
Robmore (S)	C	Veld	Good	74	,223	
Robmore (S)	C	Forest + 35 % Rock	Good	80	,002	4
Robmore (S)	C	Forest	Fair	73	,034	
Robmore (S)	B	Straight row crop	Poor	77	,013	
Robmore (D)	B	Veld	Good	61	,141	5
Robmore (D)	B	Forest	Fair	60	,003	
Oatsdale	A	Veld	Good	39	,307	
Oatsdale	A	Forest	Fair	36	,015	6
Oatsdale	A	Straight row crop	Poor	66	,012	

CN Unit	1	2	3	4	5	6
CN	55,0	98,0	87,2	74,1	61,0	39,8
Proportion	0,02	0,08	0,14	0,27	0,14	0,34

(c) U2M20

Soil		Vegetation/Land-use				CN
Series	Hyd Gp	Type	Condition	CN	Prop	Unit
Mispah	C	Woods	Fair	73	,068	1
Clovelly	B	Woods	Fair	60	,107	
Clovelly	B	Veld	Fair	69	,728	
Hutton	B	Veld	Fair	69	,061	
Katspruit	D	Veld	Good	80	,036	2

CN Unit	1	2
CN	68,3	80,0
Proportion	0,96	0,04

(d) V1M28

Soil		Vegetation/Land-use				CN
Series	Hyd Gp	Type	Condition	CN	Prop	Unit
Kranskop	B	Veld	Fair	69	,383	1
Clovelly	B	Veld	Fair	69	,463	
Mispah	C	Veld	Fair	79	,014	2
Longlands	C	Veld	Fair	79	,140	

CN Unit	1	2
CN	69,0	79,0
Proportion	0,85	0,15

[illegible] V7M03

Soil		Vegetation/Land-use				CN
Series	Hyd Gp	Type	Condition	CN	Prop	Unit
Mispah	C	Veld	Fair	79	,293	1
Longlands	C	Veld	Fair	79	,219	
Clovelly	B	Veld	Fair	69	,488	2

CN Unit	1	2
CN	79,0	69,0
Proportion	0,51	0,49

APPENDIX 2

Storm rainfall, stormflow and associated antecedent rainfall, runoff and actual evapotranspiration used in testing the SCS model in catchments W1M16, W1M17, U2M20, V1M28 and V7M03:

The abbreviations used are as follows:

D = date (day, month, year)
P = storm rainfall (mm)
Q = stormflow (mm)
AP = antecedent rainfall (mm)
OAR = observed antecedent runoff (mm)
CAR = calculated antecedent runoff (mm)
OAE = 'observed' (regression equation) actual evapotranspiration (mm)
CAE = calculated actual evapotranspiration (mm)

W1M16

VARIABLE	ANTECEDENT PENTAD (DAYS) 1 (20-16)	2 (15-11)	3 (10-06)	4 (05-01)	STORM INFORMATION
AP	4.900	3.600	40.100	9.700	D:22 12 76
DAR	1.592	1.457	3.306	1.246	
CAR	1.519	1.116	12.431	3.007	P: 67.7
DAE	8.433	8.213	27.696	10.665	
CAE	6.617	6.617	18.724	6.617	Q: 10.956
AP	1.400	1.700	12.900	11.200	D:24 1 77
DAR	2.764	1.546	1.165	1.565	
CAR	.434	.527	3.999	3.472	P: 43.8
DAE	6.783	7.066	11.066	13.527	
CAE	6.210	6.210	6.210	6.210	Q: 4.538
AP	3.100	3.400	16.200	61.100	D:26 1 77
DAR	2.259	1.388	1.546	6.788	
CAR	.961	1.054	5.022	18.941	P: 61.2
DAE	.340	7.622	14.419	39.528	
CAE	.210	6.210	6.210	24.904	Q: 12.139
AP	1.700	11.600	11.500	114.200	D:29 1 77
DAR	1.587	1.213	1.565	24.409	
CAR	.527	3.596	3.565	35.402	P: 71.4
DAE	7.186	10.485	13.569	66.654	
CAE	6.210	6.210	6.210	25.642	Q: 18.547
AP	3.400	16.200	116.400	76.800	D: 1 2 77
DAR	1.336	1.529	18.943	32.615	
CAR	1.054	5.022	36.084	23.808	P: 40.9
DAE	7.622	14.419	69.412	46.201	
CAE	4.937	4.937	20.386	20.386	Q: 9.121
AP	138.100	41.400	304.200	.000	D:14 2 77
DAR	39.117	26.103	244.896	19.138	
CAR	42.811	12.834	94.302	.000	P:188.7
DAE	79.569	26.588	170.054	5.785	
CAE	20.386	13.972	20.386	4.937	Q: 71.543
AP	303.000	84.300	104.400	8.300	D:25 2 77
DAR	249.290	38.257	75.314	14.967	
CAR	93.930	26.133	32.364	2.573	P: 17.7
DAE	169.043	50.979	61.479	10.391	
CAE	20.386	20.386	20.386	4.937	Q: 1.716
AP	1.900	24.100	12.900	5.700	D:10 3 77
DAR	20.706	14.112	9.784	6.818	
CAR	.589	7.471	3.999	1.767	P: 25.3
DAE	6.932	19.050	12.153	7.538	
CAE	3.994	3.994	3.994	3.994	Q: 2.338
AP	24.100	12.800	3.500	28.600	D:14 3 77
DAR	15.233	10.174	7.209	9.245	
CAR	7.471	3.968	1.085	8.866	P:104.0
DAE	18.688	11.857	6.107	20.999	
CAE	3.994	3.994	3.994	6.296	Q: 30.049

VARIABLE	ANTECEDENT PENTAD (DAYS) 1 (20-16)	2 (15-11)	3 (10-06)	4 (05-01)	STORM INFORMATION
AP	12.600	3.500	74.100	58.500	D:20 3 77
DAR	10.146	7.000	14.987	39.836	
CAR	3.968	1.085	22.971	18.135	P: 27.8
DAE	12.099	6.349	45.346	35.709	
CAE	3.994	3.994	13.574	13.183	Q: 5.161
AP	.000	5.200	6.000	1.100	D:10 4 77
DAR	10.849	6.498	5.653	4.242	
CAR	.000	1.612	1.860	.341	P: 18.3
DAE	.000	.069	.716	.000	
CAE	2.679	5.130	5.130	2.679	Q: 1.155
AP	.000	2.500	9.100	21.600	D:24 9 77
DAR	.315	.254	.377	.440	
CAR	.000	.775	2.821	6.696	P: 72.4
DAE	.000	.000	3.356	13.658	
CAE	4.758	4.758	9.112	17.529	Q: 6.091
AP	.000	.000	24.600	123.500	D:27 9 77
DAR	.302	.236	.507	8.454	
CAR	.000	.000	7.625	38.285	P: 30.1
DAE	.000	.000	16.119	98.617	
CAE	4.758	4.758	17.529	19.647	Q: 3.249
AP	48.600	113.500	2.400	26.800	D: 9 10 77
DAR	.479	15.461	2.666	2.776	
CAR	15.066	35.185	.744	8.308	P: 23.1
DAE	30.721	65.069	7.082	19.785	
CAE	20.243	22.689	5.495	5.495	Q: 6.446
AP	20.300	16.500	72.600	9.100	D: 9 11 77
DAR	5.529	2.665	1.864	1.038	
CAR	6.293	5.115	22.568	2.821	P: 52.1
DAE	15.910	15.305	44.402	10.099	
CAE	5.843	5.843	24.123	5.843	Q: 10.549
AP	16.500	72.800	7.100	57.100	D:14 11 77
DAR	2.365	2.622	1.002	14.587	
CAR	5.115	22.568	2.201	17.701	P: 24.8
DAE	15.305	44.402	9.018	36.763	
CAE	5.843	24.123	5.843	23.428	Q: 1.541
AP	10.000	.000	30.300	9.300	D:19 12 77
DAR	1.778	.703	.727	2.368	
CAR	3.100	.000	9.393	2.883	P: 56.5
DAE	10.827	5.182	22.883	12.983	
CAE	6.725	6.725	12.878	6.725	Q: 8.256
AP	.000	10.600	28.900	73.100	D:23 12 77
DAR	.727	.692	2.502	11.194	
CAR	.000	3.286	8.959	22.661	P: 28.6
DAE	5.302	12.237	22.972	47.099	
CAE	6.725	6.725	12.878	27.766	Q: 3.045

VARIABLE	ANTECEDENT PENTAD (DAYS)				STORM INFORMATION
	1 (20-16)	2 (15-11)	3 (10-06)	4 (05-01)	
AP	18.400	7.800	199.500	38.900	D:27 1 78
DAR	4.685	9.373	68.342	34.467	
CAR	5.704	2.418	61.845	12.059	P: 27.3
DAE	16.368	9.879	112.388	26.686	
CAE	5.887	5.887	24.306	16.659	Q: 3.065
AP	26.500	6.000	7.300	27.900	D:12 2 78
DAR	20.724	13.363	5.220	6.777	
CAR	8.215	1.860	2.263	8.649	P: 34.0
DAE	19.297	8.545	10.092	19.172	
CAE	4.885	4.885	4.885	9.355	Q: 3.178
AP	7.300	27.900	34.000	44.200	D:21 2 78
DAR	5.554	6.447	11.632	5.567	
CAR	2.263	8.649	10.540	13.702	P: 24.5
DAE	10.370	19.897	23.314	29.429	
CAE	4.885	9.355	9.355	13.824	Q: 13.876
AP	50.900	8.900	61.200	15.700	D: 1 3 78
DAR	10.984	7.331	21.752	8.475	
CAR	15.779	2.759	18.972	4.867	P: 39.5
DAE	32.724	9.388	39.099	14.028	
CAE	14.121	3.833	15.371	3.833	Q: 7.364
AP	61.900	10.300	53.600	5.600	D: 9 3 78
DAR	7.074	22.132	18.776	7.479	
CAR	19.189	3.193	16.616	1.736	P: 69.3
DAE	38.548	11.472	34.147	7.846	
CAE	15.371	3.833	14.121	3.833	Q: 19.021
AP	73.500	.000	2.800	29.500	D:27 3 78
DAR	30.202	8.161	4.757	2.887	
CAR	22.785	.000	.868	9.145	P:107.2
DAE	44.816	4.819	6.574	21.847	
CAE	15.827	3.833	3.833	7.341	Q: 16.864
AP	.000	2.800	39.500	78.800	D: 1 4 78
DAR	8.161	4.757	2.893	23.549	
CAR	.000	.868	12.245	24.428	P: 19.8
DAE	.000	.000	28.855	61.487	
CAE	2.322	2.322	9.588	9.588	Q: 2.569
AP	.000	27.200	3.800	25.000	D:22 4 78
DAR	4.865	5.817	3.319	4.511	
CAR	.000	8.432	1.178	7.750	P: 75.4
DAE	.000	18.456	.000	16.434	
CAE	2.322	8.554	4.447	8.554	Q: 17.054
AP	3.000	24.500	19.700	84.800	D:26 4 78
DAR	3.615	5.692	4.468	24.687	
CAR	.930	7.595	6.107	26.288	P: 26.3
DAE	.000	16.074	12.018	66.202	
CAE	2.322	8.554	6.572	9.588	Q: 1.113

VARIABLE	ANTECEDENT PENTAD (DAYS) 1 (20-16)	2 (15-11)	3 (10-06)	4 (05-01)	STORM INFORMATION
AP	1.700	4.600	.000	6.200	D: 3 6 78
DAR	3.208	2.539	2.084	2.279	
CAR	.527	1.426	.000	1.922	P: 22.7
DAE	.000	.000	.000	.845	
CAE	2.330	4.463	2.330	4.463	Q: 2.345
AP	.000	7.300	7.200	20.300	D:11 7 78
DAR	1.808	1.460	2.666	2.345	
CAR	.000	2.263	2.232	6.293	P: 21.4
DAE	.000	1.705	1.527	12.404	
CAE	2.960	5.668	5.668	8.376	Q: 2.564
AP	29.800	4.000	.000	4.900	D: 8 9 78
DAR	2.879	1.705	1.165	.687	
CAR	9.238	1.240	.000	1.519	P: 56.0
DAE	20.401	.000	.000	.000	
CAE	16.404	7.834	4.091	7.384	Q: 6.611
AP	6.800	4.000	1.200	60.700	D:12 9 78
DAR	2.743	1.292	.730	10.370	
CAR	2.108	1.240	.372	18.817	P: 21.0
DAE	1.237	.000	.000	46.292	
CAE	7.834	7.834	4.091	16.890	Q: 1.301

W1M17

VARIABLE	ANTECEDENT PENTAD (DAYS) 1 (20-16)	2 (15-11)	3 (10-06)	4 (05-01)	STORM INFORMATION
AP	18.800	16.600	26.100	8.900	D:24 11 76
DAR	9.645	5.928	10.270	4.824	
CAR	5.826	5.146	3.091	2.759	P: 16.0
DAE	12.372	11.541	16.924	7.252	
CAE	5.007	5.007	5.007	5.007	Q: 1.090
AP	16.600	4.600	7.500	7.500	D:13 12 76
DAR	5.637	3.214	5.353	2.959	
CAR	5.146	1.426	2.263	2.325	P: 18.6
DAE	11.661	6.364	6.266	7.574	
CAE	5.447	5.447	5.447	5.447	Q: 1.426
AP	4.900	3.600	40.100	10.300	D:22 12 76
DAR	4.401	4.007	6.899	2.279	
CAR	1.519	1.116	12.431	3.193	P: 67.5
DAE	5.327	4.623	24.984	9.330	
CAE	5.447	5.447	18.932	5.447	Q: 12.448
AP	1.400	1.700	12.500	11.600	D:24 1 77
DAR	3.408	2.181	1.913	2.407	
CAR	.434	.527	3.875	3.596	P: 44.8
DAE	2.832	2.994	9.441	8.834	
CAE	5.113	5.113	5.113	5.113	Q: 5.092
AP	3.100	3.400	16.200	59.300	D:26 1 77
DAR	2.967	2.201	2.338	7.714	
CAR	.961	1.054	5.022	18.383	P: 61.2
DAE	3.872	4.394	11.324	35.259	
CAE	5.113	5.113	5.113	25.211	Q: 13.325
AP	1.700	11.600	11.500	114.200	D:29 1 77
DAR	2.232	1.868	2.472	26.159	
CAR	.527	3.596	3.565	35.402	P: 71.4
DAE	2.994	8.954	8.780	64.502	
CAE	5.113	5.113	5.113	25.642	Q: 25.456
AP	3.400	16.200	114.900	75.500	D: 1 2 77
DAR	1.885	2.511	21.067	38.615	
CAR	1.054	5.022	35.619	23.405	P: 40.9
DAE	4.394	11.324	65.361	42.349	
CAE	4.065	4.065	20.386	20.386	Q: 8.908
AP	.000	188.700	1.900	24.500	D: 1 3 77
DAR	20.856	119.234	21.937	17.429	
CAR	.000	58.497	.589	7.595	P: 11.9
DAE	2.314	103.276	3.102	15.698	
CAE	2.707	13.574	2.707	2.707	Q: 1.084
AP	1.900	24.100	12.900	4.700	D:10 3 77
DAR	24.305	18.583	13.782	9.846	
CAR	.589	7.471	3.999	1.457	P: 25.3
DAE	2.502	15.721	8.578	3.658	
CAE	2.707	2.707	2.707	2.707	Q: 2.991

VARIABLE	ANTECEDENT PENTAD (DAYS) 1 (20-16)	2 (15-11)	3 (10-06)	4 (05-01)	STORM INFORMATION
AP	24.100	12.800	3.500	28.600	D:14 3 77
DAR	18.283	14.025	10.490	12.757	
CAR	7.471	3.968	1.085	8.866	P:104.0
DAE	15.241	8.524	2.889	17.678	
CAE	2.707	2.707	2.707	6.138	Q: 34.264
AP	12.800	3.500	60.200	72.400	D:19 3 77
DAR	14.196	10.623	18.881	44.587	
CAR	3.968	1.085	18.662	22.444	P: 28.0
DAE	8.524	2.889	34.786	39.831	
CAE	2.707	2.707	13.346	13.574	Q: 5.715
AP	.000	.000	11.100	.200	D:10 4 77
DAR	12.369	11.247	6.491	6.336	
CAR	.000	.000	3.441	.062	P: 18.4
DAE	.000	.000	4.362	.000	
CAE	2.205	2.205	5.001	2.205	Q: 1.604
AP	.000	.000	1.800	2.100	D:14 6 77
DAR	3.361	2.808	2.648	2.163	
CAR	.000	.000	.558	.651	P: 26.1
DAE	.000	.000	.000	.000	
CAE	2.220	2.220	2.220	2.220	Q: 1.312
AP	.000	2.500	9.100	6.800	D:24 9 77
DAR	1.071	.723	.962	1.045	
CAR	.000	.775	2.821	2.108	P: 74.3
DAE	.000	.000	1.574	.000	
CAE	3.918	3.918	6.884	8.884	Q: 8.122
AP	.000	2.500	11.600	81.900	D:27 9 77
DAR	.837	.806	1.152	11.032	
CAR	.000	.775	3.596	25.389	P: 29.4
DAE	.000	.000	3.821	65.188	
CAE	3.918	3.918	8.884	19.647	Q: 3.417
AP	11.600	105.800	6.500	5.700	D: 7 10 77
DAR	1.227	13.346	7.492	1.741	
CAR	3.596	32.798	2.015	1.767	P: 21.7
DAE	6.914	58.514	4.153	6.120	
CAE	4.524	22.689	4.524	4.524	Q: 1.031
AP	28.300	85.500	2.400	26.700	D: 9 10 77
DAR	1.231	18.241	2.956	3.843	
CAR	8.773	26.505	.744	8.277	P: 33.3
DAE	16.195	46.803	3.493	15.929	
CAE	10.260	22.689	4.524	4.524	Q: 5.703
AP	.000	63.800	10.800	19.700	D:22 10 77
DAR	1.846	12.754	5.264	4.666	
CAR	.000	19.778	3.348	6.107	P: 17.5
DAE	6.154	36.015	8.161	11.659	
CAE	4.524	22.689	4.524	4.524	Q: 1.172

VARIABLE	ANTECEDENT PENTAD (DAYS) 1 (20-16)	2 (15-11)	3 (10-06)	4 (05-01)	STORM INFORMATION
AP	46.300	13.200	24.100	6.100	D:29 10 77
DAR	13.131	3.914	6.288	2.794	
CAR	14.503	4.092	7.471	1.891	P: 15.6
DAE	27.411	9.220	14.281	5.856	
CAE	20.810	4.524	4.524	4.524	Q: .657
AP	20.300	16.500	72.600	9.100	D: 9 11 77
DAR	5.611	3.485	2.554	1.988	
CAR	6.293	5.115	22.568	2.821	P: 52.1
DAE	12.344	11.967	41.128	6.880	
CAE	4.810	4.810	24.123	4.810	Q: 11.550
AP	15.400	73.900	6.800	54.100	D:14 11 77
DAR	2.960	3.417	1.940	16.013	
CAR	4.774	22.909	2.108	16.771	P: 15.0
DAE	11.371	41.723	5.635	31.843	
CAE	4.810	24.123	4.810	23.718	Q: 2.206
AP	1.100	15.800	4.300	10.900	D:14 12 77
DAR	1.962	3.186	1.211	1.329	
CAR	.341	4.898	1.333	3.379	P: 25.7
DAE	2.429	11.348	4.282	8.335	
CAE	5.537	5.537	5.537	5.537	Q: .996
AP	237.100	30.700	1.100	19.300	D:10 2 78
DAR	44.465	19.759	7.704	8.045	
CAR	73.501	9.517	.341	5.983	P: 16.9
DAE	129.960	17.735	3.629	11.923	
CAE	20.170	9.121	4.022	4.022	Q: 1.193
AP	25.800	6.700	7.300	27.900	D:12 2 78
DAR	20.779	14.940	7.009	9.747	
CAR	7.998	2.077	2.263	8.649	P: 34.0
DAE	15.682	5.461	6.626	15.979	
CAE	4.022	4.022	4.022	9.121	Q: 5.214
AP	.000	24.000	44.500	9.000	D:20 2 78
DAR	7.686	8.150	16.552	7.937	
CAR	.000	7.440	13.795	2.790	P: 33.8
DAE	3.034	14.467	25.566	6.706	
CAE	4.022	4.022	13.978	4.022	Q: .111
AP	7.300	27.900	34.000	44.000	D:21 2 78
DAR	7.346	9.458	15.107	7.798	
CAR	2.263	8.649	10.540	13.640	P: 26.2
DAE	6.986	16.339	20.121	25.895	
CAE	4.022	9.121	9.121	13.978	Q: 16.092
AP	50.900	8.900	61.200	17.200	D: 1 3 78
DAR	15.197	9.723	25.463	9.478	
CAR	15.779	2.759	18.972	5.332	P: 39.3
DAE	29.271	6.052	35.807	11.506	
CAE	14.516	3.156	15.561	3.156	Q: 7.830

VARIABLE	ANTECEDENT PENTAD (DAYS) 1 (20-16)	2 (15-11)	3 (10-06)	4 (05-01)	STORM INFORMATION
AP	54.800	17.100	15.500	1.600	D: 8 3 78
DAR	7.984	26.567	20.042	9.422	
CAR	16.988	5.301	4.805	.496	P: 73.3
DAE	31.742	11.812	9.625	2.700	
CAE	15.561	3.156	3.156	3.156	Q: 20.843
AP	73.500	.000	2.800	1.900	D:27 3 78
DAR	32.981	9.591	6.852	4.722	
CAR	22.785	.000	.568	.589	P:108.7
DAE	41.507	1.354	3.230	3.582	
CAE	15.827	3.156	3.156	3.156	Q: 32.621
AP	.100	2.800	1.900	107.100	D: 1 4 78
DAR	9.425	6.852	4.751	41.197	
CAR	.031	.868	.589	33.201	P: 15.6
DAE	.000	.000	.000	88.036	
CAE	1.912	1.912	1.912	9.538	Q: 1.451
AP	3.800	25.900	5.100	18.600	D:22 4 78
DAR	6.991	7.703	4.874	6.511	
CAR	1.178	8.029	1.581	5.766	P: 75.6
DAE	.000	16.306	.000	10.072	
CAE	4.336	8.794	4.336	6.644	Q: 19.027
AP	3.400	4.600	.000	7.500	D: 3 6 78
DAR	4.869	4.365	3.775	4.158	
CAR	1.054	1.426	.000	2.325	P: 22.7
DAE	.000	.000	.000	.389	
CAE	1.919	4.351	1.919	4.351	Q: 2.146
AP	.000	.000	14.500	14.400	D:11 7 78
DAR	2.935	2.630	3.691	3.410	
CAR	.000	.000	4.495	4.464	P: 22.7
DAE	.000	.000	6.717	6.663	
CAE	2.437	2.437	8.469	8.469	Q: 2.163
AP	18.800	15.800	4.000	2.200	D: 8 9 78
DAR	4.084	2.505	1.838	1.653	
CAR	5.828	4.898	1.240	.682	P: 56.0
DAE	10.313	7.540	.000	.000	
CAE	11.705	11.705	7.638	3.368	Q: 11.531

U2M20

VARIABLE	ANTECEDENT PERIOD (DAYS)				STORM INFORMATION
	1 (20-15)	2 (15-11)	3 (10-05)	4 (05-01)	
AP	27.740	43.700	2.760	27.500	D:24 1 76
UAR	.000	.000	.000	.000	
CAR	2.920	4.060	.260	2.550	P: 29.7
UAE	.000	.000	.000	.000	
CAE	9.309	14.697	3.066	9.309	Q: 2.265
AP	22.620	.760	35.080	18.220	D:14 3 76
UAR	.000	.000	.000	.000	
CAR	2.100	.770	3.260	1.670	P: 29.2
UAE	.000	.000	.000	.000	
CAE	2.701	2.701	5.195	2.701	Q: 1.041
AP	31.030	8.460	23.200	22.530	D:12 11 76
UAR	.000	.000	.000	.000	
CAR	2.890	.790	1.080	2.100	P: 37.9
UAE	.000	.000	.000	.000	
CAE	7.926	2.613	2.613	2.613	Q: 1.363
AP	39.460	16.480	14.570	10.580	D: 5 12 76
UAR	.000	.000	.000	.000	
CAR	3.670	1.530	1.380	.900	P: 25.6
UAE	.000	.000	.000	.000	
CAE	14.486	3.024	3.024	3.024	Q: .103
AP	19.340	24.410	13.950	52.130	D: 4 12 76
UAR	.000	.000	.000	.000	
CAR	1.800	2.270	1.020	2.990	P: 27.5
UAE	.000	.000	.000	.000	
CAE	3.024	3.024	3.024	9.175	Q: 3.022
AP	10.530	65.770	7.580	6.090	D:22 12 76
UAR	.000	.000	.000	.000	
CAR	.980	6.120	.710	.570	P: 17.3
UAE	.000	.000	.000	.000	
CAE	3.024	20.579	3.024	3.024	Q: .253
AP	65.770	9.370	33.380	25.240	D:26 12 76
UAR	.000	.000	.000	.000	
CAR	6.120	.920	3.150	2.440	P: 36.0
UAE	.000	.000	.000	.000	
CAE	20.579	3.024	9.175	3.024	Q: 3.965
AP	6.870	33.980	26.240	40.330	D: 2 1 77
UAR	.000	.000	.000	.000	
CAR	.820	3.150	2.440	3.750	P: 24.0
UAE	.000	.000	.000	.000	
CAE	2.995	9.086	2.995	14.345	Q: 1.390
AP	27.400	16.700	3.690	9.680	D:13 2 77
UAR	.000	.000	.000	.000	
CAR	2.460	1.550	.330	.900	P: 38.1
UAE	.000	.000	.000	.000	
CAE	4.007	4.007	4.007	4.007	Q: 1.292

VARIABLE	ANTECEDENT PERIOD (DAYS) 1 (20-16)	2 (15-11)	3 (10-06)	4 (05-01)	EXTRA INFORMATION
AP	46.790	27.930	31.370	7.240	D: _ 3 75
DAR	.000	.000	.000	.000	
CAR	4.370	7.560	2.920	.670	P: 40.3
DAE	.000	.000	.000	.000	
CAE	15.636	2.466	7.435	2.406	Q: 7.429
AP	7.240	44.490	10.070	7.030	D:17 3 75
DAR	.000	.000	.000	.000	
CAR	.670	4.140	.000	.650	P: 16.9
DAE	.000	.000	.000	.000	
CAE	2.466	11.314	2.460	2.406	Q: .251

V1M28

VARIABLE	ANTECEDENT PENTAD (DAYS) 1 (20-16)	2 (15-11)	3 (10-06)	4 (05-01)	STORM INFORMATION
AP	.000	14.600	31.900	31.400	D:26 1 70
DAR	.000	.000	.000	.000	
CAR	.000	1.562	3.413	3.360	P: 28.9
DAE	.000	.000	.000	.000	
CAE	3.162	3.162	10.113	10.133	Q: 3.938
AP	42.400	31.300	57.200	36.600	D: 3 2 76
DAR	.000	.000	.000	.000	
CAR	4.537	3.349	6.120	3.916	P: 31.5
DAE	.000	.000	.000	.000	
CAE	15.375	9.433	18.330	15.375	Q: 16.383
AP	66.000	20.200	26.000	9.400	D:23 1 72
DAR	.000	.000	.000	.000	
CAR	7.062	2.161	2.782	1.006	P: 25.9
DAE	.000	.000	.000	.000	
CAE	19.652	3.162	3.162	3.162	Q: 4.128
AP	50.000	22.600	10.800	11.600	D:21 12 76
DAR	.000	.000	.000	.000	
CAR	5.350	2.418	1.156	1.241	P: 23.0
DAE	.000	.000	.000	.000	
CAE	19.523	3.225	3.225	3.225	Q: .395
AP	6.100	16.900	14.400	11.700	D:25 1 77
DAR	.000	.000	.000	.000	
CAR	.653	1.808	1.541	1.252	P: 22.4
DAE	.000	.000	.000	.000	
CAE	3.370	3.370	3.370	3.370	Q: .370
AP	1.100	.700	7.100	.300	D: 1 3 77
DAR	.000	.000	.000	.000	
CAR	.118	.075	.760	.032	P: 22.5
DAE	.000	.000	.000	.000	
CAE	2.187	2.187	2.187	2.187	Q: .195
AP	6.200	1.500	17.000	2.600	D: 7 4 77
DAR	.000	.000	.000	.000	
CAR	.663	.160	1.819	.278	P: 18.5
DAE	.000	.000	.000	.000	
CAE	5.560	1.739	9.063	1.739	Q: 1.984
AP	20.800	.200	1.000	.000	D:23 4 77
DAR	.000	.000	.000	.000	
CAR	2.226	.021	.107	.000	P: 18.3
DAE	.000	.000	.000	.000	
CAE	10.254	1.739	1.739	1.739	Q: 1.984
AP	36.600	9.400	23.900	.000	D:29 10 77
DAR	.000	.000	.000	.000	
CAR	3.916	1.006	2.557	.000	P: 24.7
DAE	.000	.000	.000	.000	
CAE	12.033	2.308	2.308	2.308	Q: 1.548

VARIABLE	ANTECEDENT PENTAD (DAYS) 1 (20-16)	2 (15-11)	3 (10-06)	4 (05-01)	STORM INFORMATION
AP	15.900	9.900	4.900	6.500	D:22 12 77
DAR	.000	.000	.000	.000	
CAR	1.701	1.059	.524	.696	P: 24.7
DAE	.000	.000	.000	.000	
CAE	3.429	3.429	3.429	3.429	Q: .400
AP	4.400	1.900	26.500	.500	D:30 12 77
DAR	.000	.000	.000	.000	
CAR	.471	.203	2.836	.054	P: 27.0
DAE	.000	.000	.000	.000	
CAE	3.429	3.429	3.429	3.429	Q: .800
AP	6.500	20.500	38.000	8.300	D: 6 1 78
DAR	.000	.000	.000	.000	
CAR	.696	2.194	4.066	.888	P: 49.6
DAE	.000	.000	.000	.000	
CAE	3.047	3.047	15.886	3.047	Q: 7.189
AP	52.200	17.200	19.500	15.500	D:23 1 78
DAR	.000	.000	.000	.000	
CAR	5.585	1.840	2.086	1.658	P: 72.7
DAE	.000	.000	.000	.000	
CAE	18.446	3.047	3.047	3.047	Q: 32.998
AP	19.500	15.500	81.200	2.900	D: 2 2 78
DAR	.000	.000	.000	.000	
CAR	2.086	1.658	8.688	.310	P: 26.6
DAE	.000	.000	.000	.000	
CAE	2.942	2.942	18.282	2.942	Q: 4.311
AP	17.100	19.400	7.200	10.000	D:26 9 78
DAR	.000	.000	.000	.000	
CAR	1.830	2.076	.770	1.070	P: 21.4
DAE	.000	.000	.000	.000	
CAE	6.895	6.895	4.229	4.229	Q: .474

V7M03

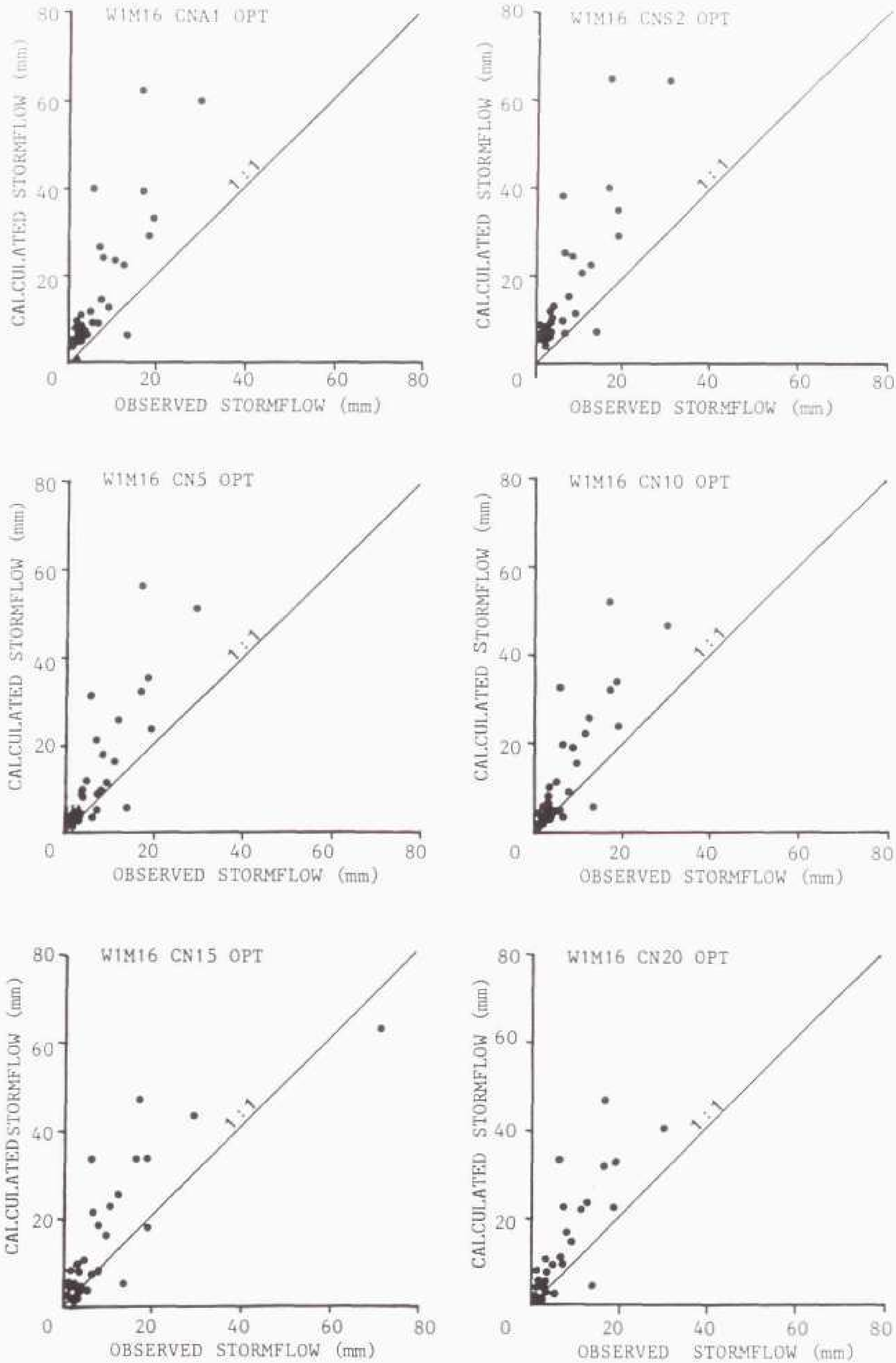
VARIABLE	ANTECEDENT PENTAD (DAYS) 1 (20-16)	2 (15-11)	3 (10-06)	4 (05-01)	STORM INFORMATION
AP	.000	14.600	31.900	31.400	D:25 1 70
DAR	.000	.000	.000	.000	
CAR	.000	1.562	3.413	3.360	P: 39.0
DAE	.000	.000	.000	.000	
CAE	4.671	4.671	13.442	13.442	Q: 7.259
AP	66.000	20.200	26.000	9.400	D:28 1 72
DAR	.000	.000	.000	.000	
CAR	7.062	2.161	2.782	1.006	P: 25.9
DAE	.000	.000	.000	.000	
CAE	19.652	4.671	4.671	4.671	Q: 7.244
AP	15.900	3.800	6.500	13.400	D: 2 12 76
DAR	.000	.000	.000	.000	
CAR	1.701	.407	.096	1.434	P: 27.1
DAE	.000	.000	.000	.000	
CAE	4.764	4.764	4.764	4.764	Q: 1.375
AP	50.000	22.600	10.800	11.600	D:21 12 76
DAR	.000	.000	.000	.000	
CAR	5.350	2.418	1.156	1.241	P: 24.1
DAE	.000	.000	.000	.000	
CAE	19.824	4.764	4.764	4.764	Q: .387
AP	6.100	16.900	14.400	11.700	D:25 1 77
DAR	.000	.000	.000	.000	
CAR	.653	1.808	1.541	1.252	P: 22.4
DAE	.000	.000	.000	.000	
CAE	4.978	4.978	4.978	4.978	Q: .487
AP	15.700	42.400	29.800	1.400	D: 7 2 77
DAR	.000	.000	.000	.000	
CAR	1.680	4.537	3.189	.150	P: 16.3
DAE	.000	.000	.000	.000	
CAE	4.754	18.634	13.679	4.754	Q: .909
AP	6.200	1.500	17.000	2.600	D: 7 4 77
DAR	.000	.000	.000	.000	
CAR	.663	.160	1.819	.278	P: 18.5
DAE	.000	.000	.000	.000	
CAE	7.391	2.569	10.068	2.569	Q: 1.530
AP	20.800	.200	1.000	.000	D:23 4 77
DAR	.000	.000	.000	.000	
CAR	2.226	.021	.107	.000	P: 18.4
DAE	.000	.000	.000	.000	
CAE	10.685	2.569	2.569	2.569	Q: .255
AP	36.600	9.400	23.900	.000	D:29 10 77
DAR	.000	.000	.000	.000	
CAR	3.916	1.006	2.557	.000	P: 24.7
DAE	.000	.000	.000	.000	
CAE	13.367	3.410	3.410	3.410	Q: 3.992

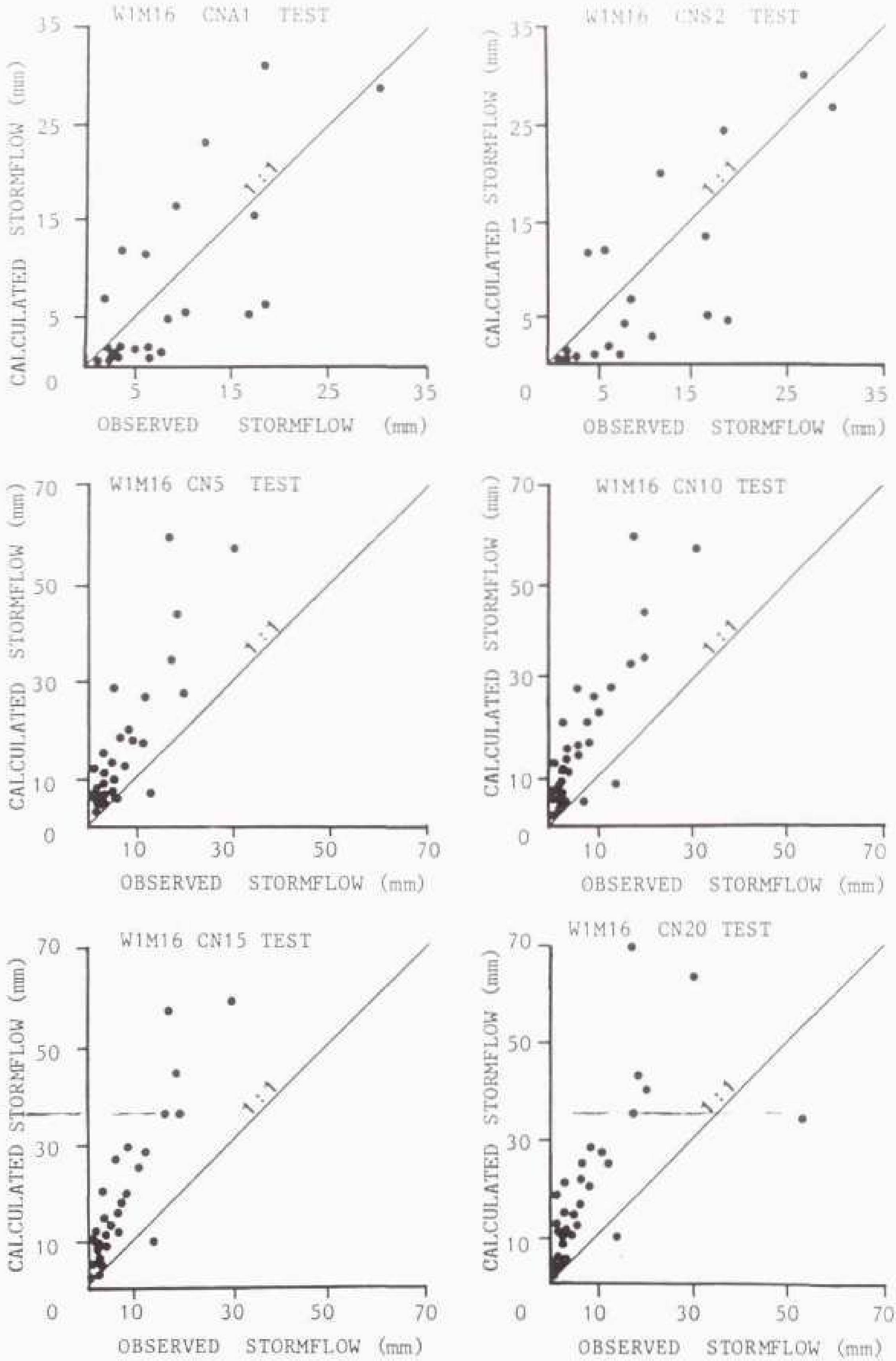
VARIABLE	ANTECEDENT PENTAD (DAYS) 1 (20-16)	2 (15-11)	3 (10-06)	4 (05-01)	STORM INFORMATION
AP	15.900	9.900	4.900	6.500	D:22 12 77
DAR	.000	.000	.000	.000	
CAR	1.701	1.059	.524	.696	P: 24.7
DAE	.000	.000	.000	.000	
CAE	5.064	5.064	5.064	5.064	Q: .481
AP	4.400	1.900	25.500	.500	D:30 12 77
DAR	.000	.000	.000	.000	
CAR	.471	.203	2.836	.054	P: 27.0
DAE	.000	.000	.000	.000	
CAE	5.064	5.064	5.064	5.064	Q: .323
AP	6.500	20.500	38.000	8.300	D: 6 1 78
DAR	.000	.000	.000	.000	
CAR	.696	2.194	4.066	.888	P: 36.9
DAE	.000	.000	.000	.000	
CAE	4.501	4.501	17.648	4.501	Q: 6.646
AP	19.500	15.500	81.200	2.900	D: 2 2 78
DAR	.000	.000	.000	.000	
CAR	2.086	1.658	8.688	.310	P: 26.6
DAE	.000	.000	.000	.000	
CAE	4.346	4.346	18.282	4.346	Q: 7.097
AP	17.100	19.400	7.200	10.000	D:26 9 78
DAR	.000	.000	.000	.000	
CAR	1.830	2.076	.770	1.070	P: 25.5
DAE	.000	.000	.000	.000	
CAE	7.659	7.659	5.622	5.622	Q: 2.010

APPENDIX 3

Scattergrams of calculated versus observed stormflow
for catchment W1M16 based on optimum (OPT) and
test (TEST) data for selected CN procedures:

CNA1 = average pentad CN
CNS2 = moving average pentad CN
CN5 = change in Ψ calculated over 5 days
CN10 = change in Ψ calculated over 10 days
CN15 = change in Ψ calculated over 15 days
CN20 = change in Ψ calculated over 20 days

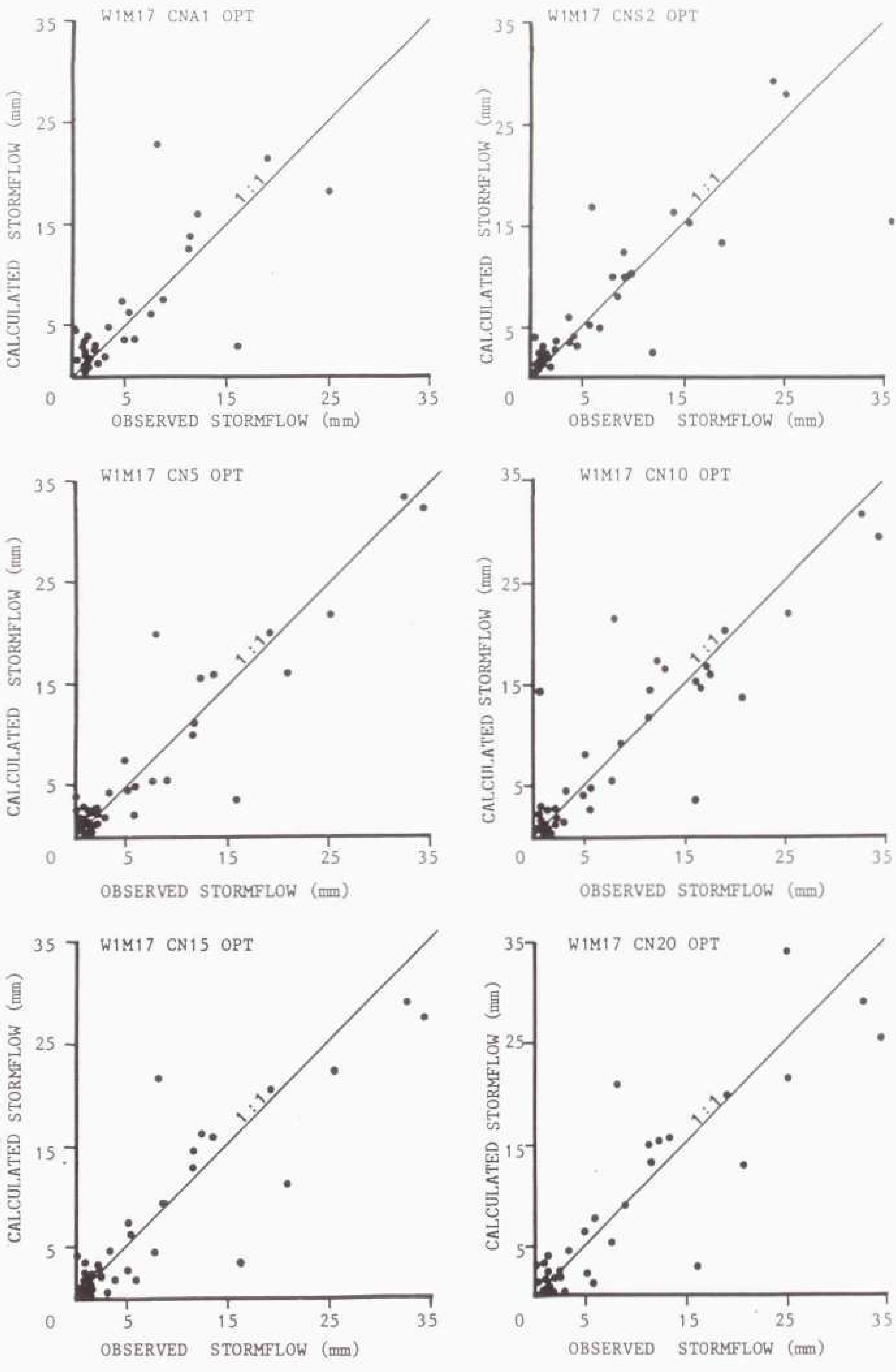

W1M16 CNA1 OPT
W1M16 CNS2 OPT
W1M16 CN5 OPT
W1M16 CN10 OPT
W1M16 CN15 OPT
W1M16 CN20 OPT
CALCULATED STORMFLOW (mm)
OBSERVED STORMFLOW (mm)
1:1
0
20
40
60
80

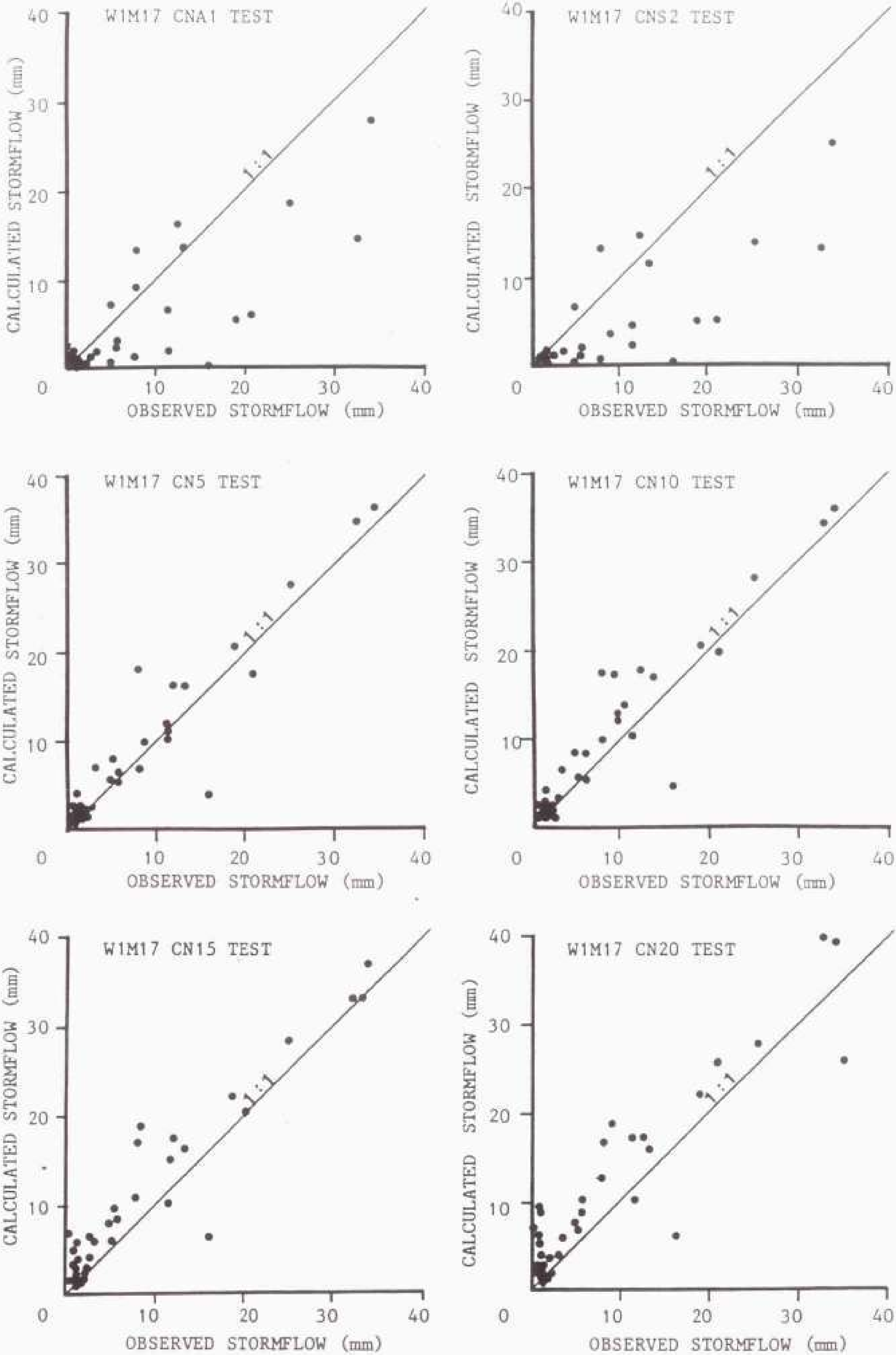

W1M16 CNA1 TEST
W1M16 CNS2 TEST
W1M16 CN5 TEST
W1M16 CN10 TEST
W1M16 CN15 TEST
W1M16 CN20 TEST
CALCULATED STORMFLOW (mm)
OBSERVED STORMFLOW (mm)
1:1
0
5
15
25
35
10
30
50
70

APPENDIX 4

Scattergrams of calculated versus observed stormflow
for catchment W1M17 based on optimum (OPT) and
test (TEST) data for selected CN procedures:

CNA1 = average pentad CN
CNS2 = moving average pentad CN
CN5 = change in Ψ calculated over 5 days
CN10 = change in Ψ calculated over 10 days
CN15 = change in Ψ calculated over 15 days
CN20 = change in Ψ calculated over 20 days

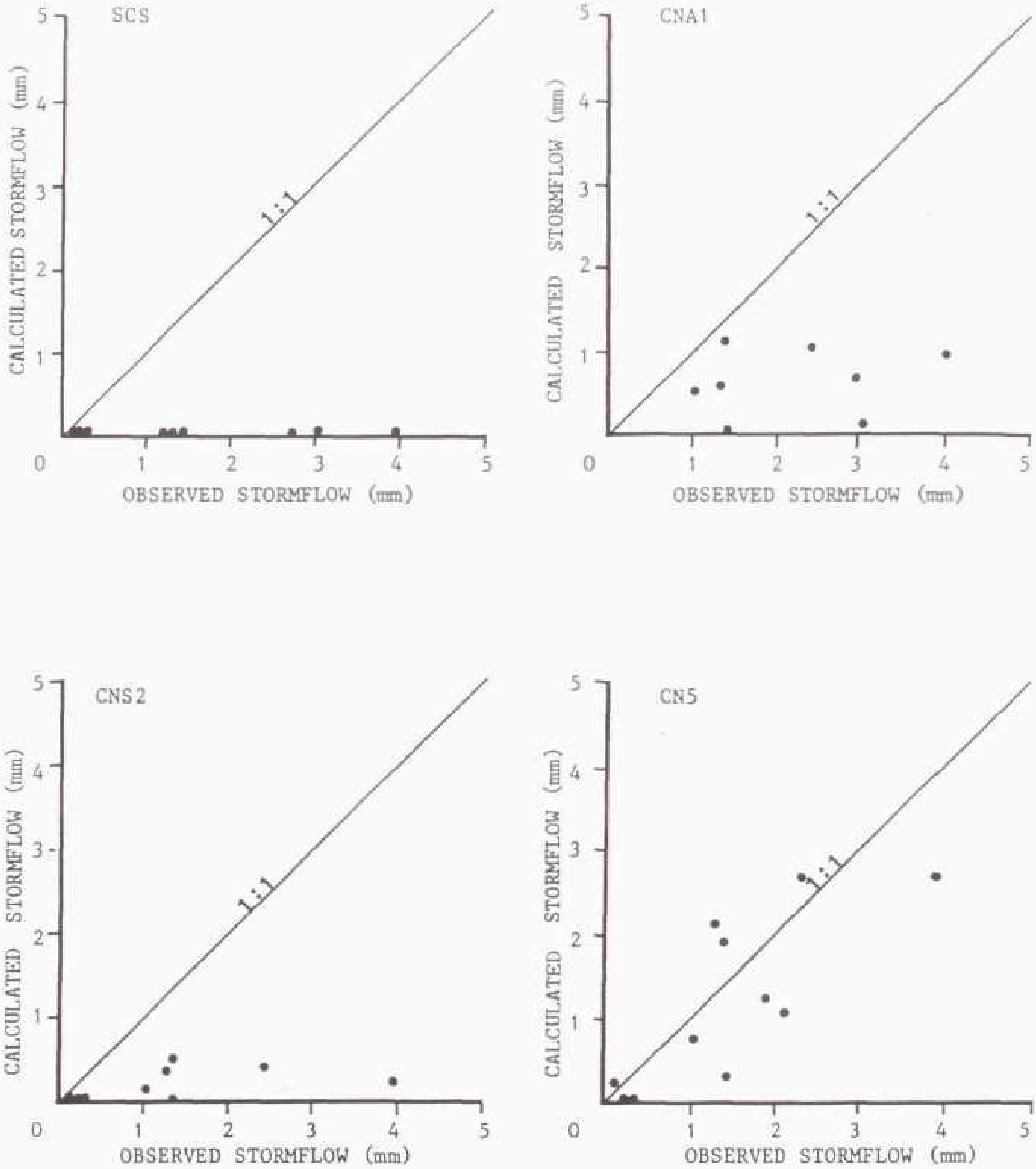

W1M17 CNA1 OPT
W1M17 CNS2 OPT
W1M17 CN5 OPT
W1M17 CN10 OPT
W1M17 CN15 OPT
W1M17 CN20 OPT
CALCULATED STORMFLOW (mm)
OBSERVED STORMFLOW (mm)
1:1
0
5
15
25
35

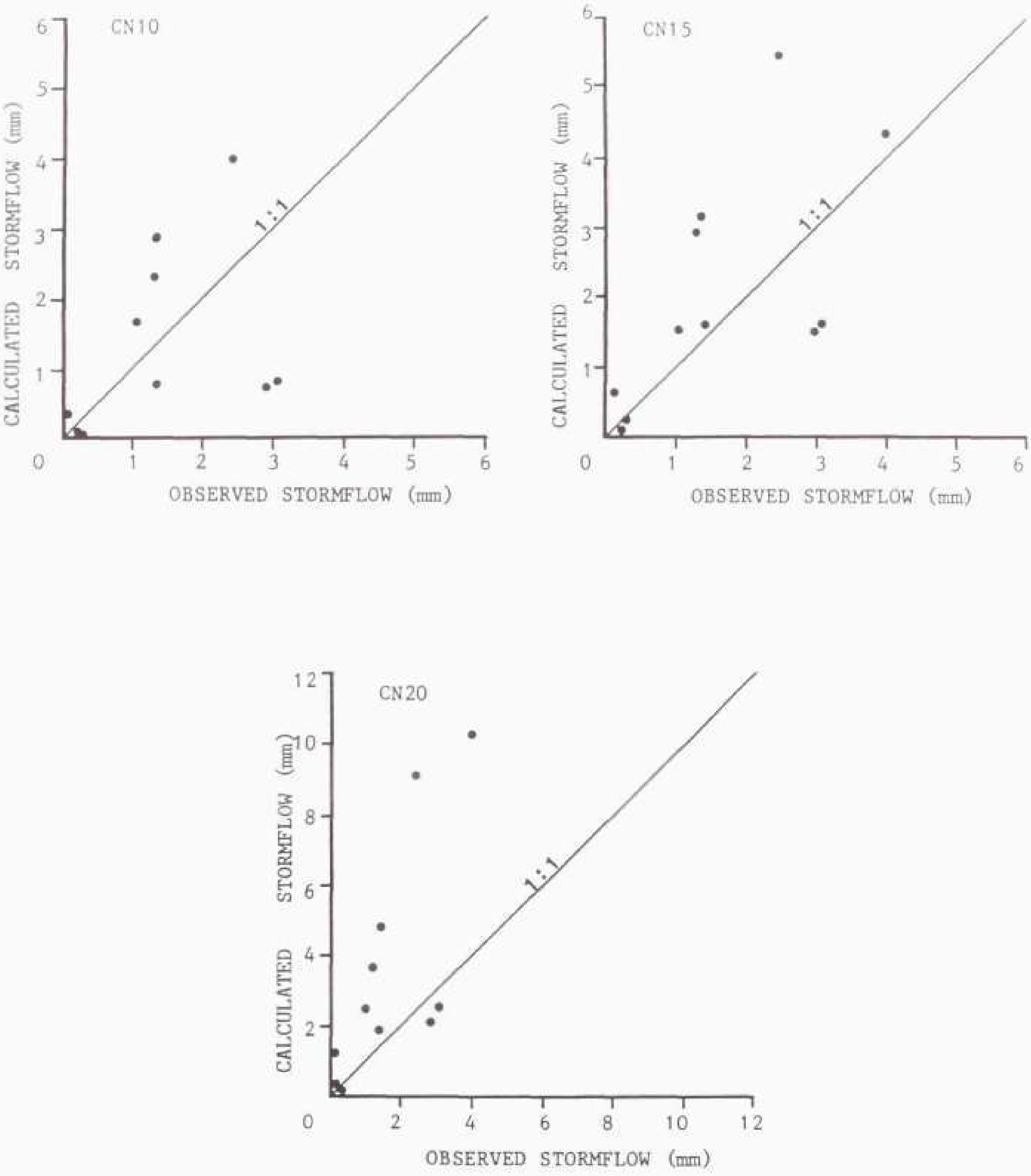

W1M17 CNA1 TEST
W1M17 CNS2 TEST
W1M17 CN5 TEST
W1M17 CN10 TEST
W1M17 CN15 TEST
W1M17 CN20 TEST
CALCULATED STORMFLOW (mm)
OBSERVED STORMFLOW (mm)
1:1
0
10
20
30
40

APPENDIX 5

Scattergrams of calculated versus observed stormflow for catchment U2M20 based on optimum (OPT) and test (TEST) data for selected CN procedures:

CNA1	=	average pentad CN
CNS2	=	moving average pentad CN
CN5	=	change in ¥ calculated over 5 days
CN10	=	change in ¥ calculated over 10 days
CN15	=	change in ¥ calculated over 15 days
CN20	=	change in ¥ calculated over 20 days


SCS
CNA1
CNS2
CN5
1:1
CALCULATED STORMFLOW (mm)
OBSERVED STORMFLOW (mm)
0
1
2
3
4
5


CN10
CALCULATED STORMFLOW (mm)
OBSERVED STORMFLOW (mm)
1:1
0
1
2
3
4
5
6
CN15
CALCULATED STORMFLOW (mm)
OBSERVED STORMFLOW (mm)
1:1
0
1
2
3
4
5
6
CN20
CALCULATED STORMFLOW (mm)
OBSERVED STORMFLOW (mm)
1:1
0
2
4
6
8
10
12

APPENDIX 6

Scattergrams of calculated versus observed stormflow
for catchment V1M28 based on optimum (OPT) and
test (TEST) data for selected CN procedures:

CNA1 = average pentad CN

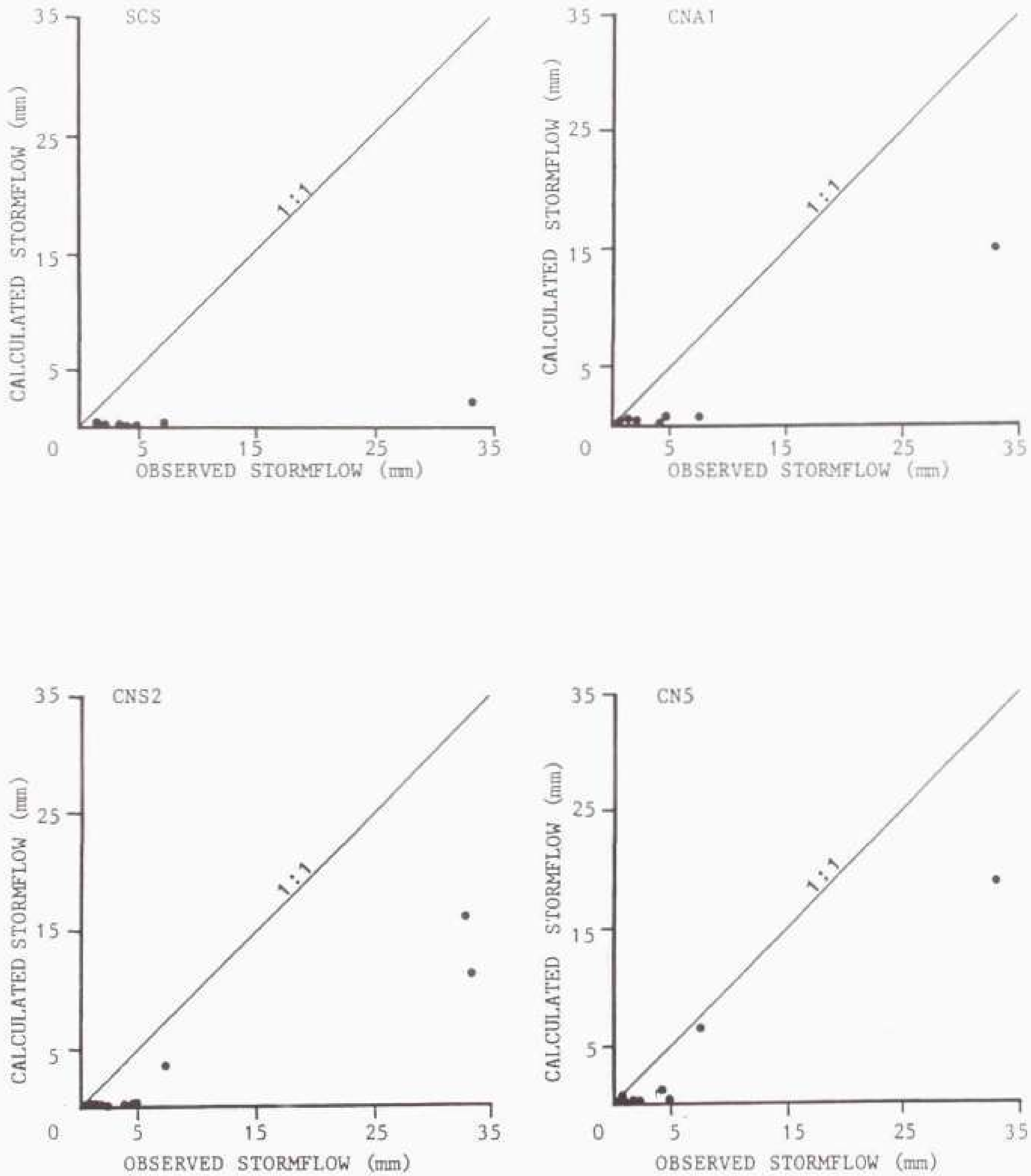
CNS2 = moving average pentad CN

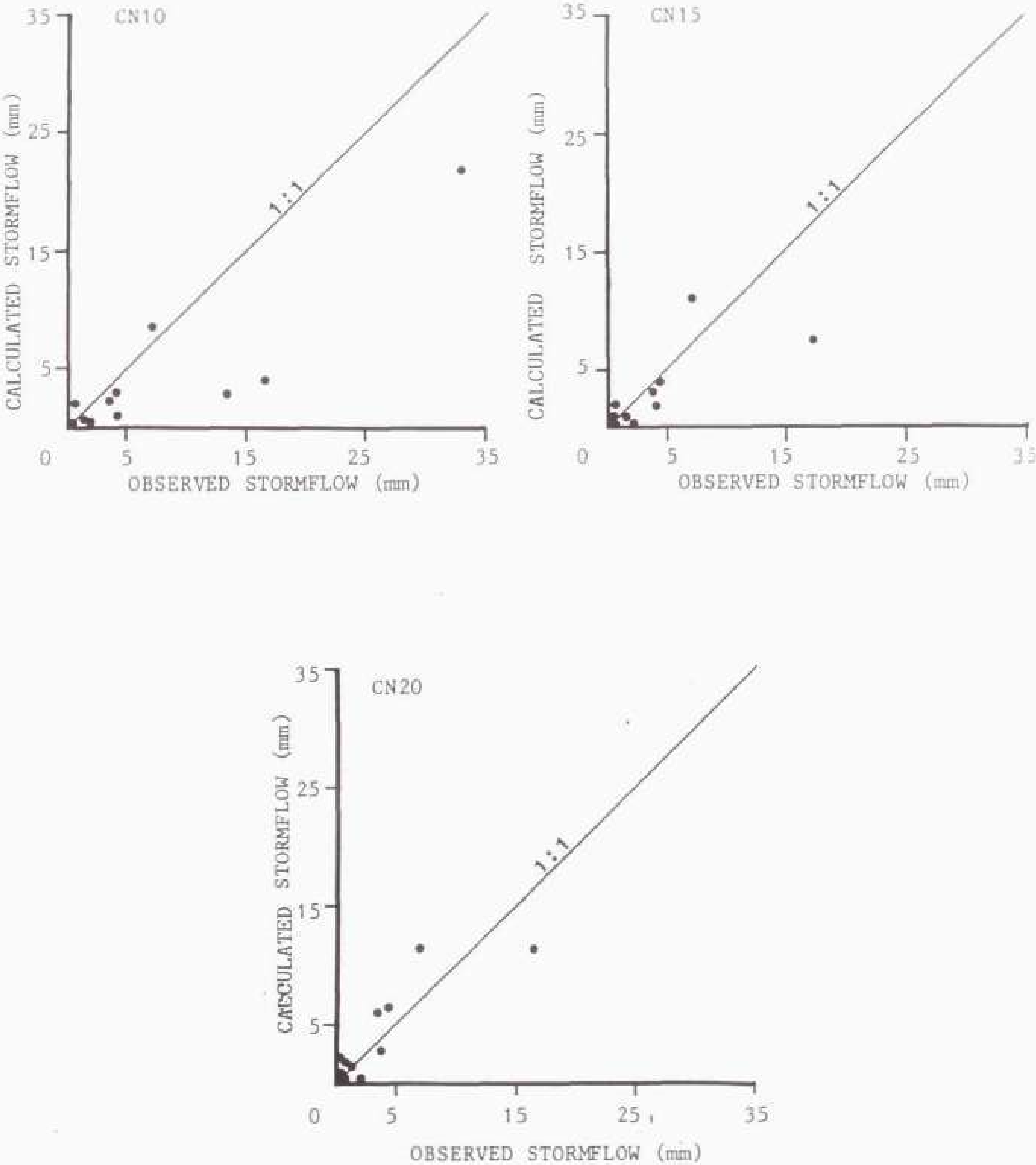
CN5 = change in Ψ calculated over 5 days

CN10 = change in Ψ calculated over 10 days

CN15 = change in Ψ calculated over 15 days

CN20 = change in Ψ calculated over 20 days


SCS
CNA1
CNS2
CN5
CALCULATED STORMFLOW (mm)
OBSERVED STORMFLOW (mm)
1:1
0
5
15
25
35


CN10
CALCULATED STORMFLOW (mm)
OBSERVED STORMFLOW (mm)
1:1
CN15
CALCULATED STORMFLOW (mm)
OBSERVED STORMFLOW (mm)
1:1
CN20
CALCULATED STORMFLOW (mm)
OBSERVED STORMFLOW (mm)
1:1
0
5
15
25
35

APPENDIX 7

Scattergrams of calculated versus observed stormflow for catchment V7M03 based on optimum (OPT) and test (TEST) data for selected CN procedures:

CNA1 = average pentad CN

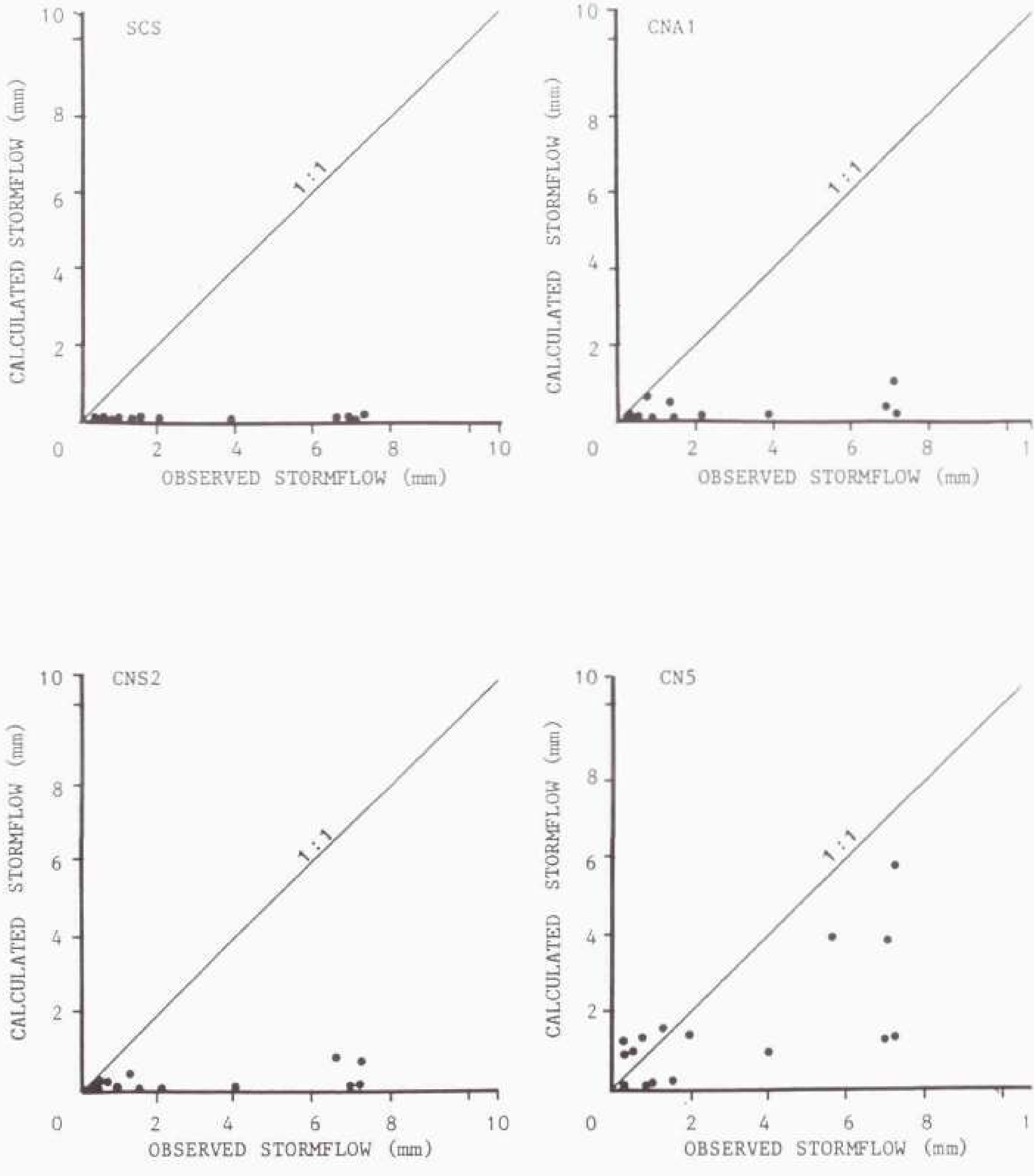
CNS2 = moving average pentad CN

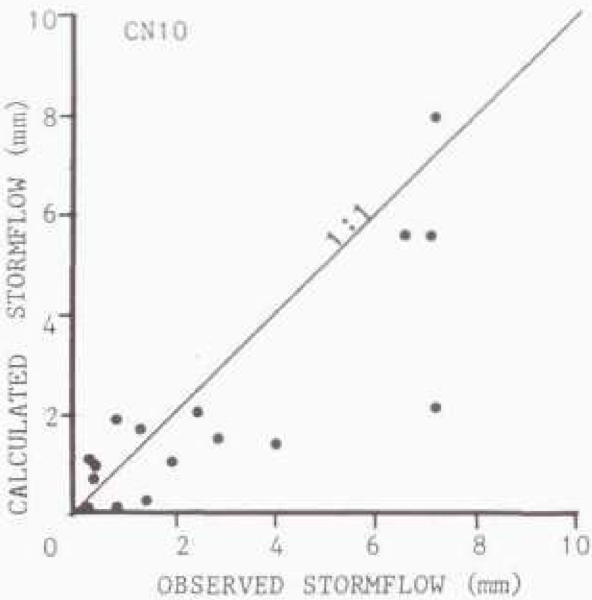
CN5 = change in Ψ calculated over 5 days

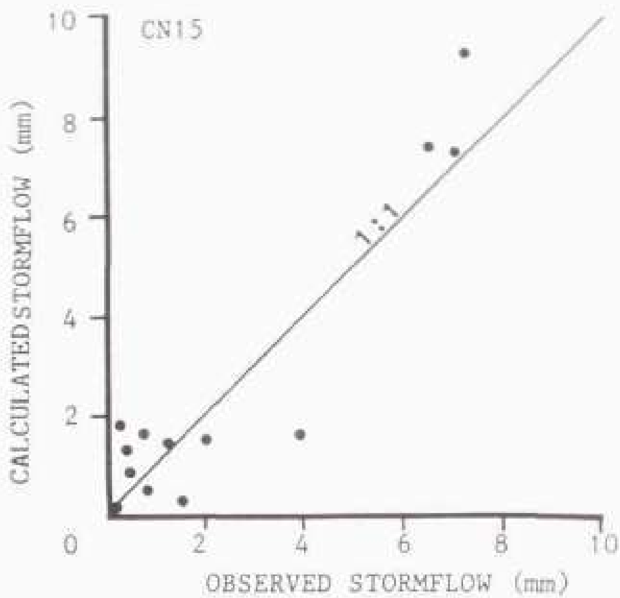
CN10 = change in Ψ calculated over 10 days

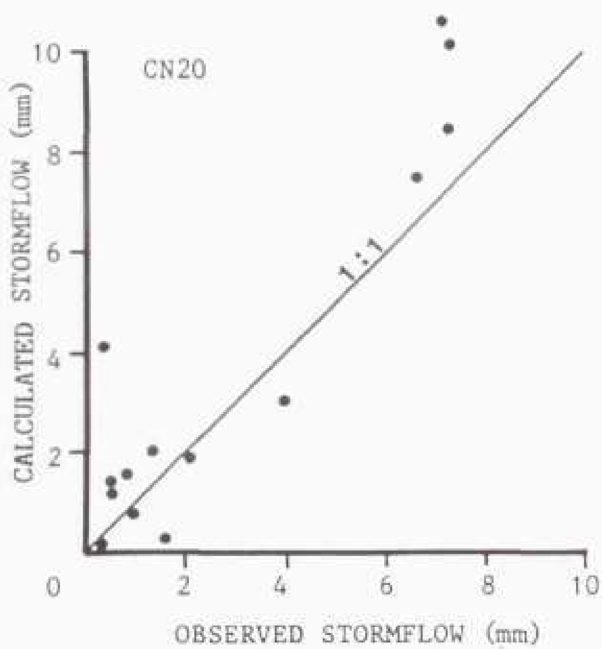
CN15 = change in Ψ calculated over 15 days

CN20 = change in Ψ calculated over 20 days


SCS
CALCULATED STORMFLOW (mm)
OBSERVED STORMFLOW (mm)
1:1
0
2
4
6
8
10
CNA1
CALCULATED STORMFLOW (mm)
OBSERVED STORMFLOW (mm)
1:1
CNS2
CALCULATED STORMFLOW (mm)
OBSERVED STORMFLOW (mm)
1:1
CN5
CALCULATED STORMFLOW (mm)
OBSERVED STORMFLOW (mm)
1:1


CN10
1:1
CALCULATED STORMFLOW (mm)
OBSERVED STORMFLOW (mm)
0
2
4
6
8
10


CN15
1:1
CALCULATED STORMFLOW (mm)
OBSERVED STORMFLOW (mm)
0
2
4
6
8
10


CN20
1:1
CALCULATED STORMFLOW (mm)
OBSERVED STORMFLOW (mm)
0
2
4
6
8
10

APPENDIX B

Storm rainfall, stormflow, the associated initial flow rate and antecedent rainfall used for testing the R-index model in catchments W1M15, W1M16, W1M17, U2M20, V1M28 and V7M03

The abbreviations used are as follows:

DY = day
MT = month
YR = year
P = storm rainfall (mm)
Q = stormflow (mm)
I = initial flow rate ($mm.h^{-1}$)
AP05 = five-day antecedent rainfall total (mm)
AP10 = ten-day antecedent rainfall total (mm)
AP15 = fifteen-day antecedent rainfall total (mm)

W1M15

DY	MT	YR	P	Q	I	AP05	AP10	AP15
16	11	76	22.9	3.302	.0222	19.6	32.5	35.9
13	12	76	17.3	.184	.0079	2.0	7.3	12.0
22	12	76	54.6	8.074	.0103	7.2	43.0	45.6
24	1	77	29.1	1.959	.0073	7.9	14.4	20.1
29	1	77	57.1	20.131	.0441	105.8	113.7	120.2
1	2	77	27.0	6.938	.0716	76.3	167.7	180.8
6	2	77	50.3	8.764	.0565	39.0	115.3	206.7
14	2	77	65.4	13.470	.0723	2.2	281.8	322.3
10	3	77	20.7	1.331	.0323	3.8	14.2	35.2
14	3	77	97.1	29.255	.0321	23.2	27.0	47.1
20	3	77	21.8	3.513	.0752	70.9	120.0	124.0
10	4	77	15.5	.605	.0240	4.7	12.1	16.3
14	6	77	17.9	.375	.0077	.6	4.0	6.8
2	7	77	19.3	.433	.0075	3.5	20.7	20.7
24	9	77	61.2	5.637	.0043	5.2	10.6	12.1
27	9	77	29.3	2.305	.0230	69.4	76.9	79.3
9	10	77	34.2	6.311	.0213	24.6	26.3	128.7
9	11	77	40.2	.791	.0086	4.9	36.0	43.1
19	12	77	54.7	7.947	.0044	19.4	29.1	30.2
23	12	77	20.4	1.789	.0205	60.4	82.4	89.5
31	12	77	23.3	.639	.0198	6.8	41.1	95.9
19	1	78	38.4	.698	.0145	.0	11.4	41.9
27	1	78	27.2	2.650	.0053	42.0	244.8	256.1
12	2	78	20.3	1.581	.0321	24.6	29.1	45.5
1	3	78	35.4	14.082	.0608	16.8	85.6	95.2
27	3	78	60.3	11.617	.0176	.0	1.5	1.5
22	4	78	63.9	6.263	2.2040	23.0	31.4	53.4
3	6	78	29.3	4.114	.0225	1.4	1.4	6.9

W1M15

DY	MT	YR	P	Q	I	AP05	AP10	AP15
11	7	78	23.4	3.759	.0307	.0	.9	10.2
8	9	78	54.2	7.897	.0080	9.5	11.5	16.0
12	9	78	14.3	.632	.0268	53.4	53.6	62.2
4	10	78	51.6	8.064	.0095	2.8	12.7	12.8
4	10	78	51.6	8.064	.0095	11.4	46.6	109.4
24	10	78	21.0	2.907	.0471	41.6	60.3	97.7
18	11	78	30.8	3.318	.0160	14.4	25.6	32.4
21	11	78	19.8	2.349	.0243	34.7	52.7	62.9
26	11	78	8.5	2.687	.0681	40.0	74.7	92.7
2	1	79	17.1	.224	.0088	5.1	15.3	16.7
27	1	79	40.9	1.609	.0049	18.7	42.5	42.7
3	3	79	31.7	.697	.0049	1.4	4.3	29.2
4	5	79	41.3	.765	.0036	.0	11.4	13.5
15	10	79	43.9	4.179	.0117	27.4	28.5	48.2
12	12	79	30.0	2.005	.0090	22.0	44.4	59.2

W1M16

DY	MT	YR	P	Q	I	AP05	AP10	AP15
16	11	76	19.4	3.364	.0300	15.6	30.3	35.7
13	12	76	18.5	.370	.0099	2.7	8.6	13.2
22	12	76	66.8	10.956	.0143	9.3	47.9	51.5
24	1	77	43.8	4.538	.0092	12.3	19.8	21.5
29	1	77	71.4	18.547	.0610	117.5	129.8	137.3
1	2	77	40.9	9.121	.0939	87.2	189.1	205.3
6	2	77	302.2	227.336	.0747	42.7	129.9	188.6
14	2	77	188.7	71.543	.0920	3.8	304.7	348.6
10	3	77	23.4	2.338	.0410	3.5	16.4	40.5
14	3	77	104.0	30.049	.0441	28.6	32.1	45.0
20	3	77	27.8	5.161	.1034	66.6	112.7	136.1
10	4	77	17.4	1.155	.0344	.0	6.2	11.2
14	6	77	16.3	.535	.0185	.0	1.9	1.9
2	7	77	16.3	.448	.0103	2.2	6.7	6.7
24	9	77	68.8	6.091	.0047	3.7	13.1	14.2
27	9	77	25.5	3.249	.0249	78.0	89.6	92.2
9	10	77	33.3	6.446	.0266	25.3	27.8	143.0
9	11	77	52.1	10.549	.0099	5.1	85.1	94.4
19	12	77	56.4	8.256	.0037	28.9	39.5	39.5
23	12	77	27.9	3.045	.0289	63.5	95.5	103.0
31	12	77	20.7	.856	.0289	7.8	46.7	102.8
19	1	78	236.4	77.259	.0179	.0	.0	31.7
27	1	78	26.3	3.065	.0954	42.2	236.9	236.9
12	2	78	34.0	3.178	.0415	29.5	36.2	51.6
1	3	78	38.3	7.364	.0712	15.8	77.0	88.6
27	3	78	79.5	16.864	.0203	.0	2.8	2.8
22	4	78	74.0	17.054	.0255	20.6	34.5	49.5
3	6	78	22.1	2.345	.0164	7.5	7.5	12.1

W1M16

DY	MT	YR	P	Q	I	AP05	AP10	AP15
11	7	78	21.1	2.564	.0365	.0	.0	8.1
8	9	78	55.2	6.646	.0070	1.2	5.2	8.9
12	9	78	20.9	1.301	.0255	55.6	56.0	60.0
4	10	78	64.7	10.483	.0118	3.4	14.5	14.7
18	10	78	41.8	12.506	.0502	11.3	51.2	118.4
23	10	78	22.5	2.892	.0577	47.5	58.8	98.7
18	10	78	30.8	3.647	.0212	14.0	28.4	33.0
21	11	78	21.1	3.120	.0321	36.0	57.5	65.6
25	11	78	24.8	4.291	.0557	36.5	78.6	94.0
2	1	79	28.6	.693	.0058	5.2	15.1	18.4
27	1	79	40.9	2.636	.0050	15.1	45.2	45.5
3	3	79	37.4	1.600	.0060	1.8	4.7	35.4
4	5	79	36.3	.962	.0044	.0	14.4	16.2
14	10	79	37.6	6.119	.0106	16.5	16.6	46.2
12	12	79	28.5	2.922	.0081	22.2	45.0	61.9

W1M17

DY	MT	YR	P	Q	I	AP05	AP10	AP15
16	11	76	23.2	3.751	.0360	15.6	30.3	35.7
13	12	76	18.5	1.426	.0349	2.7	8.6	13.2
22	12	76	65.4	12.448	.0220	9.3	47.9	51.5
24	1	77	43.8	5.092	.0123	12.3	19.8	21.5
29	1	77	71.4	25.456	.0511	117.5	129.8	137.3
1	2	79	40.9	8.908	.0817	87.2	189.1	205.3
6	2	77	302.2	206.923	.0817	42.7	129.9	188.6
14	2	77	188.7	94.474	.1130	3.8	304.7	348.6
10	3	77	24.5	2.991	.0640	3.5	16.4	40.5
14	3	77	104.0	34.264	.0688	28.6	32.1	45.0
19	3	77	27.8	5.715	.1000	104.0	132.6	136.1
10	4	77	18.3	1.604	.0522	.0	6.2	11.2
14	6	77	23.8	1.312	.0172	.0	1.9	1.9
2	7	77	18.0	.872	.0172	2.2	6.7	.7
24	9	77	74.7	8.122	.0113	3.7	13.1	14.2
27	9	77	29.4	3.417	.0360	78.0	89.6	92.2
9	10	77	33.3	5.703	.0328	25.3	27.8	143.0
9	11	77	52.1	11.550	.2206	5.1	85.1	94.4
19	12	77	58.2	16.027	.0075	28.9	39.5	39.5
23	12	77	26.5	3.133	.0473	63.5	95.5	103.0
31	12	77	20.7	.839	.0365	7.8	46.1	102.8
19	1	78	236.4	98.592	.0247	.0	.0	31.7
27	1	78	26.3	4.275	.1038	42.2	236.9	236.9
12	2	78	34.0	5.214	.0511	29.5	36.2	51.6
1	3	78	38.4	7.830	.0827	15.8	77.0	88.6
27	3	79	107.1	32.621	.0365	.0	2.8	2.8
22	4	78	74.0	19.027	.0398	20.6	34.5	49.5
3	6	78	22.7	2.146	.0322	7.5	7.5	12.1

W1M17

DY	MT	YR	P	Q	I	AP05	AP10	AP15
11	7	78	21.1	2.163	.0414	.0	.0	8.1
8	9	78	55.6	11.531	.0183	1.2	5.2	8.9
1	9	78	20.9	3.059	.0430	55.6	56.0	60.0
4	10	78	64.9	11.434	.0177	3.4	14.5	14.7
18	10	78	43.6	12.489	.0538	11.3	51.2	118.4
23	10	78	23.5	3.086	.0565	47.5	58.8	98.7
18	11	78	34.0	3.615	.0290	14.0	28.4	33.0
21	11	78	22.1	3.505	.0371	36.0	57.5	65.5
25	11	78	24.6	4.742	.0688	36.5	78.6	94.0
2	1	79	28.6	1.241	.0123	5.2	15.1	18.4
20	1	79	15.6	.314	.0118	15.1	45.2	45.5
3	3	79	47.8	2.611	.0091	1.8	4.7	35.4
4	5	79	51.0	1.783	.0037	.0	14.4	16.2
14	10	79	50.0	6.923	.0172	16.5	16.6	46.2
12	12	79	31.2	4.143	.0113	22.2	45.0	61.9

U2M20

DY	MT	YR	P	Q	I	AP05	AP10	AP15
24	1	78	29.7	2.960	.2000	27.5	30.3	74.0
14	3	78	29.2	1.040	.1000	18.2	53.3	54.1
12	11	78	33.9	1.360	1.1000	22.5	42.7	51.2
6	12	78	25.6	.100	.1000	10.6	25.5	41.9
9	12	78	27.5	3.080	.5000	32.1	43.1	67.5
22	12	78	17.8	.260	.2000	6.1	13.8	79.6
28	12	78	36.0	3.980	1.0000	26.2	60.1	69.0
2	1	78	24.0	1.390	1.0000	40.3	66.6	100.5
13	2	79	38.1	1.290	.0000	9.7	18.6	35.3
2	3	79	40.3	2.420	.0000	7.2	38.6	66.5
17	3	79	16.9	.250	.1000	7.0	17.0	61.5

V1M28

DY	MT	YR	P	Q	I	AP05	AP10	AP15
21	12	76	23.0	.390	.0000	11.6	22.4	45.0
25	1	77	22.4	.370	.0000	11.7	26.1	43.0
1	3	77	22.5	.190	.0000	.3	7.4	8.1
7	4	77	18.5	1.980	5.0000	2.6	19.6	21.1
23	4	77	18.3	.410	.0000	.0	1.0	1.2
29	10	77	24.7	1.540	1.0000	.0	23.9	34.3
22	12	77	24.7	.400	.0000	6.5	11.4	21.3
30	12	77	27.0	.800	3.0000	.5	27.0	28.9
6	1	78	49.5	7.180	12.0000	8.3	46.3	66.8
23	1	78	72.7	32.990	8.0000	15.5	35.0	52.2
2	2	78	26.6	4.310	45.0000	2.9	84.1	99.6
26	9	78	21.4	.470	1.0000	10.0	17.2	31.6

V7M03

DY	MT	YR	P	Q	I	AP05	AP10	AP15
28	1	72	25.9	7.240	.7000	9.4	35.4	55.6
21	12	76	24.1	.380	.4000	11.6	22.4	45.0
25	1	77	22.4	.480	.2000	11.7	26.1	43.0
7	2	77	16.3	.900	3.6000	1.4	31.2	73.6
7	4	77	18.5	1.530	1.0000	2.6	19.6	21.1
23	4	77	18.4	.250	.2000	.0	1.0	1.2
29	10	77	24.7	3.990	.5000	.0	23.9	33.3
22	12	77	24.7	.480	.0000	6.5	11.4	21.3
30	12	77	27.0	.820	.0000	.5	27.0	23.9
6	1	78	36.9	6.640	.4000	8.3	46.3	66.8
2	2	78	26.6	7.090	2.9000	2.9	84.1	99.6
26	9	78	25.5	2.010	.3000	10.0	17.2	36.6

APPENDIX 9

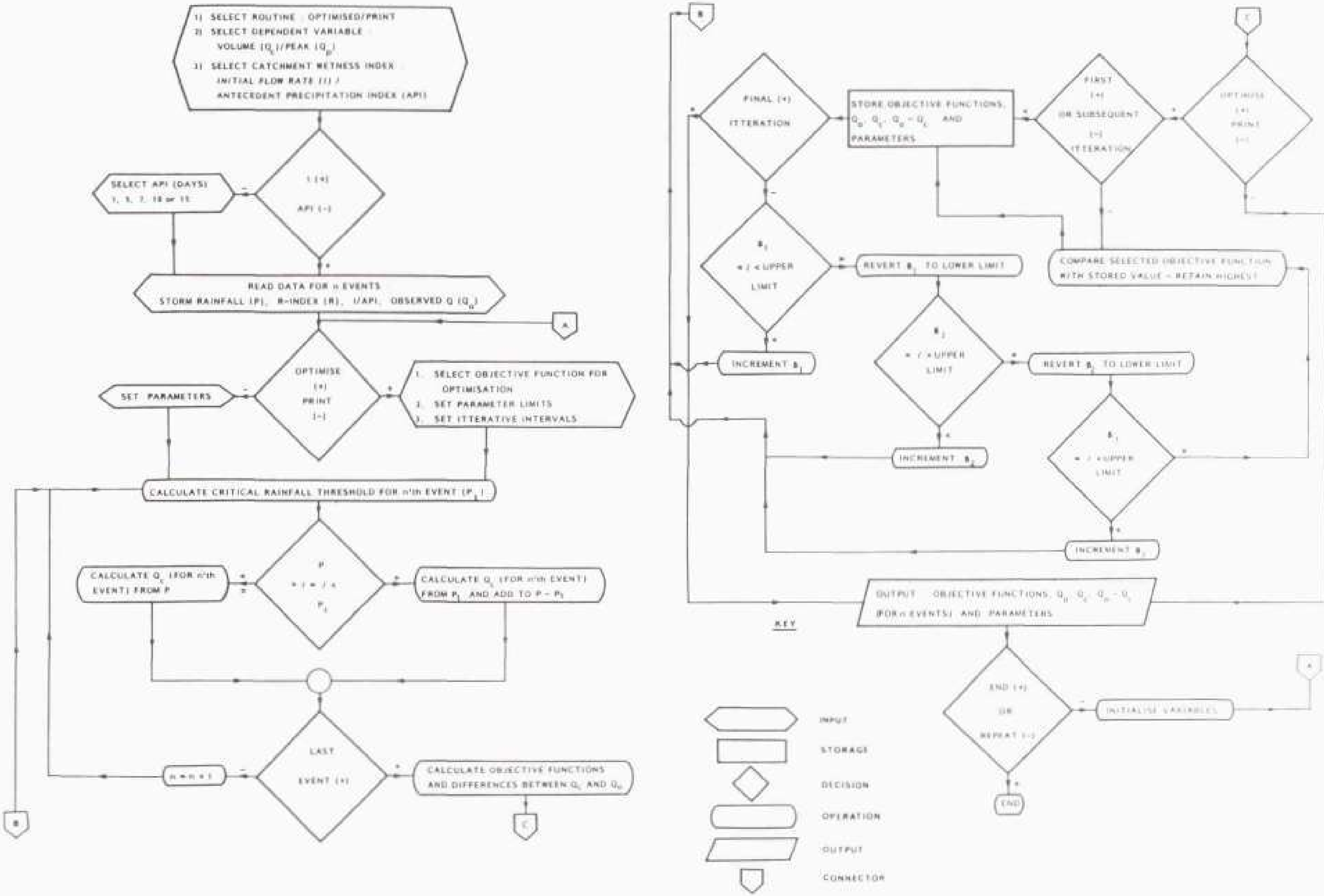
Computer programme INDEX

(a) Flow diagram

(b) Fortran programme

(c) Input and operation instructions

(d) Example of output



a) FLOW DIAGRAM OF PROGRAM INDEX

b) FORTRAN PROGRAM

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C**************************************************************
C
C       PROGRAM INDEX
C       A.S.HOPE
C       HYDROLOGICAL RESEARCH UNIT
C       UNIVERSITY OF ZULULAND
C
C**************************************************************
C
C-----PROGRAM TO CALCULATE STORMFLOW DEPTHS (MM) OR PEAK
C-----FLOW RATE(MM/H)USING THE R-INDEX MODEL
C-----PROGRAM CALCULATES:
C
C                MEAN - OBSERVED                            (AQO)
C                     - CALCULATED                          (AQE)
C                STANDARD DEVIATION - OBSERVED              (SDO)
C                                   - CALCULATED            (SDE)
C                COEFFICIENT OF VARIATION - OBSERVED        (CVO)
C                                         - CALCULATED(CVE)
C                COEFFICIENT OF DETERMINATION               (D)
C                COEFFICIENT OF EFFICIENCY                  (E)
C                D-E                                        (F)
C                STANDARD.ERROR                             (SE)
C                REGRESSION COEFFICIENT                     (REGC)
C                BASE CONSTANT                              (BC)
C
C**************************************************************
C
C-----THE PROGRAM ALLOWS FOR INTERACTIVE CHANGES OF
C-----THE MODEL PARAMETERS BETA-1 (B1) ,BETA-2 (B2)
C-----AND BETA-3 (B3) OR AUTOMATIC OPTIMISATION FOR A
C-----SPECIFIC OBJECTIVE FUNCTION
C
C--------------------------------------------------------------
C
C-----INPUTS  R-INDEX                        (-)   (R)
C-----        NO. OF OBSERVATIONS            (-)   (N)
C-----        STORM RAINFALL                 (MM)  (P)
C-----        OBSERVED STORMFLOW/PEAK        (MM)  (QO/IOP)
C-----        BASEFLOW AT START OF EVENT     (MM)  (AI)
C-----        ANTECEDENT RAINFALL            (MM)  (AI)
C-----        CATCHMENT AREA                 (SQ.KM) (A)
C
C-----OUTPUTS  OBJECTIVE FUNCTIONS
C-----         OBSERVED STORMFLOW   /PEAK
C-----         CALCULATED STORMFLOW /PEAK
C-----         BETA VALUES
C
C--------------------------------------------------------------
C
C-----SYMBOLS IN ALPHABETICAL ORDER
C
C-----A=AREA (SQ.KM)
C-----AI=BASEFLOW (MM/H) OR API(MM)
C-----AI2=BASEFLOW (QU.FT/SEC/SQ.ML) OR API(CM)
C-----AQE=MEAN QE (MM)
C-----AQO=MEAN QO (MM)
C-----BC=BASE CONSTANT
```

```
C-----B1,B2,B3=MODEL PARAMETERS (BETA)
C-----              (B1L=LOWER LIMIT)
C-----              (B1U=UPPER LIMIT)
C-----CAT=CATCHMENT WETNESS INDEX
C-----CVE=COEFFICIENT OF VARIATION OF ESTIMATED VALUES (%)
C-----CVO=COEFFICIENT OF VARIATION OF OBSERVED VALUES (%)
C-----C=COEFFICIENT OF DETERMINATION
C-----DIFS=QO-QE (MM)
C-----E=COEFFICIENT OF EFFICIENCY
C-----F=C-E
C-----IAMC=BASEFLOW/API FLAG
C-----IAPI=API (N DAYS)
C-----ISEL=MANUAL/ITTERATIVE FLAG
C-----IVP=VOLUME/PEAK FLAG
C-----N=NUMBER OF OBSERVATIONS
C-----IOBFN=OBJECTIVE FN. TO BE OPT.
C-----OP=OPTIMISATION/PRINT FLAG
C-----P=STORM RAINFALL (MM)
C-----PCRIT=CRITICAL RAINFALL THRESHOLD (MM)
C-----PER=DIFS/QO*100 (%)
C-----QE=ESTIMATED STORMFLOW (MM)
C-----QO=OBSERVED STORMFLOW (MM)
C-----QP=PEAK STORMFLOW (MM)
C-----R=R-INDEX (-)
C-----REGC=REGRESSION COEFFICIENT
C-----SDE=SD QE (MM)
C-----SDO=SD QO (MM)
C-----SE=STANDARD ERROR
C-----STEP0,STEP1,STEP2=ITTERATIVE INTERVALS
C
C*************************************************************
C
      CHARACTER TITLE*60,CAT*6
      DIMENSION QO(100),QE(100),P(100),AI(100),A2(100),
     1X(100),B22(100),Y(100),AI2(100),DIFS(100),PER(100),
     2PCRIT(100),R(100),A(100),QP(100),ZQE(100),ZDIFS(100),
     3ZPER(100),PEP(100),ZQO(100)
C
C-----INITIALISE ARRAYS
C
      DO   1 I=1,100
      QO(I)=0.0
      QE(I)=0.0
      P(I)=0.0
      AI(I)=0.0
      A2(I)=0.0
      X(I)=0.0
      B22(I)=0.0
      Y(I)=0.0
      AI2(I)=0.0
      DIFS(I)=0.0
      PEP(I)=0.0
      PCRIT(I)=0.0
      R(I)=0.0
      A(I)=0.0
      QP(I)=0.0
      ZQO(I)=0.0
      ZQE(I)=0.0
      ZDIFS(I)=0.0
      ZPER(I)=0.0
```

```
    1 CONTINUE
C
C-----INITIALISE
C
      BD=0.0
      BE=0.0
      BSE=99.9
C
C-----SELECT OPTIMISATION/PRINT
C
      WRITE(6,1000)
      READ(5,1001)IOP
C
C-----SELECT VOLUME (0) OR PEAK (1)
C
      WRITE(6,1002)
      READ(5,1003)IVP
C
C-----A
C
C-----SET ALTERNATIVES
C
C-----BASEFLOW(0) OR API(1)
C
      WRITE(6,1004)
      READ(5,1005)IAMC
C
C-----ENTER TITLE
C
      WRITE(6,1006)
      READ(5,1007)TITLE
C
C-----BASEFLOW OR API FLAG
C
      IF(IAMC)  3,  3,  2
C
C-----API SELECTION
C
    2 WRITE(6,1008)
      READ(5,1009)IAPI
C
C-----READ NO. OBSERVATIONS + CATCHMENT INDEX
C
    3 READ(5,1010)N,CAT
C
C-----READ R-INDEX,AREA,OBSERVED Q/PK,BASEFLOW/API
C
      DO  14 I=1,N
C
C-----API FLAG TO FORMAT
C
      IF(IAPI-1)  4,  9,  4
    4 IF(IAPI-5)  5, 10,  5
    5 IF(IAPI-7)  6, 11,  6
    6 IF(IAPI-10)  7, 12,  7
    7 IF(IAPI-15)  8, 13,  8
C
C-----BASEFLOW
C
    8 READ(5,1011)P(I),R(I),A(I),QO(I),QP(I),AI(I)
```

```
      GO TO  14
C
C-----API 1
C
    9 READ(5,1012)P(I),R(I),A(I),QO(I),QP(I),AI(I)
      GO TO  14
C
C-----API 5
C
   10 READ(5,1013)P(I),R(I),A(I),QO(I),QP(I),AI(I)
      GO TO  14
C
C-----API 7
C
   11 READ(5,1014)P(I),R(I),A(I),QO(I),QP(I),AI(I)
      GO TO  14
C
C-----API 10
C
   12 READ(5,1015)P(I),R(I),A(I),QO(I),QP(I),AI(I)
      GO TO  14
C
C-----API 15
C
   13 READ (5,1016)P(I),R(I),A(I),QO(I),QP(I),AI(I)
   14 CONTINUE
C
C-----TEST FOR VOLUME OR PEAK,IF PEAK LET QO(I)=QP(I)
C
      IF (IVP) 16, 16, 15
   15 DO  16 I=1,N
      QO(I)=QP(I)
   16 CONTINUE
C
C-----TEST FOR OPT/PRINT
C
      IF(IOP) 18, 18, 17
   17 WRITE(6,1017)
      READ(5,1018)B1,B2,B3
      GO TO  24
C
C-----ITTERATIVE ROUTINE
C
C-----SELECT OBJECTIVE FUNCTION
C
   18 WRITE(6,1019)
      READ(5,1020)IOBFN
C
C-----SET PARAMETER LIMITS
C
   19 WRITE(6,1021)
      READ(5,1022)B1L,B1U,B2L,B2U,B3L,B3U
C
C-----SET ITTERATIVE INTERVALS
C
      WRITE(6,1023)
      READ(5,1024)STEP0,STEP1,STEP2
C
C-----INITIALISE
C
```

```
   20 B1=B1L
      B2=B2L
      B3=B3L
C
C-----LOOP FOR BETA-1
C
   21 DO  51 I1=1,100
      B2=B2L
      IF(B1U-B1) 52, 22, 22
C
C-----LOOP FOR BETA-2
C
   22 DO  49 I2=1,100
      B3=B3L
      IF(B2U-B2) 50, 23, 23
C
C-----LOOP FOR BETA-3
C
   23 DO  47 I3=1,100
      IF(B3U-B3) 48, 24, 24
   24 DO  33 I=1,N
C
C-----TEST FOR BASEFLOW OR API
C
      IF(IAMC-1) 25, 26, 26
C
C-----CONVERT BF (MM/H) TO BF (QU.FT/SEC/SQ.ML)
C
   25 AI2(I)=AI(I)*25.404006/A(I)
      GO TO  27
C
C-----CONVERT API(MM) TO API(CM)
C
   26 AI2(I)=AI(I)/10.0
C
C----CALCULATE CRITICAL RAINFALL THRESHOLD
C
   27 DERIV=B2*B1
      IF(1.0-B2) 28, 32, 32
   28 DERA=1.0/(B2-1.0)
      IF(B3) 32, 32, 29
   29 PCRIT(I)=1.0/(DERIV*R(I)*(1.0+AI2(I)**B3))**DERA*25.4
      IF(P(I)-PCRIT(I)) 31, 31, 30
C
C-----CALCULATE STORMFLOW/PEAK
C
C-----P > PCRIT
C
   30 QE(I)=(B1*R(I)*((PCRIT(I)/25.4)**B2)*(1.C+(AI2(I)**B3
     1)))*25.4
      QE(I)=QE(I)+P(I)-PCRIT(I)
      GO TO  33
C
C-----P < PCRIT
C
   31 QE(I)=(B1*R(I)*((P(I)/25.4)**B2)*(1.0+(AI2(I)**B3)))
     1*25.4
      GO TO  33
C
C-----B2=0.0
```

```
C
   32 QE(I)=(B1*R(I)*((P(I)/25.4)**B2))*25.4
   33 CONTINUE
C
C-----INITIALISE
C
      A3=0.0
      B4=0.0
      A4=0.0
      D1=0.0
      B5=0.0
C
C-----CALCULATE THE DIFFERENCE BETWEEN OBSERVED AND
C-----CALCULATED
C
C     STORMFLOW
C
      DO  34 I=1,N
      DIFS(I)=QO(I)-QE(I)
      PER(I)=DIFS(I)/QO(I)*100.0
   34 CONTINUE
C
C-----CALCULATE OBJECTIVE FUNCTIONS
C
C-----CALCULATE COMPONENTS FOR OBJECTIVE FUNCTIONS
C
      DO  35 I=1,N
      A2(I)=QO(I)**2.0
      A3=A3+QO(I)
      B22(I)=QE(I)**2.0
      B4=B4+QE(I)
      A4=A4+A2(I)
      B5=B5+B22(I)
   35 CONTINUE
C
C-----CALCULATE MEANS
C
      Z=FLOAT(N)
      AQO=A3/Z
      AQE=B4/Z
C
C-----CALCULATE STANDARD DEVIATIONS
C
      SDO=SQRT((A4/Z)-AQO**2.0)
      SDE=SQRT((B5/Z)-AQE**2.0)
C
C-----CALCULATE COEFFICIENTS OF VARIATION
C
      CVO=(SDO/AQO)*100.0
      CVE=(SDE/AQE)*100.0
C
C-----CALCULATE COEFFICIENTS OF EFFICIENCY
C
      DO  36 I=1,N
      X(I)=0.0
      Y(I)=0.0
   36 CONTINUE
      DO  37 I=1,N
      X(I)=X(I-1)+(QO(I)-AQO)**2.0
      Y(I)=Y(I-1)+(QO(I)-QE(I))**2.0
```

```
   37 CONTINUE
      E=(X(N)-Y(N))/X(N)
C
C-----CALCULATE COEFFICIENTS OF DETERMINATION
C
      DO  38 I=1,N
      D1=D1+(QO(I)*QE(I))
   38 CONTINUE
      COR=(Z*D1-A3*B4)/SQRT((Z*A4-(A3)**2.0)*(Z*B5-B4**2.0))
      D=COR**2.0
C
C-----CALCULATE THE DIFFERENCE BETWEEN D AND E
C
      F=D-E
C
C-----CALCULATE STD.ERROR
C
      SE=SQRT(Y(N)/FLOAT(N-2))
C
C-----CALCULATE REG.COEFFICIENT
C
      REGC=COR*SDO/SDE
C
C-----CALCULATE BASE CONSTANT
C
      BC=AQE-(SDO/SDE*AQO)
C
C-----TEST FOR OPT/PRINT
C
      IF(IOP) 39, 39, 43
C
C-----OPTIMISE OBJECTIVE FUNCTION
C
C-----FLAG TO SELECTED OBJ.FN.
C
   39 IF(IOBFN) 40, 41, 42
C
C-----TEST OBJ.FN. AND FLAG TO NEXT LOOP OR STORAGE
C
   40 AD=BD-D
      IF(AD) 43, 43, 46
   41 AE=BE-E
      IF(AE) 43, 43, 46
   42 ASE=BSE-SE
      IF(ASE) 46, 46, 43
C
C-----STORE BETAS,OBT.FNS AND OBS/EST VALUES
C
   43 ZD=D
      ZE=E
      ZSE=SE
      ZAQO=AQO
      ZAQE=AQE
      ZF=F
      ZSDO=SDO
      ZSDE=SDE
      ZREGC=REGC
      ZBC=BC
      ZB1=B1
      ZB2=B2
```

```
      ZB3=B3
      DO  44  I=1,N
      ZQO(I)=QO(I)
      ZQE(I)=QE(I)
      ZDIFS(I)=DIFS(I)
      ZPER(I)=PER(I)
   44 CONTINUE
C
C-----TEST FOR OPT/PRINT
C
      IF(IOP) 45, 45, 52
   45 BD=D
      BE=E
      BSE=SE
   46 B3=B3+STEP2
   47 CONTINUE
   48 B2=B2+STEP1
      B3=B3L
   49 CONTINUE
   50 B1=B1+STEP0
      B2=B2L
   51 CONTINUE
C
C-----OUTPUT OPTIMISED DATA AND RESULTS
C
   52 WRITE(6,1025)TITLE,N
      IF(IAMC) 53, 53, 54
   53 WRITE(6,1026)CAT,IVP,IAMC,IOBFN
      GO TO  55
   54 WRITE(6,1027)CAT,IVP,IAMC,IOBFN
   55 WRITE(6,1028)
      WRITE(6,1029)ZB1,ZB2,ZB3,ZD,ZE,ZF,ZSE,ZAQO,ZAQE,ZSDO,
     1ZSDE,ZREGC,
     2ZBC
      WRITE(6,1030)
      DO  56 I=1,N
      WRITE(6,1031)ZQO(I),ZQE(I),ZDIFS(I),ZPER(I)
   56 CONTINUE
      WRITE(6,1032)
      READ(5,1033)IS
      IF(IS) 57, 57, 14
   57 CALL EXIT
C
 1000 FORMAT(5X,'SELECT OPTIMISATION (0)/PRINT(1)',/)
 1001 FORMAT(I2)
 1002 FORMAT(5X,'SELECT VOLUME(0) OR PEAK(1)'/)
 1003 FORMAT(I2)
 1004 FORMAT(5X,'INDICATE BASEFLOW(0) OR API(1)',/)
 1005 FORMAT(I2)
 1006 FORMAT(5X,'ENTER TITLE',/)
 1007 FORMAT(A60)
 1008 FORMAT(5X,'API SELECTION:API1(1),API5(5),API7(7),
     1API10(10)
     2API15(15)',/)
 1009 FORMAT (I2)
 1010 FORMAT(I5,A6)
 1011 FORMAT(7X,F5.1,F5.3,2F8.3,2F9.5,/)
 1012 FORMAT(7X,F5.1,F5.3,2F8.3,F9.5,/,7X,F5.1)
 1013 FORMAT(7X,F5.1,F5.3,2F8.3,F9.5,/,13X,F5.1)
 1014 FORMAT(7X,F5.1,F5.3,2F8.3,F9.5,/,19X,F5.1)
```

```
1015 FORMAT(7X,F5.1,F5.3,2F8.3,F9.5,/,25X,F5.1)
1016 FORMAT(7X,F5.1,F5.3,2F8.3,F9.5,/,31X,F5.1)
1017 FORMAT(5X,'ENTER PARAMETERS-3F6.3',/)
1018 FORMAT(3F6.3)
1019 FORMAT(5X,'SELECT OBJECTIVE FUNCTION:D(-1),E(0),
    1SE(1)')
1020 FORMAT(I2)
1021 FORMAT(5X,'SET PARAMETER LIMITS',/)
1022 FORMAT(2F6.3,/,2F6.3,/,2F6.3)
1023 FORMAT(5X,'SET ITTERATIVE INTERVALS',/)
1024 FORMAT (3F6.3)
1025 FORMAT(1H1,2X,'ANALYSIS:',2X,A60,2X,'N=',I4,/)
1026 FORMAT(2X,'CODE: ',A6,3I3,/,80('*'),/)
1027 FORMAT(2X,'CODE: ',A6,3I3,/,80('*'),/)
1028 FORMAT(14X,'PARAMETERS',30X,'OBJECTIVE FUNCTIONS',10X
    1,/,2X,33('-'),5X,42('-'),/)
1029 FORMAT(2X,'B1 = ',F5.3,2X,'B2 = ',F5.3,2X,'B3 = ',
    1F5.3,5X,'D = ',F6.5,2X,'E = ',F6.5,2X,'F = ',F6.5,/,
    241X,'SE = ',F9.5,/,41X,'MEANS: OBS = ',F9.5,2X,
    3'EST = ',F9.5,/,41X,'STD DEV: OBS = ',F9.5,2X,'EST = '
    4,F9.5,/,41X,'REG COEF = ',F9.5,2X,'BASE CONS = ',F9.5,
    5/,2X,81('='),/)
1030 FORMAT(11X,'OBS',11X,'EST',11X,'DIF',11X,'PER',/,8X,
    19('-'),5X,9('-'),5X,9('-'),5X,9('-'),/)
1031 FORMAT(8X,F9.5,2(5X,F9.5),5X,F9.4)
1032 FORMAT(5X,'END(0)/REPEAT(1)????',/)
1033 FORMAT(I2)
     END
```

(c) INPUT AND OPERATION INSTRUCTIONS

The following are typical runs for the programme INDEX using the

(a) optimisation routine and

(b) print routine.

The optimisation routine allows the operator to set limits for each para= meter (β_1, β_2, β_3) and iterative steps for parameters increments. Each combination of parameter values is tested in the model and the set giving the highest value of a specified objective function is printed along with observed and estimated stormflow values and other statistics (See Section D). The objective functions which may be optimised are the

(a) coefficient of determination (D)
(b) coefficient of efficiency (E) and
(c) standard error (SE)

After the printout, the operator is given the choice of repeating the ana= lysis with new parameter limits or terminating the run.

The operator is also required to indicate if volumes or peaks are being tested, whether baseflow (initial flow rate) or antecedent rainfall (API) is to be used in the model and the number of days antecedent rainfall if this variable is selected. Allowance is also made for a title to be entered for the analysis which is printed at the top of the final output.

In the following example of the input requirements for the operation of the optimisation routine, the programme and data are stored in a file ALAN, the element for the programme is INDEX and that for the data is IND17. Operator inputs are indicated by and other statements are as they would appear on a terminal screen.

		Format
@XQT ALAN.INDEX		
SELECT OPTIMISATION (O)/PRINT(1)		
>0		I2
SELECT VOLUME (O)/PEAK(1)		
>0		I2
INDICATE BASEFLOW (O)/APT(1)		
>0		I2
ENTER TITLE AND DATA		
> CATCHMENT W1M17 + INITIAL FLOW		A80
> @ADD ALAN.IND17		
SELECT OBJECTIVE FUNCTION:D(-1), E(0), SE(1)		
>0		I2
SET PARAMETER LIMITS		
> 0.100 0.300	(B_1)	2F6.3
> 1.400 1.500	(B_2)	2F6.3
> 0.200 0.300	(B_3)	2F6.3
SET ITERATIVE INTERVALS		
> 0.100 0.100 0.100	(B_1, B_2,B_3)	3F6.3

PRINTOUT

END (O)/REPEAT(1)	
>0	I2

NOTE: 1) If API had have been selected then the following would have appeared after the title

API SELECTION: API1(1), AP15(5), AP17(7) API10(10), AP115(15)	
>10	I2

ie, the 10-day antecedent rainfall would be used.

2) If the operator selects to repeat the analysis the programme reverts to the selection of an objective function.

Operation of the print routine is identical to the optimisation routine up to the input of the data file. This is followed by entering the three selected parameters as follows:

```
                                                          Format

>@ADD ALAN.IND17
ENTER PARAMETERS
> 0.400 1.500 0.250                                       3F6.3

                         PRINTOUT
END (0)/REPEAT(1)
> 0                                                       I2
```

Note: Repeat would return the operator to the point of entering parameters.

d) EXAMPLE OF PRINTOUT

```
ANALYSIS:  W1M17   INITIAL FLOW(CW1) * EASTERN USA PARAMETERS                  N=  43
CODE:  W1M17  0  0  0
ooooooooooooooooooooooooooooooooooooooooooooooooooooooooooooooooooooooooooooooooooooooo

              PARAMETERS                                 OBJECTIVE FUNCTIONS
-----------------------------------------     -----------------------------------------------

B1 =  .400  B2 = 1.500  B3 =  .250            D = .98712  E = .98091  F = .00621
                                              SE =    5.65773
                                              MEANS: OBS =   16.19467  EST =   16.95013
                                              STD DEV: OBS =   35.74674  EST =   32.80163
                                              REG COEF =   1.08275  BASE CONS =   -.6796
=========================================================================================
```

OBS	EST	DIF	PER
3.75100	3.45246	.29854	7.9589
1.42600	2.44882	-1.02282	-71.7268
12.44800	15.35935	-2.91135	-23.3881
5.09200	7.86467	-2.77267	-54.4515
25.45600	19.52367	5.93233	23.3042
8.90800	9.03576	-.12776	-1.4342
206.92300	181.47698	25.44602	12.2973
94.47400	93.84266	.63134	.6683
2.99100	4.04733	-1.05633	-35.3171
34.26400	35.75938	-1.49538	-4.3643
5.71500	5.21298	.50202	8.7842
1.60400	2.54051	-.93651	-58.3860
1.31200	3.27289	-1.96089	-149.4577
.87200	2.15265	-1.28065	-146.8639
8.12200	17.33761	-9.21561	-113.4648
3.41700	4.92513	-1.50813	-44.1361
5.70300	5.86563	-.16263	-2.8516
11.55000	15.07674	-3.52674	-30.5346
16.02700	11.40853	4.61847	28.8168
3.13300	4.36918	-1.23618	-39.4567
.83900	2.91536	-2.07636	-247.4802
98.59200	107.06078	-8.46878	-8.5897
4.27500	4.82277	-.54777	-12.8132
5.21400	6.41553	-1.20153	-23.0443
7.83000	8.23308	-.40308	-5.1479
32.62100	34.31000	-1.68900	-5.1776
19.02700	19.92459	-.89759	-4.7174
2.14600	3.29403	-1.14803	-53.4964
2.16300	3.04953	-.88653	-40.9863
11.53100	11.77110	-.24010	-2.0822
3.05900	3.02158	.03742	1.2232
11.43400	14.79187	-3.35787	-29.3674
12.48900	9.38139	3.10761	24.8873
3.08600	3.73707	-.65107	-21.0975
3.61500	5.95816	-2.34316	-64.8176
3.50500	3.22221	.28279	8.0682
4.74200	4.11379	.62821	13.2477
1.24100	4.14972	-2.90872	-234.3849
.31400	1.66330	-1.34930	-429.7123
2.61100	8.67060	-6.05960	-232.0798
1.78300	8.73057	-6.94757	-389.6563
6.92300	9.96599	-3.04299	-43.9548
4.14300	4.67994	-.53694	-12.9602

Note: $\underline{\text{PER}} = \frac{\text{DIF}}{\text{OBS}} \times 100$

APPENDIX 10

Storm rainfall, stormflow, the associated initial flow rate and antecedent rainfall used for testing the R-index model in the Grahamstown catchments I, II and III

The abbreviations used are as follows:

DY = day
MT = month
YR = year
P = storm rainfall (mm)
Q = stormflow (mm)
I = initial flow rate ($mm.h^{-1}$)
AP05 = five-day antecedent rainfall total (mm)
AP10 = ten-day antecedent rainfall total (mm)
AP15 = fifteen-day antecedent rainfall total (mm)

GRAHAMSTOWN I

DY	MT	YR	P	Q	I	AP01	AP07	AP10
21	3	76	13.6	.011	.0019	16.4	36.5	40.5
21	3	76	40.1	3.998	.0086	23.3	50.2	54.2
29	3	76	14.4	.015	.0060	.0	1.6	72.0
27	2	77	30.8	.022	.0001	.0	3.3	21.9
28	2	77	27.9	.281	.0008	30.8	34.1	52.7
6	3	77	7.0	.483	.0002	5.5	64.2	64.9
7	5	77	21.5	.216	.0027	33.8	42.2	42.3
1	12	77	15.8	.028	.0012	5.0	42.5	42.5
30	12	77	11.4	.033	.0019	35.9	63.1	63.6
10	1	78	19.5	.028	.0001	.4	2.9	21.1
11	1	78	8.0	.031	.0044	19.6	22.6	27.7
4	2	78	22.4	.001	.0019	.0	7.1	21.9
20	4	78	33.7	.041	.0004	11.8	19.6	20.1
21	4	78	36.3	.886	.0032	33.2	54.7	54.7
28	2	79	26.9	.014	.0000	27.1	61.2	61.7
21	7	79	125.4	24.615	.0001	28.9	29.4	29.4
24	7	79	29.0	5.819	.0751	1.4	155.6	156.1
20	8	79	105.2	36.054	.0041	.0	5.9	12.3
26	8	79	4.9	.051	.0686	.0	105.2	110.0
15	9	79	5.8	.002	.0158	15.4	15.4	16.0

GRAHAMSTOWN II

DY	MT	YR	P	Q	I	AP01	AP07	AP10
3	1	10	20.9	.004	.0000	.0	6.3	28.0
9	1	76	17.9	.489	.0000	.0	21.9	24.5
6	2	76	21.0	.021	.0000	11.8	15.7	18.3
10	2	76	8.0	.001	.0000	9.3	50.0	50.0
2	3	76	11.7	.006	.0000	5.2	18.3	18.3
21	3	76	13.8	.068	.0034	15.4	34.9	37.3
21	3	76	39.6	3.575	.0078	19.9	48.7	48.7
28	3	76	6.5	.006	.0029	5.9	7.4	77.9
27	2	77	37.1	.481	.0000	.0	3.2	22.0
28	2	77	30.5	.877	.0000	37.1	37.5	69.0
6	3	77	11.0	.679	.0000	6.8	74.4	74.8
24	4	77	13.4	.028	.0000	16.0	16.5	25.6
7	5	77	15.4	.020	.0000	20.8	29.8	29.8
7	5	77	15.2	1.458	.0029	36.2	45.2	45.2
26	11	77	15.0	.014	.0000	14.5	14.5	16.2
1	12	77	19.8	.415	.0000	6.5	41.1	41.1
30	12	77	41.5	.137	.0000	23.7	25.4	25.4
30	12	77	7.9	.001	.0126	56.8	58.0	58.5
1	1	78	2.5	.001	.0044	10.9	78.9	79.4
9	1	78	20.6	.159	.0000	.1	2.9	64.3
20	4	78	23.9	.077	.0000	20.0	27.3	27.8
21	4	78	38.2	.907	.0000	20.3	55.7	55.7
2	11	78	15.5	.009	.0000	7.0	7.0	21.5
21	2	79	16.7	.001	.0000	16.5	16.8	18.7
28	2	77	27.1	.197	.0000	11.9	15.6	49.1
20	7	79	126.7	23.610	.0000	29.5	30.3	30.3
24	7	79	29.4	.406	.0775	1.4	157.5	158.4
11	8	79	3.5	.001	.0041	1.9	1.9	1.9
20	8	79	21.2	.001	.0019	7.7	13.5	20.2
20	8	79	79.5	21.287	.0060	18.5	24.2	31.0
26	8	79	3.7	.086	.0545	.0	98.0	102.5
31	8	79	7.4	.001	.0319	.0	3.7	26.2
15	9	79	14.9	.023	.0226	.0	.0	.6

GRAHAMSTOWN III

DY	MT	YR	P	Q	I	AP01	AP07	AP10
21	3	76	27.5	1.650	.0000	32.5	70.5	70.5
28	3	76	14.5	.005	.0025	.0	.6	77.0
7	5	77	19.7	.214	.0000	46.8	55.6	55.7
3	2	78	23.4	.007	.0000	.0	4.2	21.7
21	7	79	95.3	14.774	.0000	57.1	57.7	57.7
23	7	79	29.9	5.372	.0521	1.7	154.2	154.8
20	8	79	109.9	14.650	.0000	.0	4.7	11.4
26	8	79	5.8	.132	.0583	.0	99.9	114.6
31	8	79	7.8	.007	.0235	.0	5.8	35.4
1	9	79	6.5	.001	.0251	.0	13.7	.0
15	9	79	14.7	.001	.0080	.0	.0	.6
15	9	79	4.2	.004	.0134	14.7	14.7	19.5
15	9	79	5.4	.005	.0188	18.9	18.9	19.5
10	10	79	11.8	.018	.0000	5.5	7.0	7.0
19	10	79	8.8	.003	.0004	.1	7.5	26.2

APPENDIX 11

Computer programme INDST

(a) Fortran programme

(b) Input and operation instructions

a) FORTRAN PROGRAM

```
C*************************************************************
C
C       PROGRAM INDST
C       A.S.HOPE
C       HYDROLOGICAL RESEARCH UNIT
C       UNIVERSITY OF ZULULAND
C
C*************************************************************
C
C-----PROGRAM TO CALCULATE STORMFLOW DEPTHS (MM) OR PEAK
C-----FLOW RATE(MM/H)USING THE DISTRIBUTED R-INDEX MODEL TO
C-----PROGRAM CALCULATES:
C
C                  MEAN - OBSERVED                          (AQO)
C                       - CALCULATED                        (AQE)
C                  STANDARD DEVIATION - OBSERVED            (SDO)
C                                     - CALCULATED          (SDE)
C                  COEFFICIENT OF VARIATION - OBSERVED      (CVO)
C                                           - CALCULATED(CVE)
C                  COEFFICIENT OF DETERMINATION             (D)
C                  COEFFICIENT OF EFFICIENCY                (E)
C                  D-E                                      (F)
C                  STANDARD.ERROR                           (SE)
C                  REGRESSION COEFFICIENT                   (REGC)
C                  BASE CONSTANT                            (BC)
C
C*************************************************************
C
C-----THE PROGRAM ALLOWS FOR INTERACTIVE CHANGES OF
C-----THE MODEL PARAMETERS BETA-1 (B1) ,BETA-2 (B2)
C-----AND BETA-3 (B3) OR AUTOMATIC OPTIMISATION FOR A
C-----SPECIFIC OBJECTIVE FUNCTION
C
C-------------------------------------------------------------
C
C-----INPUTS   R-INDEX                         (-)   (R)
C-----         NO. OF OBSERVATIONS             (-)   (N)
C-----         STORM RAINFALL                  (MM)  (P)
C-----         OBSERVED STORMFLOW/PEAK         (MM)  (QO/IOP)
C-----         BASEFLOW AT START OF EVENT      (MM)  (AI)
C-----         ANTECEDENT RAINFALL             (MM)  (AI)
C-----         CATCHMENT AREA               (SQ.KM)  (A)
C
C-----OUTPUTS  OBJECTIVE FUNCTIONS
C-----         OBSERVED STORMFLOW   /PEAK
C-----         CALCULATED STORMFLOW /PEAK
C-----         BETA VALUES
C
C-------------------------------------------------------------
C
C-----SYMBOLS IN ALPHABETICAL ORDER
C
C-----A=AREA OF SUB-UNITS(SQ.KM)
C-----AI=BASEFLOW (MM/H) OR API(MM)
C-----AI2=BASEFLOW (QU.FT/SEC/SQ.ML) OR API(CM)
C-----AQE=MEAN QE (MM)
C-----AQO=MEAN QO (MM)
C-----ATOT=TOTAL AREA(SQ.KM)
```

```
C-----BC=BASE CONSTANT
C-----B1,B2,B3=MODEL PARAMETERS (BETA)
C-----          (B1L=LOWER LIMIT)
C-----          (B1U=UPPER LIMIT)
C-----CAT=CATCHMENT WETNESS INDEX
C-----CVE=COEFFICIENT OF VARIATION OF ESTIMATED VALUES (%)
C-----CVO=COEFFICIENT OF VARIATION OF OBSERVED VALUES (%)
C-----D=COEFFICIENT OF DETERMINATION
C-----DIFS=QO-QE (MM)
C-----E=COEFFICIENT OF EFFICIENCY
C-----F=D-E
C-----IAMC=BASEFLOW/API FLAG
C-----IAPI=API (N DAYS)
C-----ISEL=MANUAL/ITTERATIVE FLAG
C-----IVP=VOLUME/PEAK FLAG
C-----N=NUMBER OF OBSERVATIONS
C-----NSU=NUMBER OF SUB-UNITS
C-----IOBFN=OBJECTIVE FN. TO BE OPT.
C-----OP=OPTIMISATION/PRINT FLAG
C-----P=STORM RAINFALL (MM)
C-----PCRIT=CRITICAL RAINFALL THRESHOLD (MM)
C-----PER=DIFS/QO*100 (%)
C-----QE=ESTIMATED STORMFLOW (MM)
C-----QE1=SUB-AREA ESTIMATED STORMFLOW
C-----QO=OBSERVED STORMFLOW (MM)
C-----QP=PEAK STORMFLOW (MM)
C-----R=R-INDEX (-)
C-----REGC=REGRESSION COEFFICIENT
C-----SDE=SD QE (MM)
C-----SDO=SD QO (MM)
C-----SE=STANDARD ERROR
C-----STEP0,STEP1,STEP2=ITTERATIVE INTERVALS
C
C*************************************************************
C
      CHARACTER TITLE*60,CAT*6
      DIMENSION QE(100),P(100),AI(100),A2(100),X(100),
     1B22(100),Y(100),DIFS(100),PER(100),R(10),A(10),QP(100)
     2,QO(100),ZQE(100),ZDIFS(100),ZPER(100),PEP(100),ZQO
     3(100),QE1(100,100),AI2(100,100),PCRIT(100,100)
C
C-----INITIALISE ARRAYS
C
      DO   2 I=1,100
      QO(I)=0.0
      QE(I)=0.0
      P(I)=0.0
      AI(I)=0.0
      A2(I)=0.0
      X(I)=0.0
      B22(I)=0.0
      Y(I)=0.0
      DIFS(I)=0.0
      PEP(I)=0.0
      R(I)=0.0
      QP(I)=0.0
      ZQO(I)=0.0
      ZQE(I)=0.0
      ZDIFS(I)=0.0
      ZPER(I)=0.0
```

```
      DO    1 J = 1,100
      A(J)=0.0
      QE1(I,J)=0.0
      AI2(I,J)=0.0
      PCRIT(I,J)=0.0
    1 CONTINUE
    2 CONTINUE
C
C-----INITIALISE
C
      BD=0.0
      BE=0.0
      BSE=99.9
C
C-----SELECT OPTIMISATION/PRINT
C
      WRITE(6,1001)
      READ(5,1002)IOP
C
C-----SELECT VOLUME (0) OR PEAK (1)
C
      WRITE(6,1003)
      READ(5,1004)IVP
C
C-----A
C
C-----SET ALTERNATIVES
C
C-----BASEFLOW(0) OR API(1)
C
      WRITE(6,1005)
      READ(5,1006)IAMC
C
C-----ENTER TITLE
C
      WRITE(6,1007)
      READ(5,1008)TITLE
C
C-----DEFINE NO. OF SUB-UNITS (NSU)
C
      WRITE(6,1009)
      READ(5,1010)NSU
C
C-----INPUT AREA OF EACH SUB-UNIT (A)
C
      WRITE(6,1011)
      READ(5,1012)(A(I),I=1,10)
C
C-----INPUT R-INDEX FOR EACH UNIT (R)
C
      WRITE(6,1013)
      READ(5,1014)(R(I),I=1,10)
C
C-----CALCULATE TOTAL AREA (ATOT)
C
      ATOT=0.0
      DO    3 J=1,NSU
      ATOT=ATOT+A(J)
    3 CONTINUE
C
```

```
C-----BASEFLOW OR API FLAG
C
      IF(IAMC)  5,  5,  4
C
C-----API SELECTION
C
    4 WRITE(6,1015)
      READ(5,1016)IAPI
C
C-----READ NO. OBSERVATIONS + CATCHMENT INDEX
C
    5 READ(5,1017)N,CAT
C
C-----READ AREA,OBSERVED Q/PK,BASEFLOW/API
C
      DO  16 I=1,N
C
C-----API FLAG TO FORMAT
C
      IF(IAPI-1)   6, 11,  6
    6 IF(IAPI-5)   7, 12,  7
    7 IF(IAPI-7)   8, 13,  8
    8 IF(IAPI-10)  9, 14,  9
    9 IF(IAPI-15) 10, 15, 10
C
C-----BASEFLOW
C
   10 READ(5,1018)P(I),QO(I),QP(I),AI(I)
      GO TO  16
C
C-----API 1
C
   11 READ(5,1019)P(I),QO(I),QP(I),AI(I)
      GO TO  16
C
C-----API 5
C
   12 READ(5,1020)P(I),QO(I),QP(I),AI(I)
      GO TO  16
C
C-----API 7
C
   13 READ(5,1021)P(I),QO(I),QP(I),AI(I)
      GO TO  16
C
C-----API 10
C
   14 READ(5,1022)P(I),QO(I),QP(I),AI(I)
      GO TO  16
C
C-----API 15
C
   15 READ (5,1023)P(I),QO(I),QP(I),AI(I)
   16 CONTINUE
C
C-----TEST FOR VOLUME OR PEAK,IF PEAK LET QO(I)=QP(I)
C
      IF (IVP) 18, 18, 17
   17 DO  18 I=1,N
      QO(I)=QP(I)
```

```
   18 CONTINUE
C
C-----TEST FOR OPT/PRINT
C
      IF(IOP) 20, 20, 19
   19 WRITE(6,1024)
      READ(5,1025)B1,B2,B3
      GO TO  26
C
C-----ITTERATIVE ROUTINE
C
C-----SELECT OBJECTIVE FUNCTION
C
   20 WRITE(6,1026)
      READ(5,1027)IOBFN
C
C-----SET PARAMETER LIMITS
C
   21 WRITE(6,1028)
      READ(5,1029)B1L,B1U,B2L,B2U,B3L,B3U
C
C-----SET ITTERATIVE INTERVALS
C
      WRITE(6,1030)
      READ(5,1031)STEP0,STEP1,STEP2
C
C-----INITIALISE
C
   22 B1=B1L
      B2=B2L
      B3=B3L
C
C-----LOOP FOR BETA-1
C
   23 DO   57 I1=1,100
      B2=B2L
      IF(B1U-B1) 58, 24, 24
C
C-----LOOP FOR BETA-2
C
   24 DO   55 I2=1,100
      B3=B3L
      IF(B2U-B2) 56, 25, 25
C
C-----LOOP FOR BETA-3
C
   25 DO   53 I3=1,100
       IF(B3U-B3) 54, 26, 26
C
C-----INITIALISE ARRAYS
C
   26 DO   28 I=1,N
      DO   27 J=1,NSU
      QE1(I,J)=0.0
   27 CONTINUE
      QE(I)=0.0
   28 CONTINUE
      DO   39 I=1,N
      DO   38 J=1,NSU
C
```

```
C-----TEST FOR BASEFLOW OR API
C
      IF(IAMC-1) 29, 30, 30
C
C-----CONVERT BF (MM/H) TO BF (QU.FT/SEC/SQ.ML)
C
   29 AI2(I,J)=AI(I)*25.404006/A(J)
      GO TO  31
C
C-----CONVERT API(MM) TO API(CM)
C
   30 AI2(I,J)=AI(I)/10.0
C
C----CALCULATE CRITICAL RAINFALL THRESHOLD
C
   31 DERIV=B2*B1
      IF(1.0-B2) 32, 36, 36
   32 DERA=1.0/(B2-1.0)
      IF(B3) 36, 36, 33
   33 PCRIT(I,J)=1.0/(DERIV*R(J)*(1.0+AI2(I,J)**B3))**DERA*25.4
      IF(P(I)-PCRIT(I,J)) 35, 35, 34
C
C-----CALCULATE STORMFLOW/PEAK
C
C-----P > PCRIT
C
   34 QE1(I,J)=(B1*R(J)*((PCRIT(I,J)/25.4)**B2)*(1.0+(AI2
     1(I,J)**B3)))
     2*25.4
      QE1(I,J)=QE1(I,J)+P(I)-PCRIT(I,J)
      GO TO  37
C
C-----P < PCRIT
C
   35 QE1(I,J)=(B1*R(J)*((P(I)/25.4)**B2)*(1.0+(AI2(I,J)**B3
     1)))*25.4
      GO TO  37
C
C-----B2=0.0
C
   36 QE1(I,J)=(B1*R(J)*((P(I)/25.4)**B2))*25.4
   37 QE1(I,J)=QE1(I,J)*A(J)/ATOT
C-----SUMMATE STORMFLOW FROM SUB-UNITS
      QE(I)=QE(I)+QE1(I,J)
   38 CONTINUE
   39 CONTINUE
C
C-----INITIALISE
C
      A3=0.0
      B4=0.0
      A4=0.0
      D1=0.0
      B5=0.0
C
C-----CALCULATE THE DIFFERENCE BETWEEN OBSERVED AND
C-----CALCULATED
C
C     STORMFLOW
C
```

```
      DO  40 I=1,N
      DIFS(I)=QO(I)-QE(I)
      PER(I)=DIFS(I)/QO(I)*100.0
   40 CONTINUE
C
C-----CALCULATE OBJECTIVE FUNCTIONS
C
C-----CALCULATE COMPONENTS FOR OBJECTIVE FUNCTIONS
C
      DO  41 I=1,N
      A2(I)=QO(I)**2.0
      A3=A3+QO(I)
      B22(I)=QE(I)**2.0
      B4=B4+QE(I)
      A4=A4+A2(I)
      B5=B5+B22(I)
   41 CONTINUE
C
C-----CALCULATE MEANS
C
      Z=FLOAT(N)
      AQO=A3/Z
      AQE=B4/Z
C
C-----CALCULATE STANDARD DEVIATIONS
C
      SDO=SQRT((A4/Z)-AQO**2.0)
      SDE=SQRT((B5/Z)-AQE**2.0)
C
C-----CALCULATE COEFFICIENTS OF VARIATION
C
      CVO=(SDO/AQO)*100.0
      CVE=(SDE/AQE)*100.0
C
C-----CALCULATE COEFFICIENTS OF EFFICIENCY
C
      DO  42 I=1,N
      X(I)=0.0
      Y(I)=0.0
   42 CONTINUE
      DO  43 I=1,N
      X(I)=X(I-1)+(QO(I)-AQO)**2.0
      Y(I)=Y(I-1)+(QO(I)-QE(I))**2.0
   43 CONTINUE
      E=(X(N)-Y(N))/X(N)
C
C-----CALCULATE COEFFICIENTS OF DETERMINATION
C
      DO  44 I=1,N
      D1=D1+(QO(I)*QE(I))
   44 CONTINUE
      COR=(Z*D1-A3*B4)/SQRT((Z*A4-(A3)**2.0)*(Z*B5-B4**2.0))
      D=COR**2.0
C
C-----CALCULATE THE DIFFERENCE BETWEEN D AND E
C
      F=D-E
C
C-----CALCULATE STD.ERROR
C
```

```
      SE=SQRT(Y(N)/FLOAT(N-2))
C
C-----CALCULATE REG.COEFFICIENT
C
      REGC=COR*SDO/SDE
C
C-----CALCULATE BASE CONSTANT
C
      BC=AQE-(SDO/SDE*AQO)
C-----TEST FOR OPT/PRINT
C
      IF(IOP) 45, 45, 49
C
C-----OPTIMISE OBJECTIVE FUNCTION
C
C-----FLAG TO SELECTED OBJ.FN.
C
   45 IF(IOBFN) 46, 47, 48
C
C-----TEST OBJ.FN. AND FLAG TO NEXT LOOP OR STORAGE
C
   46 AD=BD-D
      IF(AD) 49, 49, 52
   47 AE=BE-E
      IF(AE) 49, 49, 52
   48 ASE=BSE-SE
      IF(ASE) 52, 52, 49
C
C-----STORE BETAS,OBT.FNS AND OBS/EST VALUES
C
   49 ZD=D
      ZE=E
      ZSE=SE
      ZAQO=AQO
      ZAQE=AQE
      ZF=F
      ZSDO=SDO
      ZSDE=SDE
      ZREGC=REGC
      ZBC=BC
      ZB1=B1
      ZB2=B2
      ZB3=B3
      DO  50 I=1,N
      ZQO(I)=QO(I)
      ZQE(I)=QE(I)
      ZDIFS(I)=DIFS(I)
      ZPER(I)=PER(I)
   50 CONTINUE
C
C-----TEST FOR OPT/PRINT
C
      IF(IOP) 51, 51, 58
   51 BD=D
      BE=E
      BSE=SE
   52 B3=B3+STEP2
   53 CONTINUE
   54 B2=B2+STEP1
      B3=B3L
```

```
   55 CONTINUE
   56 B1=B1+STEPO
      B2=B2L
   57 CONTINUE
C
C-----OUTPUT OPTIMISED DATA AND RESULTS
C
   58 WRITE(6,1032)TITLE,N
      WRITE(6,1033)NSU,A,R
      IF(IAMC) 59, 59, 60
   59 WRITE(6,1034)CAT,IVP,IAMC,IOBFN
      GO TO  61
   60 WRITE(6,1035)CAT,IVP,IAMC,IOBFN
   61 WRITE(6,1036)
      WRITE(6,1037)ZB1,ZB2,ZB3,ZD,ZE,ZF,ZSE,ZAQO,ZAQE,ZSDO,
     1ZSDE,ZREGC,ZBC
      WRITE(6,1038)
      DO  62 I=1,N
      WRITE(6,1039)ZQO(I),ZQE(I),ZDIFS(I),ZPER(I)
   62 CONTINUE
      WRITE(6,1040)
      READ(5,1041)IS
      IF(IS) 63, 63, 16
   63 CALL EXIT
C
 1000 FORMAT(F4.2,F6.0)
 1001 FORMAT(5X,'SELECT OPTIMIZATION (0)/PRINT(1)',/)
 1002 FORMAT(I2)
 1003 FORMAT(5X,'SELECT VOLUME(0) OR PEAK(1)'/)
 1004 FORMAT(I2)
 1005 FORMAT(5X,'INDICATE BASEFLOW(0) OR API(1)',/)
 1006 FORMAT(I2)
 1007 FORMAT(5X,'ENTER TITLE',/)
 1008 FORMAT(A60)
 1009 FORMAT(/,5X,'ENTER NO.OF SUB-UNITS)',/)
 1010 FORMAT(I2)
 1011 FORMAT(/,2X,'INPUT AREA PROPORTIONS XF7.3',/)
 1012 FORMAT(10F7.3)
 1013 FORMAT(/,2X,'INPUT R-INDEX FOR EACH UNIT XF5.3',/)
 1014 FORMAT(10F7.3)
 1015 FORMAT(5X,'API SELECTION:API1(1),API5(5),API7(7),
     1API10(10),API15(15)',/)
 1016 FORMAT (I2)
 1017 FORMAT(I5,A6)
 1018 FORMAT(7X,F5.1,13X,F8.3,2F9.5,/)
 1019 FORMAT(7X,F5.1,13X,F8.3,F9.5,/,7X,F5.1)
 1020 FORMAT(7X,F5.1,13X,F8.3,F9.5,/,13X,F5.1)
 1021 FORMAT(7X,F5.1,13X,F8.3,F9.5,/,19X,F5.1)
 1022 FORMAT(7X,F5.1,13X,F8.3,F9.5,/,25X,F5.1)
 1023 FORMAT(7X,F5.1,13X,F8.3,F9.5,/,31X,F5.1)
 1024 FORMAT(5X,'ENTER PARAMETERS-3F6.3',/)
 1025 FORMAT(3F6.3)
 1026 FORMAT(5X,'SELECT OBJECTIVE FUNCTION:D(-1),E(0),SE(1)')
 1027 FORMAT(I2)
 1028 FORMAT(5X,'SET PARAMETER LIMITS',/)
 1029 FORMAT(2F6.3,/,2F6.3,/,2F6.3)
 1030 FORMAT(5X,'SET ITTERATIVE INTERVALS',/)
 1031 FORMAT (3F6.3)
 1032 FORMAT(1H1,2X,'ANALYSIS:',2X,A60,2X,'N=',I4,/)
 1033 FORMAT(/,10X,'NO. SUB-UNITS = ',I5,//,10X,'AREAS = ',
```

```
     110F7.3,/,10X,'R-IND = ',10F7.3,//)
1034 FORMAT(2X,'CODE: ',A6,3I3,/,80('*'),/)
1035 FORMAT(2X,'CODE: ',A6,3I3,/,87('*'),/)
1036 FORMAT(14X,'PARAMETERS',30X,'OBJECTIVE FUNCTIONS',10X,
    1/,2X,33('-'),5X,47('-'),/)
1037 FORMAT(2X,'B1 = ',F5.3,2X,'B2 = ',F5.3,2X,'B3 = ',F5.3
    1,5X,'D = ',F6.5,2X,'E = ',F6.5,2X,'F = ',F6.5,/,41X,
    2'SE = ',F9.5,/,41X,'MEANS: OBS = ',F9.5,2X,'EST = ',
    3F9.5,/,41X,'STD DEV: OBS = ',F9.5,2X,'EST = ',F9.5,/,
    441X,'REG COEF = ',F9.5,2X,'BASE CONS = ',F9.5,/,2X,
    585('='),/)
1038 FORMAT(11X,'OBS',11X,'EST',11X,'DIF',11X,'PER',/,8X,
    19('-'),5X,9('-'),5X,9('-'),5X,9('-'),/)
1039 FORMAT(8X,F9.5,2(5X,F9.5),5X,F9.4)
1040 FORMAT(5X,'END(0)/REPEAT(1)????',/)
1041 FORMAT(I2)
     END
```

(b) INPUT AND OPERATION INSTRUCTIONS

The input and operation instructions for INDST are similar to those of INDEX. However, this programme requires substantially longer time for optimisation and execution is therefore generally in batch mode rather than in demand mode (from a terminal). A typical runstream is given below.

```
1    @RUN INDST.AENG-PSTAFF/ASHOPE,AENG-PASHOPE,1,10
2    @SYM PRINT$,,SO6PR3
3    @ASG,A ALAN
4    @XQT ALAN.INDST
5     0
6     0
7     1
8     W1M15  AP5
9     4
10    00.478 00.794 01.070 00.977
11    00.980 00.885 00.743 00.615
12   05
13   @ADD ALAN.IND15
14    0
15    0.020 0.070
16    1.000 1.920
17    0.300 0.400
18    0.001 0.001 0.001
19    0
```

Line	Description	Format
1		
2	Control statements for the UNIVAC 1100	
3		
4		
5	Optimisation (0)/Print(1)	I2
6	Volume (0)/Peak(1)	I2
7	Baseflow (0)/Peak(1)	I2

Line	Description	Format
8	Title	A80
9	Number of sub-units	I2
10	Areas of individual sub-units (km)	10F7.3
11	R-indices of individual sub-units (-)	10F7.3
	API selection (number of antecedent days)	I2
13	Input data file	
14	Select objective function: (D(-), E(0), SE(1)	I2
15	Parameter limits - B_1	2F6.3
16	Parameter limits - B_2	2F6.3
17	Parameter limits - B_3	2F6.3
18	Iterative intervals	3F6.3
19	End (0)/Repeat (1)	I2

c) EXAMPLE OF PRINTOUT

```
ANALYSIS:   W1M15   APS                                                           N=  43

        NO. SUB-UNITS =        4

        AREAS =    .478    .794  1.070    .977    .000    .000    .000    .000    .000    .000
        R-IND =    .980    .885   .743    .615    .000    .000    .000    .000    .000    .000

CODE:  WIM15  0  1  0
ooooooooooooooooooooooooooooooooooooooooooooooooooooooooooooooooooooooooooooooooooooooooooo
            PARAMETERS                              OBJECTIVE FUNCTIONS
---------------------------------      ----------------------------------------------------

B1 =  .050  B2 = 1.910  B3 =  .340     D = .75804  E = .75409  F = .00395
                                       SE =    2.90424
                                       MEANS: OBS =    4.97428  EST =    4.71545
                                       STD DEV: OBS    =    5.71878  EST =    5.22844
                                       REG COEF =     .95231  BASE CONS =    -.72533
===========================================================================================
```

OBS	EST	DIF	PER
3.30200	1.81896	1.48304	44.9133
.18400	.74459	-.56059	-304.6700
8.07400	8.02565	.04835	.5988
1.95900	2.44906	-.49006	-25.0160
20.13100	14.90667	5.22433	25.9517
6.93800	3.30649	3.63151	52.3423
8.76400	9.37598	-.61198	-6.9829
13.47000	9.55467	3.91533	29.0671
1.33100	1.14271	.18829	14.1468
29.25500	29.65994	-.40494	-1.3842
3.51300	2.16135	1.35165	38.4757
.60500	.67823	-.07323	-12.1041
.37500	.69685	-.32185	-85.8274
.43300	.98811	-.55511	-128.2008
5.63700	9.48665	-3.84965	-68.2925
2.30500	3.78361	-1.47861	-64.1480
6.31100	4.08821	2.22279	35.2209
.79100	4.21318	-3.42218	-432.6394
7.94700	9.57748	-1.63048	-20.5169
1.76900	1.83729	-.06829	-3.8603
.63900	1.56361	-.92461	-144.6962
.69800	2.16303	-1.46503	-209.8891
2.65000	2.94304	-.29304	-11.0581
1.58100	1.50960	.07140	4.5164
14.08200	4.06074	10.02126	71.1636
11.61700	5.12148	6.49552	55.9140
6.26300	13.31553	-7.05253	-112.6063
4.11400	1.95163	2.16237	52.5612
3.75900	.83983	2.91917	77.6582
7.89700	8.28299	-.38599	-4.8878
.63200	.90734	-.27534	-43.5669
8.06400	6.27029	1.79371	22.2434
8.06400	7.77968	.28432	3.5258
2.90700	1.79198	1.11502	38.3563
3.31800	3.02626	.29174	8.7926
2.34900	1.54223	.80677	34.3454
2.68700	.31587	2.37113	88.2445
.22400	.82826	-.60426	-269.7598
1.60900	5.45856	-3.84956	-239.2515
.69700	2.26832	-1.57132	-225.4403
.76500	2.48573	-1.72073	-224.9318
4.17900	6.72804	-2.54904	-60.9965
2.00500	3.11474	-1.10974	-55.3488

APPENDIX 12

The derivation of CN units from catchment soils and vegetation data for catchment W1M15

Soil Series	Hyd Gp	Vegetation/Land-use Type	Condition	CN	Prop	CN Unit
Trafalgar (D)	B	Forest	Good	55	,009	1
Trafalgar (D)	B	Forest + 50 % Rock	Good	78	,006	
Marsh	-	-	-	98	,127	2
Rock 100 %	-	- -	-	100	,001	
Katspruit	D	Forest	Fair	79	,003	
Katspruit	D	Veld + 50 % Rock	Good	90	,071	3
Katspruit	D	Veld + 50 % Rock	Good	87	,071	
Davel	C	Forest	Fair	73	,001	
Robmore (S)	C	Veld	Good	74	,502	
Robmore (S)	C	Forest	Good	70	,013	4
Robmore (S)	C	Forest	Fair	73	,013	
Robmore (S)	C	Forest + 35 % Rock	Good	80	,003	
Robmore (S)	C	Straight row crop	Poor	85	,010	
Robmore (D)	B	Veld	Good	61	,129	5
Robmore (D)	B	Forest	Good	55	,003	
Robmore (D)	B	Forest	Fair	60	,003	
Robmore (D)	B	Straight row crop	Poor	77	,006	
Oatsdale	A	Veld	Good	39	,014	
Oatsdale	A	Forest	Fair	36	,001	6
Oatsdale	A	Straight row crop	Poor	66	,001	
Argent	B	Veld	Good	61	,005	
Argent	B	Forest	Good	55	,002	7
Argent	B	Forest	Fair	60	,001	

CN Unit	1	2	3	4	5	6	7
CN	64,2	98,0	88,3	74,1	61,5	40,5	59,4
Proportion	0,015	0,128	0,145	0,542	0,141	0,016	0,008