AN ADAPTATION OF THE SCS-*ACRU* HYDROGRAPH GENERATING TECHNIQUE FOR APPLICATION IN ERITREA

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DECLARATION

The research described in this dissertation was carried out within the School of Bioresources Engineering and Environmental Hydrology, University of KwaZulu-Natal, Pietermaritzburg, under the supervision of Professor R.E. Schulze (School of Bioresources Engineering and Environmental Hydrology, University of KwaZulu-Natal).

I hereby certify that the research results in this dissertation are my own original investigation except where acknowledged.

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ABSTRACT

Many techniques have been developed over the years in first world countries for the estimation of flood hydrographs from small catchments for application in design, management and operations of water related issues. However, relatively little attention has been directed towards the transfer and adaptation of such techniques to developing countries in which major hydrological decisions are crucially needed, but in which a scarcity of quality hydrological data often occurs. As a result, hydrologists and engineers in developing countries are frequently unable to alleviate the problems that extreme rainfall events can create through destructive flood flows or, alternatively, they do not possess the appropriate tools with which to design economically viable hydraulic structures.

Eritrea is a typical example of a developing country which faces difficulties in regard to the adaptation of an appropriate design flood estimation technique for application on small catchments. As a result, the need has arisen to adapt a relatively simple and robust design flood model that can aid hydrologists and engineers in making economic and safe designs of hydraulic structures in small catchments. One objective of this study was, therefore, to review approaches to hydrological modelling and design flood estimation techniques on small catchments, in order to identify the barriers regarding their adaptation, as well as to assist in the selection of an appropriate technique for application, in Eritrea.

The southern African adaptation of the SCS (i.e. Soil Conservation Service) design hydrograph technique, which has become a standard method for design flood estimation from small catchments in that region, was selected for application on small catchments in Eritrea for several reasons. It relies on the determination of a simple catchment response index in the form of an initial Curve Number (CN), which reflects both the abstraction characteristics and the non-linear stormflow responses of the catchment from a discrete rainfall event. Many studies on the use of SCS-based hydrological models have identified that adjustment of the initial CN to a catchment's antecedent soil moisture (ASM) to be crucial, as the ASM has been found to be one of the most sensitive parameters for accurate estimates of design flood volumes and peak discharges. In hydrologically heterogeneous regions like Eritrea, the hypothesis was postulated that simulations using a suitable soil water budgeting procedure for CN adjustment would lead to improved estimates of design flood volumes and peak

discharges when compared with adjustments using the conventional SCS antecedent moisture conditions (SCS-AMC) method.

The primary objective of this dissertation was to develop a surrogate methodology for the soil water budgeting procedure of CN adjustment, because any direct applications of soil water budgeting techniques are impractical in most parts of Eritrea owing to a scarcity of adequate and quality controlled hydrological information. It was furthermore hypothesised that *within* reasonably similar climatic regions, median changes in soil moisture storage from the so-called "initial" catchment soil moisture conditions, i.e. ΔS, were likely to be similar, while *between* different climatic regions median ΔSs were likely to be different. Additionally, it was postulated that climatic regions may be represented by a standard climate classification system.

Based on the above hypotheses, the Köppen climate classification, which can be derived from mean monthly rainfall and temperature information, was first applied to the 712 relatively homogeneous hydrological response zones which had previously been identified in southern Africa. A high degree of homogeneity of median *values* of ΔS, derived by the daily time step *ACRU* soil moisture budgeting model, was observed for zones occurring *within* each individual Köppen climate class (KCC) - this after a homogeneity test had been performed to check if zones falling in a specific KCC had similar values of median ΔS. Further assessment *within* each KCC found in southern Africa then showed that a strong relationship existed between ΔS and Mean Annual Precipitation (MAP). This relationship was, however, different *between* KCCs. By developing regression equations, good simulations of median ΔS from MAP were observed in each KCC, illustrating the potential application of the Köppen climate classification system as an indicator of regional median ΔS, when only very basic monthly climatological information is available.

The next critical task undertaken was to test whether the estimate of median ΔS from MAP by regression equation for a specific Köppen climate class identified in southern Africa would remain similar for an identical Köppen climatic region in Eritrea. As already mentioned, ΔS may be determined from daily time step hydrological soil moisture budget models such as *ACRU* model. The performance of the *ACRU* stormflow modelling approach was, therefore, first verified on an Eritrean gauged research catchment, *viz.* the Afdeyu, in order to have confidence in the use of values of ΔS generated by it. A SCS-*ACRU* stormflow modelling approach was then tested on the same catchment by using the new approach of CN adjustment, termed the *ACRU*-Köppen method, and results were compared against stormflow volumes obtained using the SCS-AMC classes and the Hawkins' soil water budgeting procedures for CN adjustment, as well as when CNs remain unadjusted.

Despite the relatively limited level of information on climate, soils and land use for the Afdeyu research catchment, the *ACRU* model simulated both daily and monthly flows well. By comparing the outputs generated from the SCS model when using the different methods of CN adjustment, the *ACRU*-Köppen method displayed better levels of performances than either of the other two SCS-based methods. A further statistical comparison was made among the *ACRU*, the SCS adjusted by *ACRU*-Köppen, the SCS adjusted by AMC classes and the unadjusted SCS models for the five highest stormflows produced from the five highest daily rainfall amounts of each year on the Afdeyu catchment. The *ACRU* model produced highly acceptable statistics from stormflow simulations on the Afdeyu catchment when compared to the SCS-based estimates. In comparing results from the *ACRU*-Köppen method to those from the SCS-AMC and unadjusted CN methods it was found that, statistically, the *ACRU*-Köppen performed much better than either of the other two SCS based methods. On the strength of these results the following conclusions were drawn:

- Changes in soil moisture storage from so-called "initial" catchment soil moisture conditions, i.e. ΔS, are similar in similar climatic regions; and
- Using the *ACRU*-Köppen method of CN adjustment, the SCS-SA model can, therefore, be adapted for application in Eritrea, for which Köppen climates can be produced from monthly rainfall and temperature maps.

Finally, future research needs for improvements in the SCS-*ACRU*-Köppen (SAK) approach in light of data availability and the estimation of ΔS were identified.

From the findings of this research and South African experiences, a first version of a "SCS-Eritrea" user manual based on the SAK modelling approach has been produced to facilitate its use throughout Eritrea. This user manual, although not an integral part of this dissertation, is presented in its entirety as an Appendix. A first Version of the SCS-Eritrea software is also included.

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LIST OF ABBREVIATIONS AND SYMBOLS AS WELL AS EXPLANATIONS OF TERMS

ACRU Stormflow Model Variable Names

ABRESP	=	Fraction of "saturated" soil water to be redistributed daily from the topsoil into the subsoil when the topsoil is above its drained upper limit
ACRU	=	A daily time step, multipurpose agrohydrological modelling system. The acronym originally derives from the Agricultural Catchment Research Unit which was housed within the (then) Department of Agricultural Engineering at the (then) University of Natal (Schulze, 1995a)
ADJIMP	=	Impervious areas connected directly to a watercourse (fraction)
ALAT	=	Mean latitude of catchment/sub-catchment (degree/decimal)
ALONG	=	Mean longitude of catchment/sub-catchment (degree/decimal)
BFRESP	=	Fraction of "saturated" soil water to be redistributed daily from the subsoil into the intermediate and/or groundwater store when the subsoil is above its drained upper limit
CAY	=	Monthly crop (i.e. water use) coefficients (fraction), given month-by-month
CLAREA	=	Catchment area (km^2)
COFRU	=	Coefficient of baseflow response (fraction)
DEPAHO	=	Thickness of the topsoil (m)
DEPBHO	=	Thickness of the subsoil (m)
DISIMP	=	Impervious areas which are not adjacent to a watercourse (fraction)
ELEV	=	Mean altitude (m)
FC1	=	Soil water content at "drained upper limit" (i.e. field capacity) for the topsoil ($m.m^{-1}$)
FC2	=	Soil water content at "drained upper limit" (i.e. field capacity) for the subsoil ($m.m^{-1}$)
IRUN	=	Variable to request the exclusion or inclusion of baseflow from the simulation of streamflow

PO1	=	Soil water content at "total porosity" (i.e. saturation) for the topsoil ($m.m^{-1}$)
PO2	=	Soil water content at "total porosity" (i.e. saturation) for the subsoil ($m.m^{-1}$)
QFRESP	=	Catchment's quickflow response (fraction)
ROOTA	=	Fraction of active root system in the topsoil horizon, specified month-by-month
SMDDEP	=	Effective depth of the soil from which stormflow generation takes place (m)
STOIMP	=	Surface storage capacity, i.e. initial abstractions (mm), for impervious surfaces
VEGINT	=	Crop interception losses ($mm.rainday^{-1}$), given month-by-month
WP1	=	Soil water content at the "lower limit" (i.e. permanent wilting point) for the topsoil ($m.m^{-1}$)
WP2	=	Soil water content at the "lower limit" (i.e. permanent wilting point) for the subsoil ($m.m^{-1}$)

SCS Stormflow Model Variable Names

AMC	=	Antecedent moisture class
ASM	=	Antecedent soil moisture
c	=	Coefficient of initial abstractions
CN	=	Curve Number (a function of soil, land cover and hydrological wetness condition of a catchment with a range from 0-100)
CN_I	=	Initial Curve Number for "dry" catchment conditions
CN_{II}	=	Initial Curve Number for "average" catchment conditions
CN_{III}	=	Initial Curve Number for "wet" catchment conditions
CN_f	=	Final Curve Number (adjusted for antecedent soil moisture)
D	=	Interim drainage (mm)
E	=	Interim evapotranspiration (mm)
F	=	Accumulated infiltration (mm)

Hawkins' Water Budgeting Procedure	=	Method of Curve Number adjustment developed by Hawkins (1978), accounting for varying ASM conditions by soil water budgeting procedures (*P-Q-D-E*)
I_a	=	Initial abstractions by the interception and depression storages plus by the infiltration before the start of runoff (mm)
S	=	Potential maximum soil water retention (mm)
ΔS	=	Change in soil moisture storage from the "average" condition
P	=	Interim rainfall (mm)
Q	=	Interim stormflow (mm)
SCS	=	A unit hydrograph stormflow generating technique developed originally by the United States Department of Agriculture in the 1950s (abbreviation for Soil Conservation Service)
SCS-AMC	=	Method of Curve Number adjustment developed to account for varying ASM conditions by three antecedent moisture classes
SCS-SA	=	SCS-based design hydrograph model adapted for southern Africa (Schulze *et al.*, 1992)

Other Abbreviations and Symbols Used in This Dissertation

ACRU-Köppen	=	Method of Curve Number adjustment developed to account for varying ASM conditions by using ΔS and mean annual precipitation relationships for a specific Köppen climate class
Adj. r^2	=	Adjusted coefficient of determination
$CV_{\Delta S}$	=	Weighted coefficient of variation (%), of ΔS
$\overline{\Delta S}$	=	Mean of change in soil moisture storage for specified Köppen climate class and soil/land cover combinations
$SD_{(\Delta S)}$	=	Standard deviation of change in soil moisture storage for a specific KCC and soil/land cover combinations
DSDV	=	A combination of deep sand soils with dense vegetation
ILIV	=	A combination of intermediate depth loamy soils with intermediate density vegetation
KCC	=	Köppen climate class
MSE	=	Mean square error within a 5% level of significance

r^2	=	regression coefficient
SAK	=	Abbreviation for the SCS-*ACRU*-Köppen stormflow modelling approach. This is the SCS-based design hydrograph when the *ACRU*-Köppen method is employed to account for varying ASM conditions of a catchment
SCSV	=	A combination of shallow clay soils with sparse vegetation

1. INTRODUCTION

There is frequently a need for estimates to be made of flood magnitudes and peak discharges from small catchments for planning, design and management of hydraulic structures (Schmidt and Schulze, 1987). Such estimates have to be generated in order to make economic and safe design decisions, since actual measurements of flood hydrographs from extreme events are rarely available at the location of concern (Schmidt and Schulze, 1987; Schulze and Schmidt, 1995).

A wide range of hydrological studies and development of models have been undertaken over the years which have included statistical analyses of observed streamflow data and event modelling using rainfall-runoff techniques (Hall and Minns, 1999; Smithers and Schulze, 2001). However, a lack of adequate, long and accurate hydrological information in many developing countries (e.g. Eritrea) continues to be one of the fundamental problems challenging engineering hydrologists when they attempt to apply a sound design flood estimation technique on small catchments. In addition, many of these developing countries are located in arid and semi-arid regions, where hydrological processes are often more complex than to those in humid areas (Pearce, 1990; Schulze, 1998). They are in a "delicate hydrological balance" in which the climate, soil and land cover information play an important role in determining the spatial and temporal variation in the soil water balance (Pilgrim *et al.*, 1988; Schulze, 1998).

In the Eritrean context, the most serious overall climatic constraint is low rainfall as well as its distribution, which fluctuates from year to year (FAO, 1994). The rain that does fall is often torrential, unreliable and causes soil erosion, thereby removing nutrients, damaging the soil tilth and reducing the water holding capacity of the soil in most parts of the country (Iyassu, 1995). Surface runoff throughout Eritrea is also characterised by high inter-seasonal and inter-annual variability (Euroconsult, 1997).

It is clear that many years of good quality hydrological information is required by hydrologists for better estimates of stormflow volumes and peak discharges from small catchments in Eritrea. Unfortunately, relatively few meteorological stations have been established and their locations are generally limited to cities, towns and research areas. In addition, the record length of these stations is inadequate to match the level of most conceptual-physical models for design hydrology. As a result, no standard design flood estimation method has been adapted to date for Eritrea. Engineers use simple equations and/or the Rational Method to estimate peak discharge, while runoff volume is often simply taken as 10 % of the total rainfall for most small hydraulic designs (Ministry of Agriculture, 2000). A wide band of uncertainty around estimates of the flood magnitude, combined with steep increases in flood magnitude with increases in return periods, results in frequent destruction and severe damage to dams, bridges and other civil engineering structures in Eritrea or, alternatively, to the over-design of hydraulic structures.

If the scarce water resources of the country are to be managed and allocated effectively, accurate estimation of flood magnitudes and peak discharges are, therefore, crucial and hence the choice of the design method also becomes critical.

The overall objective of this project is to adapt a relatively simple and robust design flood model so that it may be applicable on small catchments, i.e. <30 km^2, throughout most of Eritrea. Following a review of approaches to design flood estimation and criteria for model selection in Chapter 2, the Soil Conservation Service (SCS) design hydrograph technique as adapted for southern Africa (Schulze and Arnold, 1979; Schmidt and Schulze, 1987; Schulze *et al.*, 1992) was selected for this study with the view to assessing its potential suitability for wider application in Eritrea.

Chapter 3 briefly describes the SCS design hydrograph model as adapted for southern Africa. It discusses the background, components and derivation of the Curve Number (CN) as an important input to the model. However, much emphasis is placed on the antecedent soil moisture (ASM) component and the factors which control it, because ASM greatly influences the stormflow generation from individual rainfall events. Various procedures have been developed over time to represent the ASM for adjustment of stormflow responses, ranging from simple Antecedent Precipitation Index (API) to more complex soil water budgeting approaches.

In the SCS method, many researchers have proposed procedures to adjust the land use and soils-based response coefficients of a catchment (CN) according to a soil water budget in order to provide more realistic estimates of stormflow and peak discharge distributions than when API-based methods are used. The relative success of soil water budgeting procedures over API-based CN adjustment methods was shown by Schulze (1984; 1989), Schmidt *et al.* (1986) and Schmidt and Schulze (1987), who employed the conceptual physical, daily soil water budgeting *ACRU* model (Schulze, 1995a) to estimate changes in antecedent soil moisture storage, ΔS, from so-called "initial" conditions, in order to enhance the capabilities of the SCS technique when simulating design floods from small catchments.

Eritrea is located in an arid and semi-arid environment in which very marked changes in soil water status are evident between runoff producing events. In such an environment, estimates of stormflow volumes and peak discharges are highly sensitive to ASM, as the antecedent wetness conditions of the catchment play a fundamental role in the hydrological responses of individual rainfall events.

In physiographically and climatically heterogeneous regions like Eritrea, it becomes evident that the simple modelling approach utilising only rainfall amounts and "average" catchment conditions to represent the ASM will not provide a sound basis for determining the spatial and temporal variations in soil water balances. Hence, there is the need for a more accurate method of ASM representation, and the application of daily soil water budgeting is adapted in this study. The direct application of soil water budgeting procedures, however, also requires long and accurate daily rainfall and temperature records, in addition to soil and land use information. The problem then still arises as to how to estimate the values of ΔS in regions such as Eritrea, where only limited hydrological data and generally only very basic monthly climatological information is available.

Since most of the factors that affect the soil water budget, *viz.* precipitation, evapotranspiration, moisture storage in the soil, surface runoff and the drainage of water through the root zone within the soil profile, are implicit in climatic parameters, the soil water status of a catchment was approached as a climatologically driven variable. It was based upon three hypotheses (Schulze, 2003a) from which a methodology was to be developed for soil water budgeting procedures in areas with limited hydrological and climatological information. These three hypotheses are as follows:

Hypothesis 1: Changes in the land use and soils-based initial Curve Numbers due to antecedent soil moisture conditions are similar universally for similar climatic regions;

Hypothesis 2: Similar climatic regions may be represented by a standard climate classification system; and

Hypothesis 3: Changes in antecedent soil water storage, ΔS, in Eritrea would be similar to ΔS in southern Africa for the same defined climatic region.

If the approach was shown to be successful, it was hypothesised that values of ΔS from defined climatic regions could be transferred from southern Africa to Eritrea and other areas of the world with limited hydrological information, where such climatic regions have been defined.

Based on the above approach and hypotheses, three of the widely used standard climate classification systems are reviewed in Chapter 4, with the view to selecting one of them as the classification to use when disaggregating a region/country into relatively homogenous climatic response zones. The Köppen (1931) climate classification was selected for this study because of its simplicity, as well as the availability of spatially detailed monthly rainfall and temperature information in Eritrea. In southern Africa, Schmidt and Schulze (1987) had previously analysed ΔS for design storms from so-called "initial" catchment response conditions (CN) based on land use and soils characteristics for each of 712 relatively homogenous response zones into which southern Africa has been delineated by Dent *et al.* (1988). Chapter 4 also presents the grouping of these 712 hydrological zones according to each of 14 Köppen climate classes (KCC) identified in southern Africa. A further assessment is made as to whether unique relationships exist between ΔS and the distribution of Mean Annual Precipitation (MAP) within each KCC identified in southern Africa. The chapter ends with a conclusion on the results and on the hypotheses made.

Before transferring the typical values of ΔS from South Africa to Eritrea by applying the same climate classification system, the SCS-*ACRU* approach to stormflow modelling is first tested and verified on an Eritrean research catchment, in order to enable confident application of both the SCS and *ACRU* models, as well as the values of ΔS for specified KCCs, in Eritrea. The results and evaluation component of the dissertation begin in Chapter 5 with an overview of Eritrea from an hydrological perspective. This is followed in Chapter 6 by some general background on the test catchment, *viz.* the Afdeyu research catchment, and the verification of the simulated stormflow volumes by the *ACRU* model and the SCS technique, with estimates by the latter model made using different methods of CN adjustments. In this chapter a statistical comparison is also made between simulated stormflow values of both models from the five highest daily rainfall events in the Afdeyu catchment, for each year of record. The chapter ends with a conclusion on the results of, and hypotheses on, the verification of outputs from both the *ACRU* and SCS models in the Afdeyu research catchment.

The various results are discussed and summarised in Chapter 7. Recommendations for further consideration of model improvements are highlighted in Chapter 8.

Based on the concepts tested in this dissertation and South African experiences, a first version of a user design manual for the application of SCS-Based techniques for the estimation of design floods from small catchments in Eritrea has been derived (cf. Appendix A). A *VISUAL BASIC* coded program has also been developed, in order to allow quicker computation of all the calculations required to simulate the stormflows and peak discharges from small catchments.

2. APPROACHES TO DESIGN FLOOD ESTIMATION FROM SMALL CATCHMENTS, AND MODEL SELECTION

A wide range of hydrological models has been developed for design flood estimation on small catchments. These range from simple empirical methods to complex deterministic models and there are numerous commercial hydrological software packages available either on the internet or from universities (Euroconsult, 1997). Hydrological modelling has, to some extent, become fashionable since the advent of more powerful computers. The resultant advances have led to models of increased complexity and sophistication being developed. A complex model, however, does not necessarily perform better than a simpler model merely by virtue of its increased complexity alone (Angus, 1987; Schulze, 1998). It should always first be tested and proven (Angus, 1987). Thus, it is necessary to discuss the various stormflow modelling approaches and the criteria for their selection in order to obtain an idea of model complexity, uncertainty and applicability that would help in the selection of an appropriate model (or models) for use on small catchments in Eritrea. As a background to evaluating the various models, some theories of stormflow generation are first reviewed briefly in Section 2.1, since these models may vary conceptually in the mechanism (s) by which stormflow is generated.

2.1 Stormflow Generation Theories: A Brief Overview

Traditional Hortonian infiltration models assume that the ASM content is constant across the entire catchment, despite the fact that even in small catchments ASM exhibits marked spatial heterogeneity (Plaza *et al.*, 2000). In recent years these traditional theories have been seriously challenged following field observations and catchment experiments, which have frequently failed to confirm the existence of overland flow as originally conceptualised by Horton (1933). Hope (1980) classified stormflow theories into two broad categories, *viz.*

- those based on the infiltration theory of runoff and
- those based on the unit source area theories, which include the variable source area and the partial area theories.

The Horton theory is based on the assumption that stormflow is generated by rainfall excess, which is the rainfall failing to infiltrate into the soil and thereby becoming overland flow. According to Ward (1984), Descroix *et al.* (2002) and Royappen *et al.* (2002), the Horton theory might well be applicable to areas exhibiting low infiltrabilities into the soil profile and receiving very high intensity storms, as well as to areas of sparse vegetation cover, as in arid areas where, additionally, sodic soils may exhibit crusting. Rates of Hortonian overland flow may vary with storm size, rainfall intensity and factors that affect infiltration (Royappen *et al.*, 2002).

The unit source area theories of stormflow are associated with one or more of the following principles (Hope, 1980):

- the production of stormflow in a catchment is non-uniform,
- stormflow is not synonymous with rainfall excess or surface flow, but occurs either as subsurface flow or a combination of subsurface and surface flows, and
- certain areas of a catchment may seldom, if ever, contribute directly to the production of stormflow.

The variable source area theory focuses on the role of subsurface flow in producing saturated overland flow, in addition to that generated at the surface. Under saturated conditions, water moves vertically within an element of the landscape, or is routed laterally along the flow trajectory according to Darcy's law. If the subsurface flow from upslope sources exceeds the transmitting capacity of the soil at a point, this water rises to the surface to produce surface flow and thereby increases the area under surface flow (Bonell, 1993; Davis *et al.*, 1999). Subsurface lateral flow for a given element is expressed by Davis *et al.* (1999) as

$$q\ (out) = K_{sat}\, bmh \qquad 2.1$$

where

$q\ (out)$	=	the flux out of the element ($mm^2.s^{-1}$),
K_{sat}	=	the saturated hydraulic conductivity ($mm.s^{-1}$),
b	=	the element width (mm),
m	=	the element slope (%), and
h	=	the thickness of the saturated layer (mm).

The partial area stormflow theory is based on the premise that certain areas of the catchment are effective stormflow producing areas. It has been hypothesised that partial areas with high runoff coefficients in certain parts of a catchment are often wetlands, saturated areas adjunct to the stream and valleys whose locations are controlled by the topographical and hydrological configuration of the catchment (Dunne and Black, 1970; Hope, 1980; Royappen *et al.*, 2002).

Recent research (e.g. Becker *et al.*, 2002) have shown that surface and subsurface processes may operate simultaneously in a given catchment and that their relative importance may fluctuate seasonally or even within the course of a single event.

2.2 Approaches to Hydrological Modelling

Categorisation of hydrological models for design flood estimation has been attempted by many researchers according to the model functions, structures and types and levels of information required. There are many textbooks, research papers and technical papers providing information on each of these approaches to classifying hydrological models (e.g. Angus, 1987; Chow *et al.*, 1988; Euroconsult, 1997; Kienzle *et al.*, 1997; Schulze, 1998; Smithers and Schulze, 2001; Görgens, 2002). Chow *et al.* (1988), for example, divided hydrological models into two categories, *viz.* physical and abstract models. Physical models represent the system on a reduced scale, while abstract models represent the system in mathematical form. Nevertheless, most hydrological and flood models are classified structurally into four broad categories, *viz.*

- Stochastic models,
- Calibration and parameter optimising models,
- Parametric (Conceptual) models, and
- Deterministic models.

2.2.1 Stochastic Models

These are so-called "black box" models, in which inputs (e.g. rainfall) are transformed to output (e.g. runoff) with little or no understanding of the processes involved in the transformation (Schulze, 1998). This type of model recognises the chance-dependence of hydrological processes and relies heavily on historical records of both input and output variables being a representative sample over time (Angus, 1987; Kienzle *et al.*, 1997). Stochastic models always have outputs that are variable in time. They may be classified as "time-independent" or "time-correlated"; a time-independent model representing a sequence of hydrological events where individual events do not influence each other, while a time-correlated model represents a sequence in which the next event is partially influenced by the current one, and possibly by others in the sequence (Chow *et al.*, 1988).

2.2.2 Calibration and Parameter Optimising Models

Parameters of this group of models are adjusted to enable the model output to match observations as closely as possible. The major limitations of these models are that they are data demanding for the calibration procedure (Schulze, 1998). Moreover, parameters are identified for a particular catchment with a particular land use and for a specific time period, making parameter transfers to ungauged catchments unsuitable (Euroconsult, 1997; Kienzle *et al.*, 1997).

2.2.3 Parametric (Conceptual) Models

Parametric models are so-called "grey box" models, representing a partial understanding of hydrological processes, but with the catchment's spatial heterogeneity (e.g. soils, vegetation, terrain, ASM) usually being spatially averaged. Consequently, hydrological processes and their variability are integrated such that their parameter expressions are often indices rather than having strictly physically meaningful values (Schulze, 1998). This group of models is probably the one most widely used in stormflow modelling. A central assumption shared by many conceptual models is that the T-year recurrence interval storm should produce the T-year flood, if the catchment is at a "typical", or "average", wetness condition (Görgens, 2002). This assumption is, however, unlikely to be valid for any particular historical storm (Schmidt and Schulze, 1987; Görgens, 2002). Most of the models require reasonable periods of good quality concurrent rainfall and flow data for calibration and verification (Euroconsult, 1997).

2.2.4 Deterministic Models

Deterministic models have a physical-conceptual basis and belong to the group of so-called "white box" models, in which the physical processes of conversion of rainfall to runoff on a catchment are described in terms of mathematical relationships (Euroconsult, 1997; Kienzle *et al.*, 1997). Deterministic models typically aim at simulating the various components of spatially and temporally varying catchment hydrological process (Kienzle *et al.*, 1997). They can be further subdivided into mechanistic and functional models. Mechanistic models are causal, or physically-based, models which depend on rate functions (e.g. soil water redistribution) which are spatially variable, while functional models depend on capacity/threshold parameters (e.g. drainage commences only once field capacity is reached) and compartmentalise the complex nature of hydrological processes (Schulze, 1998).

Deterministic models may also be structured as either lumped or distributed models, based upon the level of discretisation to which the catchment is subjected (Angus, 1987). A lumped parameter model attempts to account for the spatial variations occurring within a catchment by assuming averaged parameter values for the entire catchment, usually by area-weighting. A distributed parameter model, on the other hand, attempts to account for the heterogeneous nature of a catchment by dividing the catchment into relatively homogenous response units (Angus, 1987; Schulze, 1998).

2.3 Approaches to Design Flood Estimation

Approaches to design flood estimation have recently been categorised into two broad groups by Smithers and Schulze (2001). These are first, methods based on the analysis of flood/streamflow data and secondly, those based on rainfall events. Further classifications of each of the two broad approaches are shown in Figure 2.1. Note that snowmelt derived floods are not considered explicitly in Figure 2.1.

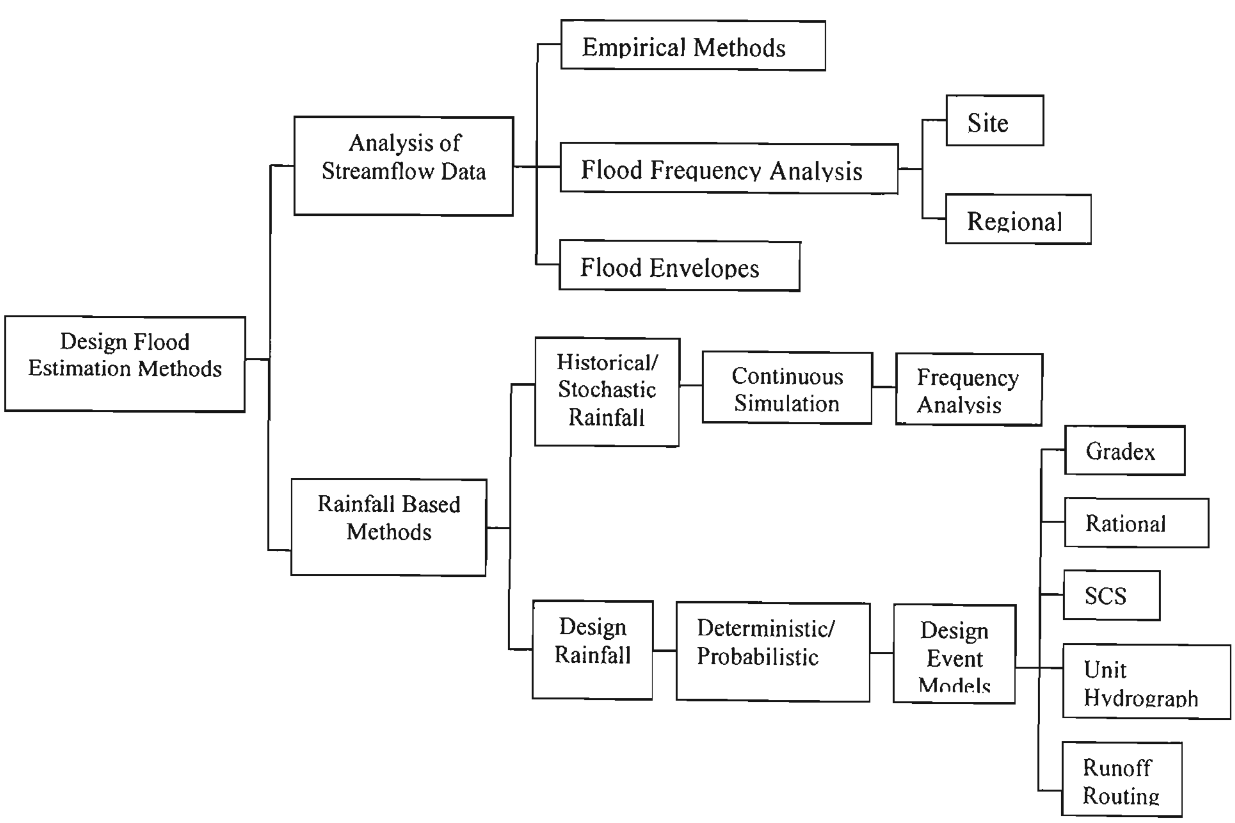


Figure 2.1 Methods for estimating design floods (after Smithers and Schulze, 2001)

2.4 Selection of an Appropriate Design Flood Estimation Method for Small Catchments in Eritrea

The first step in flood estimation is the choice of the flood estimation method to be used. Some subjectivity is always involved in the selection of an appropriate method (Smithers and Schulze, 2001). According to Euroconsult (1997) the selection criteria for a flood estimation method should include:

- *Suitability:* The method should be applicable under a wide range of environmental conditions;
- *Reliability:* It has to provide a realistic interpretation of the hydrological processes and has to be based on tried and tested methodologies from similar climatic regions;
- *Flexibility:* The method needs to be applicable to a wide range of spatial scales (in this study scale is restricted to that of small catchments only), climatic conditions and catchment responses; moreover, it has to be transferable to ungauged catchments or regions; and
- *Practicability:* It has to maximise the use of readily available rainfall and physical properties of a catchment and to rely on relatively few and easily estimated parameters.

Schulze (1995a) noted the following points of caution on modelling which are applicable also in the selection of a suitable technique for design flood estimation from small catchments, *viz.*

- models cannot substitute for a lack of knowledge,
- neither do they create new data or facts (although they create new understandings),
- models can only anticipate the possibility that conditions as simulated, indeed occur, and
- models are constantly being improved; users are, therefore, urged to obtain the most up-to-date versions of a model.

In light of the above, a selection of an appropriate design flood method that could be suitable for wide application on small catchments in Eritrea had to be made. Ideally, design flood estimation requires many years of good quality flow data, particularly for regions such as Eritrea where the inter-seasonal and inter-annual variability is high (Euroconsult, 1997). If observed flood data were available at a site, a choice would then have to be made between empirical, flood frequency or flood envelope models (Figure 2.1). Alternatively rainfall based methods would have to be used, either stochastic or deterministic. However, in Eritrea flow series and flood data exist for a very limited number of gauging stations only. Moreover, the available time series of recorded flows are too short and intermittent to be used for design determinations in almost all cases. Daily rainfall information, however, is generally more widely available across the country and records are often much longer and accurate than those of flow series data.

It is clear, therefore, that it would not be possible to employ any of the streamflow data based techniques in Eritrea at present, as the available flow database is too limited. Furthermore, transfer of model parameters from gauged to ungauged catchments would be problematic, even if calibration were possible, as a result of marked spatial and temporal variability in runoff processes in most parts of the country. A lack of experts is an additional problem, as these models are also generally relatively complex and sophisticated.

Despite the limited data currently available in Eritrea, it is likely that a rainfall-based model, ideally of the deterministic or parametric (conceptual) type, would provide a successful means of simulating design floods for ungauged areas for Eritrea, especially if model parameters could be estimated from physical properties of a small catchment and, therefore, could be transferred to ungauged catchments (Euroconsult, 1997). Of the rainfall-based models for use on small catchments the Rational, SCS, Gradex, Unit Hydrograph, Time Area, Kinematic and Runoff Routing are commonly used techniques for flood estimation around the world (Schmidt and Schulze, 1987; Smithers and Schulze, 2001). It is beyond the scope of this paper to review each of these methods. However, it is helpful to discuss the merits and limitations of some of these methods, based on experiences from other countries, in order to select an appropriate method for flood estimation for Eritrea.

The Rational Method is widely employed in many countries (Alexander, 2001). Pilgrim (1986) quotes that at that point in time, it was the dominant method employed for small catchments design all over the world, with a usage in the mid-1980s in Australia of 86%, in Canada of at least 90% and in the United Kingdom of 90%. The method has a simple and logical approach (Alexander, 1989), but its major weaknesses are the judgment required to determine the appropriate runoff coefficient and the variability of the coefficients between different hydrological regimes (Pilgrim and Cordery, 1993). The Rational Method, however, computes only flood peaks and not flood volumes, and is sensitive to the input design rainfall intensity, its successful usage depends on the experience of the user and it should not be used on catchments >15 km^2 in area (Smithers and Schulze, 2001).

The Unit Hydrograph, Time Area and Kinematic techniques essentially routing methods, require considerable computational steps to determine stormflow volume, peak discharge and hydrograph shape (Schmidt and Schulze, 1987). Campbell *et al.* (1986) conducted an evaluation of the above methods as techniques for the estimation of deign floods from small catchment in southern Africa and found that none of these methods performed adequately against observed runoff with uncalibrated parameters. However, further statistical analysis by Schulze *et al.* (1986) indicated that the SCS-based models (particularly the southern African adaptation) performed well against runoff observations when compared to the Rational Method and the more complex models such as ILLUDAS (Time Area) and WITWAT (Kinematic), and this under wide ranging environmental conditions and small catchment size categories in southern Africa.

Application of SCS-based methods has increased in many countries over the past 30 years for numerous reasons. First, inaccurate estimation of the design hydrograph from small catchments has been noted in techniques such as the Rational Method and the Unit Hydrographs (Bondelid, *et al.*, 1982; Campbell *et al.*, 1986; Schmidt and Schulze, 1987; Mishra and Singh, 2004). Secondly, coarse estimates of the catchment Curve Number (CN), or response index, can be obtained using remote sensing, which can reduce the cost of data collection greatly when compared with estimating CN from field work. Thirdly, the SCS method provides a high degree of flexibility in the type of hydrological analysis, unlike many other methods such as the Rational Method (Bondelid *et al.*, 1982).

The SCS method for design flood estimation was originally developed in the USA in the 1950s. The model has been considerably modified, both internationally and in South Africa, for the estimation of stormflow volumes, peak discharges and flood hydrograph shapes for use on small catchments (Görgens, 2002). Amongst the many SCS-based models, the SCS model adapted for southern African conditions by Schulze and Arnold (1979), and subsequently subjected to considerable research by Schulze (1982), Schmidt and Schulze (1984), Dunsmore *et al.* (1986), Schmidt and Schulze (1987), Weddepohl (1988) and Topping (1992), would appear to be an appropriate method for design flood estimation from small catchments in Eritrea for the following reasons:

- Three intermediate hydrological soil groups have been added to the coarse four-fold grouping of soils identified in the original SCS model.
- Unlike many other SCS-based models, CNs are adjusted according to a daily soil water balance instead of only 5-day accumulated antecedent rainfall depths.
- It has two options to account for typical soil moisture condition prior to a design event, *viz.* the *Median Condition Method* (the so-called "average" ΔS condition) and the *Joint Association Method*, both of which account the soil moisture variation between storm events.
- It has been tested and verified under wide environmental conditions inside and outside southern Africa countries.
- It has been computerised into a readily accessible and user friendly package (Schulze *et al.*, 1992).
- It is "driven" by the *ACRU* daily soil water budgeting model (Schulze, 1995a) to simulate the complex nature of soil moisture changes (ΔS) in the soil profile required for adjustment of CNs.
- Above all, however, typical regionalised indices of ΔS for a wide spectrum of climatic conditions, soil properties and land use characteristics are available in southern Africa for the adjustment of runoff coefficients (CNs), and it is hypothesised that these indices can be transferred to other regions with limited data, but similar climatic conditions, such as Eritrea.

* * * * *

The background, concepts and components of the SCS stormflow modelling approach used in southern Africa, and termed the SCS-*ACRU* approach, are discussed in detail in the next chapter. Note that the term "SCS-*ACRU*" is a conceptual approach and the term should not be confused with that of 'SCS-SA", which is the title of the user manual for southern Africa produced by Schulze *et al.* (1992).

3. THE SCS-*ACRU* APPROACH TO STORMFLOW MODELLING

3.1 The SCS Method and its Components

The practical applications of the SCS method are simple and direct. The method relies on the determination of catchment Curve Numbers (CNs), the values of which are widely documented in the literature for various soil types, land uses and their managements (e.g. NEH-4, 1972; Schulze and Arnold, 1979; Schmidt and Schulze, 1987; Chow *et al.,* 1988; Schulze *et al.,* 1992; Mishra and Singh, 2003). The core of the SCS technique is its stormflow equation (Equation 3.3), a simple algebraic formula relating the stormflow depth to the total rainfall depth and the CN, which determines both the rainfall abstraction characteristics and the non-linear hydrological response of the catchment (Gray *et al.*, 1982).

The rainfall magnitude, P, must be sufficient to satisfy initial abstractions, which are made up of the interception and depression storages plus the quantity of infiltration before the start of stormflow. After stormflow commences, additional losses occur mainly in the form of infiltration, F, which increases with increasing rainfall amount up to some maximum retention of the soil, S. Stormflow response, Q, also increases as the rainfall amount increases (Schmidt and Schulze, 1987). Figure 3.1 illustrates the relationship among these variables for a rainfall event of constant intensity.

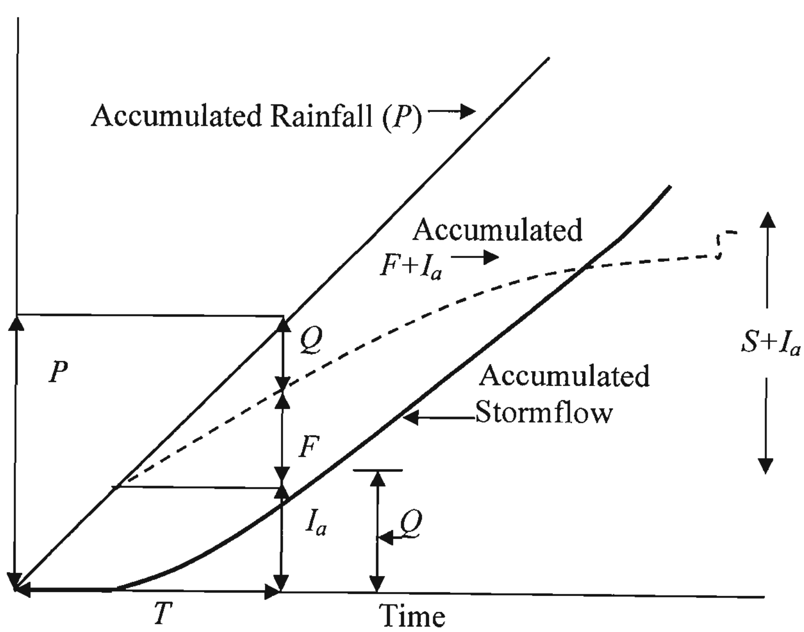


Figure 3.1 Schematic curves showing relationships used in the derivation of the SCS stormflow equation (after NEH-4, 1972; Schulze and Arnold, 1979)

In the limit, as P approaches infinity, so F approaches S and the ratio of F to S approaches unity. The ratio of Q to P - I_a also approaches unity, although it can never actually reach unity. Then the ratio of F to S is assumed to be equal to the ratio of Q to P - I_a, i.e.

$$\frac{Q}{P - I_a} = \frac{F}{S} \qquad 3.1$$

where

Q	=	stormflow depth (mm),
P	=	daily rainfall depth (mm),
F	=	accumulated infiltration (mm),
S	=	potential maximum soil water retention (mm), and
I_a	=	initial abstractions prior to the commencement of stormflow (mm), assumed to be as 0.2S in the original SCS method, but changed to a default value of 0.1S in the SCS-SA model, based on extensive research in South Africa (Arnold 1980; Schmidt *et al.*, 1984).

After stormflow commences when $P>I_a$, all rainfall becomes either stormflow or actual retention, i.e.

$$(P - I_a) = F + Q \qquad 3.2$$

Solving Equations 3.1 and 3.2 for Q, when $P> I_a$, yields

$$Q = \frac{(P - I_a)^2}{P - I_a + S} \text{ for } P>I_a \qquad 3.3$$

The potential maximum soil water retention, S, is a function of a final Curve Number, CN_f, which is a stormflow response index to rainfall. In metricated form. S is given as

$$S = \frac{25400}{CN_f} - 254 \qquad 3.4$$

where the CN_f, which can range from 0 to 100, is dependent on catchment's soil and land use characteristics as well as the antecedent soil moisture conditions (ASM) of the catchment. The determination of inputs to Equations 3.3 and 3.4, *viz.* the one day rainfall depth, hydrological soil groupings, land uses and their treatment, and thereby derivation of CNs and their adjustment to CN_f according to ASM conditions are discussed next.

3.1.1 One Day Rainfall Depth

In the SCS procedure one day rainfall depth is used to compute a daily stormflow depth. This renders the SCS method particularly attractive to users since design values of daily rainfall data are widely available for most locations of interest (Schulze *et al.*, 1992). For a specific historical storm the measured one day rainfall depth can be used directly as input in the SCS model. Engineering design of hydraulic structures and drainage schemes, the evaluation of flood risk and the economic assessment of flood damage all require the determination of design storm rainfall depths expected for selected durations and return periods (Adamson, 1981; Schmidt and Schulze, 1987). Structures are designed to be able to withstand an event for which the return period is determined by economic and acceptable risk considerations. In the SCS method, a one day expected design rainfall for a chosen frequency of recurrence is substituted as P into Equation 3.3 to compute the resulting design stormflow depth for the same frequency as the rainfall.

3.1.2 Hydrological Soil Groups

Soil plays a vital role in estimations of stormflow volumes and peaks, as it is a prime regulator of the hydrological processes of a catchment (Schulze, 1984). In the classical SCS literature (e.g. NEH-4, 1972), soil properties have been categorised hydrologically into four basic soil groups, *viz.* A, B, C and D soils. Originally, the classification was developed for soils in the USA according to "minimum infiltration rate" of soils when thoroughly wetted.

The four basic hydrological soil groups have the following attributes, as given in NEH-4 (1972):

Soil Group A: *Low stormflow potential.* Infiltration rate is high and permeability is rapid. The soils of this group are generally deep and well drained, are often sands or gravels, and display a final infiltration rate of approximately 25 $mm.h^{-1}$ and a permeability rate > 7.6 $mm.h^{-1}$.

Soil Group B: *Moderately low stormflow potential.* Infiltration rate is moderate and permeability is slightly restricted. The soils of this group are of moderate thickness with moderately fine to moderately coarse texture. Final infiltration rate is approximately 13 $mm.h^{-1}$ and the permeability rate is in the range of 3.8 to 7.6 $mm.h^{-1}$.

Soil Group C: *Moderately high stormflow potential.* The rate of infiltration deteriorates rapidly and permeability is restricted. Soils are shallow with restricted drainage. Final infiltration rate approximately ranges to 6 $mm.h^{-1}$ and the permeability rate ranges from 1.3 to 3.8 $mm.h^{-1}$.

Soil Group D: *High stormflow potential.* Infiltration rate is very slow and permeability is severely restricted. Soils are generally very shallow (<0.3m) and soils of high shrink-swell potential soils are included in this group. Final infiltration rate is approximately 3 $mm.h^{-1}$ and the permeability rate is < 1.3 $mm.h^{-1}$.

However, the application of this four-fold classification procedure has some limitations both inside and outside the USA. Wood and Blackburn (1984), for example, conducted research to evaluate the effectiveness of the hydrological soil groups in calculating runoff estimates from arid and semi-arid rangelands of the Great Basin in Nevada, Edwards Plateau and the Rolling Plains of Texas as well as from the Pecos River, Canadian River, San Juan River and Rio Grande Basins of New Mexico. Their results showed that the simulated stormflow overestimated the observed stormflow 67% of the time, while estimating correctly only 11% of the time and underestimating 22% of the values. They concluded that modification of the hydrological soil groups was necessary when the vegetation cover was in "good" condition.

The hydrological classification of soils used in southern Africa is different in concept to the one described by the NEH-4 (1972), in which soil properties were categorised according to the final "infiltration" and "permeability" rates of saturated soils. An additional three intermediate soil groups (i.e. A/B; B/C; C/D) were identified, thus giving seven hydrological soil groups in total (Schulze, 1984; Schmidt and Schulze, 1987; Schulze *et al.*, 1992).

Since the sensitivity of CN to hydrological soil group is high (Schmidt and Schulze, 1987) and local experience is usually necessary to make adjustments to soil groups in the field, some guidelines for adjustment in the field are given below, based on experience in South Africa (Schulze, 1984; Schmidt and Schulze, 1987; Schulze *et al.*, 1992):

- *Soil depth:* Where typically deep soils are in a shallow phase, for example on steep slopes, they should be downgraded one group (e.g. B becomes B/C).
- *Surface sealing:* Where surface sealing is evident, in sodic soils for example, soils should be downgraded one group (e.g. C to C/D).

- *Topographical position:* Generally soils in bottomlands may be downgraded (e.g. B to B/C) and soils formed in uplands upgraded one group (e.g. B/C to B).
- *Parent material:* Identical soil series derived from different parent materials may require regrouping, e.g. soil series formed from sandstones would be upgraded relative to the same series formed from more clayey parent rock (e.g. B/C to B).

3.1.3 Land Use and Treatment Classes

In the SCS procedure the effects of surface conditions of a catchment are evaluated by means of assessing land cover, land treatment and stormflow potential (NEH-4, 1972; Schulze *et al.*, 1992). *Land cover* defines the primary catchment cover which can comprise of a range of annual and perennial crops, grassland and forest, as well as non-agricultural areas such as water bodies and urban areas. *Land treatment* applies mainly to agricultural practices, such as conservation structures (e.g. contours, terraces, bunds) and management practices (e.g. grazing control, rotation of crops). *Stormflow potential* is influenced by management practices, mainly in agricultural areas. Three categories of stormflow potential are given, *viz.* high, moderate and low. High stormflow potential will prevail when poor hydrological conditions exist while low stormflow potential occurs when the land is in good hydrological condition. Under agricultural crops, practices such as conservation structures and minimum tillage will result in low stormflow potential. In the context of pasture or grasslands, a high stormflow potential would occur as a result of heavy grazing or recent burning. Under forest conditions, a high stormflow potential exists when undergrowth is sparse and there is a compact, shallow humus layer (Schmidt and Schulze, 1987; Schulze *et al.*, 1992).

Land use and treatment classes are obtained either by observation or by measurement of plant and litter density, moisture content and soil temperature on sample areas (NEH-4, 1972).

3.1.4 Derivation of Curve Numbers

CNs are derived from gauged catchments where soils, land cover and hydrological condition are known. The CN for a particular combination of soil and land cover characteristics was developed by plotting daily rainfall and runoff volumes for the annual maximum floods on graph paper (NEH-4, 1972). The median CN, i.e. one which had equal number of data points either side of the plotted curve, was assigned the so- called "average" CN. In this way CNs were developed for many soil and land cover combinations in the USA. The CNs represent soil/land cover combinations for "initial conditions" which assume a so-called "average" catchment wetness just prior to an event (Schulze *et al.*, 1992).

A perfectly impervious surface from which all rainfall becomes runoff would have a CN=100 while an ideal pervious surface which absorbs all rainfall would have a CN=0 (Gray *et al.*, 1982). One of the strengths in the use of the SCS model is the detailed information of CNs for a wide range of soil and land use combinations (cf. Table 4.1 in Appendix A). Nevertheless, in spite of its apparent simplicity, the application of the CN procedure leads to a diversity of interpretations and confusion resulting from ignorance regarding its limitations, these being related mainly to the classification of soils into hydrological soil groups outside the USA and the determination of the ASM, which is an index of catchment wetness (Hawkins, 1979; Dunsmore, 1985; Schmidt and Schulze, 1987; Bosnay, 1989; Silveira *et al.,* 2000).

Schulze *et al.* (1992) noted the following points when determining the value of a CN:

- CN values are based on work conducted mainly in the USA and therefore may not cover all land use characteristics found in other regions of the world. Local interpretations must be made from land uses similar to those in Table 4.1 (Appendix A).
- Users should attempt to establish the land cover/treatment conditions likely to prevail in the catchment during the design life of the structure. Urban development, projected land use changes such as afforestation, deforestation, fallowing or grassland degradation are some of the examples that should be accounted for in deriving the catchment CN.
- In the interest of safety a value of CN < 50 is not advisable in design calculations, owing to future changes in land cover/use which may increase the design stormflow.
- In physiographically heterogeneous catchments, variations in CN must be accounted for by subdividing a catchment into sub-catchments, each with relatively homogenous soil/ land cover conditions.
- Many different combinations of soil groups and land uses can give the same initial CN and thus, theoretically, respond identically in regard to stormflow generation. Perusal of any given CN (e.g. 70; Table 4.1 Appendix A) would indicate that this assumption intuitively simply cannot hold. Further refinement to the CN concept is thus necessary.

Since stormflow response is highly sensitive to a catchment's wetness (Schulze, 1982), ASM adjustments to CN have serious consequences on the estimates of stormflow Catchment soil moisture conditions are influenced by the properties of the soil, attributes of land use and management and topographical position as well as the regional climatic regime. The next section highlights these major controlling factors, followed by a description of the procedures developed to adjust runoff coefficients (CNs) when using the SCS model.

3.2 Adjustment of Curve Numbers to Antecedent Soil Moisture

3.2.1 The Need for Curve Number Adjustment

The soil moisture status prior to a stormflow producing event is the second major factor, after rainfall, affecting the stormflow response depth (Schulze, 1982). It is hydrologically intuitive that two identical rainfall events occurring on two catchments identical in every respect, except that one is initially wet and the other dry, are likely to produce stormflow events with different hydrograph characteristics because they display different pre-event CNs (Dunsmore, 1985). In testing the sensitivity of the SCS procedure to CNs, Hawkins (1979) concluded that the calculated stormflow volume was more sensitive to adjustments of CN than to inaccurate estimates of rainfall, for the rainfall up to ~230mm. According to Schmidt and Schulze (1987), the initial CNs listed in the SCS literature (e.g. Table 4.1 in Appendix A) for different soil groups and land use classes (as well as their treatment), which assume so-called "average" (NEH-4, 1972) or "initial" (Schulze *et al.,* 1992) ASM conditions, have to be adjusted for catchments which display dissimilar soil moisture regimes between storms on the same catchment, if ASM deviates from the so-called "average".

3.2.2 Major Factors Affecting Catchment Soil Moisture Variation

The potential for stormflow generation varies both temporally and spatially. Reynolds (1970) suggested that the main causes of the soil moisture variability could be divided into two broad groups. These are the static, or slowly changing, factors (e.g. state of vegetation) and the dynamic, or more rapidly changing, factors (e.g. ASM). These groups are not mutually exclusive and some factors may change groups when certain environmental conditions prevail.

The major dynamic storage component of a catchment is the soil matrix. Most of the discussion in this section thus relates to the variability of soil moisture. The temporal changes in soil moisture are governed by the sequence of inputs (rainfall) into, and outputs (stormflow, deep drainage, evapotranspiration) from, a catchment. Every phase of the hydrological cycle may give rise to spatial variations in catchment soil moisture status. However, it is possible to identify the major components governing this variability within the catchment system, assuming the rainfall distribution to be uniform. Research findings generally attribute spatial differences in a catchment's soil moisture status to variations in one or more of the following: regional climate, soil characteristics, land use and its management and topographic position in the landscape (Hope, 1980).

3.2.2.1 Regional climate

As evaporation is influenced strongly by the availability of soil moisture, catchment moisture status is sensitive to the amount of precipitation and insolation that an area receives. In turn, the regional antecedent climate regime controls surface heat and moisture fluxes into the atmosphere. Hope and Schulze (1979) found that soil moisture changes at depth in a soil profile were related to seasonal rather than to individual events. Research conducted by Plaza *et al.* (2000) and Taylor (2000) have also shown that in regions of high rainfall which is evenly distributed throughout the year, variations in soil moisture follow the intensity of solar energy available for evapotranspiration, this energy being a function principally of season. Reynolds (1970) suggested that in areas which have distinct wet and dry periods the variability of soil moisture would probably be at a minimum after an extended dry period, when the effects of soil heterogeneity on infiltration and the moisture held in the soil will be at a minimum, while the variability would be considerable after a rainfall event.

3.2.2.2 Soil characteristics

In estimation of flood volumes and peaks a vital role is played by the soil, for it is the soil that has the capacity to absorb, retain and release water (Schulze *et al.*, 1992). Pronounced differences in magnitude and sequence of hydrological processes have been observed in the soil units within a catchment (Schmidt and Schulze, 1987). According to Schulze *et al.* (1985), the limiting properties of the soil which affect moisture variation in a soil profile are:

- the infiltration rate at which water enters the soil at the surface, and which is controlled by surface conditions;
- the permeability rate at which water moves through the soil, and which is controlled by properties of the soil horizons; and
- the water storage capacity, which is dependent primarily on the soil's texture and its depth.

The temporal variations of soil moisture at different depths in the soil profile are controlled by different mechanisms. Merz and Plate (1997) assert that spatial variability of soil moisture is governed essentially by the pore size distribution within a soil, with the larger non-capillary pores (macropores) contributing to increasing infiltration, while the smaller capillary and sub-capillary pores determine the water holding characteristics of soils. Beven and Germann (1982) also proposed that it was important to distinguish between micropore (or matrix) flow and macropore flow. The macropore flow is governed by gravity, and effects of capillarity can be neglected. This can lead to the high infiltration and redistribution rates observed in nature, which cannot be explained by the matrix conductivity only. At low rainfall intensities, all water infiltrates into the soil matrix. At rates higher than the matrix infiltration capacity, macropore infiltration may start. Ponding on the surface occurs when the rainfall rate is higher than the sum of matrix and macropore infiltration (Merz and Bardossy, 1998). However, Rawlins *et al.* (1997), using a range of approaches, found that macropores contributed little to flow through a forest soil. Many researchers consider soil texture, structure and organic matter content to be the major determinants of the moisture characteristics of a soil (e.g. Schulze *et al.,* 1985). Hardening of the B-horizon, surface sealing and leaching also restrict the movement of water into the soil profile and may provide a large proportion of the stormflow response (Schmidt and Schulze, 1987).

3.2.2.3 Land use and management

The primary catchment cover which can comprise a range of annual and perennial crops, grassland and/or forest can affect the distribution of soil moisture by variations in the interception, infiltration and evapotranspiration characteristics of various types of vegetation (Schulze *et al.*, 1992). According to Hope (1980), interception is particularly important in regions of low rainfall intensity, low biomass cover and/or where rainfall events are of short duration. However, interception is generally of less importance than the effect a vegetation's biomass has on infiltration and evapotranspiration rates. Hope and Schulze (1979) found experimentally that soils in the forested areas of a catchment dried faster compared to those under grassland, particularly at soil depths exceeding 100 mm, where deeper tree rooting was most active. Roberts (2000) showed that soil water uptake by plants is strongly determined by physiological control of water loss through a combination of fluctuations in stomatal conductance and the amount of foliage. Understanding the physiological control of transpiration by plants within and between ecosystems is key to understanding their hydrological functioning.

Tillage practices modify surface-soil physical and hydraulic properties by increasing surface porosity and roughness (Schulze, 1995a). As a result, less stormflow occurs from rougher tilled surfaces than from smoother, but also bare, surfaces. The retention of water between clods on rough surfaces contributes to the high depths of water ponding in depressions, which produce longer detention times and greater hydraulic gradients (Freebairn *et al.*, 1989). However, tillage can also create surface conditions conductive to runoff (Burk *et al.*, 1998). This finding was substantiated by Freebairn *et al.* (1989) in a cultivated silt loam soil which resulted in an increase of runoff as a result of surface sealing and a lack of crop residue. Operations performed when replacing subsoil and topsoil in reclaimed lands generally cause soil compaction which could reduce infiltration, increase runoff and restrict rooting depth which, in turn, would decrease soil water content (Burk *et al.*, 1998).

3.2.2.4 Topographic position in the landscape

The research conducted in the UK by Beven (1979) indicated that soil moisture variations within a catchment are related to topographic position in the landscape. He found that the influence of topography leads to a higher initial soil moisture content within the soil at the base of the concave slope. He noted that in areas where topographical controls are important, one method of distinguishing soil moisture over space is the topographical wetness index. Hope and Schulze (1979) also observed in the Cedara research catchment in South Africa that soil moisture accumulates in the lower slopes and is also supplied from upslope there for a longer periods than in upper slopes.

Topography is also a major controlling factor of subsurface flows. Different wetness indices need to be used, depending on dominant processes. However, recent hillslope analyses of soil moisture distributions have identified that flow paths do not necessarily follow surface topography. This was confirmed by Freer *et al.* (1997) in Maimai (New Zealand) and Panola (USA), where bedrock surface is distinctly different from surficial topography. Aspect, i.e. warm versus cool facing slopes, can also have a marked influence on soil moisture, particularly at soil depths shallower than 0.5 m (Hope and Schulze, 1979).

Adjusting initial CNs to be more representative of conditions prior to flood producing rainfall events will, therefore, ideally have to consider all the above-mentioned controlling factors in order to estimate the incoming and outgoing water fluxes in the soil profile.

3.3 Methods of Curve Number Adjustment

Various procedures have been developed to adjust runoff response for soil moisture status, ranging from simple empirical methods to more complex soil moisture budgeting routines. These procedures are concerned mainly with monitoring the change in a catchment's soil moisture status over time.

For the SCS method, the original SCS-AMC classes, the Hawkins (1978) water budgeting procedure, and the SCS-*ACRU* soil water budgeting procedures (Schmidt and Schulze, 1987) have been developed to account for varying ASM conditions. These methods are overviewed in the sub-sections which follow.

3.3.1 The Original SCS-AMC Classes

In the original SCS method (NEH-4, 1972) three antecedent moisture classes (AMC) were described in terms of their stormflow potential. These are:

AMC-I : Dry antecedent conditions are found, the stormflow potential from which is low. The catchment soils are dry enough for ploughing or cultivation to take place.

AMC-II : The so-called "average" antecedent soil moisture conditions prevail.

AMC-III : Wet conditions prevail. Catchments display high stormflow potential. Soils of the catchment are close to being saturated from antecedent rains.

The antecedent soil moisture conditions are estimated from the five-day accumulated antecedent rainfall, i.e. the total of the rain in the five days preceding the stormflow event under consideration (Table 3.1). Chow *et al.* (1988) developed the following algebraic expressions (Equations 3.5 and 3.6) to compute equivalent CNs from the so-called "average" conditions (CN_{II}) for dry (CN_I) and wet (CN_{III}) conditions:

$$CN_I = \frac{4.2CN_{II}}{(10 - 0.058CN_{II})} \qquad 3.5$$

$$CN_{III} = \frac{23CN_{II}}{(10 + 0.13CN_{II})} \quad 3.6$$

Table 3.1 Antecedent rainfall limits for classifying antecedent moisture conditions (after NEH-4, 1972)

AMC Class	Accumulated 5-day antecedent rainfall (mm)	
	Dormant season	Growing season
AMC-I Dry	Less than 12	Less than 36
AMC-II Average	12 to 28	36 to 53
AMC-III Wet	Over 28	Over 53

Major weaknesses in the above AMC procedure are described pertinently by Hawkins (1978). First, in assigning the AMC, evapotranspiration is considered only in very gross terms (i.e. "dormant" vs "growing" season). Secondly, the relationship between AMC and CNs is shown to be discrete and not continuous, implying sudden shifts in CNs, with corresponding "quantum jumps" possible in calculated stormflow. Thirdly, the consideration of antecedent rainfall over five days may be too short or long a period depending on land use/soil characteristics and prevailing climate (Schulze, 1984). In addition, the net amount of rainfall entering the soil is not considered. Hjelmfelt (1991) also pointed out that in defining the AMC-II as "the average condition", it is not clear if this is to be a qualitative or quantitative definition, since "average" in one climatic region may not be "average" in another.

Many researches have attempted to improve the original SCS-AMC procedure. Among the most significant and direct attempts at developing an improved procedure for estimating ASM for application in the SCS model were probably made by Hawkins (1978) and by the soil water budgeting simulations of ASM with the daily time step *ACRU* model (Schulze, 1984; Schmidt *et al.*, 1986; Schmidt and Schulze, 1987).

3.3.2 Curve Number Adjustment using Hawkins' Water Budgeting Procedure

Having recognised the weaknesses of the ASM component of the original SCS model, Hawkins (1978) developed an alternative method which included consideration of antecedent stormflow, drainage and evapotranspiration in addition to rainfall, and expressed the relationship between CNs and ASM as a continuum rather than as the discrete classes used in the original SCS procedure. The following principle was incorporated to calculate a final CN from the CN for "average", or "initial", ASM conditions using a water budgeting approach (Hawkins, 1978):

$$V_2 = V_1 - E - D + P - Q \qquad 3.7$$

where

V_2	=	storage in the soil (mm) available at time 2,
V_1	=	storage in the soil (mm) available at time 1,
E	=	interim evapotranspiration losses (mm),
D	=	interim drainage losses (mm),
P	=	interim rainfall (mm), and
Q	=	interim stormflow (mm).

From this change in soil water status over an interim period, i.e. $V_2 - V_1$, Hawkins then derived an equation for a final CN (Equation 3.8), which in generalised form, but metricated, is:

$$CN_f = \frac{(1+c)*1000}{\frac{(1+c)*1000}{CN_{II}} - \frac{(P-Q-D-E)}{25.4}} = \frac{(1+c)*1000}{\frac{(1+c)*1000}{CN_{II}} - \frac{\Delta S}{25.4}} \qquad 3.8$$

where

CN_f	=	final Curve Number calculated for prevailing moisture status at the end of the interim period,
CN_{II}	=	initial Curve Number
c	=	coefficient of initial abstraction,
P	=	rainfall (mm) in the interim period,
Q	=	stormflow (mm) in the interim period,
D	=	drainage (mm) in the interim period,
E	=	actual evapotranspiration (mm) in the interim period, and
ΔS	=	change in soil water status (mm) in the interim period, i.e. *P-Q-D-E*.

The Hawkins approach to adjust *CN* for soil moisture status has been shown to give significantly improved estimates of stormflow volumes from experimental catchments under widely ranging environmental conditions when compared with estimates using the original SCS-AMC procedures (Arnold, 1980; Hope, 1980; Schulze, 1984).

3.3.3 The SCS-*ACRU* Procedures to Account for Antecedent Soil Moisture

The SCS-*ACRU* procedures are conceptual approaches by which a catchment's antecedent soil moisture changes from initial values are computed with the *ACRU* model. The *ACRU* agrohydrological modelling system was developed around the following basic aims (Schulze, 1984; 1995a):

- It is a *physical conceptual* model; physical in that physical processes are represented explicitly and conceptual in that it conceives of a system in which important processes are idealised.
- It is a *daily time step* model and uses daily input of climatic data. Certain more cyclic and less sensitive variables (e.g. temperature), for which values may have to be input at monthly level (if daily values are not available), are transformed internally in *ACRU* to daily values by Fourier Analysis.
- It is a *two layer soil water budgeting* model which has been structured to be sensitive to climate and land use changes on soil water, actual evapotranspiration rates and runoff regimes (both stormflow and baseflow).
- It is a *multi-purpose* model which integrates the various water budgeting and runoff producing components of the terrestrial hydrological system with risk analysis and can be employed in design hydrology, crop yield modelling, reservoir yield simulation, irrigation water demand/supply, salinity simulation and regional water resources assessment.
- It is a *multi-level* model, with either multiple options or alternative pathways available in many of its routines, depending on the level of input data available and detail output required.
- *ACRU* is not a parameter fitting or optimising model; parameters are estimated from physical characteristics of the catchment.
- *ACRU* can operate as a *point* or *lumped* model. However, for large catchments or in areas of complex land uses and soils *ACRU* can operate as a *semi-distributed* model.

A summary of the concepts of the *ACRU* model in terms of inputs, operational modes, simulation options and objectives is given in Figure 3.2. Figure 3.3 represents a schematic of the multi-layer soil water budgeting by partitioning and redistribution of soil water in the *ACRU* model. The model has been verified on a catchments in South Africa, Germany, the USA and Zimbabwe as reviewed by Schulze and Smithers (2004).

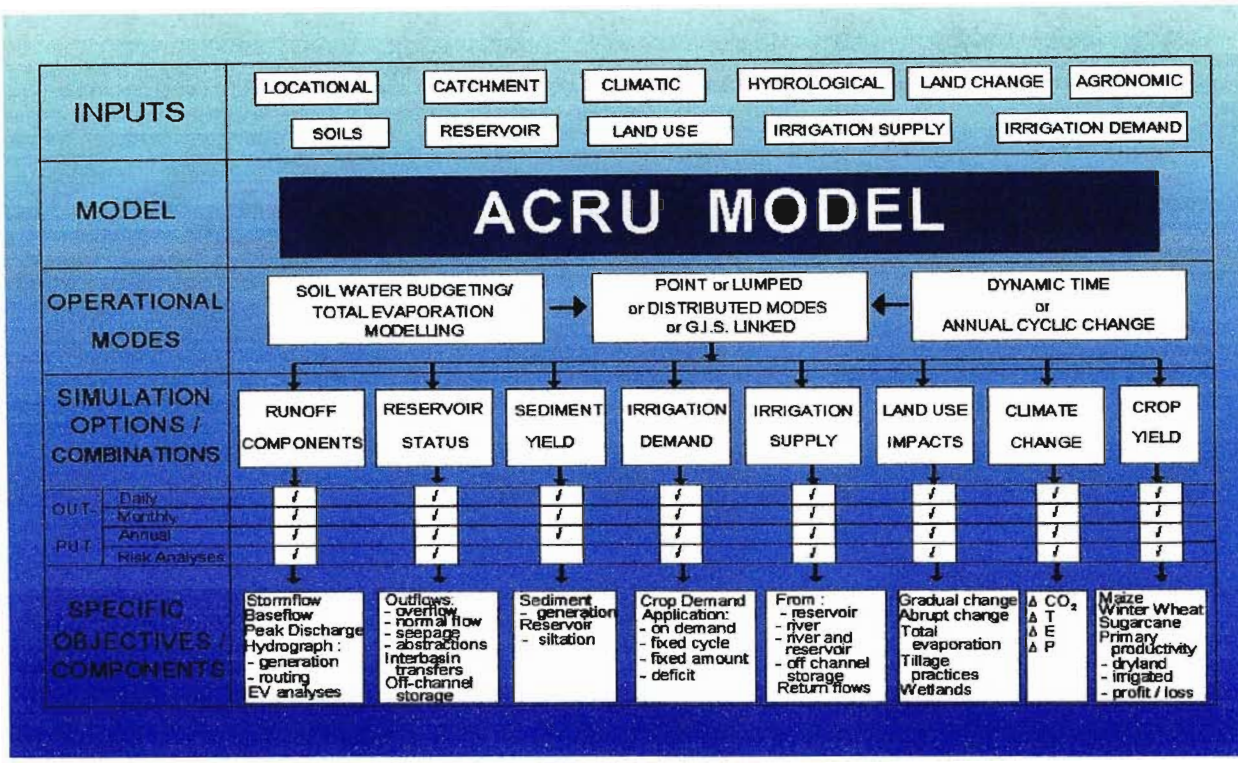


Figure 3.2 The *ACRU* agrohydrological modelling system: Concepts (after Schulze, 1995a)

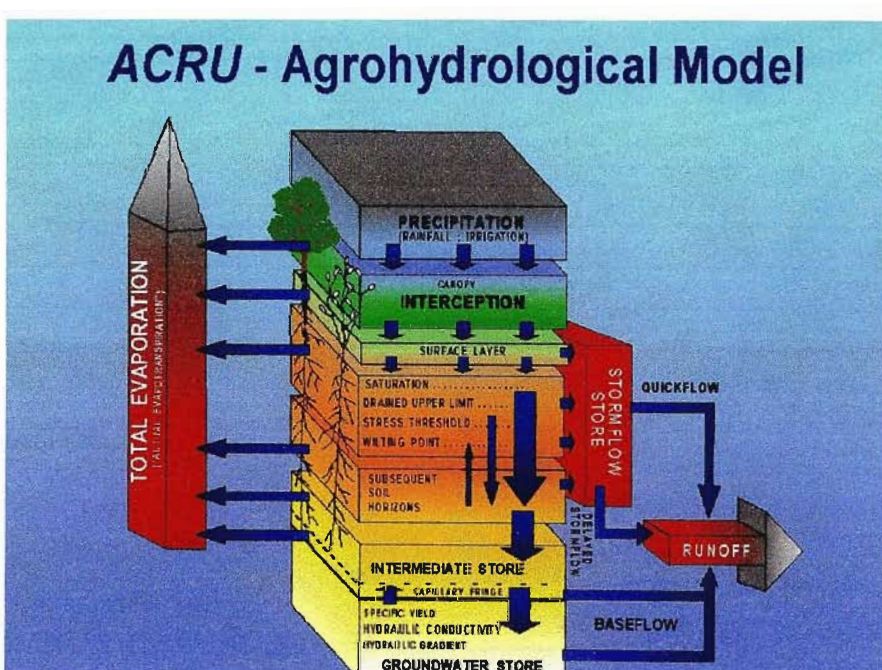


Figure 3.3 The *ACRU* agrohydrological modelling system: General structure (after Schulze, 1995a)

The *ACRU* model simulates those components and processes of the hydrological cycle which affect the soil water budget and can output any of these components on a daily basis, or as monthly and annual totals of the daily values (Figure 3.2; Schulze, 1995a).

In its application for determining the change in soil moisture storage *(ΔS)* for use in the SCS technique, two options are available to account for typical soil moisture conditions prior to design events, *viz.* the *Median Condition Method* and the *Joint Association Method.*

In the *Median Condition Method* (Schmidt and Schulze, 1987), initial soil water content was set equal to 50% plant available moisture *(PAM)* to comply with assumptions adopted in the SCS model, *viz.* that the initial CN (CN_{II}) was representative of so-called "average" moisture conditions. The *ACRU* model was then used to compute ΔS as the difference between prevailing soil water status immediately prior to a stormflow producing rainfall event and initial soil moisture conditions (for which the so-called "average" CN_{II} was considered to be representative). The median, i.e. 50th percentile, condition of ΔS is then calculated from a long term (say 30 year) daily record and this statistically expected ΔS is then used in Hawkins' equation (Equation 3.8) to compute the final CN (CN_f). Results from gauged catchments have indicted the model to provide better estimates of soil water status and event responses for an assumed initial moisture status of 50% *PAM* when it used with a 30-day antecedent period, as against a shorter antecedent period (Schulze, 1984).

In the *Joint Association Method* (Schmidt and Schulze, 1987), the *ACRU* model simulates antecedent actual evapotranspiration, stormflow and drainage for selected soil and land cover combinations, again using a 30-day antecedent period for computing soil moisture conditions prior to a specific event. The computed ΔS is then used directly in Equation 3.8 to adjust a given CN_{II} (Schulze *et al.,* 1992). Daily stormflow depths are computed for each rainfall event after adjusting CN_{II} for prevailing ASM and a frequency analysis of the annual maximum stormflow depths gives approximations of design stormflow depths. This accounting by *ACRU* for the variation of the ASM between storms falling on a catchment implies that rainfall of a given return period does not necessarily generate stormflow of equal return period, since a lesser rainfall event falling on a wet catchment could result in a bigger flood than a larger event falling on a dry catchment (Schmidt *et al.,* 1986).

The outputs of the SCS-*ACRU* moisture budgeting procedure (both the *Median Condition* and *Joint Association*) have been verified under highly varying climatic regimes on gauged catchments in South Africa and the USA (Schulze, 1984; 1989). Dunsmore (1985) and Schmidt *et al.* (1986) had previously concluded that simulating a flood of a given return period from the same return period of rainfall does not provide the hydrologist with a sound basis for analysis of design events from small catchments. It is clear that regional relationships between antecedent moisture condition and design rainfall depths are required for accurate stormflow estimations in hydrologically heterogeneous regions such as Eritrea. Both the *Median Condition Method* and *Joint Association Method* are frequently used in applied design practice in southern Africa owing to the scarcity of any other information on associations between "extreme event" rainfall and corresponding catchment ASM (Schmidt *et al.*, 1986, Schulze *et al.*, 1992).

* * * * * *

So far in this chapter an attempt has been made to review the SCS stormflow approach and its components, followed by the description of the original SCS, the Hawkins and SCS-*ACRU* approaches to adjustment of CNs to ASM for stormflow modelling.

The next question that arises is to how to adapt some of these modelling approaches to be suitable for wider application in Eritrea. Determination of one day rainfall depth can be computed from the rainfall data available throughout most of the country and CN_{II} can be obtained from field observation of soil properties, land uses and their treatment. The problem then arises how to estimate the ΔS required for adjustment of CN_{II} when using soil water budgeting procedures. As was mentioned in the introductory chapter, the main problem arises from limitations of long, adequate and accurate hydrological information needed to simulate ΔS prior to flood producing rainfall events. In the next chapter, the possibility of using standardised climate classification systems for estimation of regional indices of ΔS for adjustment of CNs are discussed as a possible solution to overcoming data limitations in developing countries. The Köppen climate classification, which has been tested in southern Africa with the 712 relatively homogeneous hydrological zones identified there, is eventually selected as the preferred climate classification.

4. THE KÖPPEN CLIMATE CLASSIFICATION SYSTEM AS AN INDICATOR OF REGIONAL INDICES OF CHANGES IN SOIL MOISTURE STORAGE

4.1 Introduction

Many researchers have demonstrated that procedures to adjust event-based runoff response coefficients according to a soil water budget provides more realistic estimates of stormflow and peak discharge distributions than when using only accumulated antecedent rainfall depths (e.g. Hawkins, 1978; Schulze, 1984; Dunsmore, 1985; Schmidt *et al.*, 1986; Schmidt and Schulze, 1987). The soil water budget at a particular place or over a geographic area consists of daily moisture inflows, outflows and changes in storages. Most of the factors that affect the soil water budget, *viz.* precipitation, evapotranspiration, moisture storage in the soil, stormflow losses and the movement of water through the root zone within the soil profile are either implicit climatic parameters or are related to them explicitly.

According to Mather (1978), the climatic water budget, can be a monthly, weekly or daily budget of water supply (precipitation) and climatic demands for water (evapotranspiration). Whenever precipitation exceeds the climatic demand for water, the soil moisture storage will increase, and a soil water surplus may develop. If it does, then percolation takes place and the groundwater table may rise, perhaps resulting in increased total runoff from the area. When climatic demands for water are greater than precipitation, soil moisture storage will be depleted, a deficit of water in the soil may develop and the water table may drop (Thornthwaite and Mather, 1955). The above scenarios imply that the soil water status will vary markedly from one region to another, and in one region also within a season, depending not only on amounts of precipitation, but also on energy related prevailing local climatic regimes which can affect the climatic water budget. This was confirmed by Schmidt and Schulze (1989) in a frequency analysis of changes in soil moisture storage *(ΔS)* undertaken by simulations with the *ACRU* model for each of the 712 hydrologically homogenous zones delimited for southern Africa. They found, for example, that a zone with a mean annual precipitation (MAP) of 472 mm could display a higher average soil water status prior to potential flood producing rains than another zone with MAP 684 mm, owing to the occurrence of winter rains associated with low evaporation rates in the first zone and summer rains, with high evaporation rates during the rainy season, in the second. This illustrates, *inter alia,* that the role of rainfall seasonality is crucial when evaluating regional soil water status.

The aim of this chapter is, therefore, to approach the soil water status of a catchment as a climatologically driven variable, based upon the hypotheses outlined in the introductory chapter. If the approach is shown to be successful, the aim is to transfer values of ΔS from southern Africa to Eritrea (and other regions with limited hydrological information), where similar climate systems are known to occur.

4.2 Climate Classification Systems

Climatic controls interact to produce such a wide array of different climates, such that no two places experience identical climates. However, the similarity of climates within a given area allows the earth to be divided into climatic regions (Ahrens, 1994). Much recent work in physical geography has been concerned with understanding the interactions of the various systems and subsystems that makes up our environment. Various methods of dividing the earth into climatic types have been developed. These are based on, *inter alia,* rainfall, temperature, wind, latitude and the distribution of vegetation (Blair, 1951). The ancient Greeks, for example, categorised the world into three climatic regions (Ahrens, 1994):

- *a low latitude (*or *"torrid") zone*, bounded by northern and southern limit of the sun's vertical rays (~23.5^0 N and 23.5^0 S) and in which the noon sun is always high, day and night are of nearly equal length, and it is relatively warm throughout the year;
- *a high latitude polar (*or *"frigid") zone*, bounded respectively by the Arctic or Antarctic circle, this being a zone which is cold all year long owing to long periods of winter darkness and a low summer sun; and
- *a temperate zone*, sandwiched between the other two zones and which has distinct summer and winter seasons and, therefore, has characteristics of both extremes.

Such a sunshine and temperature-based climatic scheme is, however, far too simplistic a classification for it excludes precipitation and there is therefore no way of distinguishing between wet and dry regions. In general, the best classification of climates would take into account as many meteorological factors as can possibly be obtained (Ahrens, 1994). This chapter reviews three of the widely used classification systems of world climates that express the input of moisture, its storage in the system and moisture output by evapotranspiration. These three are the Köppen, Thornthwaite and FAO climate classification systems.

4.2.1 Köppen's Classification System

The Köppen (1931) system is a widely used and probably the best known classification of world climates. It is based on critical thresholds of annual and monthly averages of temperature and precipitation (Köppen, 1931). Faced with the lack of adequate observing stations throughout the world, Köppen (1931) related the distribution and type of native vegetation to the various climates he classified. In this way climatic boundaries could be approximated where no climatological data were available (Mather, 1978).

Köppen (1931) recognised that the effectiveness of precipitation upon plant development and growth depends not only upon the amount of precipitation, but also upon the intensity of evaporation which causes losses of water from soil and plants. Thus, the same amount of rain falling in a hot climate, or concentrated in a hot season when evaporation rates are high, is less effective for plants (and by implication, runoff generation) than the same amount falling in a cooler climate (Trewartha, 1954). Köppen employed five major climatic types, each type being designated by a capital letter. Each group contains sub-regions which describe special regional characteristics, such as seasonal changes in temperature and precipitation, as given in Table 4.1 of this chapter.

In mountainous areas, where rapid changes in elevation bring about sharp changes in climatic types, delineating the climatic regions by the Köppen system is impossible. Such regions are designated by the letter *H*, for highland climates (Ahrens, 1994).

Some of the limitations of this classification for potential use in disaggregating a region into homogenous response zones are that the boundaries which relate vegetation to monthly temperature and precipitation values do not always correspond with the natural boundaries of individual climatic zones. In addition, the Köppen (1931) system has been often criticised for its empirical approach, implying a sharp boundary between climatic zones when in reality there is a gradual transition between one climate type and another (Ahrens, 1994). Moreover, the boundaries are subjected to checking and revision as new climate data become available (Thornthwaite and Mather, 1955).

Table 4.1 Major Köppen (1931) climate classes and their detailed climatic characteristics (after Ahrens, 1994)

Table of Köppen's Climatic Classification System				
Letter symbol			Climate characteristics	Criteria
1	2	3		
A	-	-	Humid tropical	All months have an average temperature >18°C
	f	-	Tropical wet (rain forest)	Wet all seasons; all months have at least 60 mm of rainfall
	w	-	Tropical wet and dry (savanna)	Winter dry season; rainfall in driest month is < 60 mm and < than 100P/25
	m	-	Tropical monsoon	Short dry season; rainfall in driest month is < 60 mm but equal to or > 100P/25
B	-	-	Dry	P<20(t+14) when 70% or more of rain falls in warmer 6 months (dry winter) P<20t when 70% or more of rain falls in cooler 6 months (dry summer) P<20(t+7) when neither half of the year has 70% or more of the annual rain
	S	-	Semi-arid (steppe)	10(t+14) < P<20(t+14) when 70% or more of rain falls in warmer 6 months (dry winter) 10t <P< 20t when 70% or more of rain falls in cooler 6 months (dry summer) 10(t+7) <P <20(t+7) when neither half of the year has 70% or more of the annual rain
	W	-	Arid (desert)	P <10(t+14) when 70% or more of rain falls in warmer 6 months (dry winter) P< 10t when 70% or more of rain falls in warmer 6 months (dry winter) P <10(t+7) when neither half year has 70% or more of the annual rain
	-	h	Hot and dry	Mean annual temperature is 18°C or higher
	-	k	Cool and dry	Mean annual temperature is below 18°C
C	-	-	Moist with mild winters	Average temperature of coolest month is < 18°C and > -3°C
	w	-	Dry winters	Average rainfall of wettest month at least 10 times as much as in driest winter month
	s	-	Dry summers	Average rainfall of wettest winter month at least 3 times as much as in driest summer month
	f	-	Wet all seasons	Criteria for w and s cannot be met
	-	a	Summers long and hot	Average temperature of warmest month > 22°C
	-	b	Summers long and cool	Average temperature of all months < 22°C; at least 4 months with average > 10°C
	-	c	Summers short and cool	Average temperature of all months < 22°C; 1 - 3 months with average > 10°C
D	-	-	Moist with cold winters	Average temperature of coldest month is < -3°C; average temp of warmest month is > 10°C
	w	-	Dry winters	Same as under Cw
	s	-	Dry summers	Same as under Cs
	f	-	Wet at all seasons	Same as under Cf
	-	a	Summers long and hot	Same as under Cfa
	-	b	Summers long and cool	Same as under Cfb
	-	c	Summers short and cool	Same as under Cfc
	-	d	Summers short and cool; Winters severe	Average temperature of coldest month is < -3°C and warmest month >10°C
E	-	-	Polar climates	Average temperature of warmest month is <10°C
	T	-	Tundra	Average temperature of warmest month is >0°C but < 10°C
	F	-	Ice cap	Average temperature of warmest month is 0°C or below

"P" is the mean annual precipitation (mm) and "t" the mean annual temperature (°C)

The Köppen system has been revised several times, most notably by the German climatologist Geiger (1951), who worked with Köppen on amending the climatic boundaries of certain regions. A popular modification of the Köppen system was developed by the American climatologist Trewartha (1954), who redefined some of the climatic types and altered the climatic map of the world by placing more emphasis on the lengths of growing seasons and average summer temperatures (Ahrens, 1994).

4.2.2 Thornthwaite's Classification System

Thornthwaite devised a new classification system to correct some of the deficiencies in the Köppen system (Thornthwaite, 1948; Ahrens, 1994). Both systems utilise temperature and precipitation measurements and both relate natural vegetation to climate. However, to emphasise the importance of precipitation (P) and evaporation (E) on plant growth, Thornthwaite developed a P/E ratio, which is essentially monthly precipitation divided by monthly potential evaporation. The annual sum of the (P/E) ratios multiplied by 100 gives the Moisture index (Ahrens, 1994). Using this index, the Thornthwaite system defines five major humidity provinces and their characteristic vegetation (Table 4.2).

Table 4.2 Humidity provinces according to the Thornthwaite (1948) system of climate classification (after Trewartha, 1954)

Humidity Province	Characteristic Vegetation	Moisture index
A : Wet	Rainforest	≥ 128
B : Humid	Forest	64-127
C : Sub-humid	Grassland	32-63
D : Semi-arid	Steppe	16-31
E : Arid	Desert	<16

The five principal humidity provinces (Table 4.2) are subdivided into four sub-types based upon seasonal concentration of precipitation:

r = rainfall abundant at all seasons,

s = rainfall deficient in summer,

w = rainfall deficient in winter, and

d = rainfall deficient in all seasons.

Thornthwaite also identified six temperature provinces based upon Thermal Efficiency Index (the ratio of temperature (T) to evaporation (E) multiplied by 100), as shown in Table 4.3.

Table 4.3 Temperature provinces according to the Thornthwaite (1948) climate classification system (after Trewartha, 1954)

Temperature province	Thermal Efficiency Index
A' : Tropical	≥ 128
B' : Mesothermal	64 - 127
C' : Microthermal	32 - 63
D' : Taiga	16 - 31
E' : Tundra	1 - 15
F' : Frost	0

To better describe the moisture available for the plant, Thornthwaite proposed a new classification system in 1948 and improved it slightly in 1955 (Thornthwaite and Mather, 1955). This new scheme emphasised the concept of potential evapotranspiration (PE), which is the amount of moisture that would be lost from the soil and vegetation if an adequate supply of soil moisture were available. He incorporated potential evapotranspiration into a moisture index that depends essentially on the differences between precipitation and evapotranspiration. The index is high in moist climates and negative in arid climates. An index of 0 marks the boundary between wet and dry climates (Ahrens, 1994). The temperature and humidity provinces are illustrated in Figure 4.1.

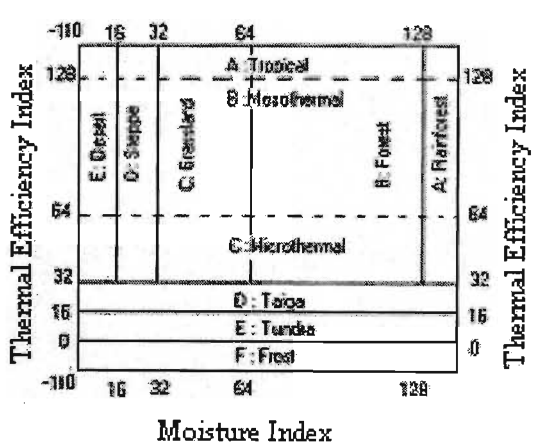


Figure 4.1 Temperature and humidity provinces according to the Thornthwaite (1948) climate classification system (after Trewartha, 1954)

Theoretically the Thornthwaite classification system may be a somewhat more refined method for disaggregating a region into relatively homogenous climate zones than that employed by the Köppen system, since evapotranspiration, one of the major variables in the soil water balance, is considered explicitly. However, in practice it is not so satisfactory since actual evaporation data are available for only very limited areas. As a result, the Thornthwaite system can potentially only be useful for disaggregation of homogenous hydrological zones in regions with adequate data on evaporation. According to Thornthwaite and Mather (1955), the moisture index employed for the climate classification indicates merely how humid or arid a given climate is, but it cannot distinguish seasonal variations within a given climate zone. Moreover, this system also requires revisions when new climate data become available. Like the Köppen system, the Thornthwaite system also implies sharp boundaries between climate zones (Thornthwaite and Mather, 1955).

4.2.3 FAO Agro-Ecological Zones (AEZ)

The Food and Agriculture Organization (FAO) of the United Nations, in collaboration with the International Institute for Applied Systems Analysis in Austria, has developed a system that enables rational land use planning on the basis of an inventory of land resources and the evaluation of biophysical limitations and potentials. This is referred to as the Agro-Ecological Zones (AEZ) methodology (FAO, 2002).

The AEZ methodology utilises a land resources inventory to assess, for specified management conditions and levels of inputs, all feasible agricultural land use options and to quantify expected production of cropping activities relevant in the specific agro-ecological context (FAO, 1996). The characterisation of land resources includes components of climate, soils and landform, which are basic for the supply of water, energy, nutrients and physical support to plants. Each zone is further divided into areas of relatively uniform climate, called agro-ecological units. A sub-zone boundary occurs when a different plant association occurs on zonal sites. The AEZ classification provides a "regional" level of ecological integration (FAO, 1996; FAO, 2002).

According to FAO (2002), the AEZ framework, in its simplest form, contains three basic elements:

- selected agricultural production systems with defined input and management relationships, and crop-specific environmental requirements and adaptability characteristics, which are termed Land Utilization Types (LUT);
- geo-referenced climate, soil and terrain data which are combined into a land resources database; and
- procedures for the calculation of potential yield and for matching crop/LUT environmental requirements with the respective environmental characteristics captured in the land resources database, by land unit and grid-cell.

The AEZ approach uses a detailed, spatially explicit methodology that is closely linked to established agronomic concepts, such as the length of growing period concept. It is also based on widely available soil, terrain and climate databases (FAO, 2002). In addition to that the AEZ approach, unlike the Köppen and Thornthwaite classification systems, employs a detailed set of climate indicators which include monthly precipitation, minimum/maximum temperature, relative humidity, sunshine fraction and wind speed, to calculate a crop-specific potential reference evapotranspiration.

The AEZ method is also capable of disaggregating a region into relatively homogenous hydrological response zones, as it utilises factors derived from moisture and energy budgets to achieve a more rational understanding of the distribution of climate and the seasonal changes in soil water status of the soil profile, even though its basic principle is to assess crop adaptability quantitatively.

4.3 Selection of a Climate Classification System

In the above section procedures and inputs required, as well as the limitations, of three standard climate classification systems for potential use in hydrological zonation were reviewed. The merits of their applicability are subjective, but depend upon their simplicity, the levels of input required, the levels input available in a region and the accuracy desired.

Many developing countries have been adopting the methodology of AEZ at national, district and sub-district levels (FAO, 1996), rather than the other climate classification systems. Despite its agronomic basis, the AEZ could be adopted for use as a methodology to disaggregate a region into relatively homogenous response zones for adjustment of runoff coefficients, owing to its wide application in developing countries and its consideration of detailed climate indicators and other land resources input.

The Thornthwaite system expresses the inputs, storage and outputs of water into the soil. This can adequately represent the surplus and deficit of soil moisture, but its application is limited as a result of a lack of evaporation data in many regions. The Köppen system is well known and widely used all over the world. It can be supported as a methodology to define hydrological zones in less developed countries because of its simplicity and low input data requirements. The selection of any particular system, therefore, should be seen from the above points of view.

The Köppen climate classification system was selected for this study because of its relative simplicity when compared to the Thornthwaite and FAO agro-ecological climate classification systems, as well as because spatially detailed monthly and annual rainfall and temperature information is available for Eritrea.

What follows below is an application of the Köppen climate classification system to the 712 relatively homogeneous zones which have been identified in southern Africa by Dent *et al.* (1988), in order to assess whether, within each Köppen climate zone in southern Africa, unique relationships exist between ΔS and a simple climatic variable, *viz.* Mean Annual Precipitation (MAP). If such relationships exist it is hypothesised that they could be transferred to corresponding Köppen climate zones in Eritrea.

4.4 Application of the Köppen Climate Classification System to 712 Relatively Homogeneous Hydrological Zones in Southern Africa

The sections below, which outline the application of the Köppen climate classification system to southern Africa's 712 relatively homogeneous hydrological zones and the analysis of the 712 zones according to each Köppen climate class (KCC), are structured as follows: In Section 4.4.1 the general background of the 712 zones is discussed, as are the procedures used to estimate typical values of ΔS which are required for the adjustment of CN_{II} in southern Africa. Section 4.4.2 the delimitation of the Köppen climate classification for southern Africa is outlined. Sections following that assess the homogeneity of ΔS within a specified KCC, before developing regression equations to estimate ΔS for each KCC identified in southern Africa according to distributions of MAP within each region.

4.4.1 Background to the 712 Relatively Homogeneous Hydrological Zones

The southern African adaptation of the SCS model, first undertaken by Schulze and Arnold (1979), has seen widespread application in estimating stormflow volumes and peak discharges from small catchments, both for design and natural storms. Since 1979, the SCS technique has been used widely by various public authorities and consulting engineers in southern Africa (Schulze *et al.,* 1992). Following the SCS method's initial wide acceptance, considerable research effort was expended in the 1980s on fundamental and applied aspects of the model. This research has been summarised by Schmidt and Schulze (1987).

Design stormflow response for an identical rainfall magnitude depends, *inter alia*, on a catchment's soil water status, S. In southern Africa, Schmidt and Schulze (1987) analysed changes in S, i.e. ΔS, for large storms from the so-called "initial" catchment response conditions based on land use and soils characteristics. The analysis required the disaggregation of southern Africa into zones of relatively homogeneous hydrological response in regard to potential moisture recharge (rainfall) and atmospheric water demand (potential evaporation), based upon long term patterns of rainfall and temperature distributions. In total, 712 such zones were delimited by Dent *et al.* (1988).

Perusal of the tabulated values of CN_{II} given by the SCS (e.g. in NEH-4, 1972; Schmidt and Schulze, 1987), shows that identical CN_{II} values can occur with completely different soil classes, land cover and treatment classes (Schulze *et al.,* 1992; Schulze, 2003). An area covered by small grains, planted on the contour without conservation tillage, for example, has the same CN_{II} as another area dominated by open spaces, parks and cemeteries with a 75% cover of grass. Theoretically, according to the SCS stormflow equation, these two areas would generate identical stormflow magnitudes for identical rainfall events, but in reality they would likely generate different volumes of stormflow because they would display different pre-event ΔSs due to different ASM conditions prior the storm events, despite starting the antecedent period with the same CN_{II}. ASM will be influenced by soil properties, which affect infiltration of rainfall as well as the retention and redistribution of soil water, and also those characteristics of vegetation which affect the drying out of the soil due to evaporation of water from the soil surface and from plant transpiration (Schulze *et al.,* 1992). Three soil depth categories, three soil texture classes and three vegetation classes, as indicated in Table 4.4, are therefore used for the estimation of ASM from a given CN_{II}, resulting in a total of 27 land use/soil combinations covering a wide range of possible hydrological response regimes.

Table 4.4 Soil and vegetation characteristics used in soil moisture budget analysis (after Schmidt and Schulze, 1987)

Soil Thickness Classes (m)			
Category		Thickness of A Horizon	Thickness of B Horizon
Deep		0.30	0.80
Intermediate		0.25	0.50
Shallow		0.15	0.15
Moisture Retention Classes (mm.m^{-1})			
Category	Porosity	Field Capacity	Permanent Wilting Point
Coarse (Sand)	430	112	50
Medium (Loam)	464	251	128
Fine (Clay)	482	416	298
Vegetation Classes			
Category	Fraction of Roots in A-horizon	Interception Loss (mm. rainday^{-1})	Crop Coefficient
Dense	0.60	3.00	1.00
Intermediate	0.80	1.75	0.75
Sparse	1.00	0.50	0.50

Long term (~30 years) daily rainfall and temperature records were used in each of the 712 zones with the *ACRU* model, which was run for each of the 3 soil texture, 3 soil depth and 3 land cover combinations to compute a soil moisture status prior to each stormflow-producing rainfall event. In these model runs daily potential evaporation was calculated by the temperature-driven Linacre (1977) method. This soil moisture status for each of the five highest rainfall events of a year was compared to an initial value of S derived from an initial catchment Curve Number, and the difference was designated ΔS. A frequency analysis of ΔS was undertaken to provide a direct estimate of ΔS for each zone and for each of the 27 soil depth, soil texture and land cover combinations for use in the Hawkins equation (Equation 3.8) of CN adjustment. The results are documented in appendices of Schmidt and Schulze (1987), and the information of these appendices are the basic references for this study.

In what follows, the abbreviation SCSV represents the combination of *S*hallow *C*lay soils with *S*parse *V*egetation, ILAV is an *I*ntermediate depth *L*oamy soil with *A*verage density *V*egetation, while DSDV represents *D*eep *S*ands with *D*ense *V*egetation. These three combinations represent a wide spectrum of hypothetical soil/vegetation combinations. They are used for a computation in each of the 712 zones irrespective of whether the combination would actually be found under natural conditions in a zone.

4.4.2 The Köppen Climate Classification for Southern Africa

The Köppen (1931) climate classification for southern Africa was accomplished by using a spatial resolution of 1' × 1' latitude by longitude grid (i.e. ~ 1.6 × 1.6m) with values of long term monthly means of daily temperature distributions and long term median monthly precipitation, as given in the "South African Atlas of Agrohydrology and –Climatology" (Schulze, 1997). A *FORTRAN* program for identification of the Köppen climate classes using the above databases was written by Maharaj (2003) and is given in Appendix B. Figure 4.2 shows the distribution of Köppen climates overlayed over the 712 relatively homogeneous hydrological zones of southern Africa. For this research, only those homogeneous zones that fell entirely within the same KCC were used for further analysis (Table 4.5). This resulted in 550 of the 712 zones (77%) being used in this study. Moreover, the KCCs *Am, Aw, Cwc* and *ET* were excluded from further analysis as no homogeneous zone within southern Africa fell entirely in these KCCs.

Table 4.5 The selected Köppen climate classes over southern Africa which were used in analyses and their climatic characteristics

Köppen Climate Class	No. of Zones	Climatic Characteristics
BWh	8	Arid, hot and dry
BWk	14	Arid, cool and dry
BSh	38	Semi-arid, hot and dry
BSk	85	Semi-arid, cool and dry
Cfa	20	Wet all seasons, summers long and hot
Cfb	29	Wet all seasons, summers long and cool
Csa	3	Summers long, dry and hot
Csb	20	Summers long, dry and cool
Cwa	130	Winters long, dry and hot
Cwb	203	Winters long, dry and cool
Total	550	

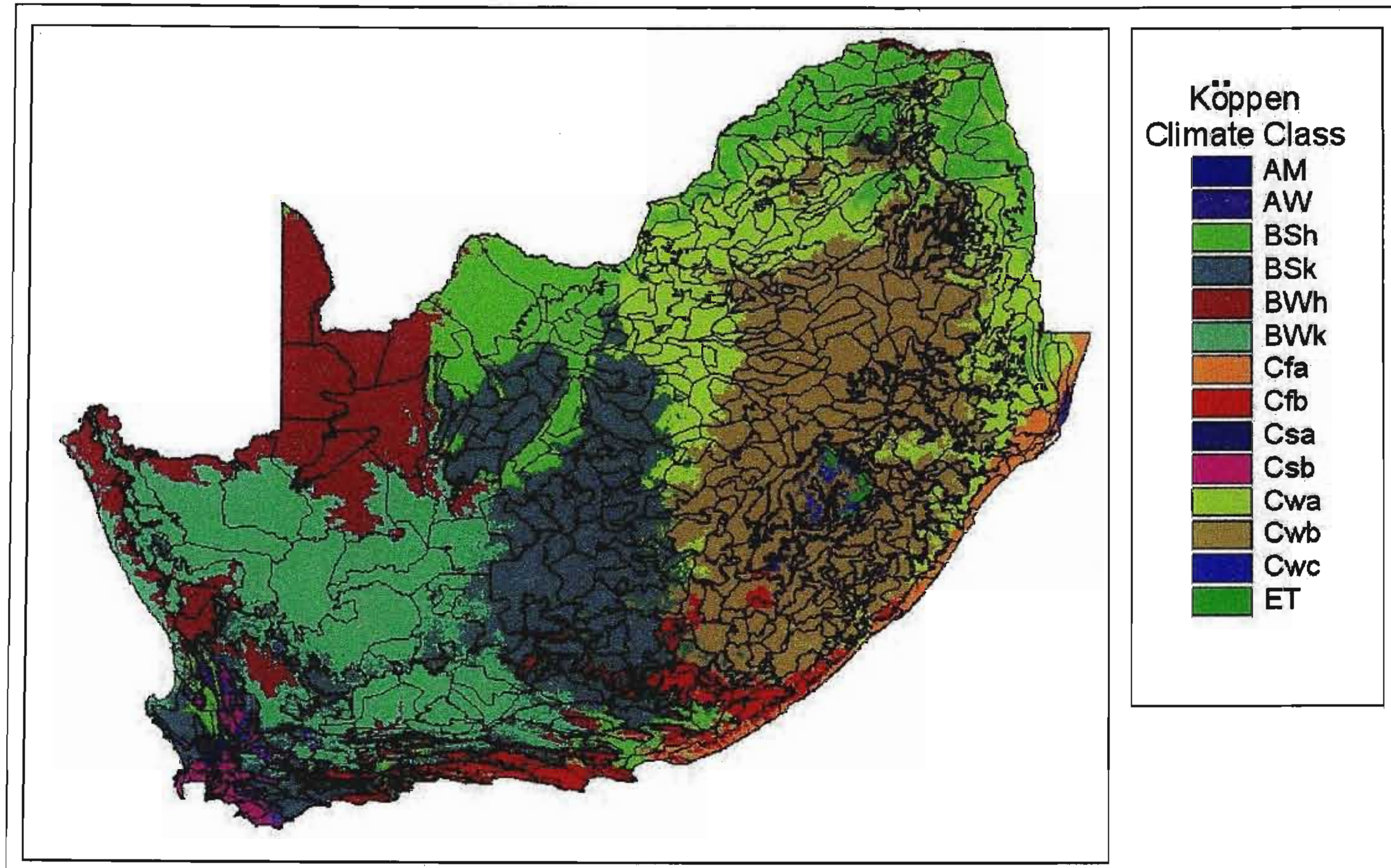


Figure 4.2 Köppen climate classes overlayed over the 712 relatively homogeneous hydrological zones of southern Africa

4.4.3 Analysis of the Variability of Soil Moisture Storage within Each Köppen Climate Class

This section describes the test of the hypothesis that similar KCCs have similar ΔS values prior to storm incidences. A homogeneity, or uniformity, test is a fundamental requirement in order to check if similar KCCs have similar ΔSs and in order to make generalisations on the 712 zones according to the Köppen climate classification system for adjustment of runoff coefficients (CNs). A coefficient of variation, $CV_{\Delta S}$, was determined to check whether uniformity of distribution of ΔS exists among hydrological zones having similar KCCs. An acceptable uniformity of the distribution of ΔS exists when weighted $CV_{\Delta S}$ values are less than double the weighted mean $CV_{\Delta S}$ value of all zones $(\overline{CV})$, i.e. "acceptable uniformity" exists if $CV_{\Delta S} \leq 2\overline{CV}$ (Bezuidenhout, 2004). The $CV_{\Delta S}$ is computed as follows:

$$CV_{\Delta S} = \frac{SD_{(\Delta S)}}{\overline{\Delta S}} \times 100 \qquad 4.1$$

where

$CV_{\Delta S}$ = weighted coefficient of variation (%) of ΔS,

$SD_{(\Delta S)}$ = standard deviation of change in soil moisture storage for each KCC and

$\overline{\Delta S}$ = mean of change in soil moisture storage for each KCC.

As may be seen from Table 4.6, the weighted $\overline{CV}$ for the 10 KCCs of the three hypothetical soil/land cover scenarios SCSV, ILIV and DSDV are 50 793.13%, 4 157.13% and 2 968.56% respectively. The weighted $CV_{\Delta S}$ values of each of these three scenarios for each of the 10 KCCs are much less than double of their weighted $\overline{CV}$, except for the *Cwa* climate with SCSV, the *Cwb* climate with ILIV and the *Csb* and *Cwb* climates with DSDV scenarios. The $CV_{\Delta S}$ of the *Cwb* climate with the ILIV scenario is quite high at 19 597.6%, and this is more than twice of the $2\overline{CV}$ (8 314.26%). The $CV_{\Delta S}$ of the *Csb* and *Cwb* climates with DSDV are 8 386.80% and 9 804.90% respectively and their $2\overline{CV}$ is 5 937.12%, reflecting a poor uniformity of distribution. However, the high $CV_{\Delta S}$ of SCSV with the *Cwa* climate (422 400%) does not compare at all to its $2\overline{CV}$ of 50 793.13%, and is highlighted for further investigation. From the above results it can be concluded that similar KCCs generally display reasonably similar values of ΔS for the same soil texture/soil depth and land cover combinations.

Table 4.6 Mean ($\overline{\Delta S}$), standard deviation ($SD_{\Delta S}$) and coefficient of variation ($CV_{\Delta S}$) of change in soil moisture status (ΔS) for the selected soil texture/soil depth and land use combinations for each of the ten KCCs identified in southern Africa

No	KCC	No of Zones in SA	Shallow Clay Soils with Sparse Vegetation, SCSV			Intermediate Loamy Soils with Average Vegetation, ILIV			Deep Sand Soils with Dense Vegetation, DSDV		
			$\overline{\Delta S}$ (mm)	$SD_{(\Delta S)}$ (mm)	Weighted $CV_{\Delta S}$(%)	$\overline{\Delta S}$ (mm)	$SD_{(\Delta S)}$ (mm)	Weighted $CV_{\Delta S}$(%)	$\overline{\Delta S}$ (mm)	$SD_{(\Delta S)}$ (mm)	Weighted $CV_{\Delta S}$(%)
1	*BWh*	8	-9.31	2.05	176.08	33.73	3.63	86.09	-32.40	1.64	40.48
2	*BWk*	14	-9.76	0.77	110.46	32.24	2.48	107.66	-31.77	1.25	55.02
3	*BSh*	38	5.27	2.78	2004.50	26.87	6.19	875.52	-28.29	4.35	584.06
4	*BSk*	84	-7.19	1.80	2102.52	29.81	2.94	828.24	-30.31	1.79	496.44
5	*Cfa*	20	5.51	3.29	1194.20	2.71	9.07	6693.60	-11.09	7.24	1305.60
6	*Cfb*	28	-1.32	5.15	10924.20	17.04	9.46	1554.28	-21.70	7.13	919.80
7	*Csa*	3	9.67	3.76	116.64	11.56	12.51	324.66	1.03	10.68	3110.67
8	*Csb*	20	11.19	6.40	1143.80	14.72	20.49	2784.00	4.29	17.99	**8386.80**
9	*Cwa*	110	0.12	4.64	**422400.0**	15.92	12.62	8719.70	-20.60	9.33	4981.90
10	*Cwb*	203	1.45	4.84	67759.37	13.56	13.09	**19597.60**	-19.45	9.40	**9804.90**
Weighted Mean $CV_{\Delta S}$ (%)					50793.13			4157.13			2968.56

4.4.4 Relationships between Soil Water Status and Mean Annual Precipitation within Specific Köppen Climate Classes

MAP and its variation in space and time is used in many relationships in water resources, agriculture, fisheries and environmental studies because of its widespread availability, also in developing countries (Schulze, 1997). It was hypothesised that within a specified KCC, with its similar rainfall seasonality and temperature distributions, ΔS was likely to be a function of the distribution of MAP. If this was found to be the case, then the Köppen system would have broad applicability as a methodology to disaggregate an area into relatively homogenous hydrological response zones for the determination of ΔS when only limited hydrological information was available. Based on the above hypothesis, regression equations were developed to estimate ΔS from the MAP for each KCC by employing the values of ΔS obtained by Schmidt and Schulze (1987) for the 712 zones. Half of the 550 zones which fell entirely within the same KCC were randomly selected for the development of regression equations (Figure 4.3) and the remaining half was used for verification of these developed regression equations (Figure 4.4).

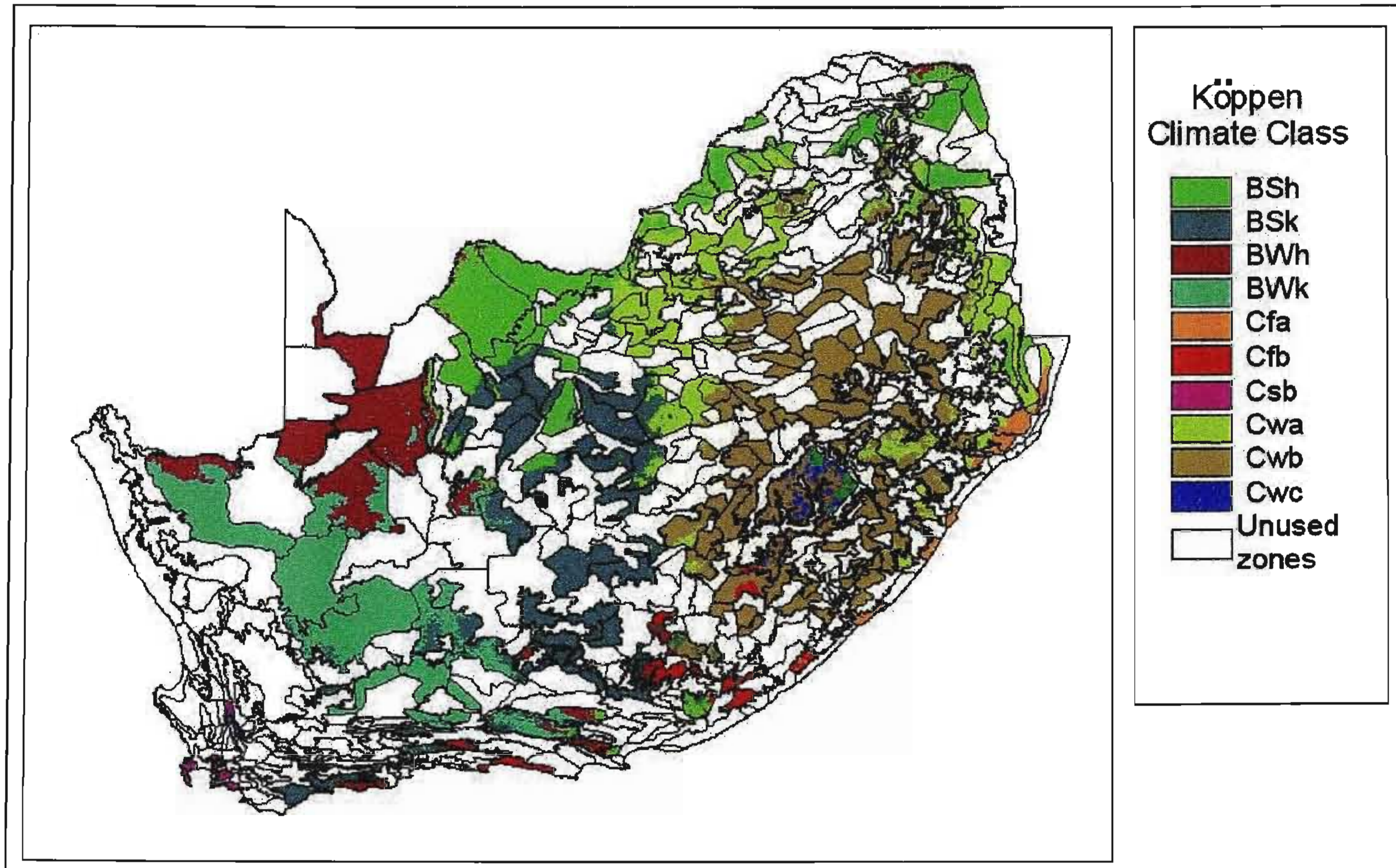


Figure 4.3 Hydrological zones used for the development of regression equations of change in soil moisture storage

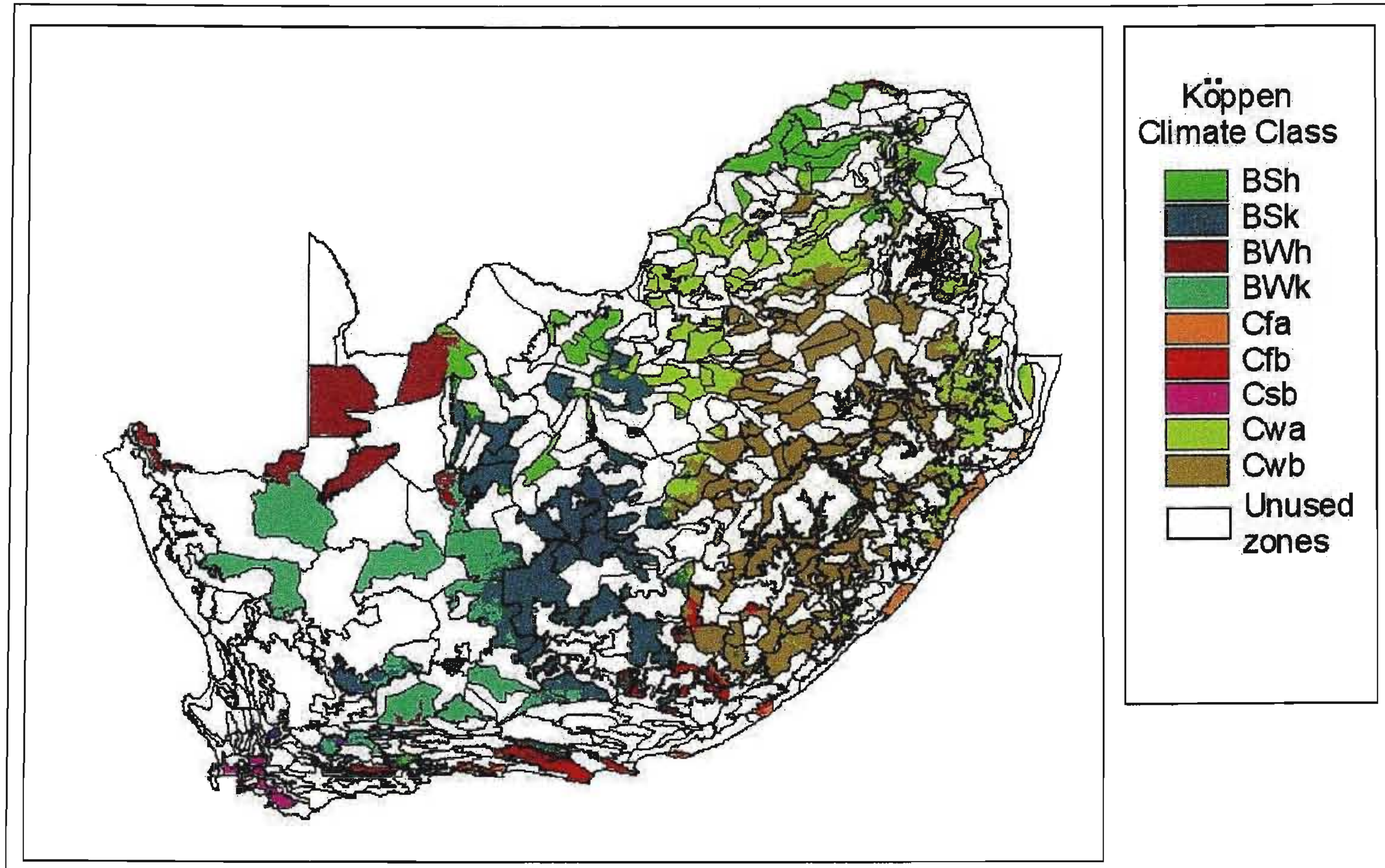


Figure 4.4 Hydrological zones used for verification of the regression equations developed

4.4.5 Result and Discussions

In order to study the relationships between ΔS and MAP, and to evaluate how effectively estimated ΔS values approximate the observed ΔS values, analysis of the regression coefficient (r^2) and Adjusted r^2 (Adj. r^2) as well as the Mean Square Error (MSE) within the 5% level of significance were performed by using *SPSS* statistical software. The r^2 and Adj. r^2 associated with a regression line indicate the goodness of fit of the regression equations. The MSE indicates the actual size of the error produced by these regression equations.

4.4.5.1 Results when all Köppen climatic zones are grouped together for southern Africa

As a starting point of the analysis, the relationship between the ΔS and MAP is examined for all climatic zones identified in southern Africa grouped together (i.e. taking no cognisance of range of rainfall nor of seasonality) for the selected soil texture/soil depth and land cover combinations. This analysis was performed in order to assess the extent to which rainfall seasonality and temperature distributions affected ΔS. The discussion therefore commences with the entire southern Africa being regarded as a unit and is then followed by analyses of ΔS vs MAP for each of the KCCs identified in southern Africa. Each of the figures which follow present a scatter plot of ΔS versus MAP for a specific climate zone and a dot graph indicating estimated against observed ΔS values for the selected soil texture/soil depth and land cover combinations. It is important to bear in mind that wherever the term "observed" ΔS values is used, these are in fact made up of values simulated with the *ACRU* model, while "modelled" values are those derived from ΔS: MAP equations.

It is evident from the scatter plots in Figures 4.5a, 4.6a and 4.7a that a general trend of increasing ΔS with increase in MAP is reflected for the three diverse hypothetical soil and land cover combinations which were selected, *viz.* SCSV, ILIV and DSDV. With r^2 ranging from 0.71 to 0.91, these scatter plots illustrate that overall, irrespective of climatic regime or soil/cover combination, a first estimate of ΔS may be obtained from MAP alone.

In the verification analysis the r^2 and Adj. r^2 in Figures 4.5b, 4.6b and 4.7b are also high, illustrating a strong association between simulated and observed ΔS values. However, the MSEs are generally also high, indicating that the high values of ΔS are not simulated as well as desired. This is hypothesised to be due to varying evaporation intensities in the different climatic zones not being taken into consideration. This influence can be seen clearly in the figures which follow for each of the KCCs identified in southern Africa.

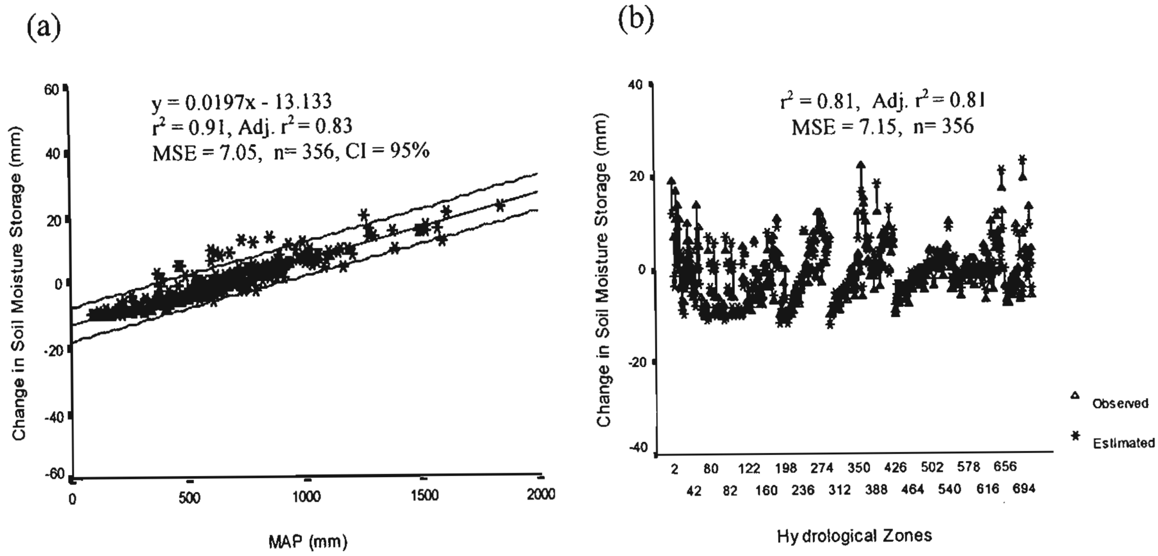


Figure 4.5 Scatter diagram of median antecedent storage changes, ΔS, vs MAP (a) and simulated vs observed ΔS values (b) for the entire set of 712 hydrologically relatively homogeneous climate zones in southern Africa, for catchments assuming sparse vegetation on shallow clay soils (SCSV)

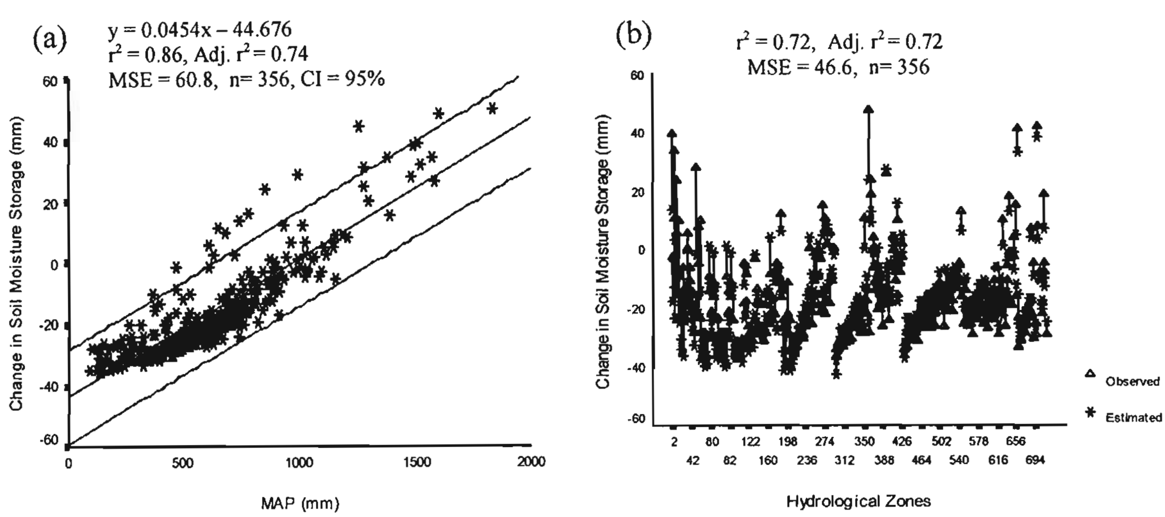


Figure 4.6 Scatter diagram of median antecedent storage changes, ΔS, vs MAP (a) and simulated vs observed ΔS values (b) for the entire set of 712 hydrologically relatively homogeneous climate zones in southern Africa, for catchments assuming intermediate vegetation on intermediate loamy soils (ILIV)

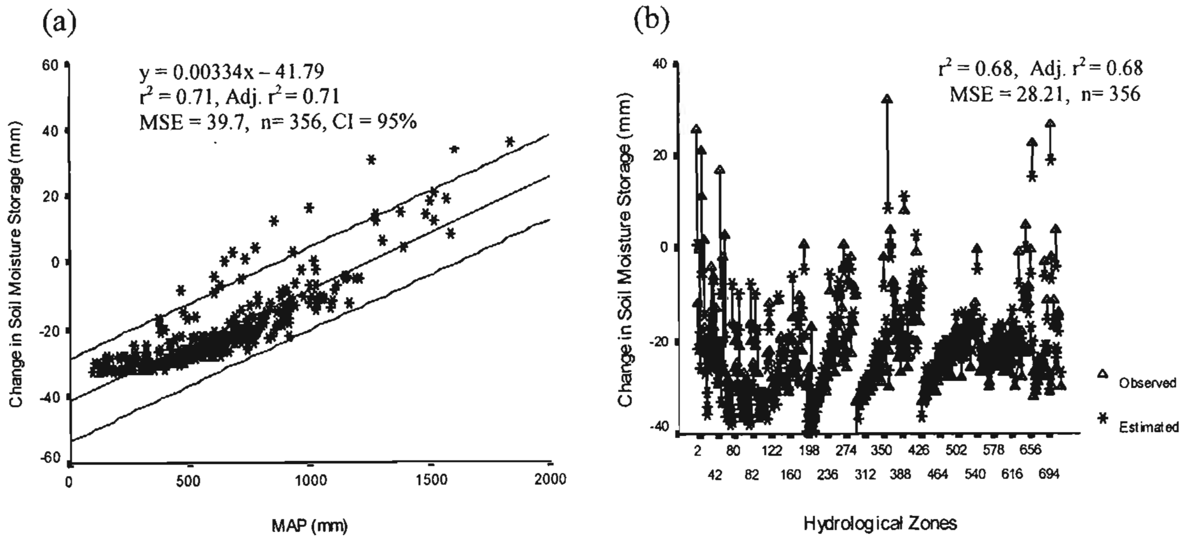


Figure 4.7 Scatter diagram of median antecedent storage changes, *ΔS*, vs MAP (a) and simulated vs observed *ΔS* values (b) for the entire set of 712 hydrologically relatively homogeneous climate zones in southern Africa, for catchments assuming dense vegetation on deep sandy soils (DSDV)

4.4.5.2 Results from individual Köppen climate classes

BW regions are arid zones in which evapotranspiration is much higher than precipitation. Temporal variability of precipitation is high. Occasionally 90% of the annual total rainfall is recorded in just one or two months of the year (Trewartha, 1954).

Climate class *BWh* occurs over the most arid regions of southern Africa which have very high temperatures and are characterised by diverging air masses, with abundant sunshine and in which diurnal ranges of temperature are higher than in any other KCC, often >20^{0}C (Ahrens, 1994). Precipitation, when it occurs, usually falls as high intensity and localised convectional showers and is quickly evaporated by the hot, dry air (Trewartha, 1954). As shown in Figures 4.8a, 4.9a and 4.10a, the r^2 and Adj. r^2 of the regression equations in *BWh* climates are highly significant, although only 8 of the 712 zones qualified for this KCC.

The gradient of *ΔS* with a change in MAP is very small, since in such arid conditions the effects of the soil and land cover characteristics are at a minimum when estimating *ΔS* prior to the very infrequent rainfall events. The estimated *ΔS* values approximate the observed *ΔS* values, having r^2 and Adj. r^2 >0.9 and MSE <1 in all scenarios (Figures 4.8b, 4.9b and 4.10b).

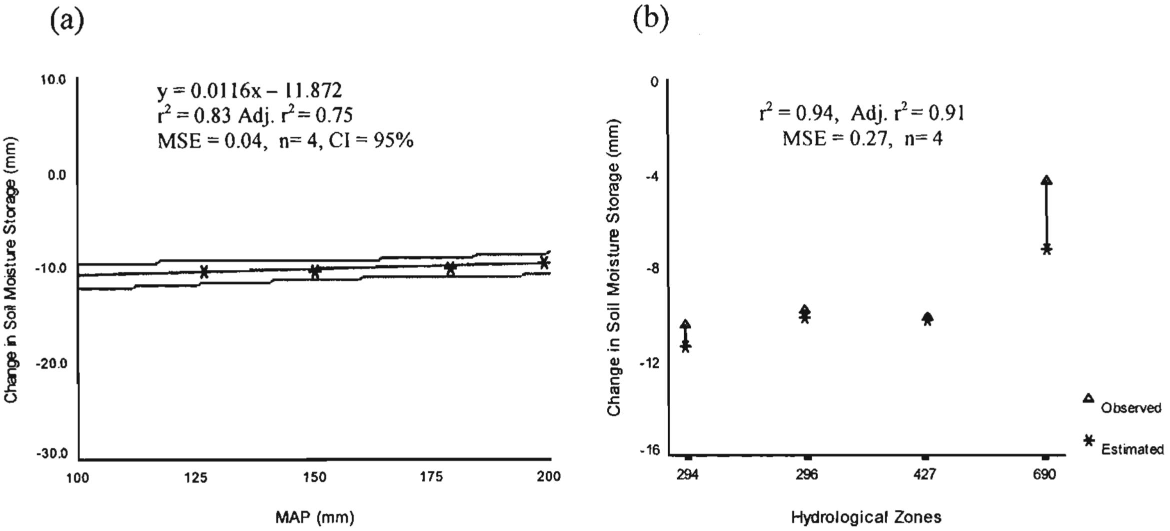


Figure 4.8 Scatter diagram of median antecedent storage changes, ΔS, vs MAP (a) and simulated vs observed ΔS values (b) for those hydrologically relatively homogeneous zones in southern Africa with a *BWh* climate, for catchments assuming sparse vegetation on shallow clay soils (SCSV)

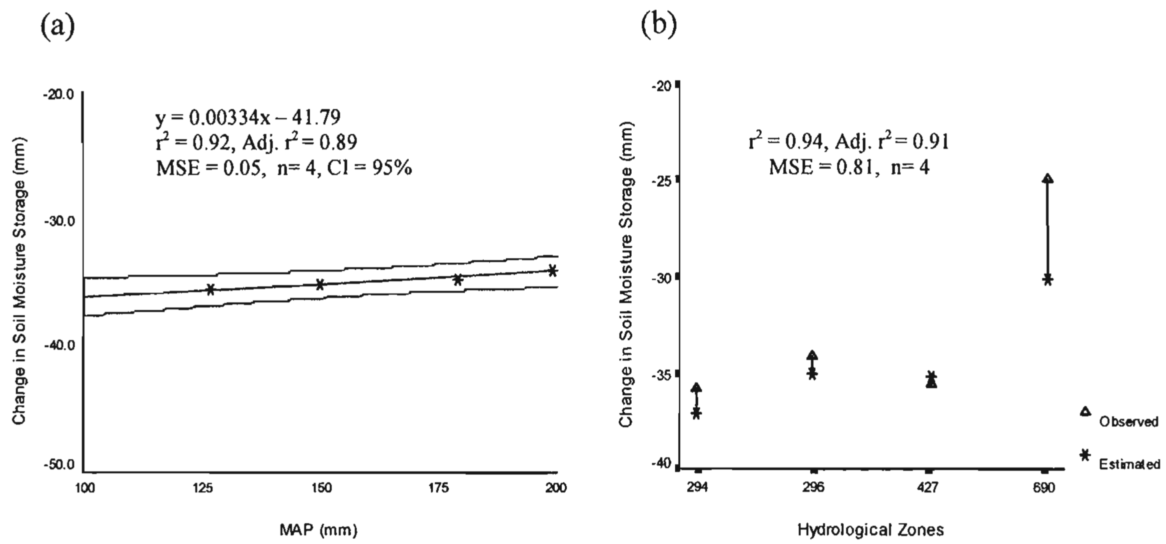


Figure 4.9 Scatter diagram of median antecedent storage changes, ΔS, vs MAP (a) and simulated vs observed ΔS values (b) for those hydrologically relatively homogeneous zones in southern Africa with a *BWh* climate, for catchments assuming intermediate vegetation on intermediate loamy soils (ILIV)

(a) (b)

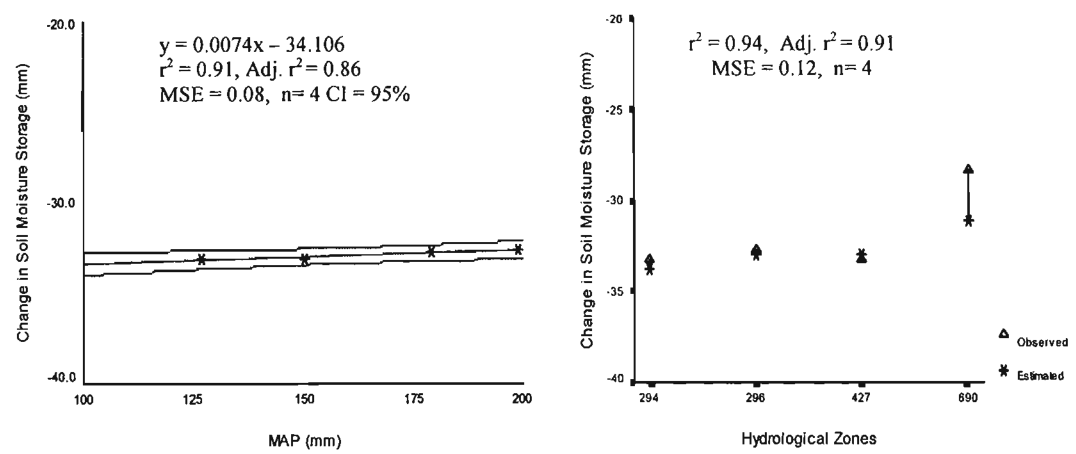


Figure 4.10 Scatter diagram of median antecedent storage changes, *ΔS,* vs MAP (a) and simulated vs observed *ΔS* values (b) for those hydrologically relatively homogeneous zones in southern Africa with a *BWh* climate, for catchments assuming dense vegetation on deep sandy soils (DSDV)

Climate class *BWk* also occurs over the arid regions of southern Africa, but where the climate is dry and cool. Because of the lower temperatures, and resultant reduced evaporation rates, the gradient of *ΔS* with change in MAP is higher than that in *BWh* regions (Figures 4.11a, 4.12a and 4.13a).

(a) (b)

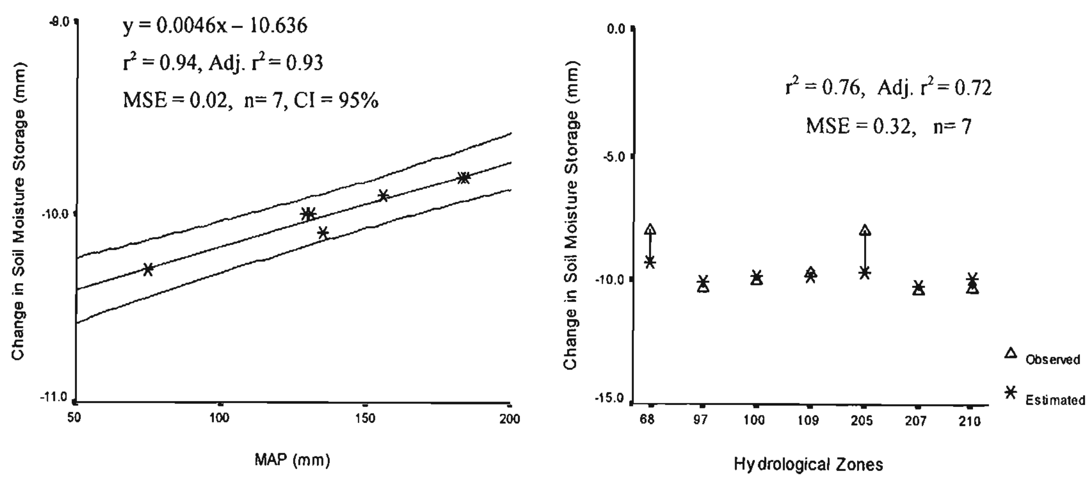


Figure 4.11 Scatter diagram of median antecedent storage changes, *ΔS,* vs MAP (a) and simulated vs observed *ΔS* values (b) for those hydrologically relatively homogeneous zones in southern Africa with a *BWk* climate, for catchments assuming sparse vegetation on shallow clay soils (SCSV)

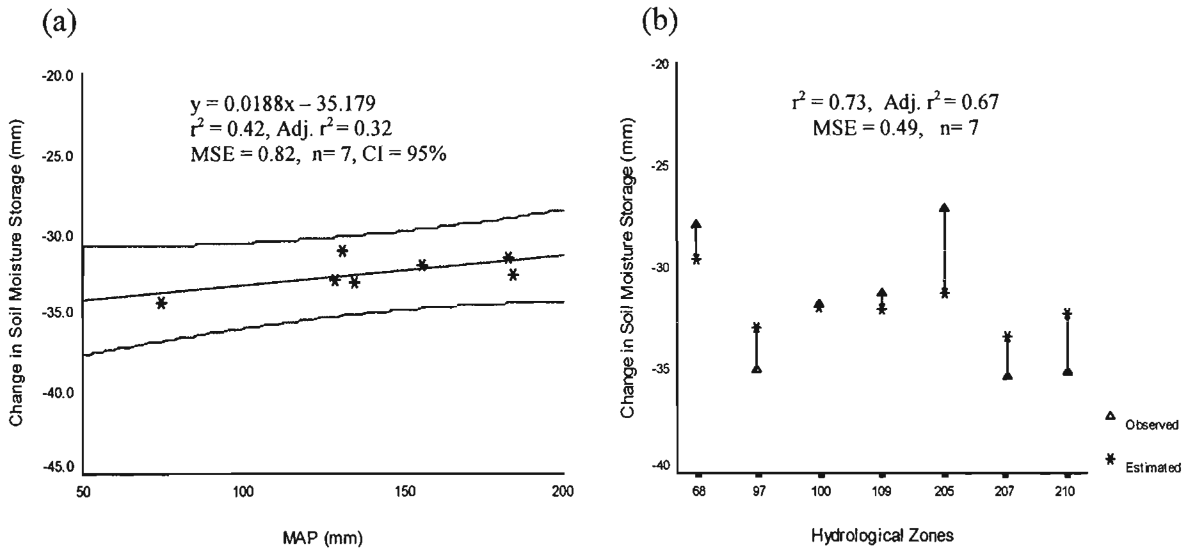


Figure 4.12 Scatter diagram of median antecedent storage changes, ΔS, vs MAP (a) and simulated vs observed ΔS values (b) for those hydrologically relatively homogeneous zones in southern Africa with a *BWk* climate, for catchments assuming intermediate vegetation on intermediate loamy soils (ILIV)

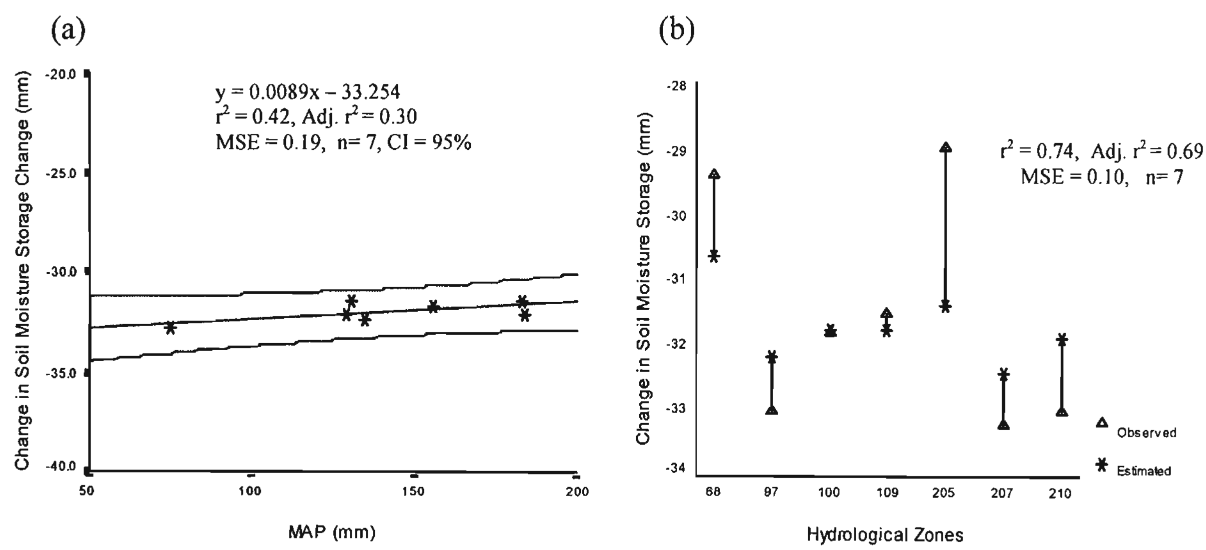


Figure 4.13 Scatter diagram of median antecedent storage changes, ΔS, vs MAP (a) and simulated vs observed ΔS values (b) for those hydrologically relatively homogeneous zones in southern Africa with a *BWk* climate, for catchments assuming dense vegetation on deep sandy soils (DSDV)

The goodness of fit of the regression equation is high for the SCSV scenario (Figure 4.11a), but poorer for the ILIV and DSDV scenarios (Figures 4.12a and 4.13a). This difference might be attributed to the more significant effects the soil and land cover properties play in the variation of ΔS in the ILIV and DSDV scenarios. As a result, the estimated ΔS values are simulated better in the SCSV (Figure 4.11b) than in the ILIV and DSDV scenarios (Figures 4.12b and 4.13b).

BS regions have semi-arid (steppe) climates which experience relatively higher rainfall than the *BW* (arid) climates. They have a short rainfall season. Rainfall in *BS* climates, like that in the *BW* regions, is generally meagre, variable and undependable (Trewartha, 1954). In southern Africa, *BS* regions generally experience summer rather than winter rainfalls (Schulze, 2003b).

BSh climates are semi-arid, dominated by dry air masses (Trewartha, 1954). Rainfall is concentrated in the summer season, evaporation is high and consequently the small amount of rainfall that occurs does not contribute much to soil water storage. Strong relationships exist between ΔS and their corresponding MAPs in all three of the selected soil and land cover scenarios (Figures 4.14a, 4.15a and 4.16a). Around 91% of the variation in ΔS is explained by the regression equations. The values of MSE are, furthermore, small (Figures 4.14b, 4.15b and 4.16b).

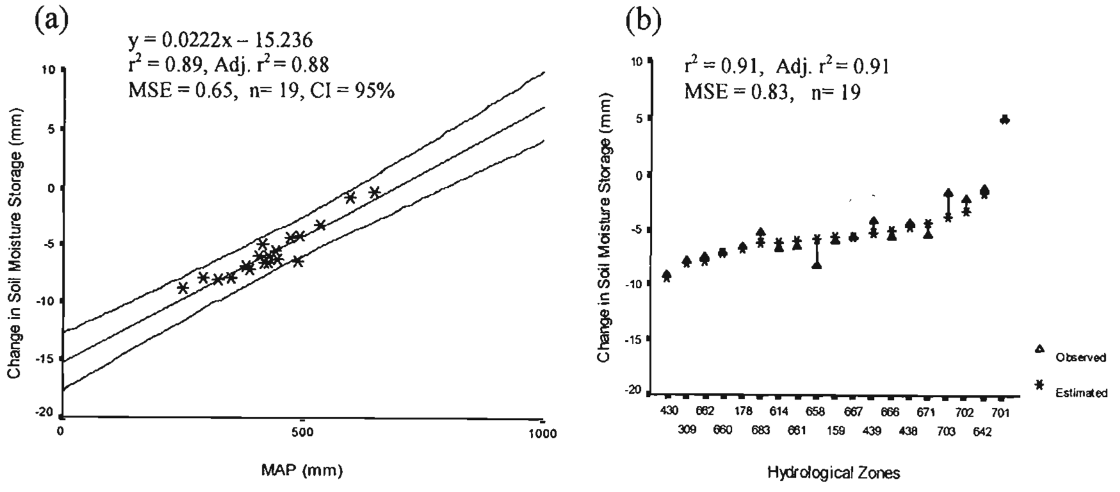


Figure 4.14 Scatter diagram of median antecedent storage changes, ΔS, vs MAP (a) and simulated vs observed ΔS values (b) for those hydrologically relatively homogeneous zones in southern Africa with a *BSh* climate, for catchments assuming sparse vegetation on shallow clay soils (SCSV)

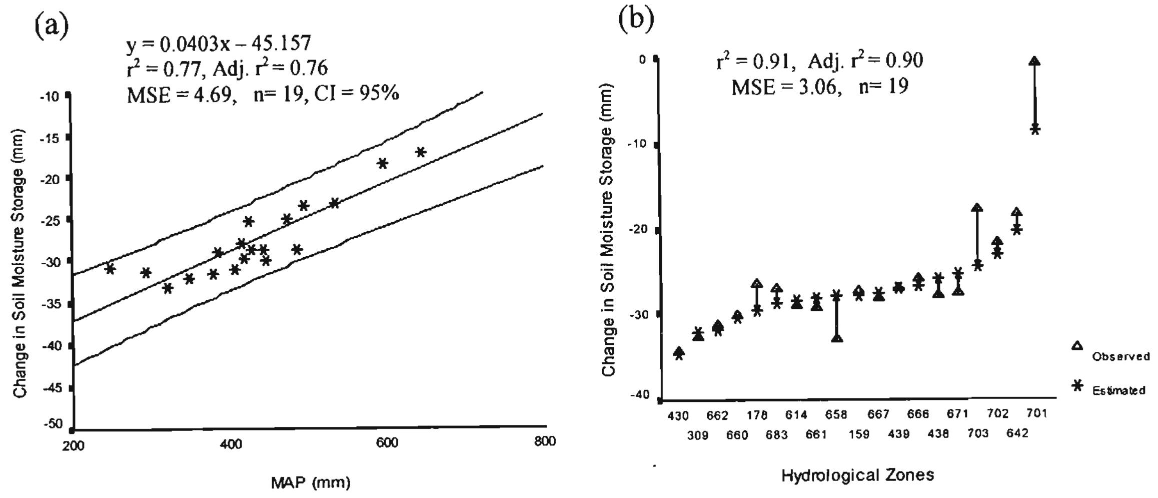


Figure 4.15 Scatter diagram of median antecedent storage changes, *ΔS,* vs MAP (a) and simulated vs observed *ΔS* values (b) for those hydrologically relatively homogeneous zones in southern Africa with a *BSh* climate, for catchments assuming intermediate vegetation on intermediate loamy soils (ILIV)

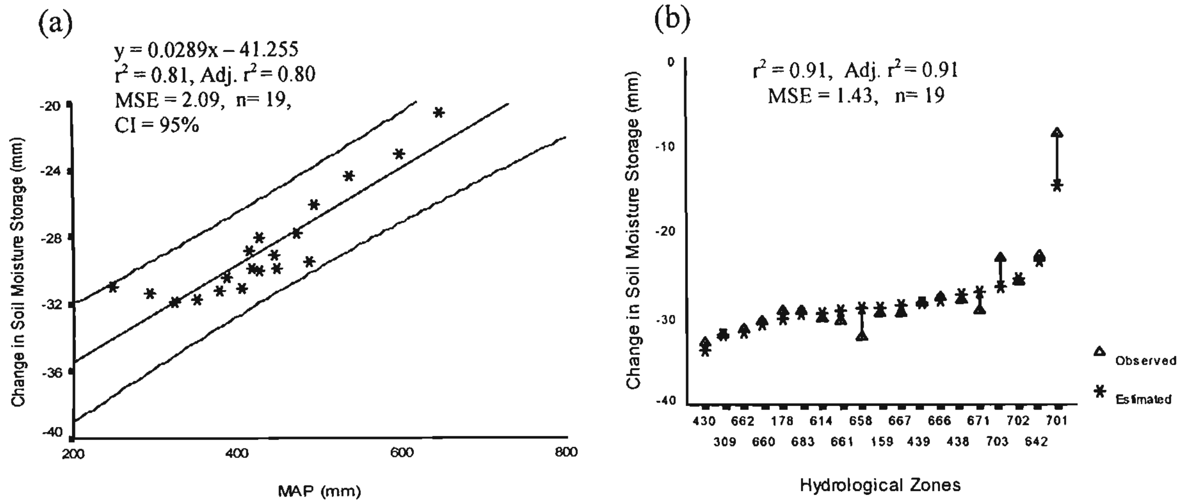


Figure 4.16 Scatter diagram of median antecedent storage changes, *ΔS,* vs MAP (a) and simulated vs observed *ΔS* values (b) for those hydrologically relatively homogeneous zones in southern Africa with a *BSh* climate, for catchments assuming dense vegetation on deep sandy soils (DSDV)

As may be gleaned from the map of Köppen climates over southern Africa (Figure 4.2), regions with *BSk* climates are in transitional positions between the arid *(BW)* regions and the humid *(C)* regions. They are characterised by a cool, but dry climate. Because of the lower temperature values, the gradients of *ΔS* with increase of MAP are found to be a little steeper than those in the *BSh* regions (Figures 4.17a, 4.18a and 4.19a). In the SCSV scenario (Figure

4.17b) the regression coefficient is high, but in the ILIV (Figure 4.18b) and DSDV (Figure 4.19b) scenarios the regression coefficients are not significant at the 95% confidence interval, even though the estimated *ΔS* values appear close to the observed *ΔS* values.

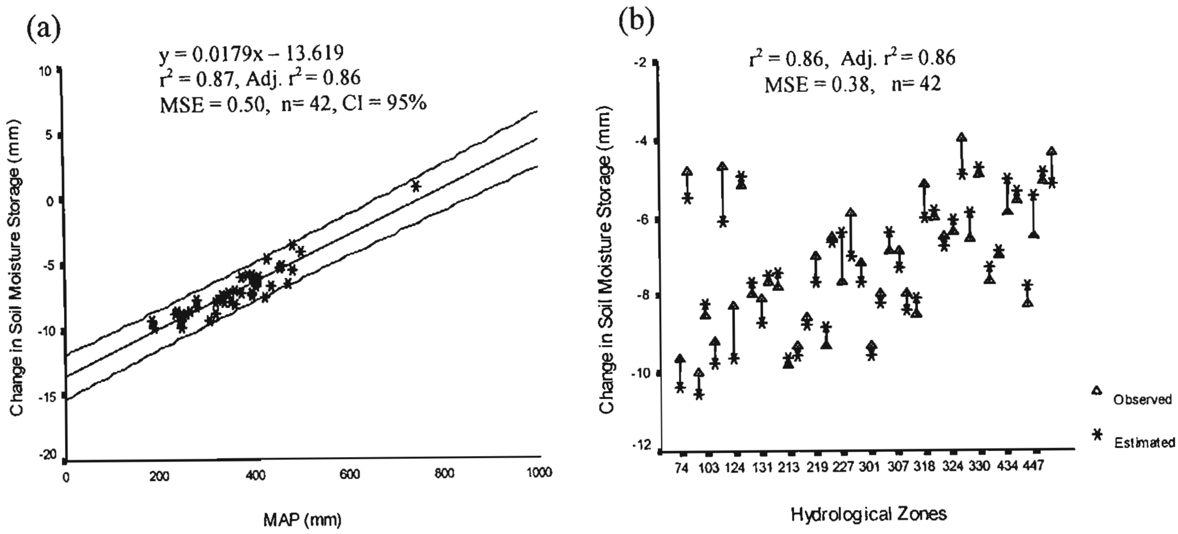


Figure 4.17 Scatter diagram of median antecedent storage changes, *ΔS,* vs MAP (a) and simulated vs observed *ΔS* values (b) for those hydrologically relatively homogeneous zones in southern Africa with a *BSk* climate, for catchments assuming sparse vegetation on shallow clay soils (SCSV)

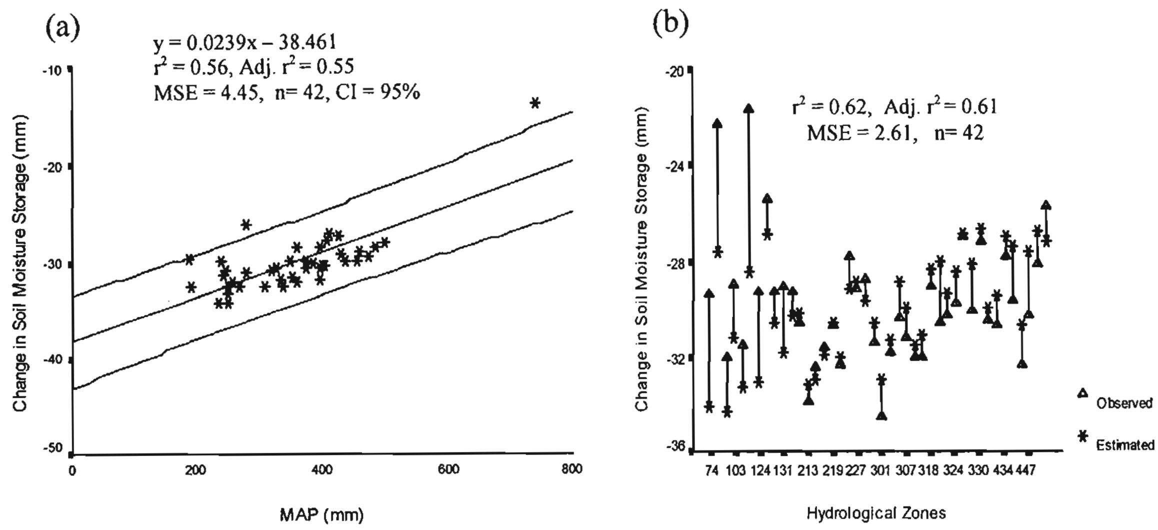


Figure 4.18 Scatter diagram of median antecedent storage changes, *ΔS,* vs MAP (a) and simulated vs observed *ΔS* values (b) for those hydrologically relatively homogeneous zones in southern Africa with a *BSk* climate, for catchments assuming intermediate vegetation on intermediate loamy soils (ILIV)

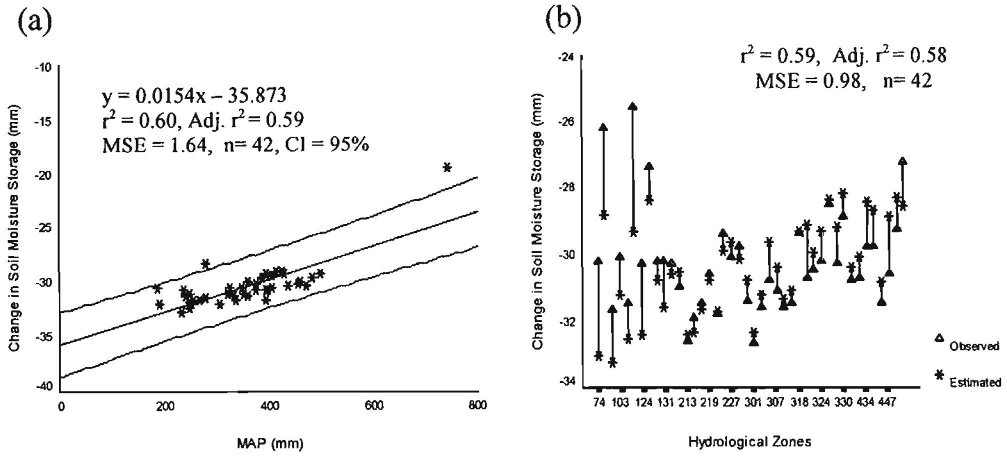


Figure 4.19 Scatter diagram of median antecedent storage changes, *ΔS,* vs MAP (a) and simulated vs observed *ΔS* values (b) for those hydrologically relatively homogeneous zones in southern Africa with a *BSk* climate, for catchments assuming dense vegetation on deep sandy soils (DSDV)

According to Trewartha (1954), *Cfa* regions are characterised by a hot and humid climate during the summer months and by cool and humid conditions during the winter season. They are transitional between tropical rainy climates *(A)* and more severe continental climates *(D)*. Strong relationships may be observed between *ΔS* and MAP in *Cfa* regions, with r^2 = *0.96* in the SCSV scenario (Figure 4.20a) and r^2 = 0.97 in the ILIV (Figure 4.21a) and DSDV (Figure 4.22a) scenarios. The r^2 and Adj. r^2 and MSEs between the estimated and observed *ΔS* values are at acceptable levels for all the selected soil texture/soil depth and land cover combinations (Figures: 4.20b, 4.21b and 4.22b).

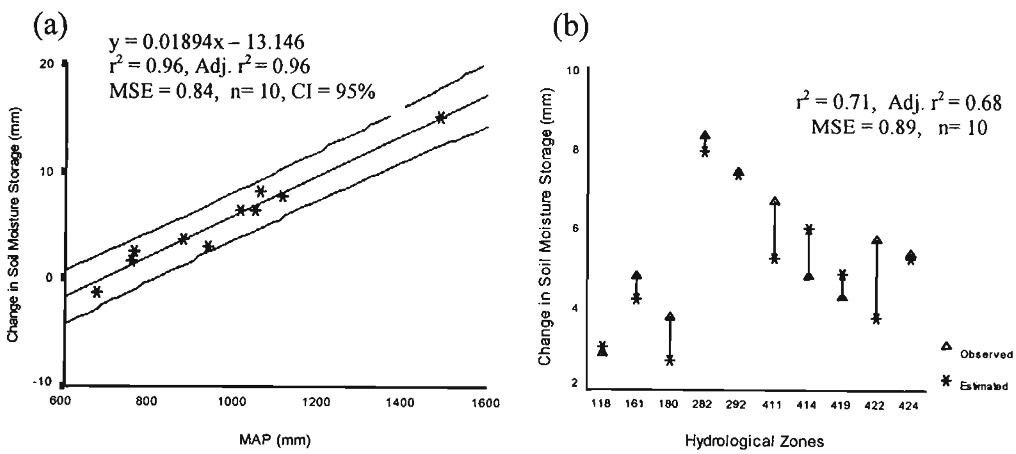


Figure 4.20 Scatter diagram of median antecedent storage changes, *ΔS,* vs MAP (a) and simulated vs observed *ΔS* values (b) for those hydrologically relatively homogeneous zones in southern Africa with a *Cfa* climate, for catchments assuming sparse vegetation on shallow clay soils (SCSV)

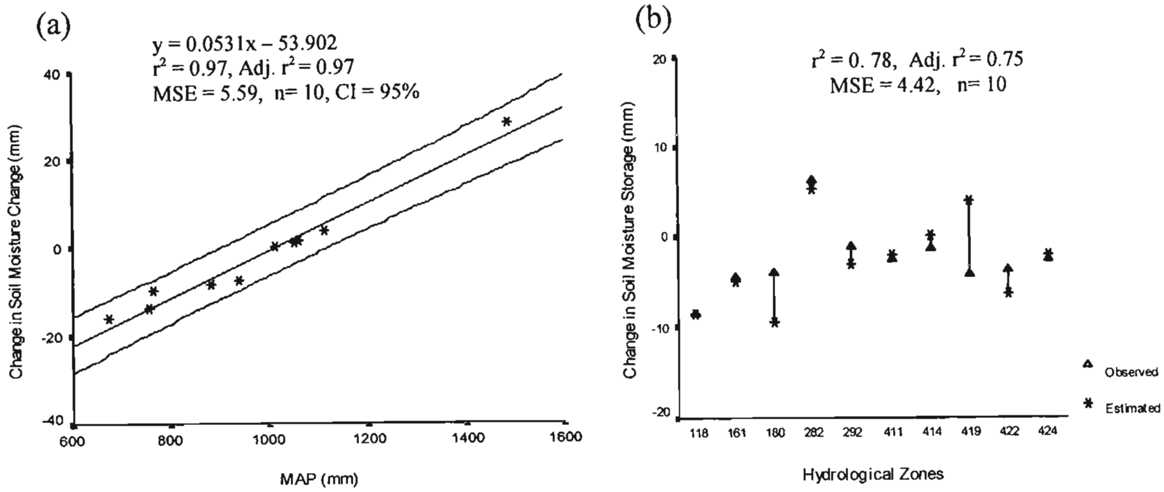


Figure 4.21 Scatter diagram of median antecedent storage changes, *ΔS,* vs MAP (a) and simulated vs observed *ΔS* values (b) for those hydrologically relatively homogeneous zones in southern Africa with a *Cfa* climate, for catchments assuming intermediate vegetation on intermediate loamy soils (ILIV)

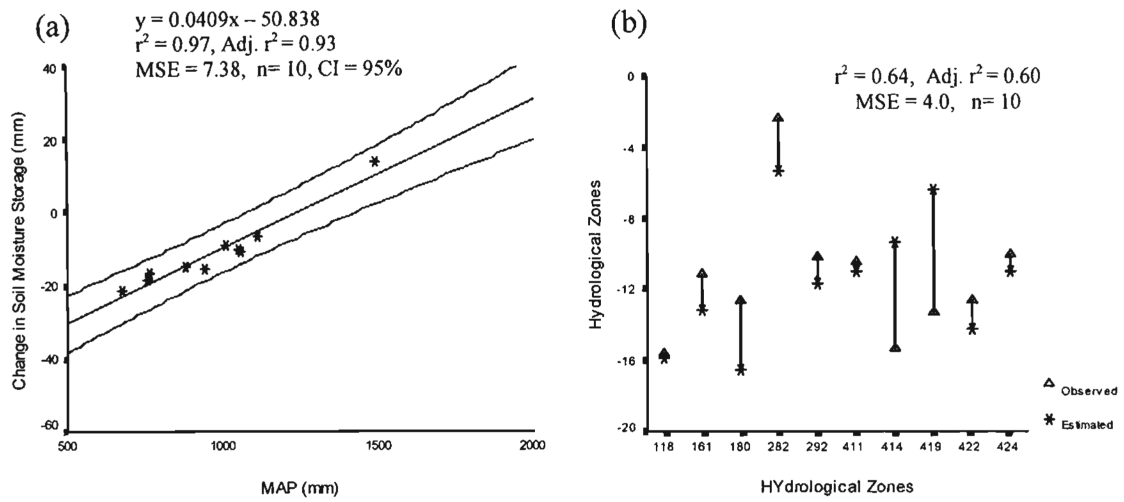


Figure 4.22 Scatter diagram of median antecedent storage changes, *ΔS,* vs MAP (a) and simulated vs observed *ΔS* values (b) for those hydrologically relatively homogeneous zones in southern Africa with a *Cfa* climate, for catchments assuming dense vegetation on deep sandy soils (DSDV)

Cfb regions have marine climates with prevailing winds bringing in moisture from the oceans (Ahrens, 1994). In southern Africa, *Cfb* climates are distributed mostly along the south coast of the country (cf. Figure 4.2). The climate is mild because of modifying effects of the ocean. Rainfall is adequate throughout the year and evaporation rates are relatively low. As may be seen in Figures 4.23a, 4.24a and 4.25a, the association between *ΔS* and MAP is satisfactory.

However, large errors were observed in the ILIV (MSE = 25.5%) and DSDV (MSE = 15.3%) scenarios. The *ΔS* values are overestimated in all cases, even though the regression coefficients are acceptable (Figures 4.23b, 4.24b and 4.25b).

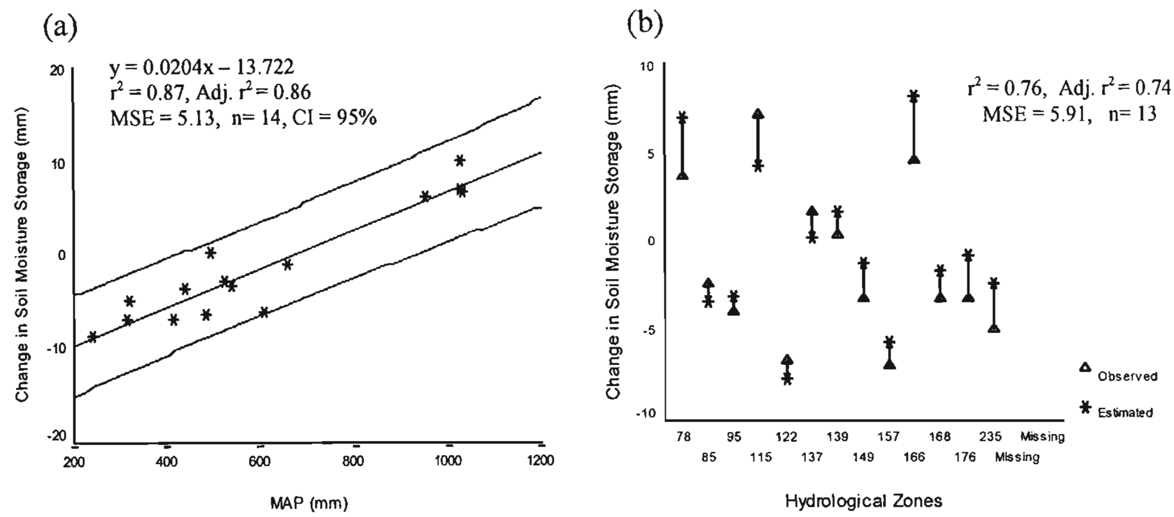


Figure 4.23 Scatter diagram of median antecedent storage changes, *ΔS,* vs MAP (a) and simulated vs observed *ΔS* values (b) for those hydrologically relatively homogeneous zones in southern Africa with a *Cfb* climate, for catchments assuming sparse vegetation on shallow clay soils (SCSV)

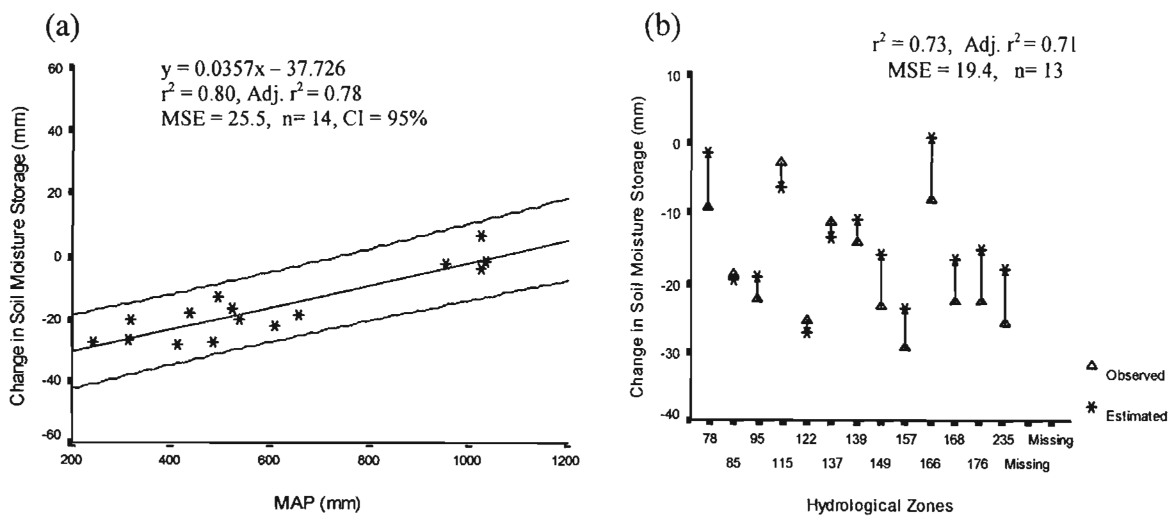


Figure 4.24 Scatter diagram of median antecedent storage changes, *ΔS,* vs MAP (a) and simulated vs observed *ΔS* values (b) for those hydrologically relatively homogeneous zones in southern Africa with a *Cfb* climate, for catchments assuming intermediate vegetation on intermediate loamy soils (ILIV)

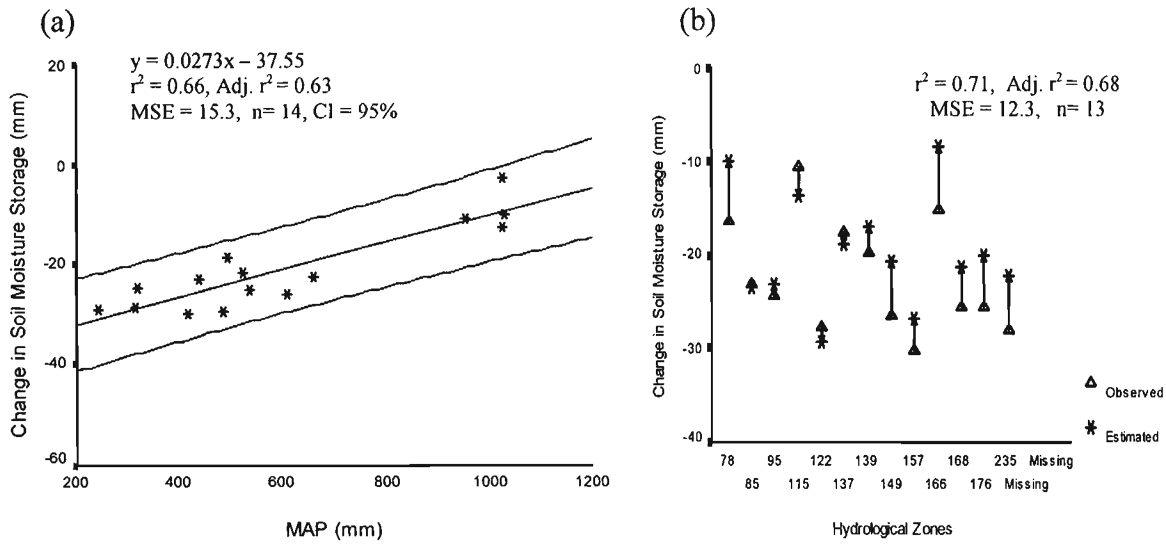


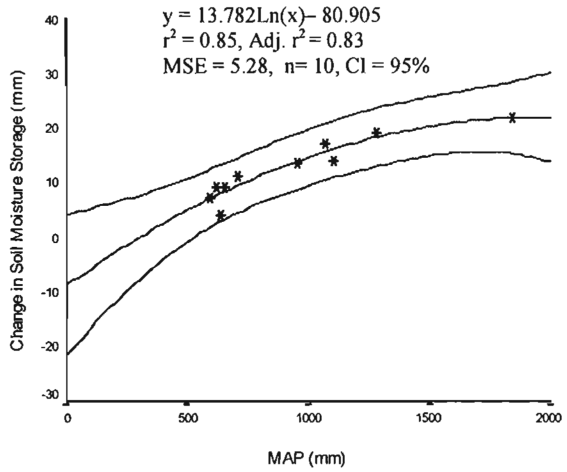
Figure 4.25 Scatter diagram of median antecedent storage changes, *ΔS,* vs MAP (a) and simulated vs observed *ΔS* values (b) for those hydrologically relatively homogeneous zones in southern Africa with a *Cfb* climate, for catchments assuming dense vegetation on deep sandy soils (DSDV)

Cs regions have Mediterranean climates characterised by rainfall in winter and dry summers. With the rain falling in the cooler season, much less soil water is evaporated in the rainy season and more is therefore available in the soil reservoir (Trewartha, 1954). Based upon summer temperature regime, two subdivisions of *Cs* are recognised, *viz. Csa* and *Csb* (Ahrens, 1994).

Csa regions are characterised by long, hot, dry summers and mild rainy winters (Trewartha, 1954). The soil water status varies from a surplus in winter to a deficit in the long summer period. However, this KCC does not cover an extensive area in southern Africa; only 3 out of the 712 zones belong to this group. Because of the small sample, it was excluded from the statistical analysis.

Csb regions are characterised by cool summers and humid winters. The summers are relatively cool, as a consequence of their general marine location (Trewartha, 1954). While statistically significant linear relationships exist between *ΔS* and MAP, they are even more strongly explained by non-linear (logarithmic) relationships, as may be seen in Figures 4.26a, 4.27a and 4.28a. This indicates that the atmospheric demand for water is low, as a result of which no significant increases in *ΔS* are observed once the soil profile attains its maximum retention capacity. The estimated ΔS values are well simulated and are very close to the observed ΔS values, with about 90% of the ΔS being explained by the regression equations (Figures 4.26b, 4.27b and 4.28b). The MSEs are, however, large in the ILIV (Figure 4.27b) and DSDV (Figure 4.28b) scenarios.

(a)



(b)

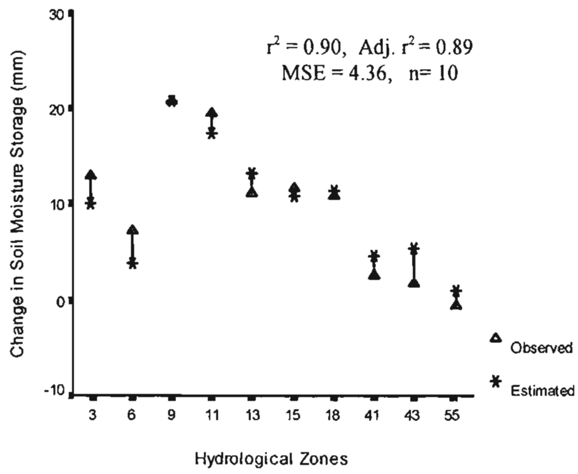
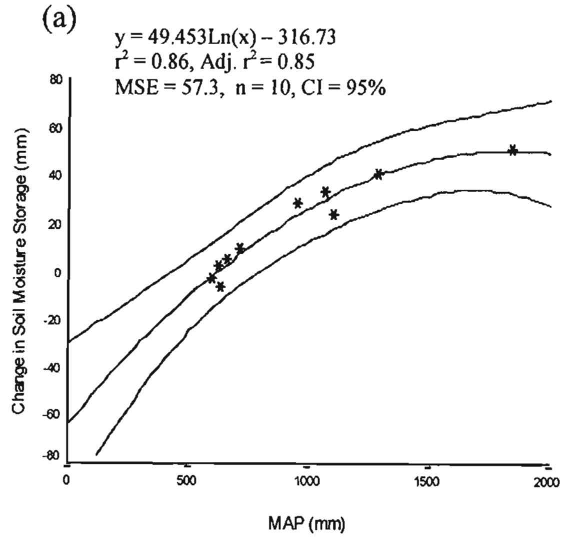


Figure 4.26 Scatter diagram of median antecedent storage changes, ΔS, vs MAP (a) and simulated vs observed ΔS values (b) for those hydrologically relatively homogeneous zones in southern Africa with a *Csb* climate, for catchments assuming sparse vegetation on shallow clay soils (SCSV)

(a)



(b)

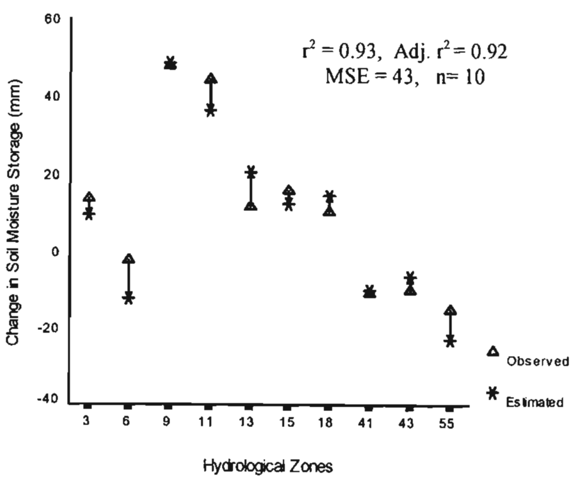


Figure 4.27 Scatter diagram of median antecedent storage changes, ΔS, vs MAP (a) and simulated vs observed ΔS values (b) for those hydrologically relatively homogeneous zones in southern Africa with a *Csb* climate, for catchments assuming intermediate vegetation on intermediate loamy soils (ILIV)

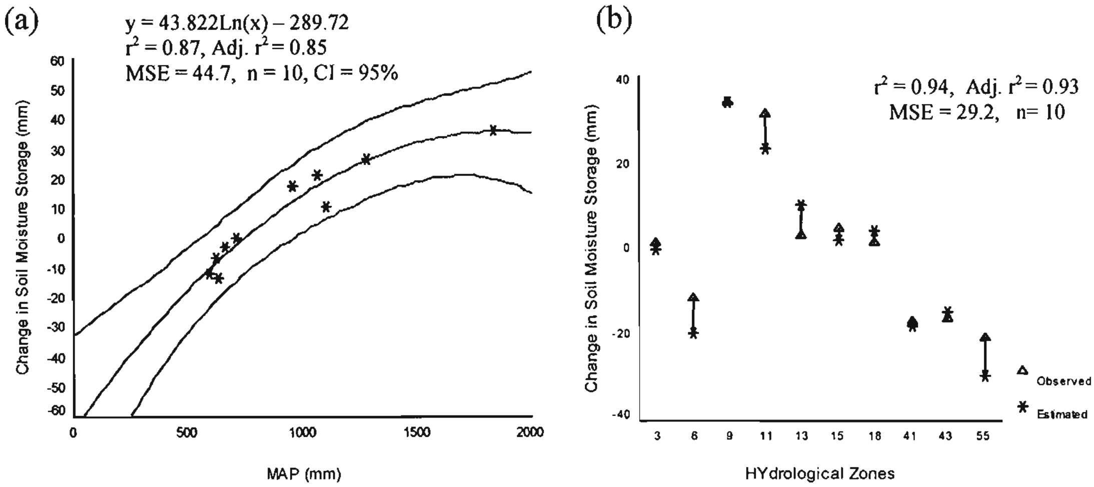


Figure 4.28 Scatter diagram of median antecedent storage changes, ΔS, vs MAP (a) and simulated vs observed ΔS values (b) for those hydrologically relatively homogeneous zones in southern Africa with a *Csb* climate, for catchments assuming dense vegetation on deep sandy soils (DSDV)

Cwa regions are characterised by abundant precipitation, distributed throughout much of the year, but concentrated in the hot summer season. Winters are relatively dry. In addition to plentiful summer rainfall, atmospheric demand is also very high (Trewartha, 1954). This KCC is the second largest in its coverage of the study area, with an extensive area in the north and east coast parts of South Africa (cf. Figure 4.2).

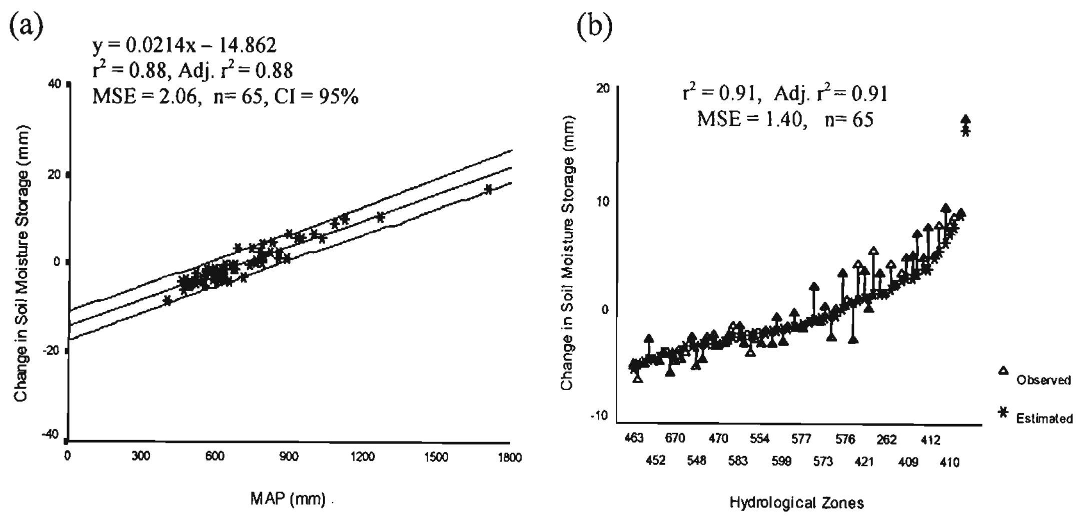


Figure 4.29 Scatter diagram of median antecedent storage changes, ΔS, vs MAP (a) and simulated vs observed ΔS values (b) for those hydrologically relatively homogeneous zones in southern Africa with a *Cwa* climate, for catchments assuming sparse vegetation on shallow clay soils (SCSV)

The values of ΔS are well explained by the distributions of MAP, with r^2 and Adj. r^2 >0.87 (Figures 4.29a, 4.30a and 4.31a). The r^2 and Adj. r^2 between the estimated and observed ΔS are also highly significant, i.e. around 90% of the variation in ΔS being explained by the regression equations in the SCSV (Figure 4.29b) and ILIV (Figure 4.30b) scenarios and about 87% in the DSDV (Figure 4.31b) scenario. The MSEs are somewhat higher for the ILIV and DSDV scenarios, indicating that high values of ΔS are not simulated as well as desired.

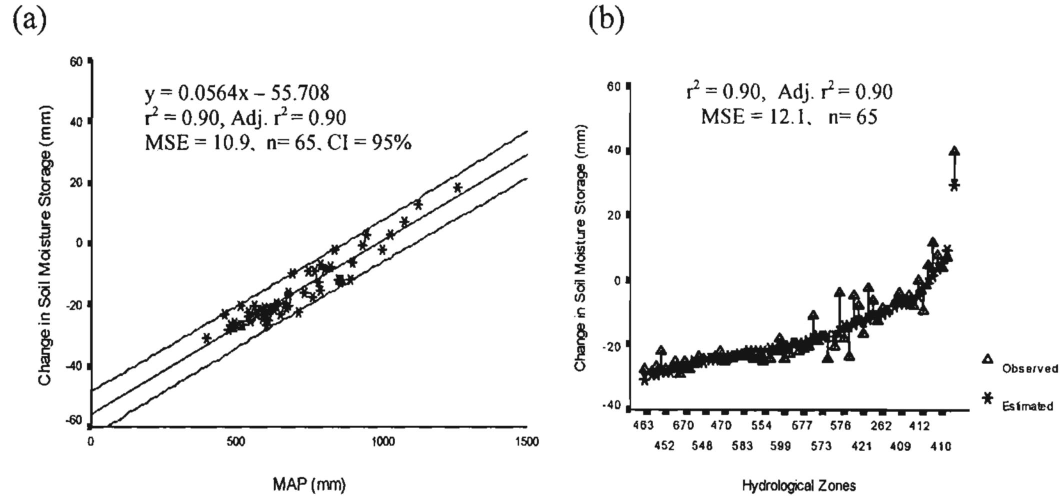


Figure 4.30 Scatter diagram of median antecedent storage changes, ΔS, vs MAP (a) and simulated vs observed ΔS values (b) for those hydrologically relatively homogeneous zones in southern Africa with a *Cwa* climate, for catchments assuming intermediate vegetation on intermediate loamy soils (ILIV)

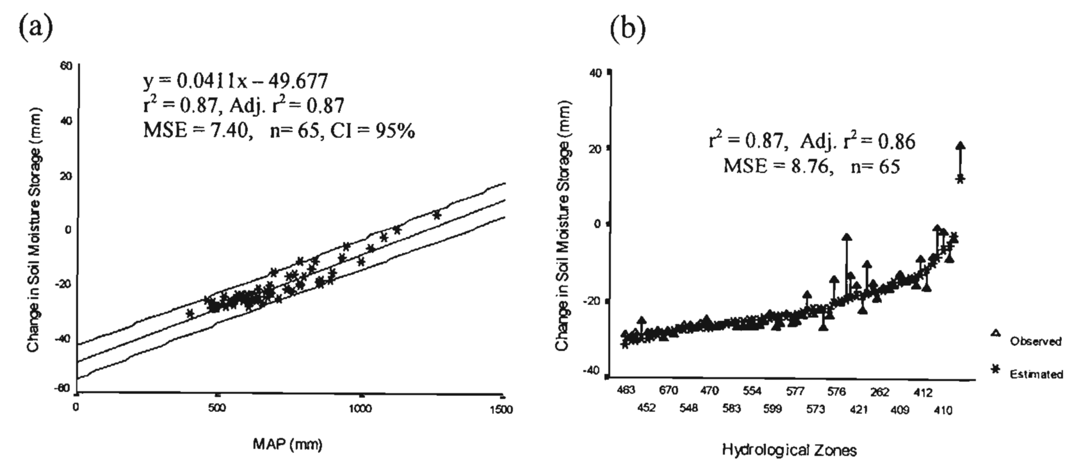


Figure 4.31 Scatter diagram of median antecedent storage changes, ΔS, vs MAP (a) and simulated vs observed ΔS values (b) for those hydrologically relatively homogeneous zones in southern Africa with a *Cwa* climate, for catchments assuming dense vegetation on deep sandy soils (DSDV)

Cwb is the areally largest KCC identified in southern Africa (cf. Figure 4.2), and it is characterised by abundant precipitation which is concentrated in summer season. Unlike *Cwa*, summers are cool in the *Cwb* climates. Similar to the above-mentioned KCCs, the values of ΔS are also well explained by the linear regression of MAP distributions in this climate zone, as shown in Figures 4.32a, 4.33a and 4.34a.

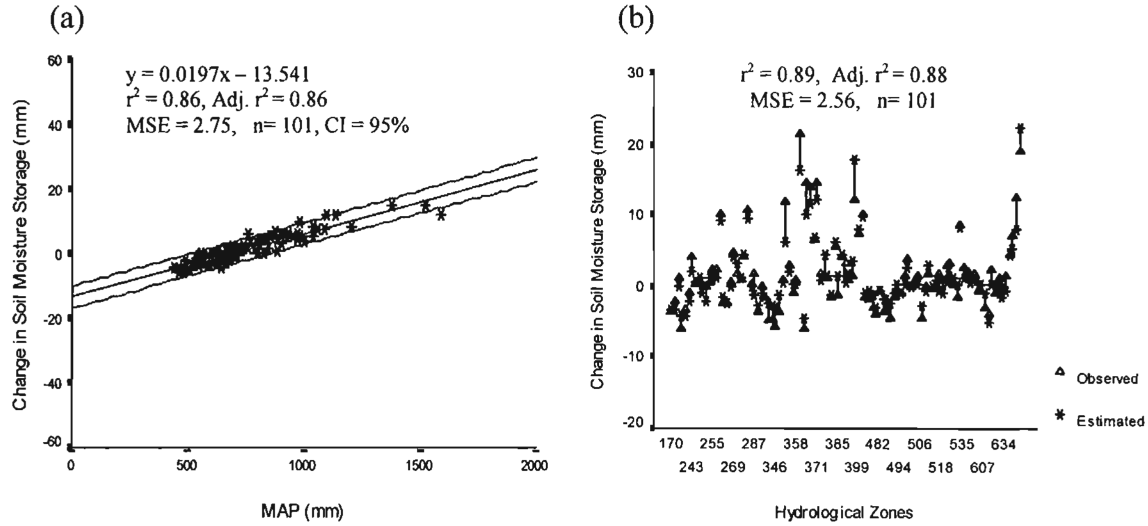


Figure 4.32 Scatter diagram of median antecedent storage changes, ΔS, vs MAP (a) and simulated vs observed ΔS values (b) for those hydrologically relatively homogeneous zones in southern Africa with a *Cwb* climate, for catchments assuming sparse vegetation on shallow clay soils (SCSV)

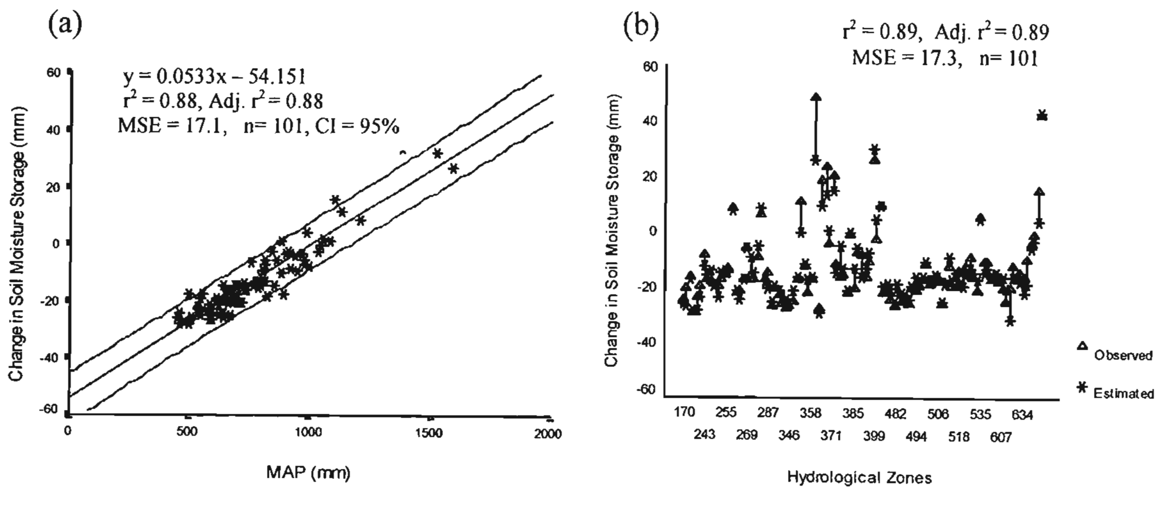


Figure 4.33 Scatter diagram of median antecedent storage changes, ΔS, vs MAP (a) and simulated vs observed ΔS values (b) for those hydrologically relatively homogeneous zones in southern Africa with a *Cwb* climate, for catchments assuming intermediate vegetation on intermediate loamy soils (ILIV)

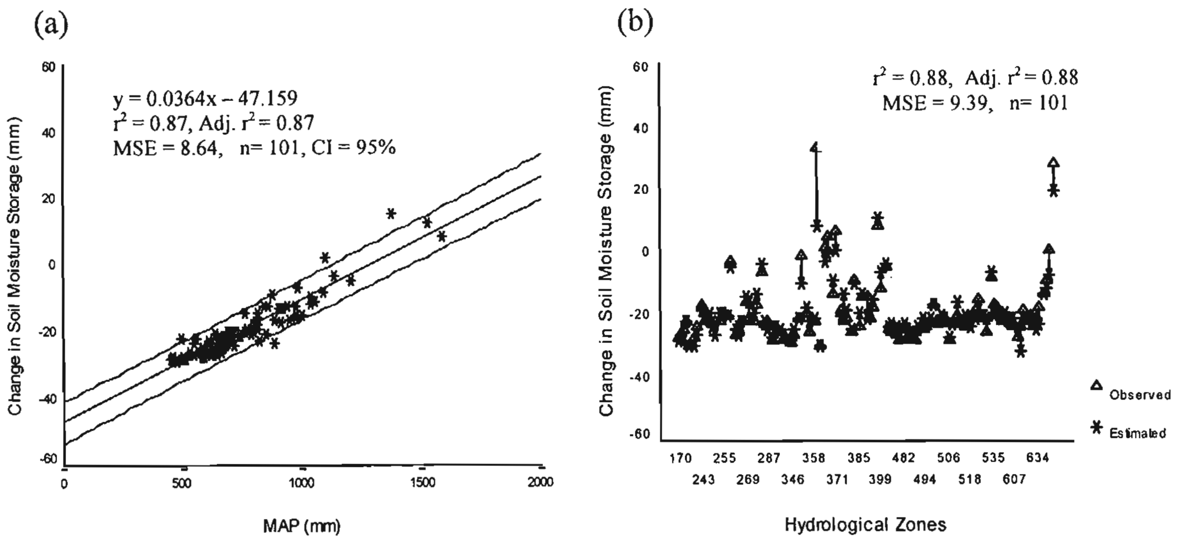


Figure 4.34 Scatter diagram of median antecedent storage changes, ΔS, vs MAP (a) and simulated vs observed ΔS values (b) for those hydrologically relatively homogeneous zones in southern Africa with a *Cwb* climate, for catchments assuming dense vegetation on deep sandy soils (DSDV)

The estimated ΔS values are also very close to the observed ΔSs. Figures 4.32b, 4.33b and 4.34b reveal the excellent performance of the regression equations of each of the selected scenarios, in which around 88% of the variation in ΔS is explained by the distributions of the MAP in the three selected scenarios.

4.5 Conclusions

This chapter first analysed the variability of ΔS within each Köppen climate class identified in southern Africa, in order to highlight the potential for the estimation of ΔS by climatic zonation. In the analysis of variance, the *CVs* of ΔS within each identified KCC were found to be minimal, except in the *Cwa* climate for the SCSV, in the *Cwb* climate for the ILIV and in the *Csb* and *Cwb* climates for the DSDV scenarios, where the variability of ΔS exceeds a threshold limit $(2\overline{CV})$. This high degree of homogeneity, or uniformity, of ΔS within each KCC for a wide representation of soil texture/soil depth and land cover combinations promoted a relationship to be sought between values of ΔS with respect to the distribution of MAP within each specified KCC. As may be seen from Figures 4.5 to 4.34, the values of ΔS are strongly correlated to the distribution of MAP within each of the KCCs, in which rainfall seasonality and temperature distributions remain similar. The good simulations of ΔS from MAP by the regression equations which are unique to each KCC shows that the Köppen climate classification system can be used as a surrogate method for disaggregating a country or region into relatively homogenous hydrological response zones for adjustments of runoff coefficients (CNs) when only limited hydrological and very basic monthly climatological information is available.

* * * * * *

The next chapter deals with an overview of Eritrea from an hydrological perspective. This is followed in Chapter 6 by some general background on the test catchment, *viz.* the Afdeyu research catchment, and the verification of the simulated stormflow volumes by the *ACRU* and SCS-based models.

5. AN OVERVIEW OF ERITREA FROM AN HYDROLOGICAL PERSPECTIVE

In this chapter, general background is presented on Eritrea from an hydrological perspective, and previous stormflow modelling attempts in Eritrea as well as their limitations and lack of general applicability throughout most of the country are also reviewed.

5.1 Introduction

Eritrea is a country with diverse natural resources. It is outside the scope of this study to discuss all the natural resources. In this chapter, therefore, only those relevant characteristics of climate, soils, topography, vegetation and surface water resources which have been shown to critically influence the hydrological behaviour within the country are briefly introduced.

5.1.1 Location

Eritrea is located in the eastern part of Africa between 12 ° 42'N and18 ° 20'N and 36 ° 30'E and 43 ° 20' E (Figure 5.1). The total area of the country is 121 900 km^2, with a Red Sea coastline of more than 1 000 km (FAO, 1994). The population is estimated at 3.19 million, giving an average overall population density of 25 persons.km^{-2}. The country borders Sudan in the west and north-west, the Red Sea in the north and north-east, Djibouti in the south-east and Ethiopia in the south (Berakhi, 2001).

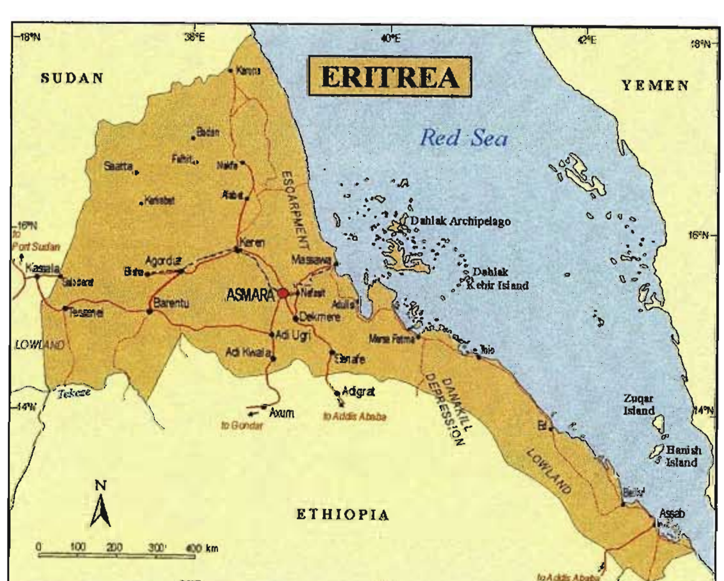


Figure 5.1 Geographic location of Eritrea (after Ministry of Agriculture, 2000)

5.1.2 Topography

The topography of Eritrea includes mountains, hills, rolling plains and flatlands with a wide range of altitudes. The lowest flatlands are 10 m above sea level around the port of Massawa (Figure 5.1) and the highest are 2 490 m above sea level in Adikeyih in the south of Eritrea, near the border with Ethiopia. In addition to these flatlands, there are two extremes of elevation, with the lowest point near *Kulul,* within the Denakil depression (Figure 5.1) at -130 m (one of the hottest places in the world) and the highest point being *Soira* at 3018 m above sea level (Ministry of Agriculture, 2000). The wide variation in elevation has a marked effect on temperatures, and thus potential evaporation (E_P), as well as rainfall and their relationships may be seen in Table 5.1 (Ministry of Land, Water and Environment, 1997).

Table 5.1 Relationships between altitude, temperature and potential evaporation (E_P) (after Ministry of Land Water and Environment, 1997)

Station	Altitude (m)	Annual E_P (mm)	MAP (mm)	Mean Max. Temp. (°C)	Mean Min. Temp. (°C)	Mean Temp. (°C)
Massawa	10	2 033	191.0	32.9	26.8	29.8
Aseb	11	2 341	113.5	35.0	25.3	30.2
Tesenay	585	1 928	409.7	36.1	21.1	28.6
Agordat	626	2 031	378.0	36.4	21.6	29.0
Ghinda	962	1 655	648.1	29.1	20.1	24.0
Barentu	980	2 044	457.5	33.5	16.9	25.1
Keren	1 460	1 808	472.6	30.8	15.3	23.1
Nakfa	1 676	1 595	515.7	25.2	12.7	18.9
Asmara	2 325	1 585	577.3	23.2	10.1	16.6
Adikeyih	2 490	1 624	364.6	24.7	10.9	17.8

5.1.3 Climate

5.1.3.1 Rainfall

Eritrea is a country with a complex series of landscape and climatic features, which give rise to a wide variety of agro-ecological zones (Berakhi, 2001). The country is characterised to a large extent by a semi-arid to arid climate. As may be seen in Figure 5.2, mean annual precipitation (MAP) over much of the mountainous central part of the country is around 500 mm. Rainfall occurs mainly during the period June to September.

Rainfall increases in the southern highlands to about 700 mm, while in the northern mountains, as well as the western and eastern lowlands, the annual rainfall declines to less than 100 mm in the most arid parts of the country. There is only one small area of significantly higher rainfall, on part of the eastern escarpment, where annual totals reach a maximum of around 1050 mm. This area and the eastern lowlands are also marked by a rainfall peak in the winter (October to March), in contrast to the June to September peak over the rest of the country (Euroconsult, 1997).

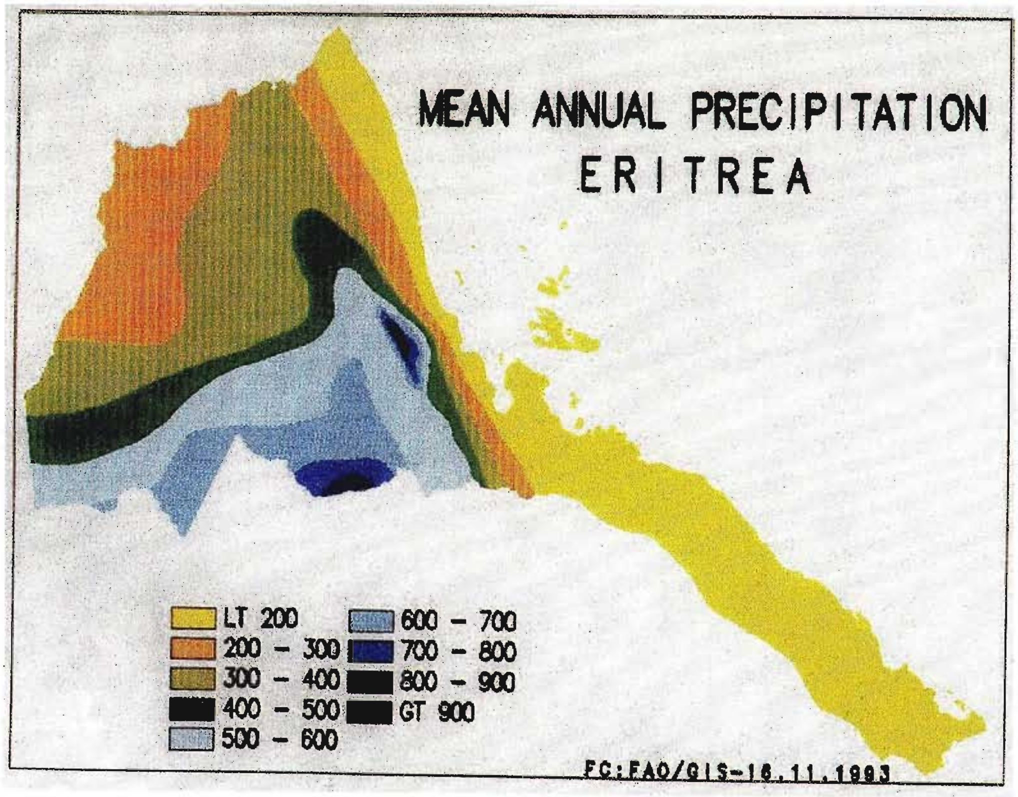


Figure 5.2 Distribution of mean annual precipitation in Eritrea (after FAO, 1994)

The problem of inadequate total rainfall over much of the country is compounded by the high variability of both total annual rainfall and its intra-annual distribution (Euroconsult, 1997). Table 5.2 shows the spatial and temporal distribution of rainfall in Eritrea for the period from 1992 to 1999 at some representative stations.

Table 5.2 Mean monthly and annual precipitation (mm) at representative stations in Eritrea for the period 1992-1999 (after Ministry of Agriculture, 2000)

Station	Aseb	Massawa	Tessenei	Keren	Agordat	Ghinda	Barentu	Nakfa	Asmara	Adikeyih
January	15.5	22.2	0.0	0.0	0.0	60.7	0.0	5.5	4.7	1.3
February	8.2	6.8	0.0	0.0	0.0	24.6	0.0	0.8	0.0	2.0
March	9.9	5.8	0.0	7.4	3.6	40.2	0.7	16.7	9.7	17.4
April	4.5	11.1	2.9	16.3	8.3	53.3	4.1	48.2	17.8	37.4
May	0.0	5.6	20.6	29.6	26.9	19.5	34.5	48.9	61.0	41.0
June	2.0	0.0	32.8	61.9	20.9	7.0	40.9	27.6	13.8	24.3
July	1.1	1.0	105.9	123.7	117	73.8	151.4	91.8	158.8	135.5
August	18.2	9.4	167.2	177.5	144.5	53.9	156.5	158.9	153.1	71.4
September	1.1	0.0	65.7	39.7	44.7	16.6	47.8	47.9	123.6	3.8
October	1.0	35.1	11.2	14.4	11.3	78.3	8.8	42.0	38.5	20.5
November	1.3	52.4	3.4	2.1	0.8	93.0	5.6	26.0	9.0	10.0
December	3.0	41.6	0.0	0.0	0.0	127.2	0.0	1.4	0.0	0.0
Total	113.5	191.0	409.7	472.6	378.0	648.1	457.5	515.7	576.2	364.6

5.1.3.2 Temperature

Temperature is a basic variable in hydrological processes, being used in estimations of net outgoing radiation fluxes, saturation deficits and the precipitable water vapour content of the atmosphere (Schulze, 1979). According to the FAO (1994), around 72% of the country is classified as very hot to hot (with mean annual temperatures >24°C), while not more than 14% is classified as mild to cool (cf. Table 5.3). In the highlands annual average temperatures range from 15 to 21 °C while the lowlands and coastal plains are hot, with average temperatures rising sometimes to 35 °C. Figure 5.3 illustrates the temperature regimes of the country.

Table 5.3 Temperature regimes of Eritrea (after FAO, 1994)

Temperature Regime	Mean Annual Temperature (°C)	Elevation Range (m)	Area	
			km^2	% of country
Very hot	29.0 - 26.5	< 0 - 500	40 705	33.4
Hot	26.5 - 24.0	500 - 1 000	47 454	38.9
Warm	24.0 - 21.5	1 000 - 1 500	16 982	13.9
Mild	21.5 - 19.0	1 500 - 2 000	11 623	9.5
Cool	< 19.0	> 2 000	7 536	4.3

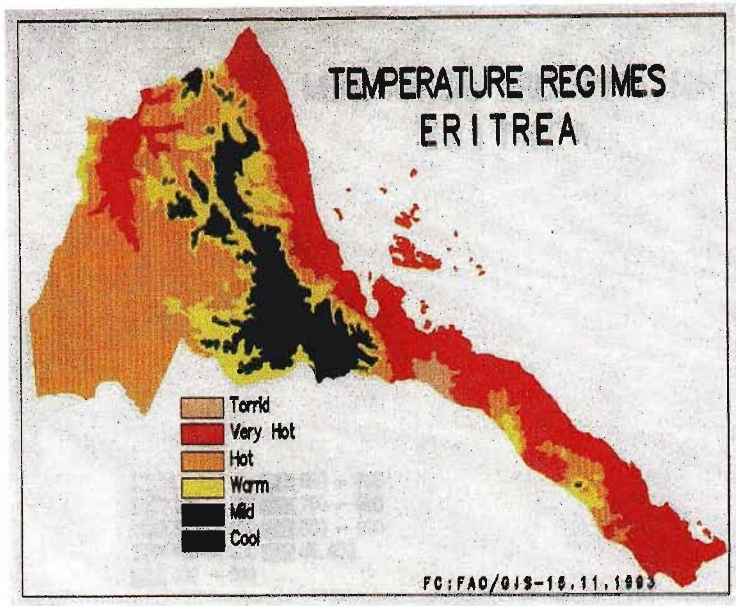


Figure 5.3 Temperature regimes of Eritrea (after FAO, 1994)

5.1.4 Soils

Knowledge of spatial and vertical properties of soils is a fundamental prerequisite for accurate hydrological design on small catchments. Unfortunately, no detailed soil survey has been undertaken to date in Eritrea that can entirely satisfy design hydrology criteria. The only soil map available in Eritrea is from the FAO-UNESCO soil map of the world. According to the FAO (1994), 12 out of the 28 Major Soil Groupings have been identified in Eritrea. These are *Arenosols, Calcisols, Gypsisols, Lixisols, Solonchaks, Leptosols, Luvisols, Cambisols, Fluvisols, Vertisols, Nitisols,* and *Regosols.* Their distribution is shown in Figure 5.4.

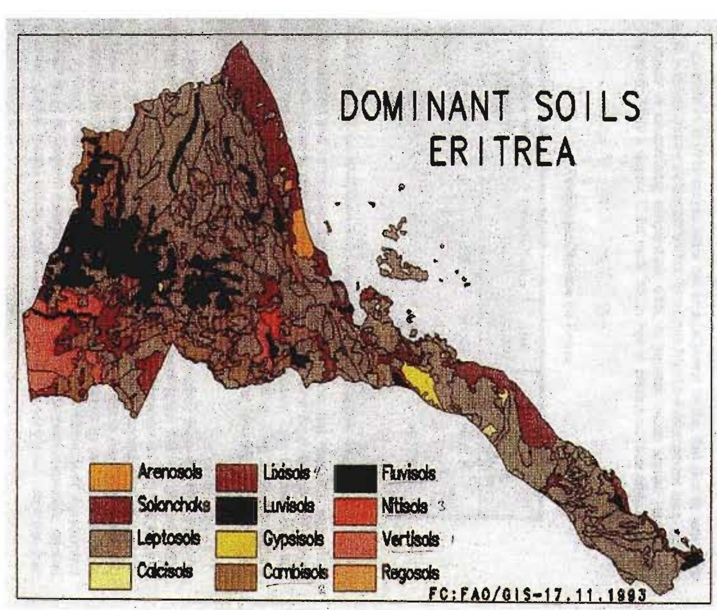


Figure 5.4 The FAO-UNESCO soil map of Eritrea (after FAO, 1994)

Some of the most important hydrological characteristics of each soil group are explained below.

Arenosols: These are soils with a texture of sand or loamy sand (Bridges, 1997). All *Arenosols* have certain features in common, e.g. their texture is coarse, which accounts for their high permeability and low water holding capacity (Landon, 1991). Eritrea has <1% of its total area covered by *Arenosols* (FAO, 1994).

Calcisols: Most *Calcisols* have a medium to fine texture and a good water holding capacity. They are dominated by the presence of lime with an ochric *A* horizon and a *cambic* or an *argic B* horizon (Bridges, 1997). *Calsisols* occupy <1 % of Eritrea's land (FAO, 1994).

Gypsisols: These soils are dominated by the presence of gypsum and have a yellowish-brown *ochric* horizon overlying a *cambic* or *argic B* horizon (Bridges, 1997). The gypsum crystals may cluster together and form a compact layer or a subsurface crust. Around 2% of Eritrea is covered by *Gypsisols* (FAO, 1994).

Lixisols: These soils have high accumulations of clay of red and yellow colour. They are erodible soils formed by strong weathering (Landon, 1991).Their percentage distribution is not more than 6% of the total area of Eritrea (FAO, 1994).

Solonchaks: These soils contain high accumulations of salts (Landon, 1991). They commonly occur where a high groundwater levels permit moisture to be drawn up to the soil surface and be evaporated, leaving a high concentration of salts in the upper part of the soil profile (Bridges, 1997). In Eritrea *Solonchaks* are found in the coastal areas of the Red Sea. These soils are not suitable for arable crop farming. Their percentage distribution is around 3% (FAO, 1994).

Leptosols: These are very shallow, but freely drained soils, with no gleyic or stagnic properties at shallow depth. They are free from high levels of soluble salts (FAO-UNESCO, 1990). Their shallowness or stoniness affects their water holding capacity. Because of their extreme shallowness they are not recommended for cultivation. *Leptosols* are one of the most widespread of the Major Soil Groupings in Eritrea, with almost 50% of its land dominated by these soils (FAO, 1994).

Luvisols: These are well developed soils on decalcified, fine or medium textured weathered residues from sedimentary rocks, loess and plateau drifts. They have an *argic B* horizon with an increased clay content of high base status and accumulation of clay content in their lower horizons (Bridges, 1997). As a result they drain poorly. According to the FAO (1994), around 3% of Eritrean soils are *Luvisols.*

Cambisols: According to FAO-UNESCO (1990), most *Cambisols* are medium textured and have a good structural stability, a high porosity, good internal drainage and a high water holding capacity. About 16% of Eritrean soils are *Cambisols* (FAO, 1994).

Fluvisols: These are soils of alluvial deposits. Being depositional and young, they display only weak horizon differentiation (FAO-UNESCO, 1990). It is evident that their recent deposition and wetness dominate as hydrological characteristics (Landon, 1991). These soil types cover around 9% of the total area of Eritrea (FAO, 1994).

Vertisols: These are clayey soils which crack widely when dry and swell when moist. They therefore have high runoff potential when wet, but it is low when they are dry. They are susceptible to erosion and cover around 10% of the total area of Eritrea (FAO, 1994).

Nitisols: These are soils with deep clay-enriched lower horizons with shiny ped surfaces (Bridges, 1997). They are well-drained and deep soils with a *nitic* horizon (Landon, 1991). They are, therefore, less susceptible to erosion than many other soils. *Nitisols* are very scarce, occupying < 1% of the total area of Eritrea (FAO, 1994).

Regosols: Weakly developed soils with a texture finer than sandy loam (Bridges, 1997), *regosols* are susceptible to erosion and possess low moisture holding capacity. In Eritrea they occupy <0.5% of the total area (FAO, 1994).

The FAO-UNESCO soil classes have been delimited at a coarse scale over Eritrea and it is difficult to distinguish the local hydrological properties from such a soil map. Detailed soil surveys are, therefore, required by hydrologists in order to asses the hydrological responses associated with different soil properties within a catchment and in the country as a whole.

5.1.5 Vegetation and Present Land Use

By and large the vegetation of Eritrea is very sparse. According to Van Buskirk (1999), Eritrean vegetation may be divided into two major categories, *viz.* highland and lowland vegetation, according to vegetation type and density. In general, the dominant vegetation types include *acacia*, *bushland*, *shrubland*, *savanna woodland*, *Juniperus procera* and *Olea africana* (Ministry of Land, Water and Environment, 1997). The *riverine* forests and *mangroves* play important ecological and economic roles in rural communities, but occupy only 1.5% and 0.1% respectively of the total area of the country.

According to Ghebru (1995), the estimated percentages of present land uses of Eritrea are as in Table 5.4.

Table 5.5 Estimated present land use of Eritrea (after Ghebru, 1995)

Land Use	Area (km^2)	Percentages of the Total Land
Cultivated land	10 848.2	8.9
Grazing and browsing land	59 848.0	49.1
Forest land	530.0	0.4
Currently unproductive land	3 660.9	3.0
Woodland and shrubland	6 703.9	5.5
Currently unutilisable land	40 309.0	33.1

5.1.6 Surface Water Resources

According to a report by Euroconsult (1997), the river basins of Eritrea may be divided into five main basins (Figure 5.5), *viz.* the *Setit (Tekeze), Gash-Mereb, Barka-Anseba, Red Sea* and the *Danakil Depression.*

The *Setit* river (known as the *Tekeze* in Ethiopia) rises in central Ethiopia and flows northwards, forming the border between Ethiopia and Eritrea in the far south-western part of the country. The *Setit* is a large basin (68 800 km^2), but only a small proportion of it is within Eritrean territory. It is also the only large perennial river in the country. In Sudan it joins the *Atbara,* one of the main tributaries of the *Nile*.

The *Gash-Mereb* basin lies north of the *Setit* and covers a total area of 23 200 km^2, of which 17 400 km^2 are within Eritrea. The *Mereb* rises near Asmara (cf. Figure 5.1) and flows southwards, then turns west to form the border between Ethiopia and Eritrea in the central part of the country. Only a relatively small part of the basin is in Ethiopia. Further west, it becomes the *Gash*. It flows into Sudan, but does not reach the sea, instead forming an inland delta north of Kassala. Flows in this basin, as throughout the rest of Eritrea, are seasonal with intermittent periods of rapid runoff in the rainy season. Generally speaking, the rivers are dry throughout the period November to April.

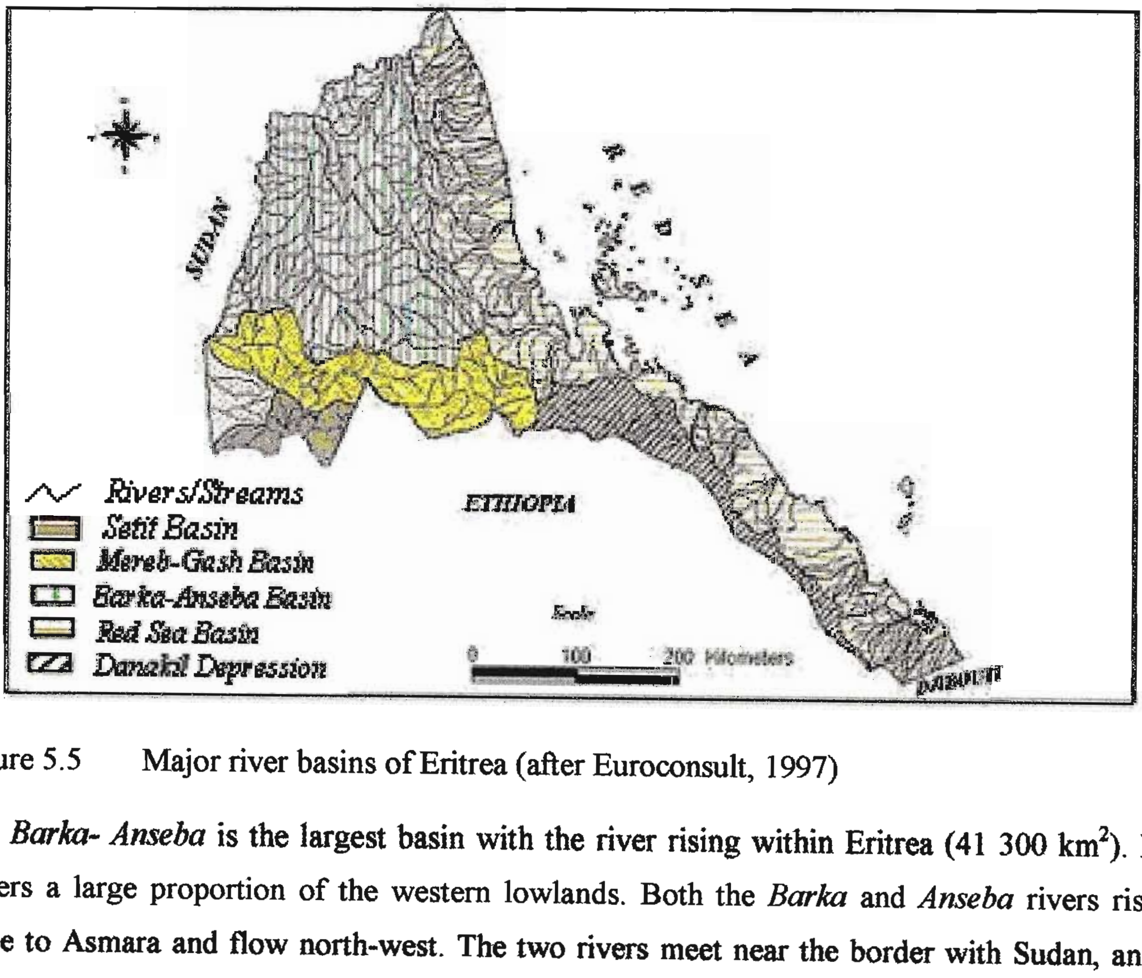


Figure 5.5 Major river basins of Eritrea (after Euroconsult, 1997)

The *Barka- Anseba* is the largest basin with the river rising within Eritrea (41 300 km^2). It covers a large proportion of the western lowlands. Both the *Barka* and *Anseba* rivers rise close to Asmara and flow north-west. The two rivers meet near the border with Sudan, and then flow into Sudan, finally flowing towards the Red Sea. Stormflows actually reach the sea only infrequently. The catchment areas for the *Anseba* and *Barka* sub-systems are 12 900 km^2 and 28 400 km^2 respectively.

The *Red Sea* basin is made up of numerous small separate basins, with a total area of about 54 500 km^2 if the *Danakil Depression* is included. The *Red Sea* rivers flow from the eastern escarpment towards the sea along the whole of Eritrea's coastline. The eastern lowlands are climatically different from the rest of the country. Generally they are much more arid and rainfall tends to be mainly in the period October to March. The eastern escarpment rivers respond to the main rainy season in the highlands (July and August), but can also experience significant runoff events during other periods.

The *Danakil Depression* and the southern part of the *Red Sea* basin lie in the most arid part of Eritrea, with mean annual rainfall of 100 mm or less. Runoff events are of very short duration and occur extremely irregularly. Many small rivers flow southwards into the *Danakil Depression*, lying in the south of the country, and into the adjoining part of Ethiopia. This is an internal drainage system from which flows do not reach the sea.

Streamflows throughout the country have, by and large, not been monitored and their magnitudes are largely unknown. Some previous attempts which have been made at stormflow modelling in Eritrea are reviewed in the section which follows.

5.2 Previous Attempts at Stormflow Modelling in Eritrea

According to a report by Euroconsult (1997), there appear to have been very few previous attempts at rainfall-runoff modelling in Eritrea. One of the first attempts at quantification of the available surface water resources of the country was that undertaken by Natural Resources Consulting Engineers (NRCE) in 1992, who estimated average monthly and annual flows using a weighed average runoff coefficient dependent upon catchment rainfall. This approach may be adequate for reconnaissance studies, but cannot yield sufficient information on the reliability of runoff or on the inter-annual variability of flows.

In a feasibility report by NRCE (1994) on the rehabilitation and expansion of the Aligidir irrigation project, a statistical analysis of recorded flows on the lower Gash was employed to derive the "median" (50% exceedance) and "firm yield" (80% exceedance) annual flows by using the log-Normal distribution. These design annual discharges were found to be distributed log-Normally and hence daily flows could be estimated using a random number generator. Single representative "unit seasonal hydrograph" was produced. This was scaled using the annual design flows derived earlier. According to Euroconsult (1997), this approach may be valid for a site such as the lower Gash where there is a reasonable quantity of flow data, but the method would be difficult to transpose to an ungauged area. Not only would it be difficult to derive suitable annual runoff volumes of the required exceedance probability, but disaggregation into realistic daily flows would be almost impossible. This modelling approach is too site specific to be more generally applicable throughout Eritrea.

The NRCE (1996) attempted to employ the SCS method to derive a dimensionless unit hydrograph using limited data available from Wadi Laba and Ruba Haddas to calibrate the model. The method could possibly be transferred to other ungauged parts of Eritrea. However, a number of uncertainties remain as to how the model was applied, particularly regarding the estimation of initial abstractions (losses of rainfall before runoff commences), which is one of the most difficult hydrological processes to model. As a result, the simulated runoff failed to approximate the observed runoff. The model, as described, was not thought to be suitable for wider application (Euroconsult, 1997).

Halcrow (1997) attempted to simulate surface runoff from storm rainfalls by plotting 3-day rainfalls over the catchment of the eastern escarpment against resulting peak flows. There was no discernible relationship at all, with the largest recorded rainfall of just over 80 mm yielding a flood peak of about 32 $m^3.s^{-1}$, whereas rainfalls of only 30 mm on other occasions produced peak flows of 400 and 512 $m^3.s^{-1}$. Halcrow's (1997) modelling approach was not meant to simulate runoff volumes or peaks from individual storm events, but rather to generate a series of flood events which reproduced the statistics of the historical data as realistically as possible. Thus, the intention was to generate the correct number of flood events for different times of year, and then to scale these flood events so that their magnitudes appeared to be representative of historical events (Euroconsult, 1997).

Colombo and Sarfatti (1996) utilised the SCS method to simulate the runoff volume of two subcatchments of the Mereb River, *viz.* the *Shiketi* and *Emni-Tzelim*, situated on the Eritrean highland. The Curve Numbers (CNs) were determined from remotely sensed information and used together with conventional field data. However, the results could not be verified against streamflow observations and, therefore, cannot be extended to other ungauged areas.

A more recent modelling study was attempted by Euroconsult (1997) for an assessment of the surface water resources throughout most of Eritrea. A SCS-based semi-distributed model which consists of two components was employed: one component to compute daily runoff volumes from daily rainfall inputs, and the second to distribute this runoff volume between flood and baseflow runoff. The approach adopted was to select as wide a range of catchments for their study and to use common adjustments to the calibration parameters across all catchments. As such, the calibration sites covered catchments in all the main river basins of the country.

The model was tested on catchments ranging from 200 to 21 000 km^2 and shown to give realistic representations of some complex hydrological processes over the wide variety of spatial scales. According to Euroconsult (1997), the model can be used for preliminary assessment of surface water resources and for assisting in the planning and development of surface water projects. However, it is not possible to apply this model for the design of hydraulic structures. The reasons are as follows:

- The flow information employed for model calibration and verification at the selected sites was insufficient and a subjective approach was used in model calibration and verification instead of using more objective calibration techniques. Hence, the model accuracy remains doubtful.
- The model used statistically generated rather than observed rainfall series as input and that could reduce the value of resulting flow series.
- The physical properties of the catchments from which final Curve Numbers, CN_f, were generated were highly oversimplified, especially when the antecedent soil moisture conditions of the catchments were considered.
- More than 90% of the *Setit* basin is outside of Eritrea and it was not possible to obtain the rainfall data needed to model this basin.

As a conclusion, therefore, it may be stated that previous hydrological modelling attempts in Eritrea cannot be used to simulate design floods from small catchments throughout most of the country because of the following reasons:

- First, there is at present no recommended hydrological model in Eritrea which has been widely verified.
- Secondly, most of the models used in previous studies were developed to solve particular problems and the solutions are too site specific for general use.

* * * * * * *

The next chapter deals with testing the SCS-*ACRU* stormflow modelling approach in Eritrea. This approach was previously proven to be successful under wide ranging environmental conditions in southern Africa (Schulze, 1984; Schmidt and Schulze, 1987).

6. TESTING THE SCS-*ACRU*-KÖPPEN APPROACH ON A SMALL CATCHMENT IN ERITREA

6.1 Introduction

The SCS-*ACRU* stormflow modelling approach has proved to be successful in many parts of southern Africa which have broadly similar climatic and physical conditions to those in Eritrea, *viz.* semi-arid to sub-humid climates with high inter- and intra-annual rainfall variability and where many operational catchments are small to medium sized (Schulze, 1982; 1984; Schmidt and Schulze, 1987). Nevertheless, if the approach is to be applicable with a high degree of confidence in Eritrea, it should be verified on Eritrean research catchments. Moreover, the regression equations developed to estimate values of *ΔS* from MAP within specified KCCs in southern Africa (Chapter 4) should be tested in Eritrea, if the hypothesis that "changes in...CN due to ASM conditions are similar universally for similar climatic regions" (Hypothesis 1, Chapter 1) is valid. For this reason, the SCS-*ACRU* stormflow modelling approach, when combined with the Köppen climate classification system as an indicator of regional indices of *ΔS,* is termed as the SCS-*ACRU*-Köppen, or SAK, stormflow modelling approach in this chapter.

Before testing the SAK modelling approach in Eritrea, it was first necessary to test the performance of the *ACRU* model *per se* on output from an Eritrean research catchment. This is done in the sections which follow. Following that, the SAK modelling approach is tested on the same catchment using the different methods of CN adjustments described in Chapter 3, and thereafter the relevant regression equations developed to estimate values of *ΔS* from MAP within a specified KCC, termed the *ACRU*-Köppen method, is evaluated.

As was mentioned in the introductory chapter (Chapter 1), a major problem in Eritrea is that of a lack of adequate input data to match the input demands of most conceptual-physical models. Unlike most soil water budgeting models, the *ACRU* model has been developed to accommodate alternative pathways to overcome data limitation problems. Where no parameter values are available, widely tested representative default values have been given as options in the *ACRU* User Manual (Smithers and Schulze, 1995). Furthermore, a hierarchy of certain input variables is available, depending on the level of resolution of information (Schulze, 1995a). Data, other than rainfall, which are required by the *ACRU* model for stormflow simulations were obtained as described in the sections which follow.

6.2 Background Information on the Afdeyu Research Catchment

For model verification, catchments representing a range of climates and which have relatively long and accurate records of rainfall and streamflow are ideally needed. Clearly, the lack of long term observed flow series in Eritrea (cf. Section 5.2) does not allow verifying output from the SCS and *ACRU* models under a range of different climatic conditions. Only one Eritrean research catchment, *viz.* the Afdeyu, with a relatively good streamflow record as well as soils and land use information, is available for verifying outputs from the two models. In the description of the catchment's attributes below, general information is usually followed by a sub-section on *ACRU* model input.

6.2.1 Location

Afdeyu is one of seven research stations of the Soil Conservation Research Programme (SCRP) which were established in the early 1980s in different agro-climatic zones of the east African highlands. It is located some 20 km north-west of Asmara, in the Maekel zone, Serejeka sub-zone, about 2 km east of the road from Asmara to Keren (cf. Figure 5.1). The catchment with an area of 1.77 km^2 has an altitudinal range of 160 m from 2300 to 2460 m above sea level (Stillhardt *et al.,* 2002). According to the agro-climatic classification of Eritrea, the catchment is located in the highland zone (Figure 6.1). Locational input required by the *ACRU* model is given in Table 6.1. The mode was run as one spatial entity, without subdivisions into subcatchments.

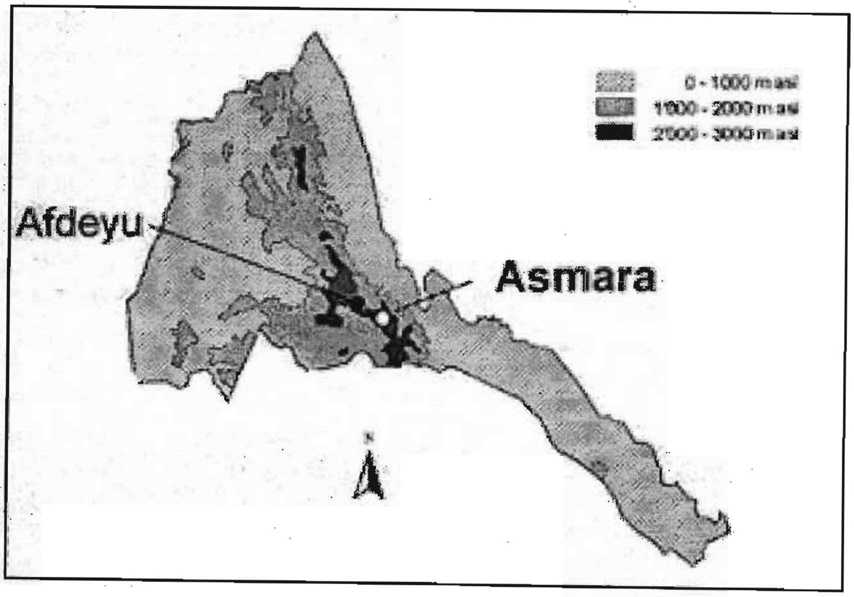


Figure 6.1 Location of the Afdeyu research site (after Stillhardt *et al.,* 2002)

Table 6.1 Locational information for the *ACRU* model, with *ACRU* model variable names in upper case in brackets

Catchment Area (CLAREA)	Mean Altitude (ELEV)	Latitude (ALAT) (degree/decimal)	Longitude (ALONG) (degree/decimal)
1.77 km^2	2350 m	15.53° N	38.87° E

6.2.2 Rainfall

According to a report of the Ministry of Agriculture (2000), the annual rainfall of the area varies considerably from year to year. The maximum and minimum annual rainfall records from 12 years show a maximum of 695.4 mm in 1995 and a minimum of 244.1 mm in 1990. The mean annual rainfall is estimated to be 556 mm. Figure 6.2 illustrates the standardised climate diagram of the research area. In some years there is a bimodal rainfall regime, but the variability during the short rainy season is high and rainfall is often erratic. The period from November to April and the month of June experience little to no rain (Stillhardt *et al.*, 2002).

Stillhardt *et al.* (2002) have calculated that, on average, rainfall is recorded on 53 days of the year on the Afdeyu research catchment. Each of the rainy months July to September has, on average, rainfall on 10 days of the month. The number of rainy days decreases towards the winter months, with November to January recording very few, if any, days with rainfall.

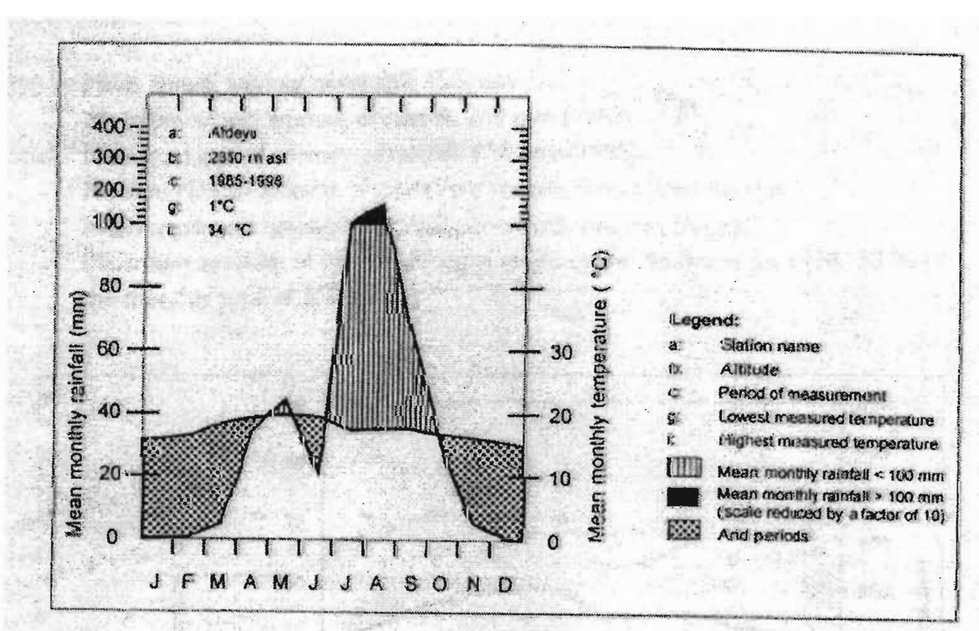


Figure 6.2 Climate diagram for the Afdeyu catchment (after Stillhardt *et al.*, 2002)

Figure 6.3 shows the relationships between the average rainfall intensity per complete event and its duration for 3 780 rainfall measurements on the research catchment. The highest rainfall intensities are observed during storms of short duration, while rainfalls with low intensity are generally recorded during events of long duration (Figure 6.3). An average of 7 thunderstorms occur per annum at Afdeyu during the rainy months of July, August and September (Stillhardt *et al.*, 2002).

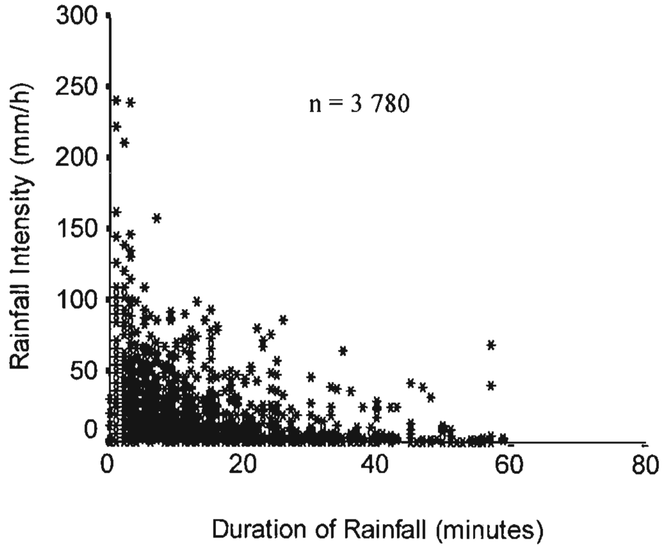


Figure 6.3 Relationship between intensity and duration of rainfall (1984-1998) for the Afdeyu catchment

An analysis of the direction of rainfall storm movement has been undertaken for the period from 1986 to 1998. It indicates that the dominant direction of rainfall is spread from the north-west to the south-east. In 89% of all recorded events, rainfall started in the afternoon (Stillhardt *et al.*, 2002).

6.2.3 Temperature and Potential Evaporation

6.2.3.1 General

Air temperature was recorded at Afdeyu on a daily basis at 1.5 m above ground level for the period 1986 to 1998. Monthly means of daily temperatures range from 15.5 °C in January to 19.5 °C in May. Figures 6.4a and 6.4b show the averaged minimum, mean and maximum values of daily air temperature and soil surface temperature respectively. The annual mean of daily minimum air temperatures is 11.2 °C and that of maximum temperature is 23.5°C.

Soil surface temperature was measured daily under shelter at 0.1 m above the ground for the period from 1988 to 1994. In more than 98% of the records the mean daily soil surface temperature was higher than the mean daily air temperature. The temperature difference between air and soil surface was greater during the dry season than during the rainy season (Stillhardt *et al.*, 2002).

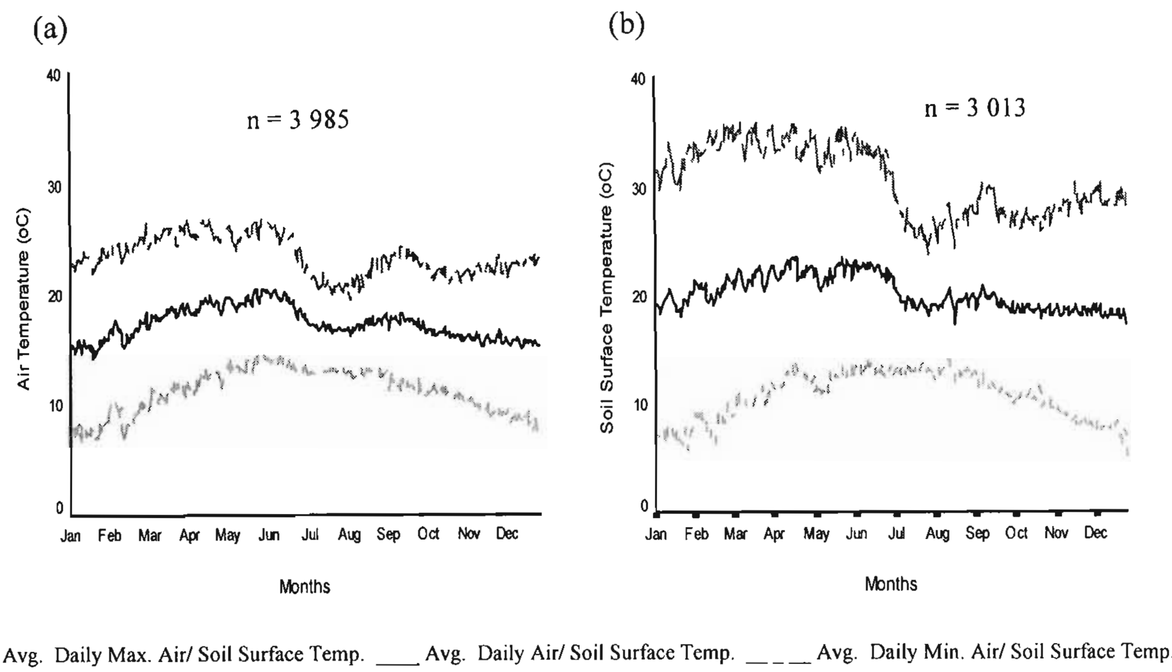


Figure 6.4 Averaged daily minimum, mean and maximum air temperatures (a) and averaged daily minimum, mean and maximum soil surface temperatures (b) for the Afdeyu catchment (after Stillhardt *et al.*, 2002)

6.2.3.2 Temperature input to the ACRU model

Temperature information is required, *inter alia,* in order to estimate A-pan equivalent reference potential evaporation in the *ACRU* model. Monthly means of daily maximum and minimum temperature at the Afdeyu catchment are given in Table 6.2.

Table 6.2 Monthly means of daily minimum and maximum temperature values (°C) at the Afdeyu catchment (after Ghebremedhin, 1998), as input to the *ACRU* model

Variable	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Maximum (°C)	24.5	24.9	26.6	25.2	26.5	25.5	21.9	22.2	24.9	24.2	23.6	23.8
Minimum (°C)	8.6	9.6	12.0	14.4	14.1	13.9	13.3	13.6	12.7	11.6	10.3	9.2

6.2.3.3 *Reference potential evaporation information*

ACRU is a multi-level model designed to accommodate different levels of available input. Values of reference potential evaporation (A-pan equivalent) may be input as daily or monthly evaporation pan data or be computed by different temperature-based equations. Monthly totals of A-pan evaporation, estimated using the local climate estimator *LocClim 2.0* developed by FAO (2002), are given in Table 6.3 below.

Table 6.3 Monthly totals of A-pan equivalent reference potential evaporation (mm) for the Afdeyu catchment

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
111.4	113.1	147.7	136.1	153.1	162.4	130.5	128.9	129.8	157.9	143.8	133.9

6.2.4 Soils

6.2.4.1 *General*

Soils of the Afdeyu catchment are mainly *Cambisols* developed on metamorphic volcanic material of the Proterozoic age (Ghebremedhin, 1998). According to Mebrahtu (1997), soil depths generally range from shallow to moderately deep and texturally they range from loam to silt clay loam. Figure 6.5 shows the points in the Afdeyu catchment from which soil samples were taken for the analysis of soil texture, with the results presented in Table 6.4.

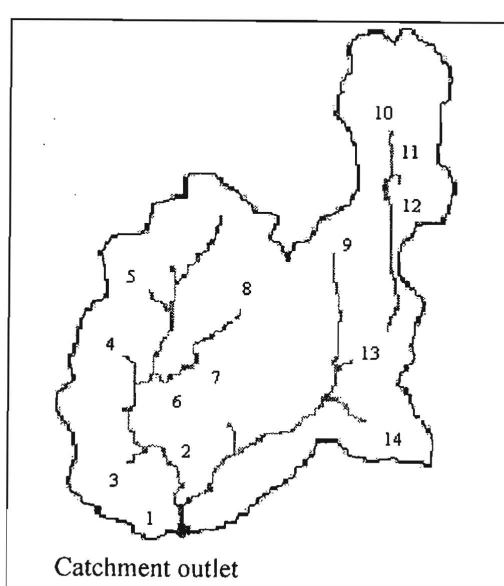


Figure 6.5 Sample points for soil texture analysis in the Afdeyu catchment (after Mebrahtu, 1997)

Table 6.4 Soil texture at the sample points shown in Figure 6.5 (after Mebrahtu, 1997)

Site No	Soil Depth (m)	Sand (%)	Silt (%)	Clay (%)	Soil Texture
1	0.00 - 0.06	27.9	45.5	26.6	Loam
	0.30 - 0.36	20.0	45.5	34.5	Clay loam
	0.60 - 0.66	20.6	48.6	30.8	Clay loam
2	0.00 - 0.06	14.8	49.1	36.1	Silt clay loam
	0.30 - 0.36	25.3	45.8	28.9	Clay loam
	0.60 - 0.66	24.6	47.5	27.9	Clay loam
3	0.00 - 0.06	46.9	41.8	11.3	Loam
	0.30 - 0.36	45.1	42.4	12.5	Loam
	0.60 - 0.66	44.5	43.3	12.2	Loam
4	0.00 - 0.06	43.5	43.2	13.3	Loam
	0.30 - 0.36	48.2	42.6	9.2	Loam
	0.60 - 0.66	30.0	51.4	18.6	Silt loam
5	0.00 - 0.06	38.2	47.1	14.7	Loam
	0.30 - 0.36	25.5	60.8	13.7	Silt loam
	0.60 - 0.66	34.7	52.6	12.7	Silt loam
6	0.00 - 0.06	47.9	41.1	14.7	Loam
	0.30 - 0.36	40.9	60.8	13.7	Loam
	0.60 - 0.66	42.4	52.6	12.7	Loam
7	0.00 - 0.06	23.7	53.5	22.8	Silt loam
	0.30 - 0.36	20.6	56.8	22.6	Silt loam
	0.60 - 0.66	22.9	52.1	25.0	Silt loam
8	0.00 - 0.06	21.8	47.7	30.5	Clay loam
	0.30 - 0.36	25.5	52.6	21.9	Silt loam
	0.60 - 0.66	13.8	57.7	28.7	Silt clay loam
9	0.00 - 0.06	42.4	38.1	19.5	Loam
	0.30 - 0.36	30.1	45.1	24.8	Loam
	0.60 - 0.66	33.3	42.5	24.2	Loam
10	0.00 - 0.06	42.6	41.4	14.0	Loam
	0.30 - 0.36	39.9	37.3	22.8	Loam
	0.60 - 0.66	47.6	33.6	18.8	Loam
11	0.00 - 0.06	36.3	44.3	19.4	Loam
	0.30 - 0.36	31.5	44.4	24.1	Loam
	0.60 - 0.66	36.4	42.1	21.5	Loam
12	0.00 - 0.06	58.9	29.8	11.3	Loam
	0.30 - 0.36	51.7	36.9	11.4	Sandy loam
	0.60 - 0.66	66.3	28.4	5.3	Sandy loam
13	0.00 - 0.06	48.7	42.0	9.3	Loam
	0.30 - 0.36	35.5	52.3	12.2	Silt loam
	0.60 - 0.66	37.2	53.5	9.3	Silt loam
14	0.00 - 0.06	22.9	46.6	30.5	Silt clay loam
	0.30 - 0.36	30.8	49.3	19.9	Silt loam
	0.60 - 0.66	28.9	53.8	17.3	Silt loam

The continuous utilisation of the land without application of fertilizers has rendered the fertility of the land to be low. The organic content of the soil is very low (Ghebremedhin, 1998). This leads to weak soil structure and, subsequently, to a high erosion risk. In certain parts of the catchment, the content of gravel and stones is remarkably high and it protects topsoil from erosion while preventing soil moisture losses by reducing evaporation from the soil surface.

6.2.4.2 Soils input to the ACRU model

In regard to soils input to the *ACRU* model, amounts of soil water content (θ) at three critical soil water retention levels, *viz.* at *total porosity* (i.e. saturation), *drained upper limit* (i.e. field capacity) and the *lower limit* (i.e. permanent wilting point) for the top- and subsoil horizons have to be estimated, either from the vertical distribution of clay content down the soil profile or from laboratory analyses of soil samples at different depths.

Since the vertical distribution of clay content along the soil profile in the research catchment is currently unknown, the soil water content at the lower limit (θ_{PWP}) for the topsoil (WP1) and subsoil (WP2), plus the soil water content at drained upper limit (θ_{DUL}) for the topsoil (FC1) and subsoil (FC2) were estimated using Equations 6.1 and 6.2, developed by Hutson (1984) and contained in the *ACRU* User Manual (Smithers and Schulze, 1995). The results are presented in Table 6.6.

$$\theta_{PWP} = 0.0602 + 0.00322Cl\% + 0.00308Si\% - 0.0260\rho b \quad (r^2 = 0.79) \qquad 6.1$$

$$\theta_{DUL} = 0.0558 + 0.00365Cl\% + 0.00554Si\% + 0.0303\rho b \quad (r^2 = 0.68) \qquad 6.2$$

where

θ_{PWP}	=	soil water content at lower limit ($m.m^{-1}$),
θ_{DUL}	=	soil water content at drained limit ($m.m^{-1}$),
ρb	=	bulk density ($mg.m^{-3}$),
Cl	=	percentage of clay content (%), and
Si	=	percentage of silt content (%).

The sand, silt and clay contents for the two horizons of the research catchment are given in Table 6.4. The typical values of bulk density as well as the water content at total porosity for the topsoil (PO1) and subsoil (PO2) are taken from Table 6.5 for each major texture class. Based on field experiences and the information contained in Table 6.4, the thickness of the topsoil (DEPAHO) and subsoil (DEPBHO) were set at 0.30 m and 0.60 m respectively. Since the soil texture of the research catchment is entirely of the loamy type (cf. Table 6.4), the fraction of "saturated" soil water to be redistributed daily from the topsoil into the subsoil when the topsoil is above its drained upper limit (ABRESP), and from the subsoil into the intermediate/groundwater store when the subsoil is above its drained upper limit (BFRESP), were both set to 0.6, based on the information given in the Table 6.5.

Table 6.5 Typical values of selected soil hydrological input values for different soil texture classes, based on various sources and given in Schulze (1995a)

Soil Texture Class	Horizon	Typical percentage of: Clay	Silt	Sand	Organic Carbon	Bulk Density (mg.m^{-3})	Total porosity (m^3.m^{-3})	Effective Porosity (m^3.m^{-3})	Redis. Fraction (day^{-1})
Clay	Topsoil (untilled)					1.22	.470	-	
	Topsoil (tilled)	50	37	13	0.38	1.20	.589* 538^	.536	.25
	Subsoil					1.37	.482	.470	
Loam	Topsoil (untilled)					1.26	.512	-	
	Topsoil (tilled)	18	25	57	0.52	1.09	.589* .524^	.512	.50
	Subsoil					1.42	.480	.464	
Sand	Topsoil (untilled)					1.32	.446	-	
	Topsoil (tilled)	3	4	93	0.71	1.17	.559* .503^	.452	.80
	Subsoil					1.50	.440	.430	
Loamy Sand	Topsoil (untilled)					1.31	.452	-	
	Topsoil (tilled)	7	7	86	0.61	1.16	.562* .505^	.457	.70
	Subsoil					1.51	.477	.432	
Sandy Loam	Topsoil (untilled)					1.26	.486	-	
	Topsoil (tilled)	10	15	75	0.71	1.11	.582* .524^	.505	.65
	Subsoil					1.46	.466	.448	
Silty Loam	Topsoil (untilled)					1.13	.530	-	
	Topsoil (tilled)	18	55	27	0.58	1.01	.619* .575^	.527	.45
	Subsoil					1.34	.500	.495	
Sandy Clay Loam	Topsoil (untilled)					1.35	.435	-	
	Topsoil (tilled)	27	8	65	0.19	1.25	.523* .500^	.486	.50
	Subsoil					1.58	.405	.393	
Clay Loam	Topsoil (untilled)					1.22	.474	-	
	Topsoil (tilled)	32	22	46	0.10	1.12	.576* .541^	.497	.40
	Subsoil					1.41	.456	.451	
Silty Clay Loam	Topsoil (untilled)					1.25	.489	-	
	Topsoil (tilled)	33	46	21	0.13	1.21	.544* .528^	.509	.35
	Subsoil					1.40	.473	.469	
Sandy Loam	Topsoil (untilled)					1.35	.393	-	
	Topsoil (tilled)	40	5	55	0.38	1.25	.529* .492^	.430	.40
	Subsoil					1.53	.428	.423	
Silty Clay	Topsoil (untilled)					1.23	.476	-	
	Topsoil (tilled)	50	37	13	0.38	1.20	.547* .536^	.531	.35
	Subsoil					1.38	.480	.476	

* Freshly tilled ^ End of season value Redis = Redistribution

Table 6.6 Horizon thickness (m), critical soil water retention constants (m.m^{-1}) and redistribution fractions for typical top- and subsoil horizons in the Afdeyu research catchment, as input to the *ACRU* model

DEPAHO (m)	DEPBHO (m)	WP1 (m.m^{-1})	WP2 (m.m^{-1})	FC1 (m.m^{-1})	FC2 (m.m^{-1})	PO1 (m.m^{-1})	PO2 (m.m^{-1})	ABRESP (fraction)	BFRESP (fraction)
0.30	0.60	0.203	0.206	0.443	0.424	0.563	0.499	0.60	0.60

6.2.5 Vegetation, Land Use and Its Management

6.2.5.1 Vegetation

Several decades ago the research area was still covered by various types of trees and shrubs. According to the local inhabitants living there, the dominant trees were *Olea africana, Maytenus senegelas, Rhus abyssinia* and species of *Eucalyptus*. At present the area has very few indigenous trees left as a result of heavy exploitation for fuel and construction purposes.

6.2.5.2 Land use and its management

The research catchment is an agricultural area dominated mainly by crops of barley and wheat, which together cover more than 50% of the total cropland, while areas of mixed crops such as maize, soyabean and potato occupy around 22%. Approximately 20% is usually reserved every year as fallow land. Grass (veld) occupies 4% while the remaining 4% is impervious areas, including stone bunds. According to Negash and Habte (1999), different types of crop rotations and intercropping have been practised in the research catchment.

Contour ploughing is the most common field preparation technique. However, in the highlands farmers plough three times after fallowing. The first contour ploughing takes place in September to promote infiltration of water and aeration in the soil. The second ploughing takes place along the slope in November to mix the soil and in January the final ploughing is undertaken, again along the contour, followed by another ploughing in May. Stone bunds along the contour of the farm fields are used for soil and water conservation (Figure 6.6). Check dams are also used along the gullies to check the water flow and retain the sediments (Ghebremedhin, 1998).

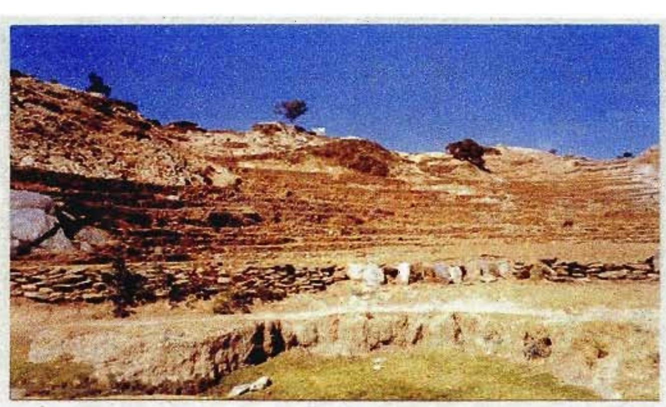


Figure 6.6 Stone bunds along the contour of fields for soil and water conservation in the Afdeyu catchment

6.2.5.3 Land use related input to the ACRU model

Land cover plays a significant role in the plant and soil water evaporation processes. This is particularly true in the case of agricultural crops, which are sown following land preparation, may be irrigated, may suffer water deficiencies and finally are harvested, all with considerable variation temporally and geographically to water usage (Schulze, 1984).

Area-weighted monthly crop (i.e water use) coefficients (CAY) were estimated from information in the *ACRU* User Manual (Smithers and Schulze, 1995) and in Stern (1979) for the crops mentioned in the above sub-section (Sub-section 6.2.5.2). Crop interception losses per rainday (VEGINT) were estimated for the crops grown and the seasonality of the rain. The fraction of active root system in the topsoil horizon (ROOTA) was set at 0.85 during the growing period, while during the dormant period evaporation losses are expected from the soil surface only and the root fraction is then 1.00. Table 6.7 gives values of the land cover parameters determined for each month of the year for the Afdeyu catchment.

Table 6.7 Land cover information used in the *ACRU* model for the Afdeyu research catchment

Variable	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
CAY	0.30	0.30	0.60	0.85	1.05	1.00	1.00	1.00	0.95	0.85	0.65	0.30
VEGINT	0.80	0.80	0.90	0.90	0.95	1.50	1.55	1.50	1.50	1.50	0.90	0.50
ROOTA	1.00	1.00	1.00	0.90	0.85	0.85	0.85	0.85	0.85	0.85	0.90	1.00

6.2.6 Streamflow

6.2.6.1 River discharge observations

River discharge is recorded autographically at the outlet of the research catchment using an Ott type R16 recorder. At an artificial channel cross-section, the automatic streamflow gauge records the changes in stage height of the water during the discharge periods (Figure 6.7). The chart rolls have a temporal resolution of 10 minutes. The water level serves as the basis for calculating the volume of discharge, once a stage-discharge relationship is established (Stillhardt *et al.*, 2002).

The following methods and devices were used to determine the stage-discharge relations: current meter, salt dilution, dye dilution and dipping bar. During every storm, when the water was considered to be coloured brown, one litre samples were taken at 10 minute intervals. When the colour of the water gradually changed from brown to clear, the frequency of sampling was reduced to a 30 minute or one hour intervals. The one litre samples were filtered and prepared for further laboratory analysis (Stillhardt *et al.*, 2002).

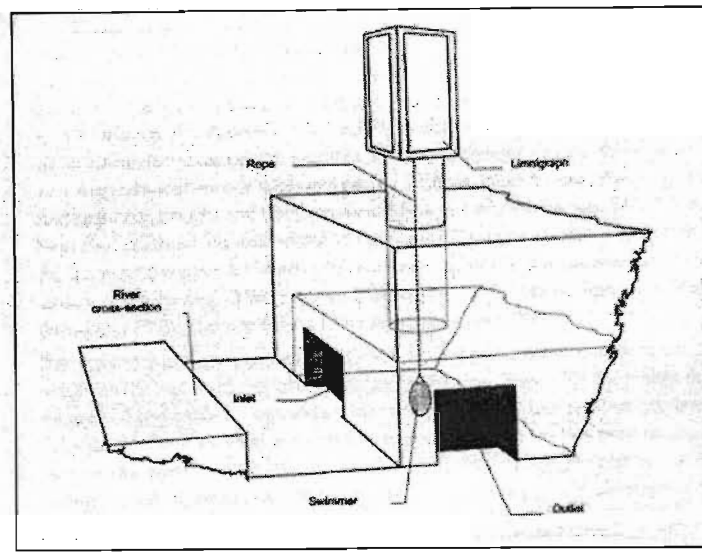


Figure 6.7 River discharge gauging technique used at the Afdeyu catchment (after Stillhardt *et al.*, 2002)

6.2.6.2 Streamflow simulation control variables to the ACRU model

Following recommendations in the *ACRU* User Manual (Smithers and Schulze, 1995), the coefficient of initial abstraction was set at 0.2 during the growing season from April- October and 0.3 during the remaining months.

Afdeyu is a very small catchment and, other than those areas under crops, is sparsely vegetated. Observations of streamflow show that 99% of the total stormflow generated passes the catchment outlet on the same day as the rainfall event. Hence the catchment's quickflow response, QFRESP, was set at 0.99. Effective depth of the soil from which stormflow is generated (SMDDEP) was set to the value of the thickness of the topsoil horizon, *viz.* 0.3 m. Baseflow was excluded from the simulated streamflow (IRUN = 0). No impervious areas are connected directly to the watercourse (ADJIMP = 0.0), but 4% is occupied by impervious areas which are not adjacent to a watercourse (DISIMP = 0.04). Impervious surface storage capacity was set at 1 mm (STOIMP =1.0). Table 6.8 presents the streamflow simulation control variables for use with the *ACRU* model in the Afdeyu catchment.

Table 6.8 *ACRU* model streamflow simulation control variables for the Afdeyu catchment

QFRESP	SMDDEP	IRUN	ADJIMP	DISIMP	STOIMP
0.99	0.30	0.00	0.00	0.04	1.00

6.3 Simulation of Stormflows from the Afdeyu Catchment with the *ACRU* Model

The purpose of this section is to evaluate the performance of the *ACRU* model's simulated flows from a research catchment in Eritrea, because the *ACRU* model's soil water budgeting procedures are employed to estimate the values of ΔS for purposes of CN adjustments for soil moisture status. Figure 6.8 shows a visual plot of the *ACRU* model simulations (monthly totals of daily values) vs observations on a month-by-month basis for the period of observation at the Afdeyu catchment from 1985-1999. Data from 1991-1993 are missing. Despite the relatively limited level of information on climate, soils and land use for the Afdeyu catchment, the monthly totals of simulated daily flows from the *ACRU* mimicked the corresponding observed flows excellently, with the one exception of August 1998, where the model overestimated by around 28%.

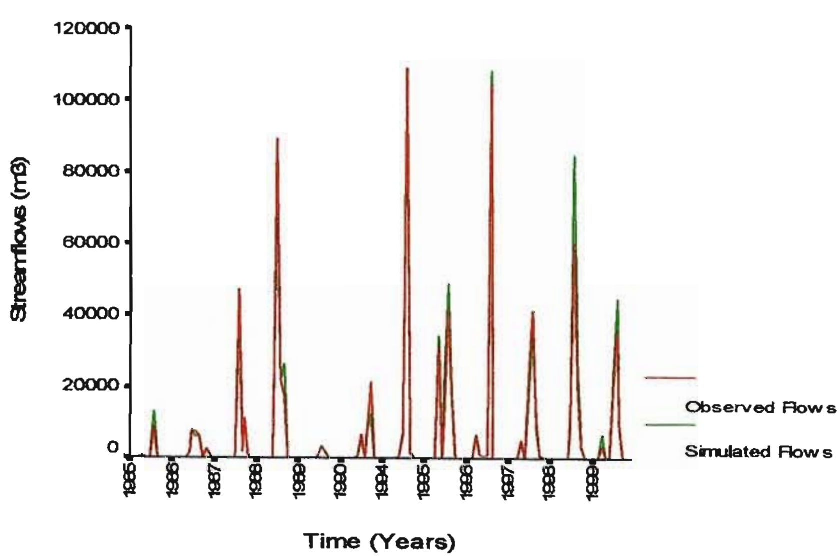


Figure 6.8 Monthly totals of daily *ACRU* simulated versus observed flows (m^3) in the Afdeyu catchment for the period of 1985- 1999, with missing data from 1991-1993

A plot of simulated versus observed daily flows, as well as monthly totals of daily flows, reveals a very high performance of the model, with r^2 = 0.94 for the analysis daily flows (Figure 6.9a) and r^2 = 0.97 for the analysis of monthly totals of daily flows (Figure 6.9b). The relationship is especially strong for less extreme events, while there is slightly more scatter at high flows. While there might have been occasional misreading of the raingauge, or wind flow causing turbulent eddies around the raingauge orifice, which occurs commonly in the torrential and erratic storm events experienced at Afdeyu, only one inlier point was found in the daily analysis (cf. Figure 6.9a).

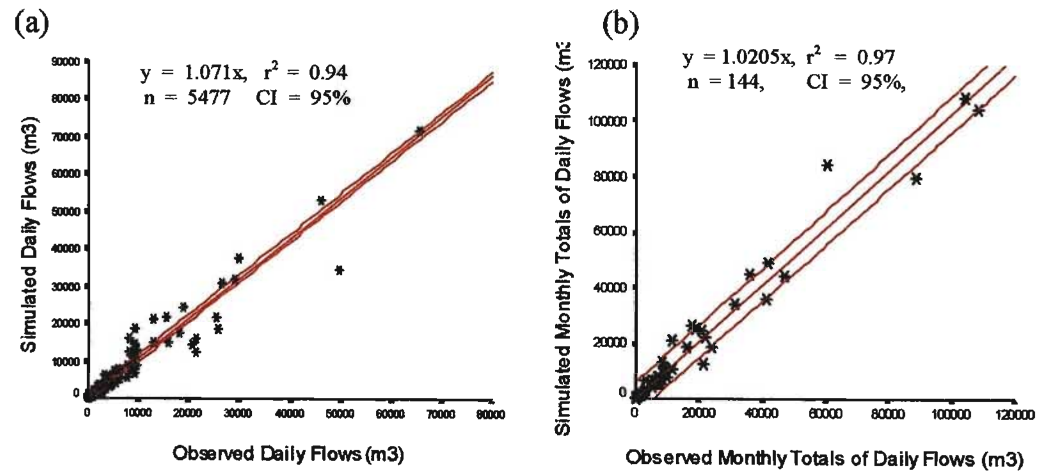


Figure 6.9 Scattergrams of *ACRU* simulated daily flows (a) and monthly totals (b) versus observed flows for the Afdeyu catchment for the period 1985-1999, with missing data from 1991-1993

The excellent simulations of the *ACRU* model are confirmed by the accumulated monthly and annual flows, as shown in Figure 6.10, which illustrate clearly that the total values of flows were simulated correctly.

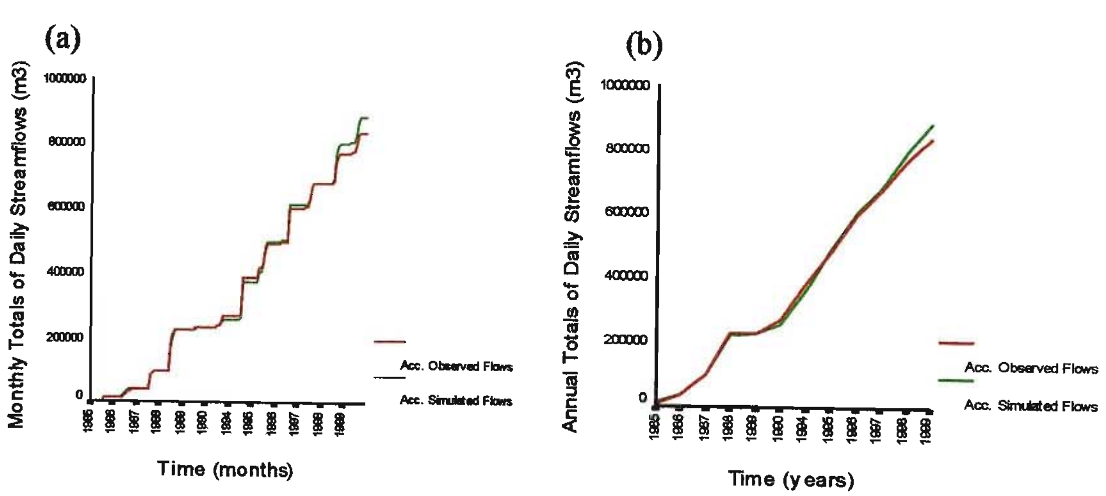


Figure 6.10 Monthly (a) and annual (b) simulated versus observed accumulated flows for the Afdeyu catchment for the period 1985-1999, with missing data from 1991-1993

The above results, although from only one research catchment in Eritrea, illustrate that the *ACRU* model may be used with confidence in further studies.

6.4 Simulation of Peak Discharges from the Afdeyu Catchment

In addition to estimating stormflows, the estimation of peak discharge is the other important component of the SCS approach. Ideally, therefore, peak discharges should also be verified, particularly with respect to the design of hydraulic structures. The lack of adequate observed peak discharge records in Eritrea does not, unfortunately, allow for verification of the peak discharge component of either the *ACRU* or SCS-SA model. However, since peak discharge from small catchments is closely related to the stormflow volume (Schmidt and Schulze, 1987; Schulze and Schmidt, 1995), it may be assumed that peak discharges would also have been simulated with a relatively high level of confidence.

6.5 Simulating Stormflows from the Afdeyu Catchment using the SCS-*ACRU*-Köppen Approach

In Chapter 4 it was concluded that, because of its conceptually sound approach, the regression equations developed to estimate values of ΔS from MAP for specified KCCs and soil/land cover combinations in southern Africa could be applied universally for the same climate classification system and similar soil/land cover combinations. However, a user can only apply the *ACRU*-Köppen estimates with confidence once the output of the SCS-SA model, using these KCC-based regression equations, has been compared for accuracy against the model outputs from the three methods of CN adjustment described in Chapter 3, *viz.* the water budget method (after Hawkins), the original SCS method of three discrete AMC classes, as well as the method where CNs remain unadjusted. Data required by the SCS method for stormflow simulation were obtained as described below.

6.5.1 Rainfall Depth

Rainfall is the major hydrological driver in rainfall-runoff models and any errors in rainfall estimates are amplified in stormflow simulations. This implies that the success of stormflow modelling studies depends to a large extent on the accurate estimate of areal rainfall within a catchment (Schulze *et al.,* 1995). In order to account for the spatial variability of the rainfall over the Afdeyu catchment, it was deemed necessary to investigate the estimation of the areal rainfall from the surrounding raingauge network. Using the Thiesssen polygon method of assessing areal rainfall with three stations, it was found that the raingauge inside the small (1.77 km^2) research area was representative of the entire catchment's rainfall. One day design rainfalls for the 2, 5, 10 and 20 year return periods were obtained by applying the log-Pearson Type 3 distribution to the annual maximum daily rainfalls for each chronological year of the 13 years of rainfall records. The design rainfalls were used to compute the corresponding daily stormflow volumes for those same selected return periods.

6.5.2 Determination of Curve Numbers and Adjustment for Antecedent Soil Moisture

An hydrological soil grouping was made from prior field observations and research based on the final infiltration rates and soil texture. The catchment was divided into two sub-catchments on the basis of major land uses, *viz.* cultivated small grains and grasssland. Initial CNs, i.e. CN_{II}s, were determined according to soils and land cover properties only, with no regard to soil moisture conditions. Table 6.9 shows the soil properties, land covers and their treatments of the Afdeyu catchment.

Table 6.9 Initial Curve Numbers obtained from the soil, land cover as well as treatment and stormflow potential characteristics of the Afdeyu catchment, based on field work

Sub-Catchment	Area (km^2)	% Area	Soil Texture	Soil Depth	SCS Soil Grouping	Land Cover	Treatment	CN_{II}
1	1.71	96.6	Loam	Moderate	B	Cultivated land (small grain)	Planted on contour	74
2	0.06	3.4	Clay Loam	Shallow	C	Grassland	Moderate condition	79

The CN_{II}s were adjusted according to the different methods of CN adjustments described in Chapter 3, in order to represent the catchment's soil moisture status typically prevailing before design rainfall events occur. In the following sub-section the results for each method of CN adjustment are discussed.

6.5.3 Result and Discussions

The design stormflow volumes from observed records for the selected return periods are given in m^3 in Table 6.10. The differences in results between the different methods of CN adjustment applied to the design flood estimation may be seen clearly from the values in

Figure 6.11. The model's simulation outputs using the water budget (after Hawkins) and *ACRU*-Köppen methods of CN adjustment are in close agreement with the observed stormflow volumes for the selected return periods, when compared to the much poorer simulation outputs when using the CN adjusted by the original SCS-AMC classes and unadjusted CN methods. Based on a ranking of results for the four selected return periods the *ACRU*-Köppen slightly outperforms the water budget technique.

Table 6.10 Design stormflows for selected return periods at the Afdeyu catchment, simulated by four SCS-based techniques and with ranking given in parenthesis

Return Period (years)	Observed Flows (m^3)	Design Flows (m^3)			
		CN Adjusted by Water Budget	CN Adjusted by *ACRU*-Köppen	CN Unadjusted	CN Adjusted by SCS-AMC Classes
2	18 074	20 723 (1)	20 947 (2)	22 380 (3)	6 186 (4)
5	41 097	45 390 (3)	45 390 (3)	41 444 (1)	29 637 (4)
10	59 415	64 007 (3)	61 978 (1)	53 725 (4)	63 612 (2)
20	78 957	81 068 (2)	77 659 (1)	67 418 (3)	121 399 (4)

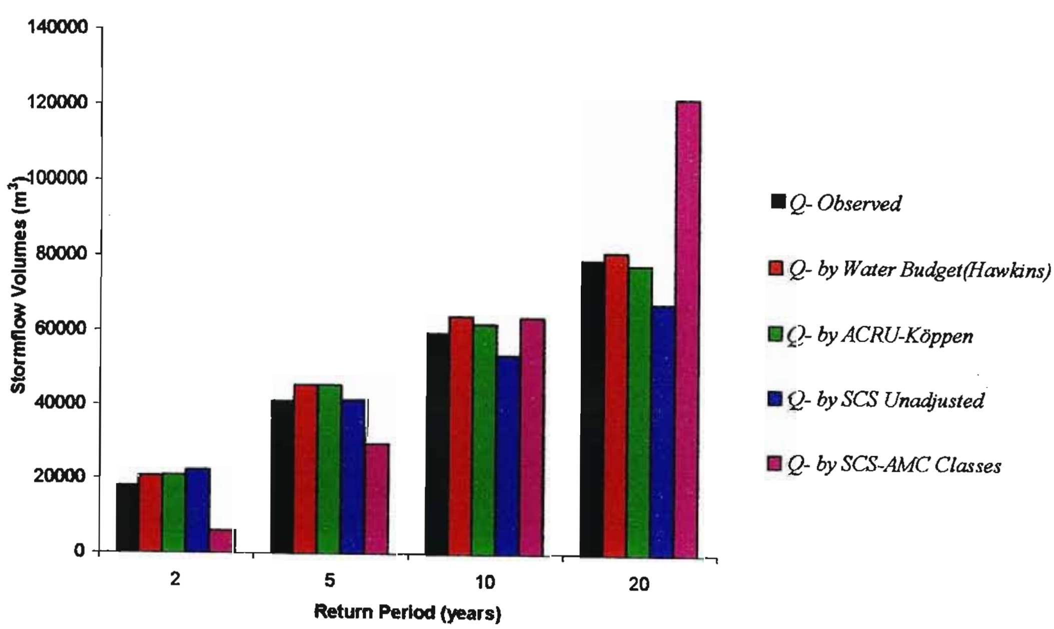


Figure 6.11 Bargraphs of design stormflow volumes for the Afdeyu research catchment generated from design daily rainfalls using water budget, *ACRU*-Köppen, SCS unadjusted and SCS-AMC methods of Curve Number adjustments

The model simulation by the original SCS-AMC classes was very poor, with stormflow volumes for 2 and 5 return year periods under-estimated by around 65% and 28% respectively, while at the 20 year return period it was over-estimated by 53%. Using the so-called "initial" catchment soil moisture conditions (CN unadjusted), the model generated realistic flow estimates for 2 and 5 return year periods, but under-estimated by around 10% and 15% for the 10 and 20 year return periods respectively.

Afdeyu is located in a semi-arid environment in which very marked event-to-event changes in soil water content can occur. The estimates of stormflow volume are highly sensitive to ASM, as in such areas the antecedent conditions of the soil play a fundamental role in the hydrological response of individual events (Schulze, 1982). The original SCS-AMC procedure failed to simulate the stormflow depths adequately as a result of ignoring the temporal variability of soil moisture which results from the interplay between rainfall, evapotranspiration and drainage variables in its representation of ASM. The sudden "quantum" jump in CNs in this method (cf. Chapter 3, Sub-section 3.3.1) also reduced the accuracy of results. The SCS method showed satisfactorily performance when using the so-called "initial" CN (CN unadjusted). Nevertheless, the assumption that "initial" or "average" ASM conditions usually prevail prior to storm events cannot provide realistic design runoff estimates, particularly in semi-arid and arid environments found in Eritrea, where the inter-seasonal and intra-seasonal soil moisture variability is high.

By comparing the outputs generated from the SCS model when using the different methods of CN adjustment, it was observed how sensitive the estimates of stormflow are to ASM. The implication is that a more advanced representation of ASM by daily soil water budgeting procedures can overcome the variability of catchment antecedent conditions. In the following section, the *ACRU* model's outputs of stormflow from the five highest daily rainfalls of each year are compared statistically to the outputs of the same rainfall events from the SCS estimates, in order to obtain an indication of how well the estimated values fit the observed values and to check whether any systematic errors were evident in the estimations.

6.6 Comparison of *ACRU* and SCS Model Performances

According to Schulze (1995b), some conceptual and practical refinements have been made to the manner in which the SCS stormflow equation is applied in the *ACRU* model, these being related mainly to the following:

- *Interception* is abstracted separately before the commencement of potential stormflow producing rainfall in the *ACRU* model and is not part of the initial abstractions, as in the SCS model.
- *The coefficient of initial abstraction (cI_a)* is a variable which can increase or decrease from month to month in *ACRU*, dependent on climatic, vegetation, site and land use management characteristics, as outlined by Schulze (1995b). Based on extensive testing in South Africa, the default value of cI_a in *ACRU* is 0.2 and not 0.1 as recommended for the SCS model in South Africa (Schulze and Arnold, 1979; Dunsmore *et al.,* 1986).
- *The potential maximum retention of the soil* is taken as the difference between water retention at porosity and the actual soil water content just prior the rainfall event, i.e. after the total evaporation for the day has been abstracted (Schulze, 1982; 1995b).
- *The critical soil depth* from which stormflow is generated is not a fixed depth in the *ACRU* model. It has been made a variable in order to attempt to account for dominant runoff producing mechanisms which prevail in different climates, under different catchment conditions and for different soil properties (Schulze, 1982; 1984; 1995b). In this study, for example, the critical depth of soil is defaulted to the topsoil horizon thickness. However, in land use with a dense canopy and/or which has deep organic layers the critical depth may be deeper than the topsoil horizon for calculations of the soil water deficit (Schulze, 1995b).

The stormflow volumes (m^3) generated by the *ACRU* and SCS models from the five largest rainfall events for each year on record are presented in Table 6.11.

Table 6.11 Observed and simulated stormflow values from the five highest daily rainfall events in the Afdeyu catchment, for each year of record, and with missing data from 1991-1993 and four events occurring in 1998

Date	Observed Stormflows (m^3)	*ACRU* (m^3)	CN adjusted by *ACRU*-Köppen (m^3)	Unadjusted SCS (m^3)	CN Adjusted by SCS-AMC Classes (m^3)
04/04/1985	34.3	19.8	1 998.8	2 037.5	19.4
08/04/1985	128.8	369.9	2 330.8	2 373.5	2 373.5
03/05/1985	399.8	287.9	2 070.6	2 110.2	16.0
21/08/1985	214.2	241.6	2 828.1	6 398.3	333.2
26/08/1985	8 075.8	12 524.5	18 159.0	18 325.1	3 674.1
26/07/1986	4 437.0	5 800.7	10 184.1	10 297.4	1 597.5
06/08/1986	7 652.9	5 547.5	8 030.9	8 127.5	663.0
07/09/1986	1 361.2	1 052.4	3 279.4	3 332.7	48.0
08/09/1986	2 083.8	3 707.2	4 314.6	5 431.2	5 431.2
10/11/1986	2 532.6	2 210.9	2 564.6	2 610.0	28.7

Date	Observed Stormflows (m^3)	*ACRU* (m^3)	CN adjusted by *ACRU*-Köppen (m^3)	Unadjusted SCS (m^3)	CN Adjusted by SCS-AMC Classes (m^3)
06/08/1987	5 583.7	5 644.1	12 527.6	12 657.7	2 369.4
15/08/1987	20 484.0	14 482.3	13 923.6	14 063.3	2 250.3
24/08/1987	8 518.5	7 401.7	8 030.9	2 773.1	48.7
06/10/1987	9 634.3	8 557.4	8 095.1	8 192.3	8 192.3
29/10/1987	1 544.3	2 229.2	2 644.7	2 691.0	25.2
15/07/1988	3 385.0	3 515.7	7 275.8	9 323.7	1 304.9
28/07/1988	65 440.1	71 423.3	64 540.5	64 914.0	25 884.1
10/09/1988	9 336.9	9 033.2	11 406.4	29 351.1	8 038.0
12/09/1988	17 998.3	17 020.1	16 254.6	27 732.8	54 291.3
18/07/1989	758.0	716.9	4 117.4	2 412.2	9.7
01/08/1989	297.8	237.0	2 766.9	2 037.4	6.8
05/08/1989	279.9	301.3	653.0	587.9	587.9
12/09/1989	104.2	126.9	2 644.7	626.3	1.2
28/09/1989	1 717.9	1 290.7	5 466.8	3 513.8	23.3
08/07/1990	772.1	770.7	4 546.7	3 199.7	38.6
09/07/1990	5 397.7	4 042.1	6 729.2	1 625.0	9.4
27/07/1990	421.7	487.7	3 595.6	4 632.8	97.0
05/09/1990	6 662.2	7 608.9	12 909.9	13 042.7	13 042.7
04/10/1990	21 407.0	12 244.0	12 300.2	5 765.1	234.8
25/08/1994	25 911.2	18 627.7	17 899.0	18 064.0	4 391.8
27/08/1994	15 892.7	15 013.3	15 290.8	15 439.4	35 110.3
29/08/1994	9 650.1	11170.1	4 876.5	7 304.2	20 484.3
30/08/1994	46 051.7	49 631.3	25 835.2	28 034.0	54 736.9
21/09/1994	1047.0	1 714.8	4 617.5	8 850.9	823.0
26/05/1995	26 632.0	30 855.1	41 924.4	42 211.2	13 965.9
29/07/1995	11 543.4	16 287.0	11 924.7	18 238.2	3 643.2
01/08/1995	5 634.8	7 248.0	3 688.2	4 736.2	15 369.7
19/08/1995	29 861.3	37 078.2	22 488.9	32 566.0	9 381.8
20/09/1995	2 927.7	2 173.4	2 933.5	8 453.3	733.6
02/04/1996	16 350.0	11 293.2	19 300.4	4 945.8	129.6
08/08/1996	29 217.3	31 758.7	29 429.0	19 473.9	41 838.1
09/08/1996	12 810.1	21 126.2	9 353.5	9 460.5	24 828.2
24/08/1996	49 927.4	34 173.1	29 123.9	29 351.1	7 976.7
28/08/1996	9 400.8	18 084.9	11 406.4	12 811.2	30 657.0
07/05/1997	2 504.3	2 497.6	6 789.1	6 875.5	415.9
18/07/1997	21 503.4	16 152.2	10 184.1	10 297.4	26 360.5
09/08/1997	8 502.8	8 121.4	13 687.2	13 825.3	438.1
18/08/1997	25 377.1	21 405.2	19 924.9	20 102.6	4 318.2
29/09/1997	8 771.0	10 583.8	18 638.6	18 852.6	3 862.4
24/07/1998	6 387.3	5 289.1	11 479.9	8 784.2	807.8
27/07/1998	1 027.9	836.8	2 933.5	2 610.0	2 610.0
17/08/1998	383.7	265.4	1 344.2	5 231.1	160.9
21/08/1998	56 878.5	59 612.3	76 171.3	76 583.0	32 548.0
16/09/1998	15 649.9	21 310.3	26 325.4	30 583.4	8 572.4
28/04/1999	3 321.0	6 615.4	10 680.8	18 852.6	3 862.4
24/07/1999	12 886.0	15 134.2	19 389.2	19 563.2	4 120.0
30/07/1999	4 342.2	4 593.5	1 344.2	3 243.8	12 128.3
10/08/1999	18 890.4	23 196.6	10 566.5	10 798.0	27 264.2
28/08/1999	9 377.1	13 759.5	14 722.3	14 867.2	2 504.1

Statistics of model performance for the *ACRU* model show excellent relationships between total flows (difference <3%), and between variances (difference in standard deviations only 2%), as may be seen in Table 6.12. It was also found for the Afdeyu catchment that the application of the *ACRU*-Köppen approach, using ΔS to calculate a CN_f by the Hawkins (1978) equation (Equation 3.8 in Section 3.3.2), gave vastly improved estimates of stormflows over those using the so-called "average" catchment soil moisture conditions (CN unadjusted) and the CN adjusted by the original SCS-AMC classes to account for ASM conditions. The percentage difference between standard deviations of observed and the *ACRU*-Köppen is 11.1% compared with differences of 35.4% and 13.6% when the original SCS-AMC classes and CN unadjusted methods were employed.

Table 6.12 Statistics of performance of the *ACRU*, SCS adjusted by *ACRU*-Köppen, SCS adjusted by AMC classes and the unadjusted SCS models for the five highest stormflows produced from the five highest daily rainfall amounts of each year at the Afdeyu catchment

Conservation Statistics				
Statistics of Daily Flows	*ACRU*	CN Adjusted by *ACRU*-Köppen	CN Adjusted by SCS-AMC Classes	Unadjusted SCS
Total observed flows (m^3)	695 325.5	695 325.5	695 325.5	695 325.5
Total simulated flows (m^3)	714 503.5	750 466.7	569 017.2	754 995.0
Percentage difference in total flows	2.8	7.9	-18.2	8.6
Standard deviation of observed flows (m^3)	14 399.4	14 399.4	14 399.4	14 399.4
Standard deviation of simulated flows (m^3)	14 696.1	12 796.5	19 495.3	12 446.0
Percentage difference in standard deviations	2.1	-11.1	-35.4	13.6
Regression Statistics				
Statistics of Daily Flows	*ACRU*	CN Adjusted by *ACRU*-Köppen	CN Adjusted by SCS-AMC Classes	Unadjusted SCS
Correlation coefficient	0.96	0.92	0.65	0.83
Slope of the regression line	0.98	1.02	0.87	0.72
Base constant for regression equation	529.4	362.4	-651.1	4305.4
Coefficient of determination	0.92	0.85	0.42	0.69
Coefficient of efficiency	0.92	0.72	0.40	0.56

The slopes for the *ACRU* and *ACRU*-Köppen methods are much closer to unity than for either of the other methods of CN adjustment. The degrees of association between the observed and simulated values (both the coefficient of determination and coefficient of efficiency) for *ACRU* estimates are markedly closer to unity than those of any of the three other SCS-based estimates. For the *ACRU* model the coefficient of efficiency is equal to the coefficient of determination, indicating no bias in the estimates. However, in the SCS estimates the coefficient of efficiency is slightly less than the coefficient of determination, illustrating a small bias in the estimates. Although the coefficients are not as highly significant for the *ACRU*-Köppen estimates as for those of the *ACRU* model, there appeared to be less systematic bias in its output when compared to that of the other SCS-based estimates.

6.7 Conclusions

It has been shown by the statistics presented in Table 6.12 that the *ACRU* soil water budgeting procedures produce highly acceptable performance statistics for stormflow simulations on the Afdeyu research catchment. This relative success of the *ACRU* model results over those of other SCS- based models implies that the application of a soil water budgeting technique provides a much better representation of ASM, and that this component appears to have significant effect on the accurate estimation of stormflow volumes.

In comparing results from the *ACRU*-Köppen method to those from the SCS-AMC and unadjusted CN methods, it was found that the *ACRU*-Köppen performed much better in terms of both goodness of fit and model efficiency. The poor simulation with the original SCS-AMC adjustment could be due mainly to the discrete relationship between catchment moisture status and CNs (cf. Table 3.1), with corresponding quantum jumps possible in calculated stormflows, as reported by many researchers (e.g. Hawkins, 1978; Arnold, 1980; Hope, 1980; Schulze, 1984; Dunsmore, 1985; Schmidt and Schulze, 1987). The fact that the *ACRU*-Köppen method displayed better levels of performances than either of the other SCS based methods in the Eritrean research catchment confirms that changes in initial CNs due to ASM appear to remain similar universally for the same KCC. A major strength of the *ACRU*-Köppen method is that it is a simple, straightforward procedure of relating ΔS to MAP, and not data demanding in its application. Finally, on the basis of the above findings, it is believed that the *ACRU*-Köppen method can be used as a surrogate method of CN adjustment in SCS-based techniques for design flood estimations on small catchments in regions where the application of soil moisture budgeting techniques (e.g. with the *ACRU* model) is impractical due to limited and/or inaccurate hydrological information.

*　*　*　*　*　*

The various approaches and results are summarised in the chapter which follows.

7. DISCUSSION AND CONCLUSIONS

The high cost of building hydraulic structures in small catchments and the additional expenditure due to over-design, on the one hand, and repairs to these structures due to under-design, on the other hand, has induced the need for the adaptation of a suitable and accurate design flood method for application in Eritrea. An attempt has been made in this dissertation to adapt the SCS-*ACRU* hydrograph generating technique to Eritrea, on the basis of South African experiences. In this study focus has been placed on the antecedent wetness conditions of a catchment, as estimates of stormflow volumes and peak discharges are very sensitive to it.

A brief review of factors which affect the antecedent soil moisture status (ASM) of a catchment, and the procedures by which the SCS technique estimates this variable, was undertaken. Following this review it was concluded that Curve Number (CN) adjustment according to the original SCS-AMC classes might be applicable in high rainfall areas in which the catchment soil water status does not vary greatly from the so-called "average" condition. However, in physiographically and climatically heterogeneous regions such as Eritrea, the soils vary from being very dry for much of the time to displaying a high soil water status after rare, but prolonged rains. In such an environment, the accurate estimation of the ASM is an important requirement for acceptable estimates of stormflow magnitudes and peak discharges. A soil water budgeting procedure was proposed by Hawkins (1978) as an alternative procedure for adjusting CNs for ASM by discrete rainfall-based classes. This method has been shown to provide significantly more realistic estimates of stormflows from small catchments than the simple ASM methods suggested in early SCS literature.

A major problem associated in the use of a daily soil water budgeting approach in Eritrea is the scarcity of long, adequate and accurate measurements of rainfall and evaporation required to estimate the change in soil moisture storage, ΔS, from so-called "initial" moisture conditions. Since most of the factors that affect the soil water budget are implicit climatic parameters, the estimation of catchment soil water status was approached from the perspective of its being a climatologically driven variable. It was hypothesised that within reasonably similar climatic regimes, ΔS would likely be relatively homogeneous, and that climatic regions may be represented by a standard climate classification.

The first hypothesis was tested by applying the Köppen climate classification to the 712 relatively homogeneous hydrological zones which have been identified in southern Africa. Indices of expected catchment soil water status prior to potential flood producing storms, obtained previously by Schmidt and Schulze (1987) for 3 of the 27 soil/vegetation cover combinations, were then analysed to check if zones having similar Köppen climate classes (KCCs) have similar values of ΔS. In the analysis of variances within each KCC identified in southern Africa, a generally high degree of homogeneity in values of ΔS was observed for the selected three soil/vegetation cover combination scenarios. Further analyses were undertaken within each KCC class to test whether unique relationships exist between ΔS and MAP. The results demonstrated that the values of ΔS are well explained by the linear regression of MAP in all nearly the KCCs identified in southern Africa However, in the *Csb* climate class the values of ΔS are more strongly explained by non-linear (quadratic) relationships, even though the linear relationship is still statistically significant (cf. Figures 4.26, 4.27 and 4.28).

Information from Chapter 4 has been summarised into Figures 7.1, 7.2 and 7.3. As may be seen in Figure 7.1 for the SCSV (shallow clay, sparse vegetation) scenario, a single trend line can explain the relationships between the ΔS and MAP for all the KCCs identified in southern Africa, except for the *Csb* class. Such a small variation in ΔS might be attributed to the relatively insignificant effect that a highly responsive shallow clay soil with sparse vegetation cover would play in the variation of ΔS, because most of a day's rainfall would be converted to runoff on the same day the rainfall event occurs.

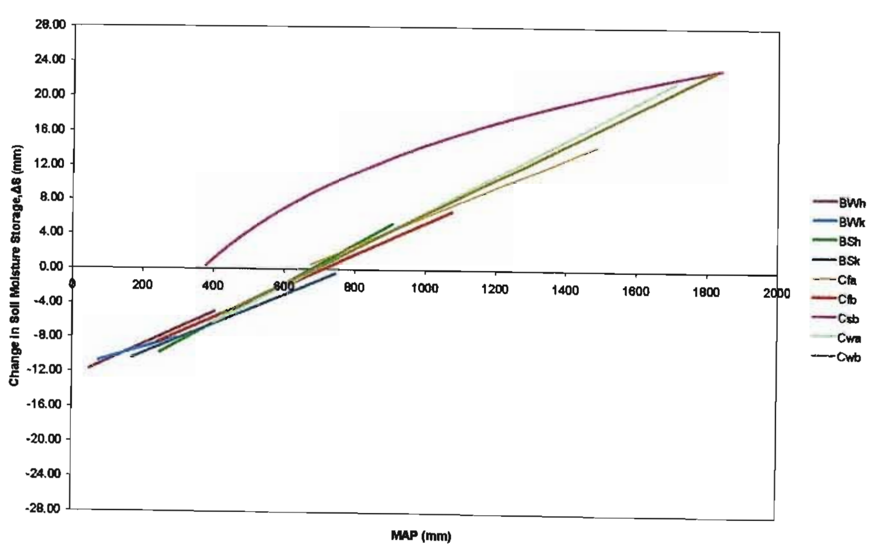


Figure 7.1 Relationships between median antecedent storage changes, ΔS, and MAP for those Köppen climate classes identified in southern Africa when catchments are covered with sparse vegetation on shallow clay soils (SCSV)

The ΔS : MAP relationship is, however, seen to vary markedly for KCCs for the ILIV (intermediate depth loams with intermediate density vegetation) and DSDV (deep sands with dense vegetation) scenarios (Figures 7.2 and 7.3), where the interplay between different soil/land use combinations and prevailing climatic conditions becomes important.

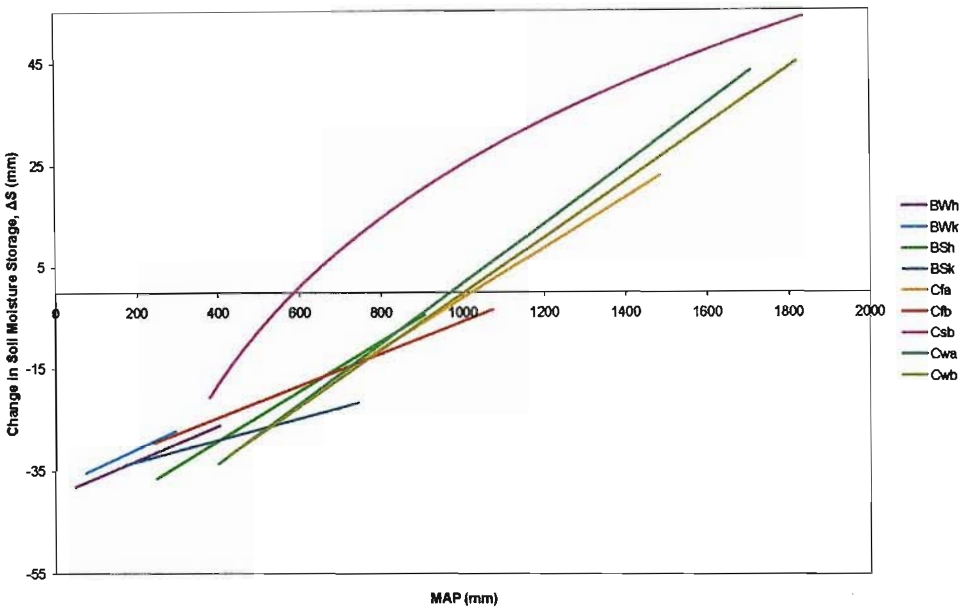


Figure 7.2 Relationships between median antecedent storage changes, ΔS, and MAP for those Köppen climate classes identified in southern Africa when catchments are covered with intermediate vegetation on intermediate depth loamy soils (ILIV)

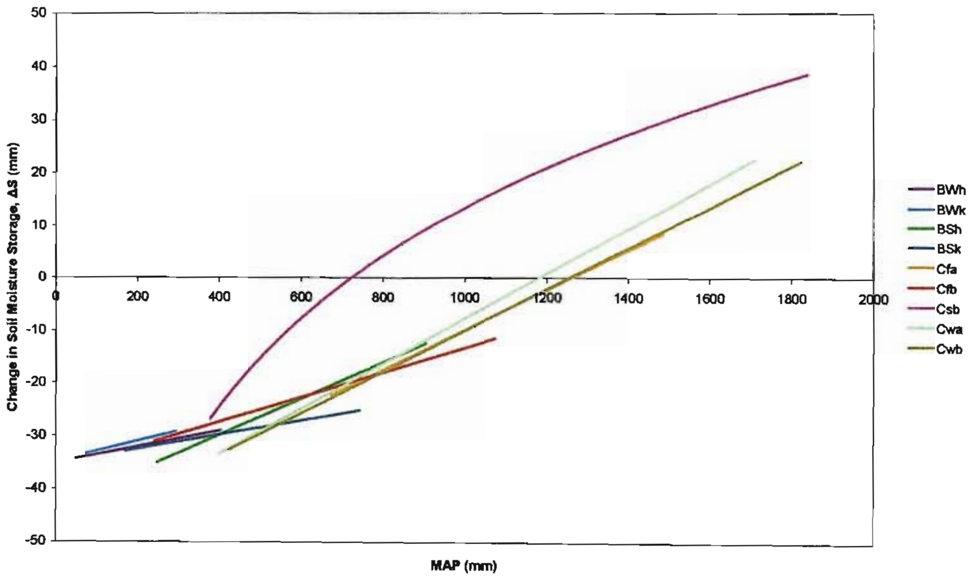


Figure 7.3 Relationships between median antecedent storage changes, ΔS, and MAP for those Köppen climate classes identified in southern Africa when catchments are covered with dense vegetation on deep sandy soils (DSDV)

The high correlation between estimated and observed ΔS values within each KCC is also an indication of a good simulation of ΔS from MAP by the regression equations which are unique to each KCC. The conclusions reached in the analysis of ΔS values within each KCC may be summarised as follows:

- A high degree of homogeneity of ΔS was observed within each individual KCC identified in southern Africa.
- The values of ΔS, which were previously computed with the *ACRU* model by Schmidt and Schulze (1987), are strongly correlated with MAP within each of the KCCs identified in southern Africa.
- The Köppen climate classification system can be used as a surrogate method for the adjustment of Curve Numbers for antecedent soil moisture status, and KCCs can be delineated when only very basic mean monthly climatological information is available.

The next critical task undertaken was to verify whether the typical regionalised indices of ΔS computed with the *ACRU* model by Schmidt and Schulze (1987) for a wide spectrum of climatic conditions, soil properties and land use characteristics could be transferred to Eritrea by application of the Köppen climate classification.

The performance of the *ACRU* stormflow modelling approach was first tested on the Afdeyu research catchment in Eritrea, in order to be confident in the use of values of ΔS generated by the model. Following that, the *ACRU*-Köppen method was tested on the same catchment and results were compared to stormflows using to the SCS-AMC classes and Hawkins' soil water budgeting procedures for CN adjustment. As discussed briefly in Chapter 6, the *ACRU* model's simulated flows from the research catchment are in very close agreement with the observed flows, illustrating its excellent performance in accounting also for antecedent catchment wetness prior to potential flood producing rainfall events.

In a comparison of estimates of design stormflows obtained using the SCS-SA model, those CNs adjusted by the water budget and by the surrogate *ACRU*-Köppen method provided results in close agreement with the observed design stormflow volumes when compared to the stormflow estimates obtained by SCS-AMC classes and CN unadjusted methods. The outputs from both the *ACRU* and SCS-based models for the five highest stormflows produced from the five highest daily rainfall amounts of each year in the Afdeyu catchment were compared statistically. The *ACRU* model provided excellent overall simulated stormflow volumes and had the lowest difference in standard deviations between observed and estimated flows. The coefficient of determination was highly acceptable and the slope was much closer to unity than for either of the SCS-based estimates. The fact that the *ACRU* model generated consistently better stormflow volumes implied that the antecedent soil moisture component appears to have a marked effect on the accurate design flood estimation. In comparing results from the different methods of CN adjustment used in the SCS model, the *ACRU*-Köppen yielded much better model efficiencies than the two other methods. The coefficient of determination and coefficient of efficiency exhibited by the *ACRU*-Köppen are markedly higher than those of either of the two methods of CN adjustments. A major strength of the *ACRU*-Köppen approach is that it is a relatively simple technique, not requiring a high level of expertise, nor it is data demanding for its application. In view of the above findings, the following conclusions were drawn regarding the suitability of the SCS-*ACRU*-Köppen modelling approach for application in Eritrea:

- In an Eritrean context it appears that the original CN adjustment which utilises only rainfall amounts and "average" catchment conditions to represent the antecedent soil moisture status does not provide a sound basis for design hydrology on small catchments.
- Using the *ACRU*-Köppen method of CN adjustment, the SCS-SA model can be adapted to Eritrea, for which Köppen climates can be classified from monthly rainfall and temperature maps. However, it remains essential to know whether a climate is relatively constant from one year to the next or whether a high variation is experienced from one season to the next, since the delimitation of such climate zones is done empirically and can, therefore, vary from year to year (climate variability) or over time (climate change).
- With improved hydrological and climatological information, the *ACRU* model can also be adapted as a tool to provide answers to a range of other water related problems in Eritrea by testing the model further on a wide range of catchment characteristics.

* * * * * *

Recommendations identified by the author for future improvements to the SAK approach are highlighted in Chapter 8. These suggestions reflect some of the problems experienced during the study of this research.

8. RECOMMENDATIONS FOR FUTURE RESEARCH

It should be noted that the surrogate method of CN adjustment which was conceptualised and verified in this study, *viz.* the SCS-*ACRU*-Köppen approach, was tested only on one research catchment in Eritrea, as there are currently no other gauged catchments available for undertaking such verifications. In future, this method should be tested against the other methods of CN adjustments under a wider range of environmental conditions. The research presented in this dissertation may, therefore, be considered as a pilot study, setting the groundwork for further research to be undertaken in the field of flood estimation from small catchments in Eritrea.

With further improvements, the SCS-*ACRU*-Köppen stormflow modelling approach has the potential to play an increasingly important role in future design hydrology on Eritrea's small catchments. A number of recommendations for the attention in the future research have been identified, based on the experiences gained from findings made in this dissertation. These recommendations are outlined in the context of two broad categories, *viz.* data availability for further model improvement and estimation of change in soil moisture storage.

8.1 Recommendations on Data Availability for Further Model Improvement

A number of research areas were identified during the course of this study that need to be addressed. However, any move towards further improvement of the SAK approach is entirely dependent on the availability, accuracy and completeness of both hydrological and climatological data. To facilitate the application of the SCS-*ACRU*-Köppen stormflow modelling approach throughout Eritrea, elsewhere, future efforts should concentrate on:

- The establishment of improved hydrological and climatological networks;
- Gridded estimates of monthly and annual precipitation and temperature data, in order to produce an improved map of Köppen climate classes within a geographic information system (GIS);
- Obtaining more detailed soil information than is presently available, in order to categorise soils into SCS hydrological groups, *viz.* A, B, C or D, or even intermediate groups, *viz.* A/B, B/C and C/D; and
- Developing surrogate methods of obtaining rainfall intensity indices, used in peak discharge estimates, as there are only few recording raingauges in Eritrea.

8.2 Recommendations on Estimation of Change in Soil Moisture Storage Change, ΔS

As indicated briefly in the literature review (Chapter 3, Section 3.2.2), spatial differences in a catchment's soil moisture status are attributed to variations in one or more of the following: regional climate, soil characteristics, land use and its management and topographical position in the landscape. The following recommendations for future investigations are therefore made:

- Using the available rainfall and runoff data from the Afdeyu catchment, CNs for the catchment should be optimised to the CNs which were input from soils and land use information. The same should be done with long rainfall: runoff data from other research catchments, in order to confirm the concepts inherent in the SAK approach.
- Further improvements might be made by including the effects of topography and land management into the estimation of regional indices of antecedent soil moisture change, ΔS. Particularly in humid and sub-humid climates (e.g. *Cfa, Cfb,* and *Cwb*), where precipitation generally exceeds evapotranspiration, topography has a significant influence on spatial patterns of antecedent soil moisture change on a catchment, as the upslope topography can modify the distribution of ΔS at a given point downslope.
- It should also be noted that in arid and semi-arid climates (e.g. *BWh, BWk, BSh* and *BSk*) most of the rainfall is recorded within a few months of the year only, and over very short time periods (convective events). Therefore, the duration and number of the storm incidences are very crucial variables that should not be ignored in determining the soil water status of a given area. In other words, to what extent do spatial patterns of ΔS persist across time in arid and semi-arid areas? Temporal variations in rainfall have influences probably as strong as those of spatial variations in the soil water balance.

* * * * * *

In Appendix A, procedures for the application of the SCS-*ACRU*-Köppen (SAK) modelling approach are presented in the form of a simple user manual, in order to guide hydrologists/ engineers in its use in design hydrology on small catchments in Eritrea. The appendix incorporates the research findings of this study with the approach adopted in the SCS-based design manual for southern Africa produced by Schulze *et al.* (1992). It provides a detailed breakdown of the steps required to determine stormflow volumes and peak discharges from small catchments in Eritrea.

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APPENDIX A

SCS-ERITREA

A FIRST VERSION OF A USER MANUAL FOR THE APPLICATION OF SCS-BASED TECHNIQUES FOR THE ESTIMATION OF DESIGN FLOODS FROM SMALL CATCHMENTS IN ERITREA

YB Ghile and RE Schulze

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1. INTRODUCTION

There is a frequent need by engineers and hydrologists to estimate flood volumes and peak discharges for specified return periods from small catchments (<30 km2). In many countries of the world SCS-based hydrograph generating techniques (NEH-4, 1972 and updates) are nowadays used for this purpose.

The SCS-*ACRU* modelling approach (Schmidt and Schulze, 1987; Schulze *et al.*, 1992) has been shown to be well suited for the estimation of design stormflow volumes from small catchments in Eritrea when the Köppen climate classification is employed in calculations of regional changes in catchment soil moisture status, ΔS, just prior to a stormflow producing rainfall event(Ghile, 2004). ΔS is used when adjusting the initial catchment response index, *viz*. the Curve Number, CN_{II}. By implication, although not verified by Ghile (2004) for lack of data, it may be assumed that the SCS-*ACRU*-Köppen (SAK) approach is also well suited to the estimation of peak discharges in Eritrea, because of the strong dependence of peak discharge on stormflow volume (NEH-4, 1972; Schmidt and Schulze, 1984).

In this user manual, the SAK modelling procedures are outlined as a tool for engineers and hydrologists responsible for design and planning of hydraulic structures on small catchments in Eritrea. The SCS-Eritrea user manual is based on the methodologies presented in the SCS design manuals for southern Africa by Schulze and Arnold (1979), Schmidt and Schulze (1987) and Schulze *et al.* (1992) as well as upon the concepts tested in Eritrea by Ghile (2004) in Chapters 4 and 6 of his dissertation. Reviews on reasons for selecting the SCS techniques for use in Eritrea, as well as SCS design principles, are given in the section which follows. This is followed in Section 3 by the various calculation options and alternative pathways required by a user to calculate design stormflow volumes and peak discharges from small catchments in Eritrea. Details of the SCS-*ACRU* approach to stormflow modelling have been given in Chapter 3 of Ghile's (2004) dissertation. For the convenience of users some of the principles and procedures are, however, repeated here.

2. SCS DESIGN PRINICIPLES AND THEIR APPLICATIONS IN ERITREA

2.1 Why the SCS Method in Eritrea?

Application of the SCS-based method for design flood estimation from small catchments has been proposed for Eritrea for the following major reasons:

- The equations are relatively simple (Schmidt and Schulze, 1987).
- The method uses readily available daily rainfall amounts and easily estimated physical properties of a catchment (e.g. soils/land cover properties).
- It has been shown to provide relatively better results than those from many other methods when simulations are compared to observations (Bondelid, *et al.,* 1982; Schulze *et al.* 1986; Schmidt and Schulze, 1987).
- Considerable research has been undertaken internationally, but especially in South Africa, regarding changes in antecedent soil moisture status (ΔS) from identified initial conditions just prior to flood producing rainfall events. Regionalised indices of ΔS for a wide spectrum of climatic conditions, soil properties and land use characteristics have been derived for southern Africa by a generic methodology using the *ACRU* daily water budgeting model (Schulze, 1995). That methodology can be readily transferred to Eritrea when adjusting runoff coefficients (CN_{II}s) for antecedent soil moisture status (Ghile, 2004).

2.2 Background to the Estimation of Stormflow Volumes in Eritrea

2.2.1 The SCS Stormflow Equation

The SCS stormflow equation is a simple formula relating the stormflow depth, Q, to the total rainfall depth, P, and a so-called Curve Number, CN, which is a catchment response index determining both the rainfall abstraction characteristics prior to the commencement of stormflow as well as the non-linear hydrological response of the catchment's stormflow to rainfall. The rainfall magnitude must be sufficient to satisfy initial abstractions, which are made up of the interception by a land cover and depression storages, plus the quantity of infiltration before the start of stormflow. After stormflow commences, additional losses occur mainly in the form of infiltration, F, which increases with increasing rainfall amount up to the maximum retention of the soil, S. Stormflow, Q, which is comprised of surface and near-surface runoff responses to a rainfall event, also increases as the rainfall amount increases (Schmidt and Schulze, 1987). Figure 2.1 illustrates the relationship among these variables for a rainfall event of constant intensity.

In the limit, as P approaches infinity, so F approaches S and the ratio of F to S approaches unity. The ratio of Q to $P - I_a$ also approaches unity, although it can never actually reach unity. Then the ratio of F to S is assumed to be equal to the ratio of Q to $P - I_a$, i.e.

$$\frac{Q}{P-I_a}=\frac{F}{S} \qquad 2.1$$

where

Q	=	stormflow depth (mm),
P	=	daily rainfall depth (mm),
F	=	accumulated infiltration (mm),
S	=	potential maximum soil water retention (mm), i.e. an index of the wetness (small values of S) or dryness (large value of S) of a catchment, and
I_a	=	initial abstractions prior to the commencement of stormflow (mm).

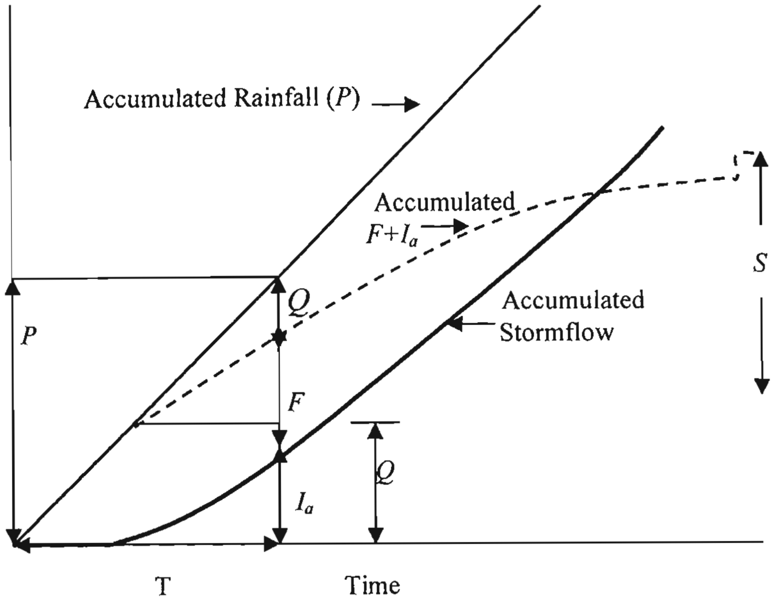

Figure 2.1 Schematic curves showing relationships used in the derivation of the SCS stormflow equation (after NEH-4, 1972; Schulze and Arnold, 1979)

After stormflow commences when $P>I_a$, all rainfall becomes either runoff or actual retention, i.e.

$$(P-I_a)=F+Q \qquad 2.2$$

Solving Equations 2.1 and 2.2 for Q, when $P>I_a$, yields

$$Q=\frac{(P-I_a)^2}{P-I_a+S} \text{ for } P>I_a \qquad 2.3$$

It has been found from experiments that I_a may be represented as a coefficient, c, of S (NEH-4, 1972). The potential maximum soil water retention, S, is a function of a final Curve Number, CN_f, which is a catchment stormflow response index. In metricated form S is given as

$$S=\frac{25400}{CN_f}-254 \qquad 2.4$$

where the CN_f, which can range from 0 to 100, is dependent on catchment's soil and land use characteristics as well as the antecedent soil moisture conditions (ASM) of the catchment just prior to the stormflow producing rainfall.

The determination of inputs to Equations 2.3 and 2.4, *viz.* the coefficient of initial abstraction losses, values of daily rainfall depth, the initial Curve Number (derived from hydrological soil groupings as well as land uses and their treatment) and the adjustment of CN_{II} to CN_f according to ASM conditions are discussed next.

2.2.2 Coefficient of Initial Abstractions

According to Schulze (1995) the coefficient c of initial abstraction losses can change from month to month and from one climatic region to another, depending on rainfall intensity and duration, as well as on vegetation, site and management characteristics. The c was assumed in its original development (NEH-4, 1972) to have a value of 0.20. Researches conducted by Schulze *et al.* (1986) and Topping (1992) have shown that the coefficient can, however, increase to (say) 0.3 or 0.4 immediately after ploughing when surface roughness is high, or under forested conditions, or where intensities of design rainfall are typically low (e.g. frontal or general rainfall), and reduce to (say) 0.05 to 0.15 under semi-arid conditions or when soils are compacted, or in peri-urban situations, or in areas where intensities of design rainfall are typically high (e.g. convective rainfall).

2.2.3 One Day Design Rainfall Depth

For a "specific" storm the measured one day rainfall depth can be used directly as the rainfall input in the SCS stormflow equation (Equation 2.3). Where rainfall amounts from several raingauges within and/or adjacent to the catchment under consideration are available, a weighted storm rainfall may be derived using any of the standard methods (e.g. Thiessen polygons, arithmetic mean etc). For design storm application, magnitudes of one day expected rainfall for a chosen frequency of recurrence (i.e. return period) are required to compute the resulting design stormflow depths (Schmidt and Schulze, 1987).

Maps depicting one day design rainfall depths over Eritrea for return periods of 2, 5, 10, 20, 50 and 100 years have been determined by Van Buskirk (2003) and are given in Figure 4.2. The approaches and procedures used to produce these design maps are available in his website <http://www. Punchdown.org>. The method has been verified at the Afdeyu research catchment in Eritrea, from which results of Van Buskirk values have been shown to be in close agreement with the manually calculated magnitudes of the 2, 5, 10 and 20 year return period daily rainfalls. However, the maps presented in Figure 4.2 are generalised maps which should be used with caution, especially in areas where there are known or anticipated marked changes in rainfall depth over a short distance (e.g. in areas of rapid change in altitude).

2.2.4 Determination of Initial Curve Numbers

Initial Curve Numbers, CN_{II}s, are determined from soils, land cover and hydrological conditions only, with no regard to prevailing soil moisture conditions. CN_{II}s for a wide range of land cover and treatment classes, stormflow potentials and hydrological soil groups are given in Table 4.1. Some background to the derivation of CN_{II}s is given below.

2.2.4.1 Hydrological Soil Groups

Soil properties have been categorised hydrologically by the SCS developers (e.g. NEH-4, 1972) into four basic soil groups, *viz.* A, B, C and D soils. The four basic hydrological soil groups have the following attributes:

Soil Group A: *Low stormflow potential.* Infiltration rate is high and permeability is rapid. The soils of this group are generally deep and well drained, often consist of sands or gravels, and display a final infiltration rate (i.e. entry rate of rainfall at the soil surface, assuming a grassed catchment and when the soil is saturated) of approximately 25 $mm.h^{-1}$ and a permeability (i.e. soil water transmission) rate > 7.6 $mm.h^{-1}$.

Soil Group B: *Moderately low stormflow potential.* Infiltration rate is moderate and permeability is slightly restricted. The soils of this group are of moderate thickness with moderately fine to moderately coarse texture. Final infiltration rate is approximately 13 $mm.h^{-1}$ and the permeability rate is in the range of 3.8 to 7.6 $mm.h^{-1}$.

Soil Group C: *Moderately high stormflow potential.* The rate of infiltration deteriorates rapidly and permeability is restricted. Soils are frequently shallow with restricted drainage. The final infiltration rate is approximately 6 $mm.h^{-1}$ and the permeability rate ranges from 1.3 to 3.8 $mm.h^{-1}$.

Soil Group D: *High stormflow potential.* Infiltration is impeded, its rate is very slow and permeability is severely restricted. Soils are generally very shallow (<0.3m) and soils of high shrink-swell potential soils are included in this group. Final infiltration rate is approximately 3 $mm.h^{-1}$ and the permeability rate is < 1.3 $mm.h^{-1}$.

From field experiences, three additional intermediate soil groups (i.e. A/B; B/C; C/D) were identified for southern African conditions, thus giving seven hydrological soil groups in all. The 7-fold categorisation may also be adapted for Eritrean conditions. Since the sensitivity of CN to the hydrological soil group is high, some guidelines for adjustment of soil groups in the field are given below, again based upon South African experiences (Schulze and Arnold, 1979).

- *Soil depth:* Where typically deep soils are in a shallow phase, for example on steep slopes, they should be downgraded one group (e.g. B becomes B/C).
- *Surface sealing:* Where surface sealing is evident, in sodic soils for example, soils should be downgraded one group (e.g. C to C/D).
- *Topographical position:* Generally soils in bottomlands may be downgraded (e.g. B to B/C) and soils formed in uplands upgraded one group (e.g. B/C to B).
- *Parent material:* Identical soil series derived from different parent materials may require regrouping, e.g. soil series formed from sandstones would be upgraded relative to the same series formed from more clayey parent material (e.g. B/C to B).

2.2.4.2 Land Use and Treatment Classes

In the SCS procedure the effects of surface conditions of a catchment are evaluated by means of assessing land cover, land treatment and stormflow potential (NEH-4, 1972; Schulze *et al.*, 1992).

Land cover defines the primary catchment cover. It can comprise of a range of annual and perennial crops, grassland and forest, as well as non-agricultural areas such as water bodies and urban areas.

Land treatment applies mainly to agricultural practices such as conservation structures (e.g. contours, terraces, bunds) and management practices (e.g. grazing control, rotation of crops).

Stormflow potential is influenced by management practices, mainly in agricultural areas. Three categories of stormflow potential are given, *viz.* high, moderate and low. High stormflow potential will prevail when poor hydrological conditions exist, while low stormflow potential occurs when the land is in good hydrological condition. Under agricultural crops, practices such as conservation structures and minimum tillage will result in low stormflow potential. In the context of pasture or grasslands, a high stormflow potential would occur as a result of heavy grazing or recent burning. Under forested conditions, a high stormflow potential exists when undergrowth is sparse and there is a compact, shallow humus layer (Schmidt and Schulze, 1987; Schulze *et al.*, 1992). Land use and treatment classes are obtained either by observation or by measurement of plant and litter density as well as moisture content on sample areas (NEH-4, 1972).

2.2.4.3 Points to be noted when determining Curve Numbers

Schulze *et al.* (1992) note the following points when determining the value of a CN:

- Initial CN values (such as those given in Table 4.1) are based on work conducted mainly in the USA. They may not cover all land use characteristics found in other regions of the world. Local interpretations must be made from land uses similar to those in Table 4.1.
- Users should attempt to establish the land cover/treatment conditions likely to prevail in the catchment during the design life of the structure. Urban development, projected land use changes such as afforestation, deforestation, fallowing or grassland degradation are some of the examples that should be accounted for in deriving the catchment CN.
- A final CN < 50 is not advisable for design calculations, owing to future changes in land cover/use which may increase the design stormflow.
- In physiographically heterogeneous catchments, variations in CN must be accounted for by subdividing a catchment into subcatchments, each with relatively homogenous soil/land cover conditions, and then area-weighting respective values of subcatchment Qs to obtain an aggregated value of Q.
- Many different combinations of soil groups and land uses can give the same initial CN (cf. Table 4.1), and thus theoretically respond identically in regard to stormflow generation. In nature this assumption intuitively does not hold. Further refinement to the CN concept is thus necessary.

2.2.5 Adjustment of Initial Curve Numbers for Antecedent Soil Moisture

The soil moisture status prior to a stormflow producing event is the second major factor, after rainfall, affecting the stormflow response depth (NEH-4, 1972). The CN_{II}s listed in Table 4.1 for different soil groups and land use classes (as well as their treatment) assume so-called "average" antecedent soil moisture (ASM) conditions. These CN_{II}s therefore have to be adjusted to account for dissimilar soil moisture regimes between storms on the same catchment, because the ASM deviates from the so-called "average" (Schmidt and Schulze, 1987).

2.2.5.1 *Major factors affecting a catchment's soil moisture variation*

Soil wetness conditions just prior to flood producing rainfall events will be influenced mainly by:

- Properties of the regional climate (e.g. the amount of precipitation and its seasonal distribution as well as the solar radiation that an area receives);
- Soil properties such as infiltrability, transsmissivity, depth, retention and soil porosity; hence its texture, bulk density, crusting and surface sealing (Schulze *et al.*, 1985);
- Properties of land cover and land use/treatment in as much as they affect plant transpiration, interception and infiltration as well as evaporation from the soil surface (NEH-4, 1972, Schulze *et al.*, 1992); and
- Topographic position such as location with respect to crest, scarp, midslope or footslope; convex or concave slopes; warm or cool aspect (Beven, 1979; Hope and Schulze, 1979; Freer *et al.*, 1997).

Adjusting CN_{II}s to be more representative of conditions prior to flood producing rainfall events should, therefore, ideally have to consider all the above-mentioned controlling factors. However, in this user manual, only three soil thickness classes (representing "shallow", "intermediate" and "deep" soil depths), three vegetation cover classes (representing "dense", "intermediate" and "sparse" cover) and three broad soil texture classes (representing "fine", "medium" and "coarse" textured soils) are adapted from the SCS-SA user manuals (Schmidt and Schulze, 1987; Schulze *et al.*, 1992) to quantify the effects of soil and cover on moisture conditions in soil moisture budget analyses (Table 2.1).

Table 2.1 Soil and vegetation characteristics used in soil moisture budget analysis (after Schmidt and Schulze, 1987)

Soil Thickness Classes (m)			
Category		Thickness of A Horizon	Thickness of B Horizon
Deep		0.30	0.80
Intermediate		0.25	0.50
Shallow		0.15	0.15
Moisture Retention Classes (mm.m^{-1})			
Category	Porosity	Drained Upper Limit	Lower limit
Coarse (Sand)	430	112	50
Medium (Loam)	464	251	128
Fine (Clay)	482	416	298
Vegetation Classes			
Category	Fraction of Roots in A-horizon	Interception Loss (mm. rainday^{-1})	Crop Coefficient
Dense	0.60	3.00	1.00
Intermediate	0.80	1.75	0.75
Sparse	1.00	0.50	0.50

Drained upper limit = Field capacity; Lower limit = Permanent wilting point

2.2.5.2 *Curve Number adjustment using Hawkins' water budgeting procedure*

In the initial SCS handbooks (e.g. NEH-4, 1972) antecedent soil moisture was accounted for by three discrete classes of 5-antecedent day accumulated rainfall for either the growing or dormant season. Having recognised the weaknesses of the ASM component of the original SCS model, Hawkins (1978) developed an alternative water budget based method which included consideration of antecedent stormflow, drainage and evapotranspiration in addition to antecedent rainfall for a defined interim period prior to the stormflow event, and expressed the relationship between CNs and ASM as a continuum rather than as the discrete classes used in the original SCS procedure, as follows:

$$CN_f = \frac{(1+c)*1000}{\frac{(1+c)*1000}{CN_{II}} - \frac{(P-Q-D-E)}{25.4}} = \frac{(1+c)*1000}{\frac{(1+c)*1000}{CN_{II}} - \frac{\Delta S}{25.4}} \qquad 2.5$$

where

CN_f	=	final Curve Number calculated for prevailing soil moisture status at the end of the defined interim period,
CN_{II}	=	initial Curve Number for the hydrological soil-cover complex of the catchment,
c	=	coefficient of initial abstraction,
P	=	rainfall (mm) in the interim period,
Q	=	stormflow (mm) in the interim period,
D	=	drainage (mm) in the interim period,
E	=	actual evapotranspiration (mm) in the interim period, and
ΔS	=	change in soil water status (mm) in the interim period, i.e. P-Q-D-E.

2.2.5.3 *Estimation of change in soil moisture storage (ΔS) using the ACRU-Köppen approach*

A major problem associated with the direct use of Hawkins' water budgeting procedure in Eritrea is the scarcity of long, adequate and accurate measurements of rainfall and temperature required to estimate the changes in soil moisture storage, ΔS, from so-called "initial" moisture conditions. A surrogate methodology was therefore developed by Ghile (2004) to estimate ΔS from mean annual precipitation (MAP), based on the following hypotheses (Schulze, 2003):

Hypothesis 1: Changes in the initial land use and soils-based Curve Numbers as a result of typical changes in antecedent soil moisture conditions are similar universally for similar climatic regions;

Hypothesis 2: Similar climatic regions may be represented by a standard climate classification system; and

Hypothesis 3: Changes in antecedent soil water storage, ΔS, in Eritrea would be similar to ΔS in southern Africa for the same defined climatic region and MAP.

The Köppen (1931) climate classification system was selected to delimit similar climatic regions because of its relative simplicity, as well as because spatially detailed monthly and annual rainfall and temperature information is available for Eritrea. The latter is important because the Köppen (1931) system uses values of long term monthly means of daily temperature distributions and long term mean monthly and annual precipitation to identify five major climatic classes, A to E. Each climate class contains sub-classes which describe special regional climate characteristics, such as seasonal changes in temperature and precipitation, as given in Table 4.2 of this user manual.

The above hypotheses were tested by applying the Köppen (1931) climate classification system to the 712 relatively homogeneous hydrological zones which have been identified in southern Africa by Dent *et al.* (1988). The results demonstrated that the expected (median) values of ΔS, determined with the daily *ACRU* soil water budgeting model (Schulze, 1995), are explained well by the linear regression of MAP in nearly all the Köppen climate classes (KCCs) identified in southern Africa, for three widely divergent selected soil and land cover scenarios, *viz.* SCSV (i.e. sparse vegetation on shallow clay soils), ILIV (i.e. intermediate vegetation on intermediate depth loamy soils) and DSDV (i.e. dense vegetation on deep sandy soils). Results are shown in Figures 2.2, 2.3 and 2.4.

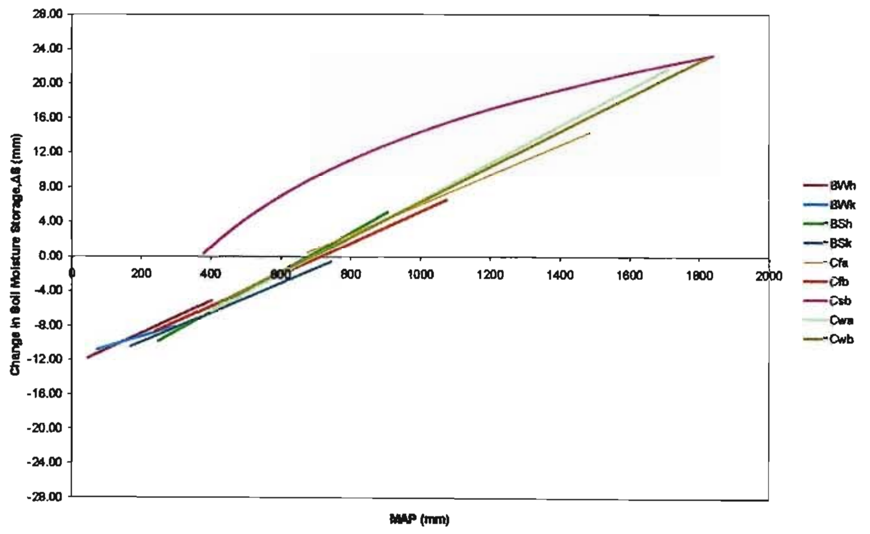

Figure 2.2 Relationships between median antecedent soil storage changes, ΔS, and MAP for the 9 Köppen climate classes identified in southern Africa, when catchments are covered with sparse vegetation on shallow clay soils (SCSV)

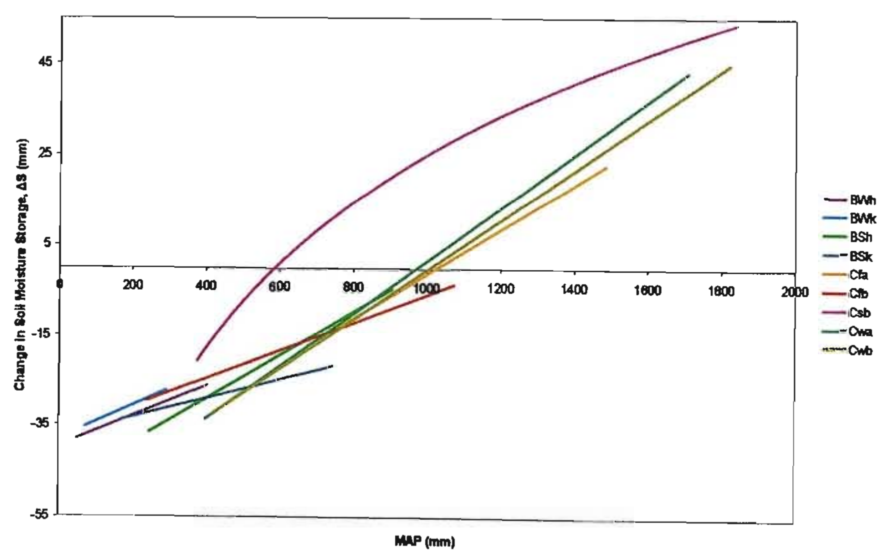

Figure 2.3 Relationships between median antecedent soil storage changes, ΔS, and MAP for the 9 Köppen climate classes identified in southern Africa, when catchments are covered with intermediate vegetation on intermediate depth loamy soils (ILIV)

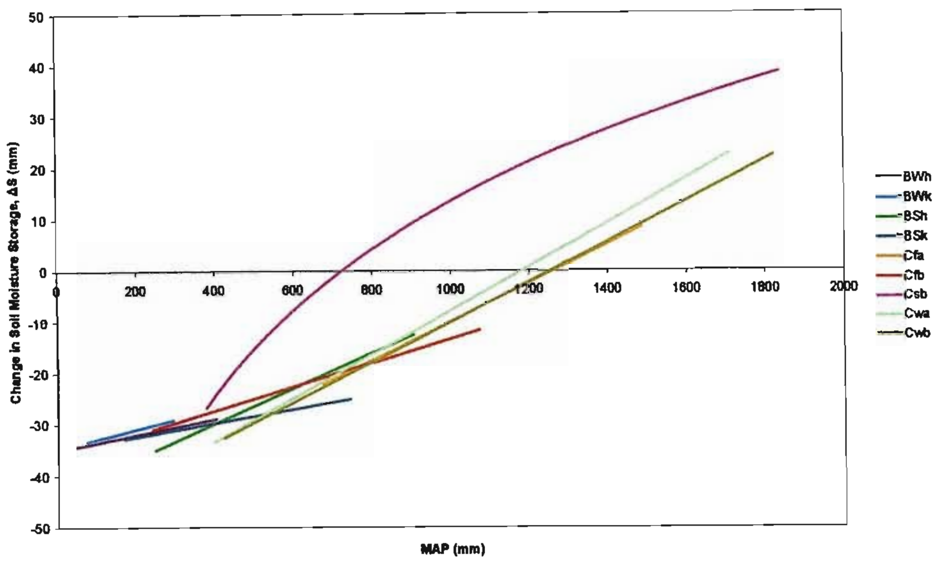

Figure 2.4 Relationships between median antecedent soil storage changes, *ΔS*, and MAP for the 9 Köppen climate classes identified in southern Africa, when catchments are covered with dense vegetation on deep sandy soils (DSDV)

However, in the *Csb* climate class the median values of *ΔS* are more strongly explained by non-linear (quadratic) relationships, even though the linear relationship is still statistically significant. The methodology described above to estimate median *ΔS* has been termed the *ACRU*-Köppen approach.

The *ACRU*-Köppen approach was tested on the Afdeyu research catchment in Eritrea. In a comparison of estimates of design stormflows obtained using the SCS-SA model, results from those CNs adjusted by the *ACRU*-Köppen approach provided close agreement with the observed design stormflows when compared to the stormflow estimates obtained by the original SCS-AMC classes and initial CNs which were left unadjusted (Ghile, 2004). Statistically, the *ACRU*-Köppen method also yielded much better model efficiencies and had relatively lower differences in standard deviations between observed and estimated stormflows than those of either of the two methods of CN adjustments. Regression equations developed by Ghile (2004) from MAP within each individual KCC identified in southern Africa, for a combination of three soil depth categories, three soil texture classes and three vegetation cover conditions are listed in Table 4.3, to be used in Eritrea for the same KCCs and similar soil/land cover characteristics.

As there is currently no adequate, detailed monthly rainfall and temperature information available in mapped form for Eritrea, a Köppen (1931) climate classification for Eritrea has been tentatively accomplished by using values of monthly temperature distributions and long term MAP from only 90 meteorological stations available in the country. The KCC was determined for each station and the Thiessen polygon method was then employed to interpolate the spatial coverage of each KCC identified in Eritrea (Figure 4.4). The map should be used with caution, especially in the central highlands of the country, where there are marked changes in rainfall and temperature distributions over short distances.

2.3 Background to Estimation of Peak Discharge

The estimation of peak discharge is the second important component of the SCS modelling system and peak discharges are more frequently used in engineering works, especially with respect to hydrological design of soil and water conservation measures and discharge rate estimations for spillway and channel capacities. Unfortunately, owing to a lack of adequate observed peak discharge records in Eritrea, the peak discharge component of the SCS method could not by verified in Ghile's (2004) study. However, since peak discharge from small catchments is very closely related to stormflow volume (Schmidt and Schulze, 1984; 1987), the peak discharge component of the SCS modelling approach would also be expected to provide realistic peak flows from small catchments in Eritrea. Based on one of the SCS user manuals (NEH-4, 1972) and the SCS-SA design user manual (Schulze *et al.,* 1992), the approach and procedures for the estimation of peak discharges from small catchments are outlined in the sub-sections which follow.

2.3.1 The SCS Peak Discharge Equation and its Derivation

The calculation of peak discharge by the SCS method is based on the triangular unit hydrograph. This unit hydrograph is a presentation of a single peaked stormflow with only one rise, one peak and one recession. From analyses of thousands of hydrographs from small catchments, the unit hydrograph is assumed to have 3/8, i.e, 37.5% of the total stormflow volume under the rising limb and 5/8 (62.5%) under the falling limb. Its geometric shape (Figure 2.4) can be easily described mathematically (NEH-4, 1972) as shown below:

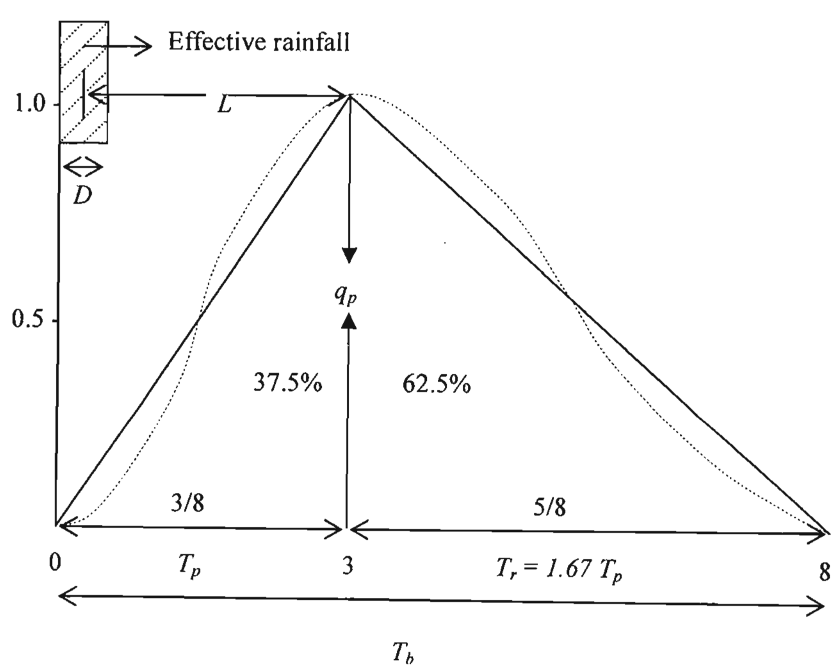

Figure 2.4 Geometric shape of the triangular unit hydrograph and the proportion of stormflow volume under the rising and the recession limbs (after NEH-4, 1972)

The proportion of stormflow volume under the rising limb to the total volume may be expressed as a ratio of the time to peak, T_p, to the time of the base of the triangular unit hydrograph, T_b. Since both triangles have a common height, q_p (Figure 2.5) and

$$\frac{T_p}{T_b} = 0.375 \tag{2.6}$$

with

$$T_b = T_p + T_r \tag{2.7}$$

where

T_b	=	time of base of triangular hydrograph (h),
T_p	=	time to peak (h), and
T_r	=	time of recession (h)

when combining Equations 2.6 and 2.7,

$$T_r = 1.67T_p \tag{2.8}$$

and

$$Q = \frac{1}{2} q_p (T_p + T_r) \tag{2.9}$$

where

Q	=	stormflow volume (mm),
q_p	=	peak discharge (mm.h^{-1}),

Solving Equation 2.9 for q_p gives

$$q_p = \frac{2Q}{T_p + T_r} = \frac{2Q}{2.67T_p} = \frac{0.75Q}{T_p} \text{ (mm.h}^{-1}\text{)} \tag{2.10}$$

Introducing catchment area, A (km^2), allows conversion of q_p from mm.h^{-1} to m^3.s^{-1} as follows:

$$q_p = \frac{0.75 \times 10^{-3} \times 10^6 AQ}{3600T_p} = \frac{0.2083AQ}{T_p} \text{ (m}^3\text{.s}^{-1}\text{)} \tag{2.11}$$

According to SCS conventions the T_p, as illustrated in Figure 2.5, is given by Equation 2.12 below as

$$T_p = D/2 + L \tag{2.12}$$

where

D	=	stormflow producing storm duration (h), i.e. the duration after initial abstractions have been satisfied, and
L	=	catchment lag (h).

Therefore, the equation for the estimation of peak discharge flows becomes

$$q_p = \frac{0.2083AQ}{D/2 + L} \tag{2.13}$$

Equation 2.13 assumes storms with a uniform rainfall distribution. However, total storm rainfall rarely, if ever, occurs uniformly with respect to time. It is, therefore, necessary to divide the storm into increments of shorter duration each with an assumed uniform intensity, and to then compute the corresponding increments of stormflow volume. The peak discharge for an incremental unit depth of stormflow, ΔQ, occurring in unit duration of time, ΔD, is defined by Equation 2.14 as

$$\Delta q_p = \frac{0.2083 A \Delta Q}{\Delta D / 2 + L} \qquad 2.14$$

where

Δq_p	=	peak discharge of incremental unit hydrograph (m^3s^{-1}),
ΔQ	=	incremental stormflow depth (mm), and
ΔD	=	incremental duration of time (h).

Figure 2.6 illustrates how the ordinates of the individual incremental triangular hydrographs are added to produce a composite hydrograph, using the principle of super-positioning. Thus the discharge rate may be computed at any time during the storm.

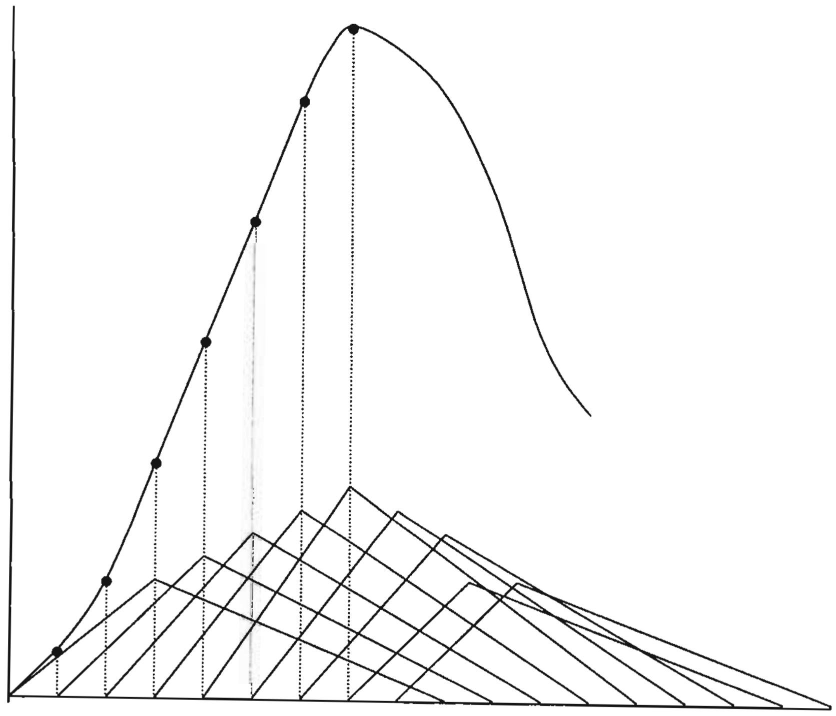

Figure 2.6 Composite hydrograph from individual hydrographs for storm increment ΔD (after NEH-4, 1972)

However, when using a daily rainfall amount, and in the absence of a realistic synthetic rainfall distribution over time for a particular event, a uniform rainfall distribution can be assumed (Schulze and Schmidt, 1995). Hence, in the SAK modelling approach, a single rather than an incremental unit hydrograph is used for peak discharge computation.

The determination of the two unknowns in Equation 2.14, *viz.* the time distribution of design rainfall intensity and catchment response time, are discussed in sub-sections which follow.

2.3.2 Time Distribution of Design Rainfall Intensity

The distribution of storm rainfall with respect to time has a marked effect on timing and magnitude of the peak discharge. In earlier SCS publications two storm rainfall distributions, Type 1 and Type 2 had been established by plotting a ratio of rainfall amount for any duration to the 24-hour amount against duration for a number of locations covering the USA. The Type 1 represents regions with more uniform general/frontal rainfall and/or marine climates producing design storms while the Type 2 distribution, yielding high peak discharges, is typical of regions characterised by shorter, relatively high intensity rainfall events producing design events.

These two rainfall distributions were provisionally adopted for use in southern Africa by Schulze and Arnold (1979). However, many researchers (e.g. Kent, 1973; Cronshey, 1982; Schulze, 1984; Weddepohl, 1988) highlighted the need for additional more "intense" distributions than Type 2 to accommodate higher rainfall intensities that could occur over short durations and could create destructive flood flows.

Schulze (1984) developed four revised synthetic rainfall distributions using digitised rainfall data for KwaZulu-Natal province of South Africa. The D-hour to 24-hour ratios, modified slightly by Schmidt and Schulze (1987), for the four proposed storm rainfall distributions for southern Africa is shown in Table 4.4. For incremental unit hydrographs, the Type 2 and Type 3 storm rainfall distributions may be adapted for Eritrean conditions. The Type 2 should be used for areas associated with lower rainfall intensities, produced often by a frontal rain of longer duration, while the Type 3 should be used for areas in which typical design rainfalls are convective thunderstorms falling over a short duration.

According to Schulze and Schmidt (1995), in the absence of realistic information for individual rainfall events, the effective storm duration, D, could be assumed to be equal to the catchment's time of concentration, T_c, which is related empirically to lag time as $L = 0.6T_c$. The denominator in Equation 2.14 may then be expressed as $1.83L$ and the equation is simplified to

$$q_p = \frac{0.2083AQ}{1.83L} \qquad 2.15$$

The simplified peak discharge equation developed by Schulze and Schmidt (1995) is used in the SAK, as there are only few recording raingauges with short record length in Eritrea. The effect of rainfall intensity in the estimation of q_p is, however, accommodated in one of the methods of estimating catchment response time.

2.3.3 Catchment Response Time

The catchment response time is an index of the rate at which the stormflow which has been generated moves through a catchment. It is an important factor in determining the timing as well as the magnitude of the peak discharge and, hence, the hydrograph shape. In the SCS procedures the response time is termed the catchment lag. Lag is defined as the time from the centre of mass of effective, or stormflow producing, rainfall $(P - I_a)$ to the peak discharge (Schmidt and Schulze, 1987). Four options are available for a user to estimate this lag. These are outlined below.

2.3.3.1 *Time of concentration*

The so-called Time of Concentration, T_c, is an index of a catchment's response time. T_c may be defined as the time it takes for stormflow to travel from the hydraulically most distant point in a catchment to its outlet (i.e. point of longest water travel time). The SCS lag time, *L*, can be considered as a weighted T_c from a single peaked hydrograph (NEH-4, 1972). *L* has been related empirically to T_c (in hours) as follows:

$$L = 0.6T_c \qquad 2.16$$

where

L	=	catchment lag time (h) and
T_c	=	time of concentration (h).

2.3.3.2 *Summation of travel times along flow path reaches*

T_c may be estimated by summing the flow travel times along the various reaches comprising the flow path of water from the hydraulically most distant point in a catchment. The travel time in each flow reach is determined by dividing reach length (m) by flow velocity (m.s^{-1}), as determined from uniform flow equations (e.g. Manning's equation) for full flow conditions. Flow velocities can also be estimated from Figure 4.5 using the so-called Uplands nomograph. The T_c can be calculated from Equation 2.17 and then catchment lag can be computed using Equation 2.16.

$$T_c = \sum_{i=1}^{n} \frac{H_{li}}{V_i * 3600} \qquad 2.17$$

where

T_c	=	time of concentration (h),
H_{li}	=	hydraulic length (m) of reach *i*,
V_i	=	flow velocity (m.s^{-1}) in reach *i*, and
n	=	total number of reaches.

2.3.3.3 *SCS lag equation*

A catchment's lag may also be estimated by the following equation (NEH-4, 1972), expressed in metric units:

$$L = \frac{l^{0.8}(S' + 25.4)^{0.7}}{7069y^{0.5}} \qquad 2.18$$

where

L	=	catchment lag time (h),
l	=	hydraulic length of the catchment along the main channel (m), i.e. the length of the longest stream,
y	=	average catchment slope (%),
S'	=	$\frac{25400}{CN_{II}} - 254$, and
CN_{II}	=	retardance factor approximated by the initial Curve Number (Table 4.1).

The length (l) of the main stream from the catchment outlet to the farthest catchment divide can be measured from a contour map. Average catchment slope, y, may be determined from Equation 2.19 below, as follows:

$$y = \frac{M * N * 10^{-4}}{A} \qquad 2.19$$

where

M	=	total length of all contour lines (m) within the catchment, according to the scale of the map,
N	=	contour interval (m), and
A	=	catchment area (km^2).

2.3.3.4 Schmidt-Schulze lag equation

Schmidt and Schulze (1984) developed the following equation (Equation 2.20) to estimate the lag using observed hydrograph data from a wide range of small catchments in the USA and South Africa, *viz.*

$$L = \frac{A^{0.35} MAP^{1.1}}{41.67 y^{0.3} \bar{I}_{30}^{\ 0.87}} \qquad 2.20$$

where

L	=	catchment lag time (h),
A	=	catchment area (km^2),
MAP	=	mean annual precipitation (mm),
y	=	average catchment slope (%), and
$\bar{I}_{30}$	=	mean of the annual maximum series of 30 minute rainfall intensity ($mm.\ h^{-1}$)
	~	2 year return period 30-minute rainfall intensity ($mm.\ h^{-1}$).

The 2 year return period 30- minute rainfall intensity, $\bar{I}_{30}$, is determined by multiplying the 2 year return period, one day rainfall depth by a factor (Table 2.2) which is related to the four rainfall intensity distribution types, 1 – 4, identified for southern Africa (Schmidt and Schulze, 1987). For example, if the 2 year return period, one day rainfall depth = 30mm, and the point of interest is located in rainfall distribution Type 3, then the product of the multiplication factor = 0.974 and $\bar{I}_{30}$ = 30 * 0.974 = 29.22 $mm.h^{-1}$ (for application in Eritrea, cf. Section 2.3.2).

Table 2.2 Multiplication factors for the different rainfall intensity distribution types identified for southern Africa when determining the 2 year return period 30- minute rainfall intensity (after Schmidt and Schulze, 1987)

Multiplication Factor	Rainfall Intensity Distribution Type			
	1	2	3	4
	0.430	0.664	0.974	1.236

3. USING SCS-ERITREA

This section outlines the use of the SCS program for flood volume and peak discharge calculations in Eritrea. The user should refer to the sections below, as they provide guidance on the information and data that must be input to run the program. The procedures should, however, be used as a design aid only for use with less expensive structures until further verifications have been performed under more diverse climate, land use and soil conditions in Eritrea. The model inputs are either explicit, in which case they need to be obtained directly by the user, or implicit, in which case they can be derived by other means from elsewhere (if they are not available). In the sub-sections which follow, the user will be taken step by step through the various calculation options and alternative pathways required to run the program. The flow chart in Figure 4.1 illustrates the sequence of operations available in the SCS-Eritrea program.

3.1 MAIN MENU OPTIONS

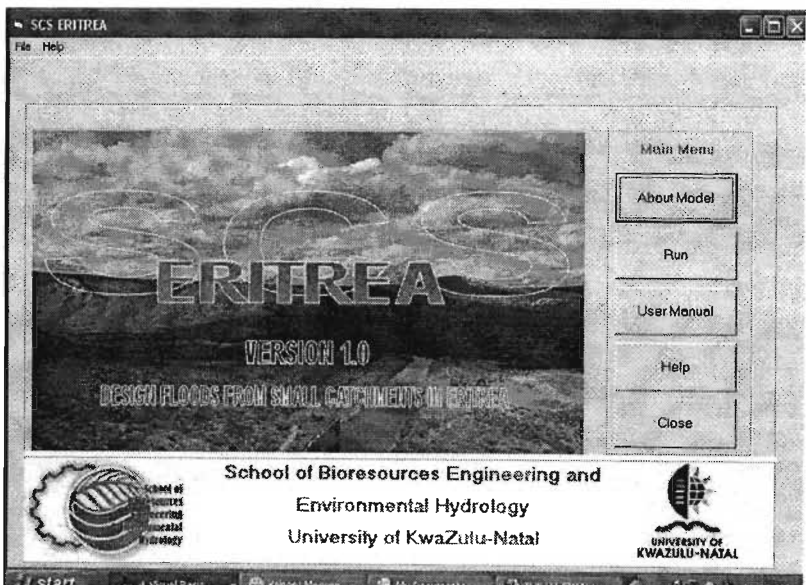

Figure 3.1 *Main Menu* screen

The *Main Menu* contains (Figure 3.1):

ABOUT THE MODEL

The user may obtain a contact address by selecting the About Model button if there are any queries (Figure 3.2).

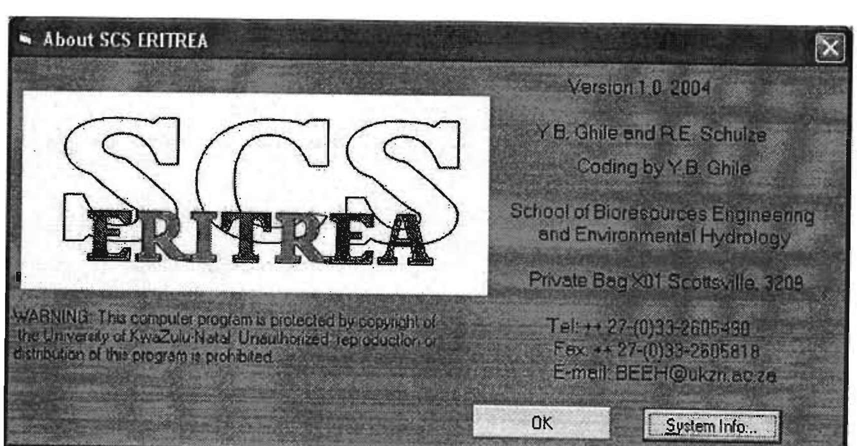

Figure 3.2 *About Model* screen

USER MANUAL

The SCS User Manual, as they provides guidance on the information and data that must be input to run the program. The user requires Adobe Acrobat software to gain an access to the electronic version of the SCS-LHI User Manual.

RUN

The Run button leads the user step-by-step through the SCS procedures before computing the stormflows and peak discharges from small catchments for selected return periods.

HELP

The user can press the "Help" button for further information about the *Main Menu.*

CLOSE

The Close Button terminates the program.

3.2 GENERAL CATCHMENT INFORMATION

The *General Catchment Information* screen is shown in Figure 3.3.

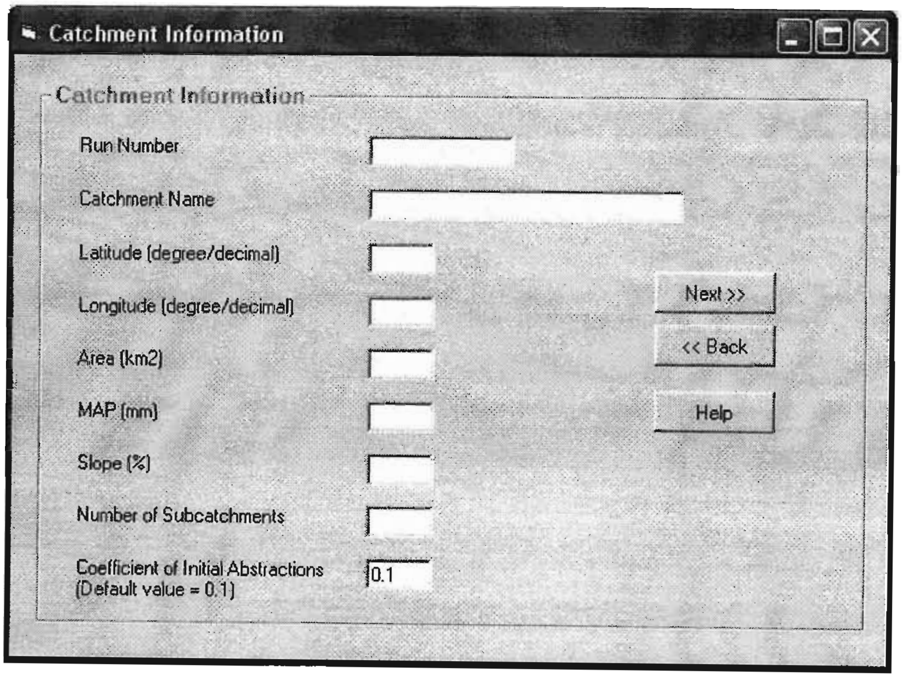

Figure 3.3 *General Catchment Information* screen

- Input *Run Number*

  The *Run Number* will be saved together with the results in the output file. This information may be used as a reference if a user runs the program many times for the same catchment.

- Input the *Catchment Name*

  The *Catchment Name* will also be saved together with the results in the output file.

- Input the catchment's *Latitude* and *Longitude* (in degree/decimal)

  Latitude and *Longitude* may be obtained either by using a Global Positioning System (GPS) or from existing detailed maps. The values of *Latitude* and *Longitude* are required when looking up one day design storm rainfall amounts for selected return periods and the Köppen climate class.

- Input the total catchment *Area* (A in km^2)

  The total catchment *Area* may be obtained either from existing large scale and detailed maps, from a Digital Elevation Model (DEM), or from field surveys. The total catchment area is used in the calculation of stormflow volume (Q, m^3), peak discharge (q_p, m^3s^{-1}) and in one of the options to determine the catchment's response time (L, h).

- Input the catchment's *MAP*, i.e. Mean Annual Precipitation (mm).

  The *MAP* may be obtained from large scale maps (e.g. Figure 4.3) and is used to estimate values of ΔS within a specified KCC and also in one of the options to determine the catchment's response time, L.

- Input the average catchment *Slope* (y, %).

  The average catchment *Slope* may be obtained from contour plan/maps of a catchment (cf. Equation 2.19) and it is used to calculate the catchment's response time, L.

- Input *Number of Subcatchments* (cf. Section 2.2.4.3)

  If a catchment is "1", it is considered to be a single areal entity, i.e. hydrologically relatively uniform. Alternatively, a catchment simulation can be run in semi- distributed mode, i.e. the heterogeneous catchment is delineated into relatively uniform "subcatchments". In physiographically heterogeneous small catchments, the catchment may be sub-divided on the basis of relatively homogenous soils or land cover/uses. As in the SCS-SA (Schulze *et al.*, 1992), the maximum number of subcatchments permissible in SCS-Eritrea is 9 and the sum of all subcatchment areas should be checked to be equal to the total catchment area.

- Input *Coefficient of Initial Abstraction* (*fraction*).

  The *Coefficient of Initial Abstraction* losses can change from month to month and from one climatic region to another, depending on rainfall intensity and duration, as well as on vegetation, site and management characteristics. The c was assumed in its original development (NEH-4, 1972) to have a value of 0.20. Researches conducted by Schulze and Arnold (1979), Schulze *et al.* (1986) Jewitt (1991) and Topping (1992) have shown that the coefficient can, however, increase up to 0.3 or 0.4 immediately after ploughing when surface roughness is high, or under forested conditions, or where intensities of design rainfall are typically low (e.g. frontal or general rainfall), and also decrease to 0.05-0.15 under semi-arid conditions or when soils are compacted, or in peri-urban situations, or in areas where intensities of design rainfall are typically high (e.g. convective rainfall).

3.3 DETERMINATION OF INITIAL CURVE NUMBERS

Input *Initial Curve Numbers*, values of CN_i which can be determined from soils, land cover and hydrological conditions only, with no regard to prevailing soil moisture conditions (cf. Section 2.2.4.). Values of CN_i for a wide range of land cover and treatment classes, stormflow potentials and hydrological soil groups are given in Table 4.1.

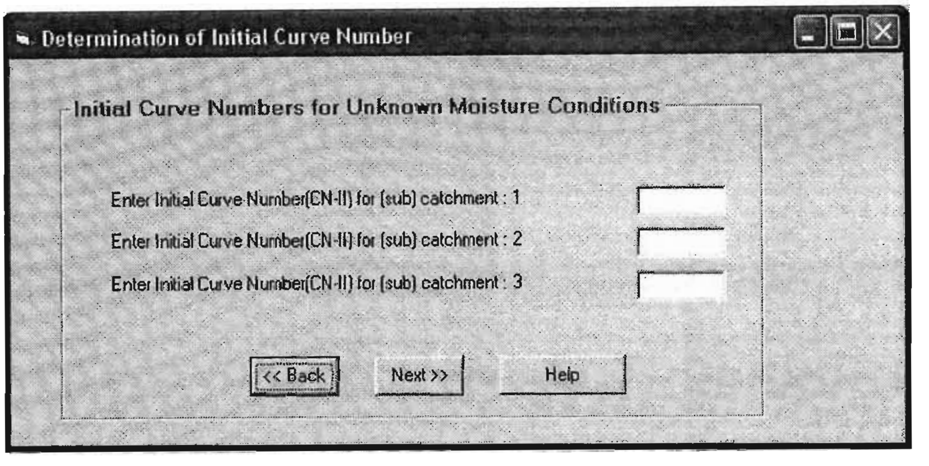

Figure 3.4 *Initial Curve Numbers* screen

3.4 METHOD OF CURVE NUMBER ADJUSTMENT

- The user will be asked if he/she wishes to adjust the *Initial Curve Numbers* (yes or no).
  For less important designs it may not be necessary to adjust the Curve Number for antecedent soil moisture. For important designs, however, adjustment for a region's typically expected soil moisture conditions should be made.

- If the choice is *Yes*, decide on the method of Curve Number adjustment to account for antecedent soil moisture conditions. Two options are available, *viz.* the *Soil Water Budget* or the *ACRU-Köppen* method (Figure 3.5).

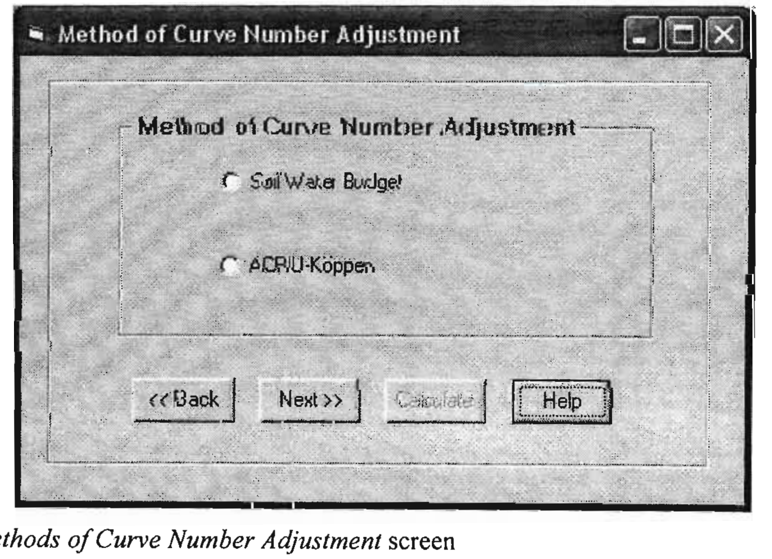

Figure 3.5 *Methods of Curve Number Adjustment* screen

- If the choice is *Soil Water Budget* (Figure 3.6), input the accumulated rainfall (*P*, mm), stormflow (*Q*, mm), actual evapotranspiration (*E*, mm) and drainage (*D*, mm) for a specified antecedent period (e.g. 5 or 30 days).

The change in antecedent soil moisture storage from the initial conditions, ΔS (*P-Q-D-E*), is substituted in the Hawkins' equation (cf. Section 2.2.5.2) to calculate the final Curve Number, CN_f.

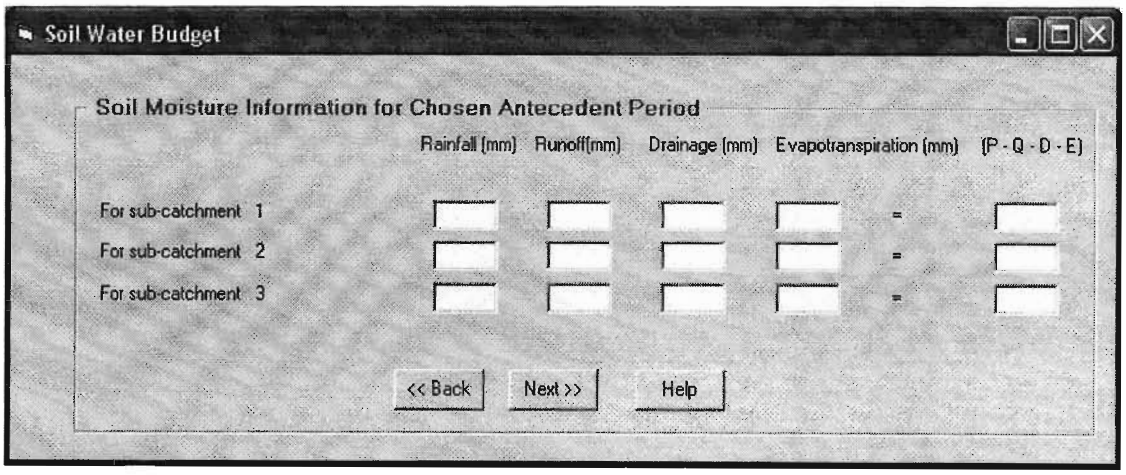

Figure 3.6 *Soil Water Budgeting Procedures of Curve Number Adjustment* screen

- If the choice is *ACRU-Köppen*, the user will be asked if he/she knows the Köppen climate class, KCC, for the catchment. If the answer is *No* mean monthly rainfall and temperature values for the catchment are required to determine the KCC (Figure 3.7).

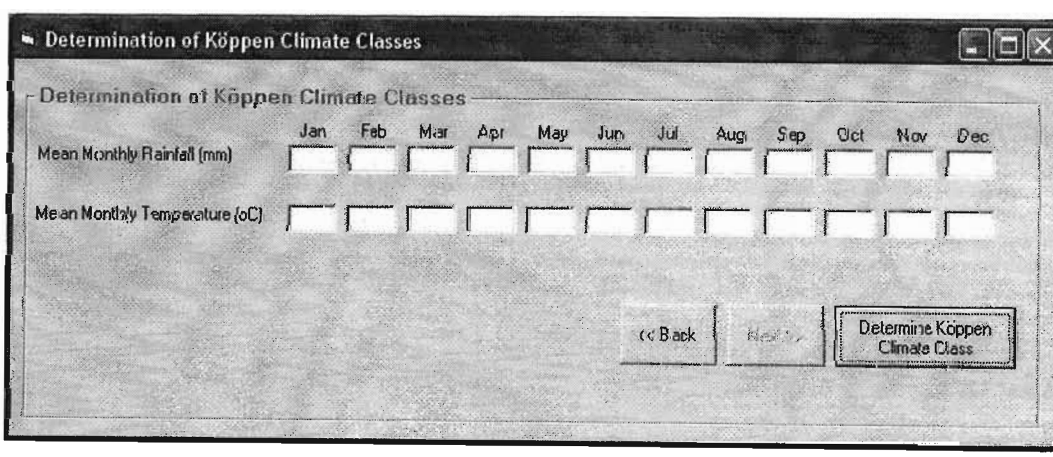

Figure 3.7 Determination of Köppen climate class from mean monthly rainfall and temperature values

- If the answer is *Yes* select the KCC and based on field work, specify the soil depth, soil texture and vegetation cover class using the information contained in Table 2.1 (Figure 3.8).

The change in soil moisture storage, ΔS, can be estimated from MAP (mm) for a given KCC and soil/land use combination from the regression equations given in Table 4.3.

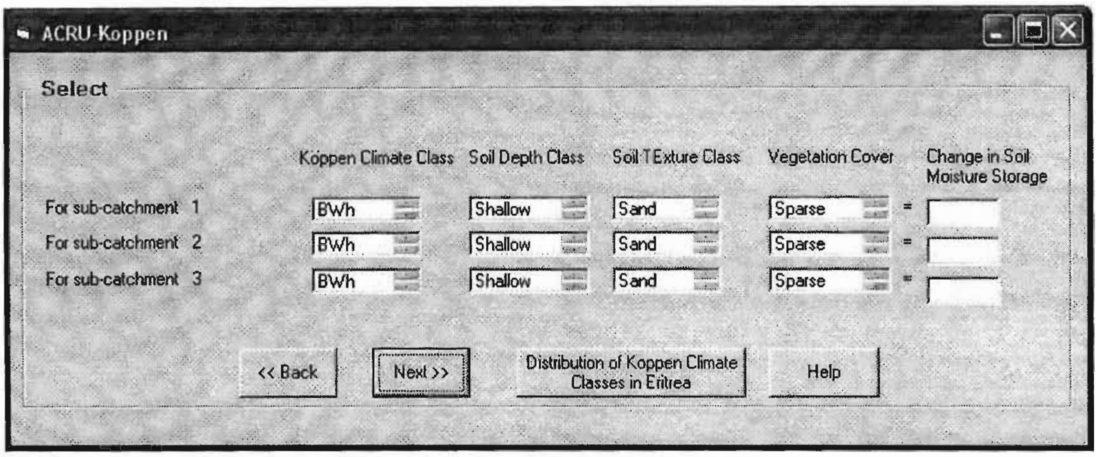

Figure 3.8 *ACRU- Köppen* method of Curve Number adjustment screen

3.5 ONE DAY DESIGN RAINFALL DEPTH

- Input *One Day Design Rainfall Depth* (mm) for selected return periods (Figure 3.9).

Magnitudes of one day expected maximum rainfall over Eritrea are given in a series of maps making up Figure 4.2 for return periods of 2, 5, 10, 20, 50 and 100 years (Van Buskirk, 2003). Note that the SCS-Eritrea computer program does not recognise the maps *per se*, as given in Figure 4.2. The user must enter the values manually for the location of the catchment by referring to those maps.

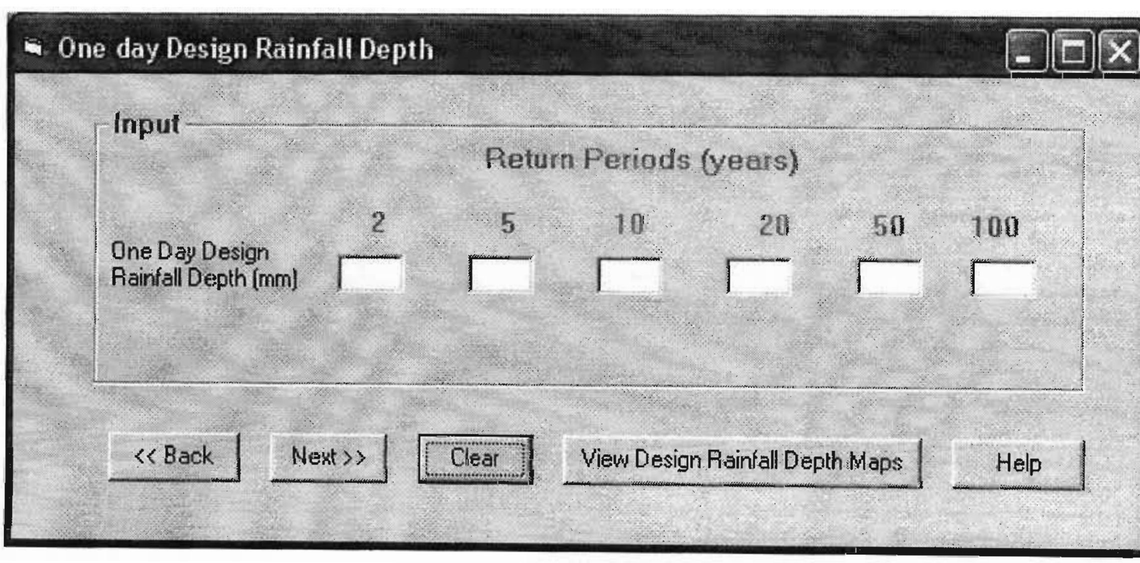

Figure 3.9 *One Day Design Rainfall Depth* screen

3.6 CATCHMENT RESPONSE TIME

- Four options are provided to determine the catchment's response time, *L* (Figure 3.10).

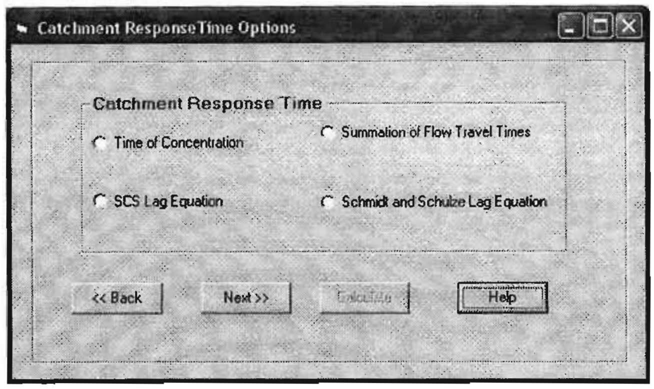

Figure 3.10 *Catchment Response Time Options* screen

- Option 1 = *Time of Concentration* (Figure 3.11)

This option is used if *Time of Concentration*, T_c, has been determined previously (cf. Section 2.3.3.1).

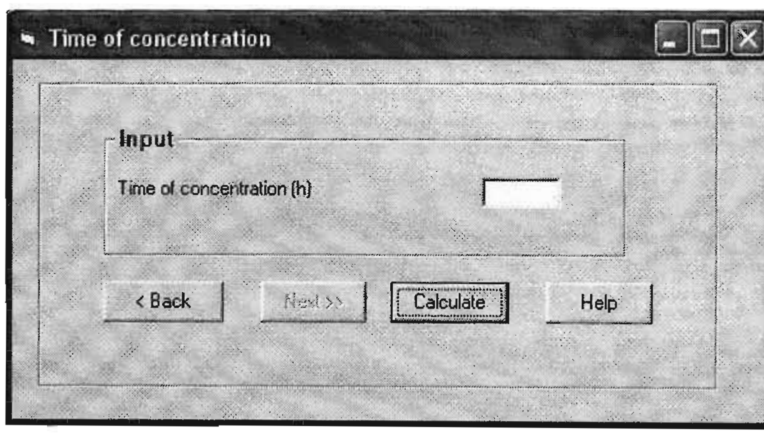

Figure 3.11 *Time of Concentration* method

- Option 2 = *Summation of Flow Travel Times* (Figure 3.12)

This is the preferred method and is recommended when flow velocities can be determined accurately for each of the flow reaches. Flow velocities may be estimated for given slopes of reaches and their hydraulic characteristics by making use of Figure 4.2 (cf. Section 2.3.3.2).

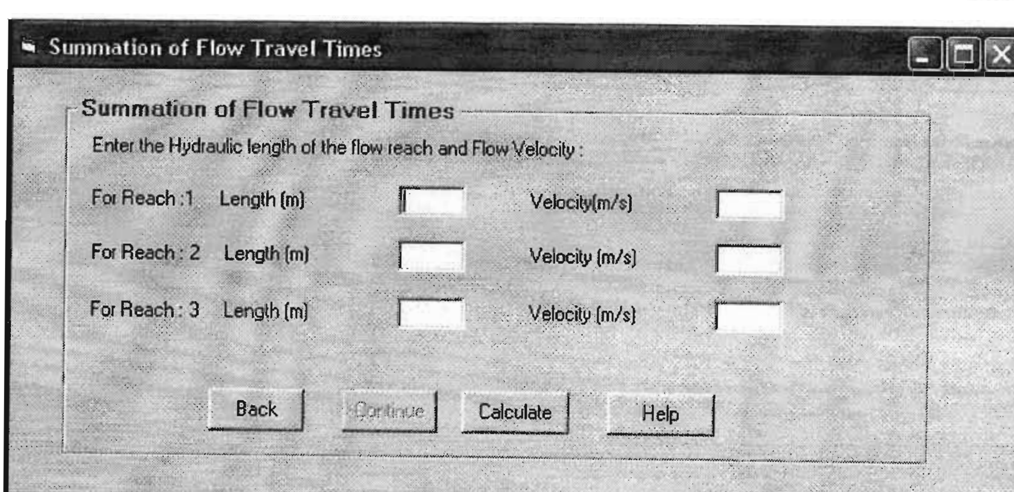

Figure 3.12 *Summation of Flow Travel Times* method

- Option 3 = *SCS Lag Equation* (Figure 3.13)

This empirical equation (cf. Section 2.3.3.3) was developed in the USA. It has been found suitable in southern Africa for use in more semi-arid areas with limited vegetation cover and in areas with shallow soils (Schulze *et al.*, 1992).

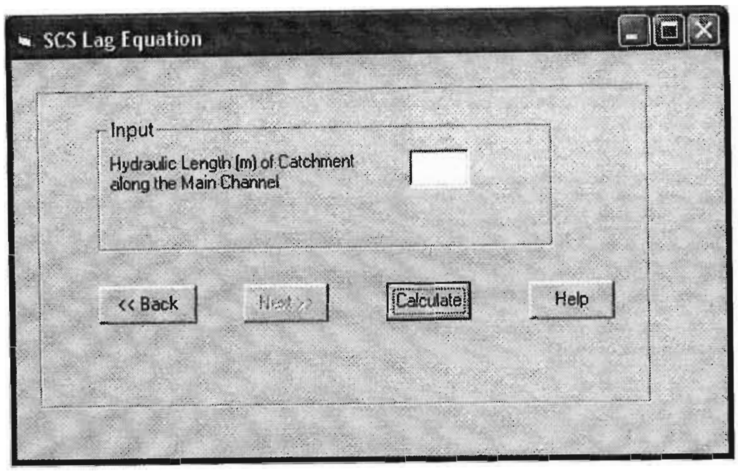

Figure 3.13 *SCS Lag Equation* method

- Option 4 = *Schmidt and Schulze Lag Equation* (Figure 3.14)

This empirical equation (cf. Section 2.3.3.4) was developed using data from rural catchments in the USA and South Africa under natural vegetation and is recommended in sub-humid and more humid areas with a relatively high MAP and/or with a good vegetation cover (Schulze *et al.*, 1992).

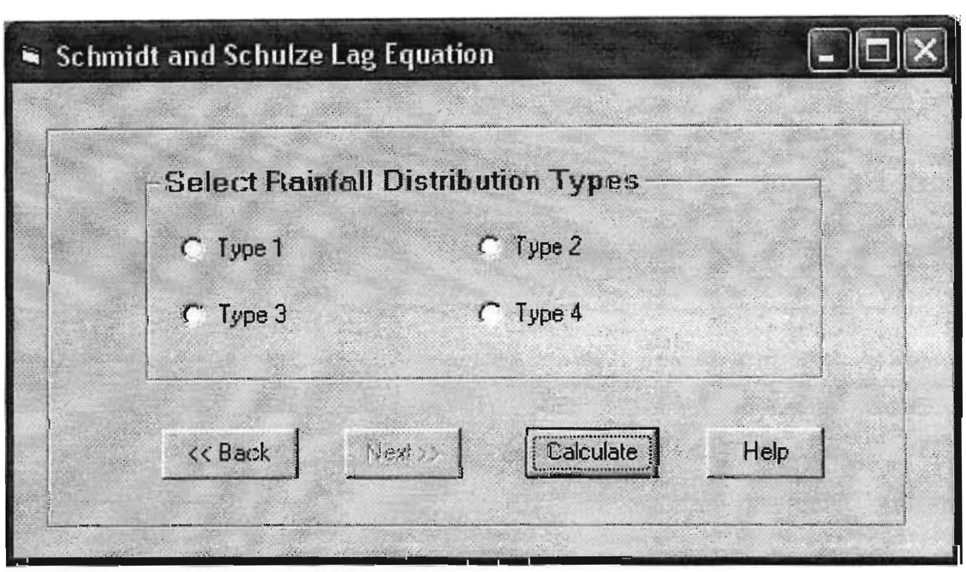

Figure 3.14 *Schmidt and Schulze Lag Equation* method

The program ends by summarising the results on the screen (Figure 3.15). Results include the:

- run number,
- catchment name,
- latitude and longitude, mean annual precipitation (mm),

- catchment slope(%),
- catchment area (km^2)
- final Curve Number,
- maximum soil water retention,
- one day design rainfall depths (mm) for the selected return periods,
- one day design stormflow depths (mm) and associated stormflow volumes (m^3) for the selected return periods , and
- computed peak discharges (m^3.s^{-1}) for the selected return periods.

Results can be saved as a text file in a chosen drive and directory

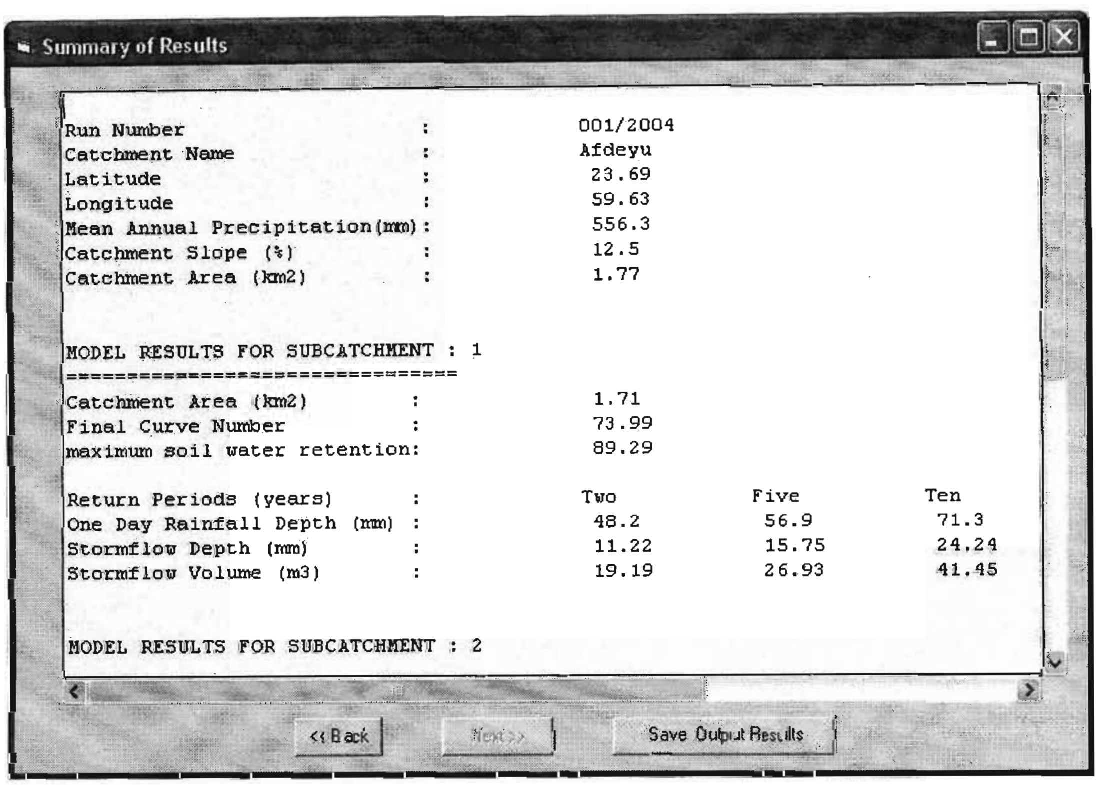

Figure 3.15 Summary of results screen

A most important component of this user manual remains the transfer of technology to the professional designer requiring a comprehensive guide to modelling of stormflow volumes and peak discharges from small catchments in Eritrea. With further improvements, it is believed that the SCS-Eritrea will play an increasingly important role in future design hydrology on Eritrea's small catchments.

4 ADDITIONAL FIGURES AND TABLES

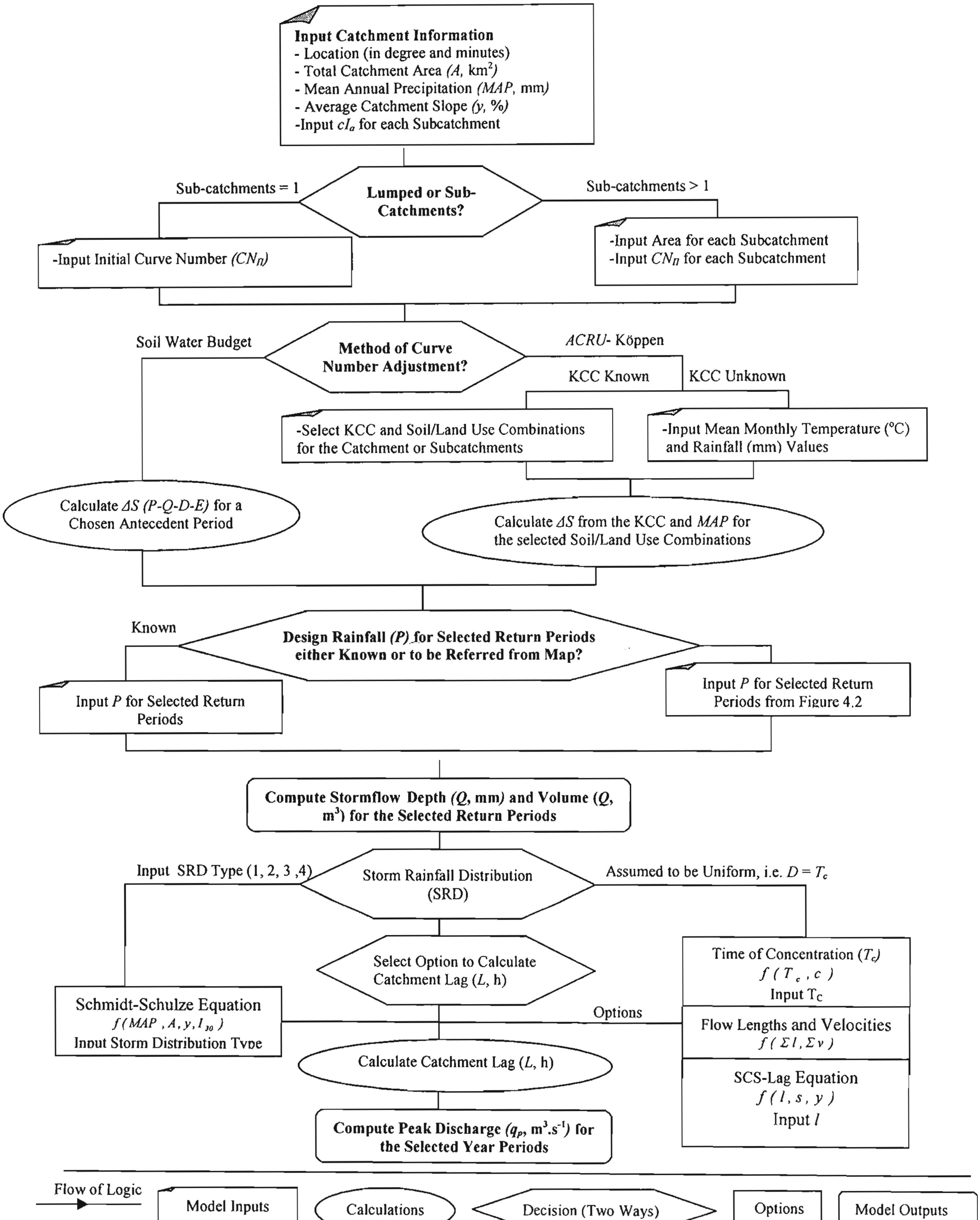

Figure 4.1 Flow chart illustrating the various calculation options and paths for the SCS-*ACRU*-Köppen (SAK) modelling approach in Eritrea

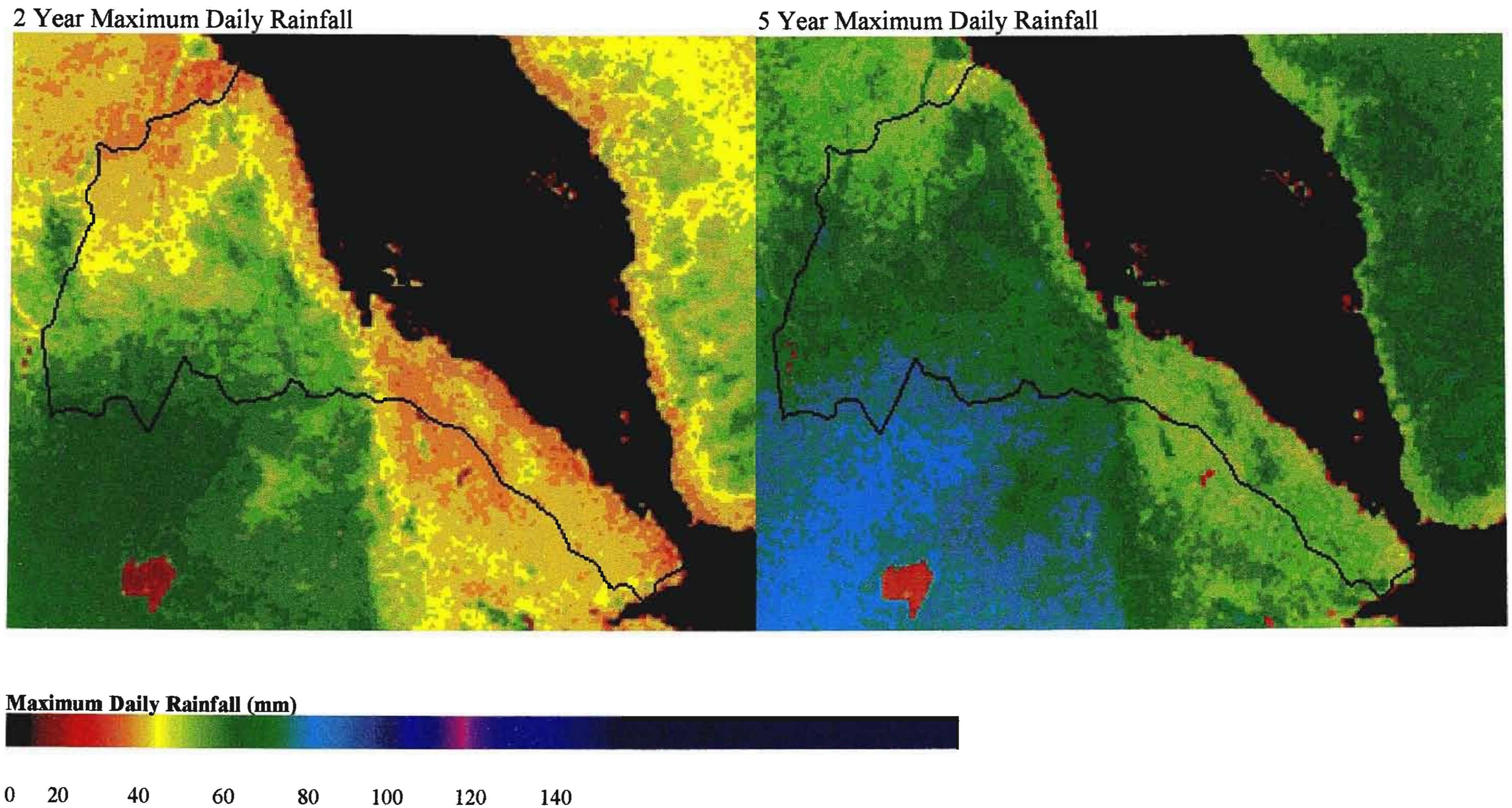

Figure 4.2 One day design rainfall distribution over Eritrea for 2, 5, 10, 20, 50 and 100 return year periods (after Van Buskirk, 2003)

10 Year Maximum Daily Rainfall

20 Year Maximum Daily Rainfall

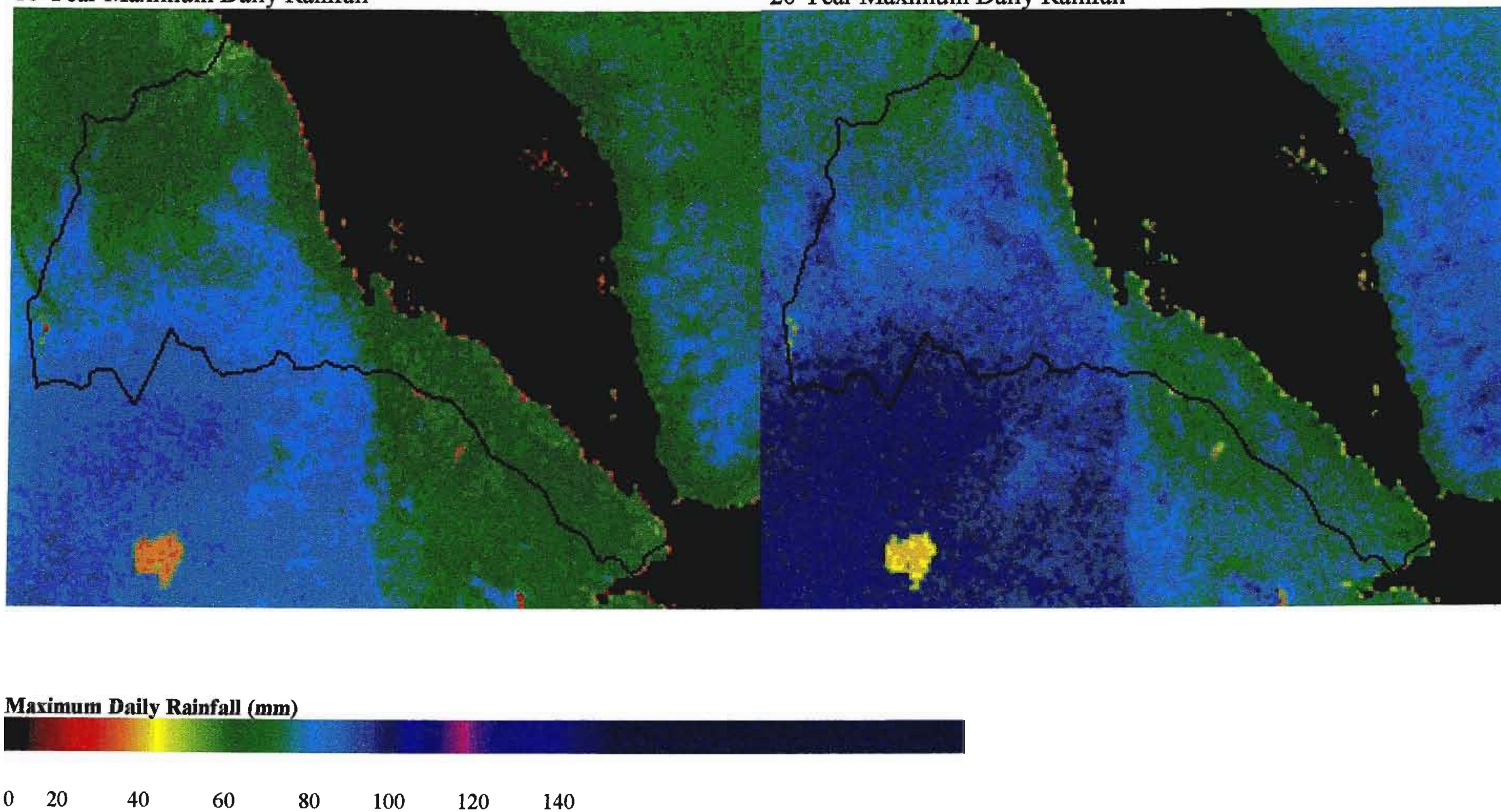

Figure 4.2 (continued)

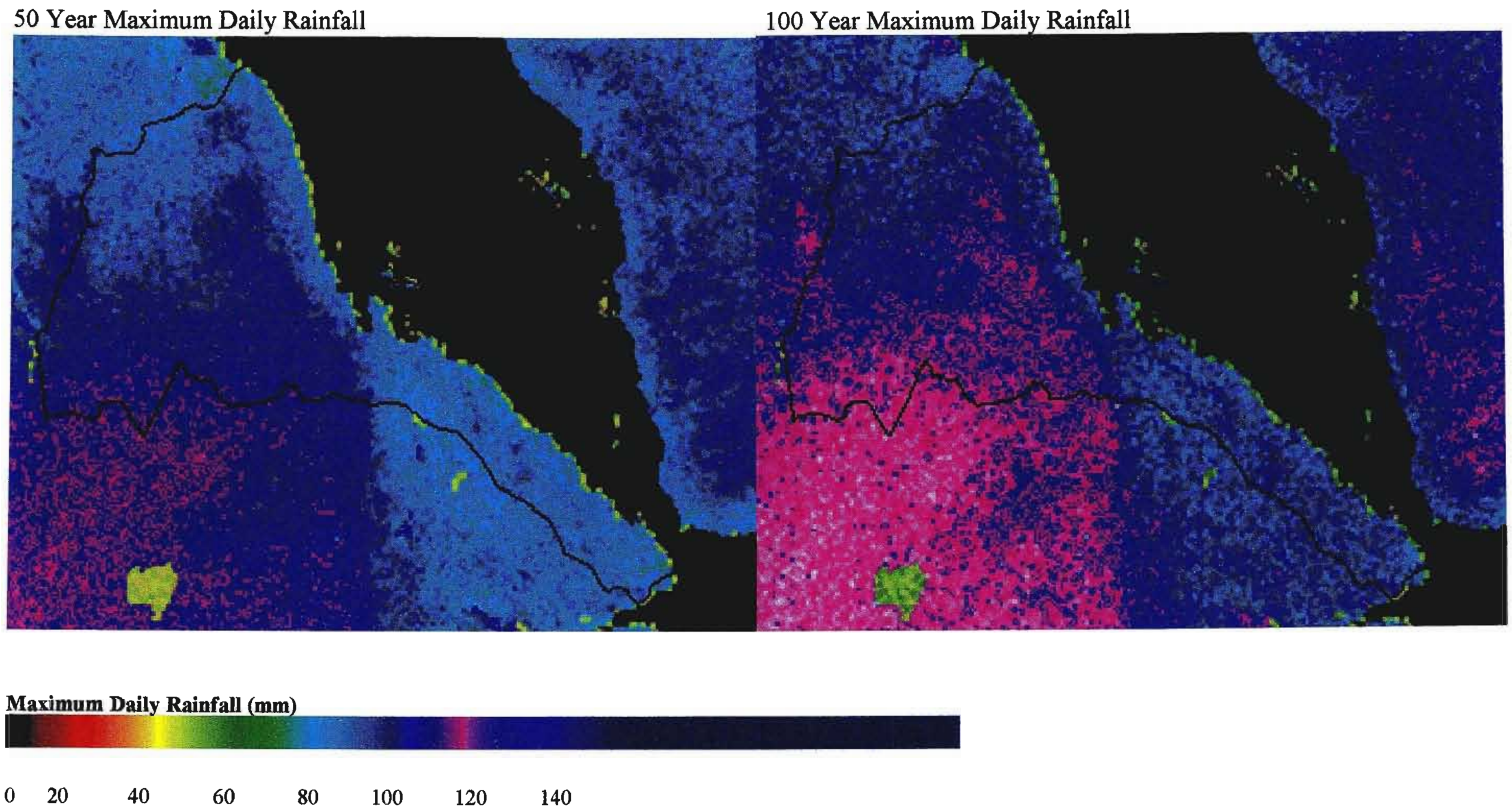

Figure 4.2 (continued)

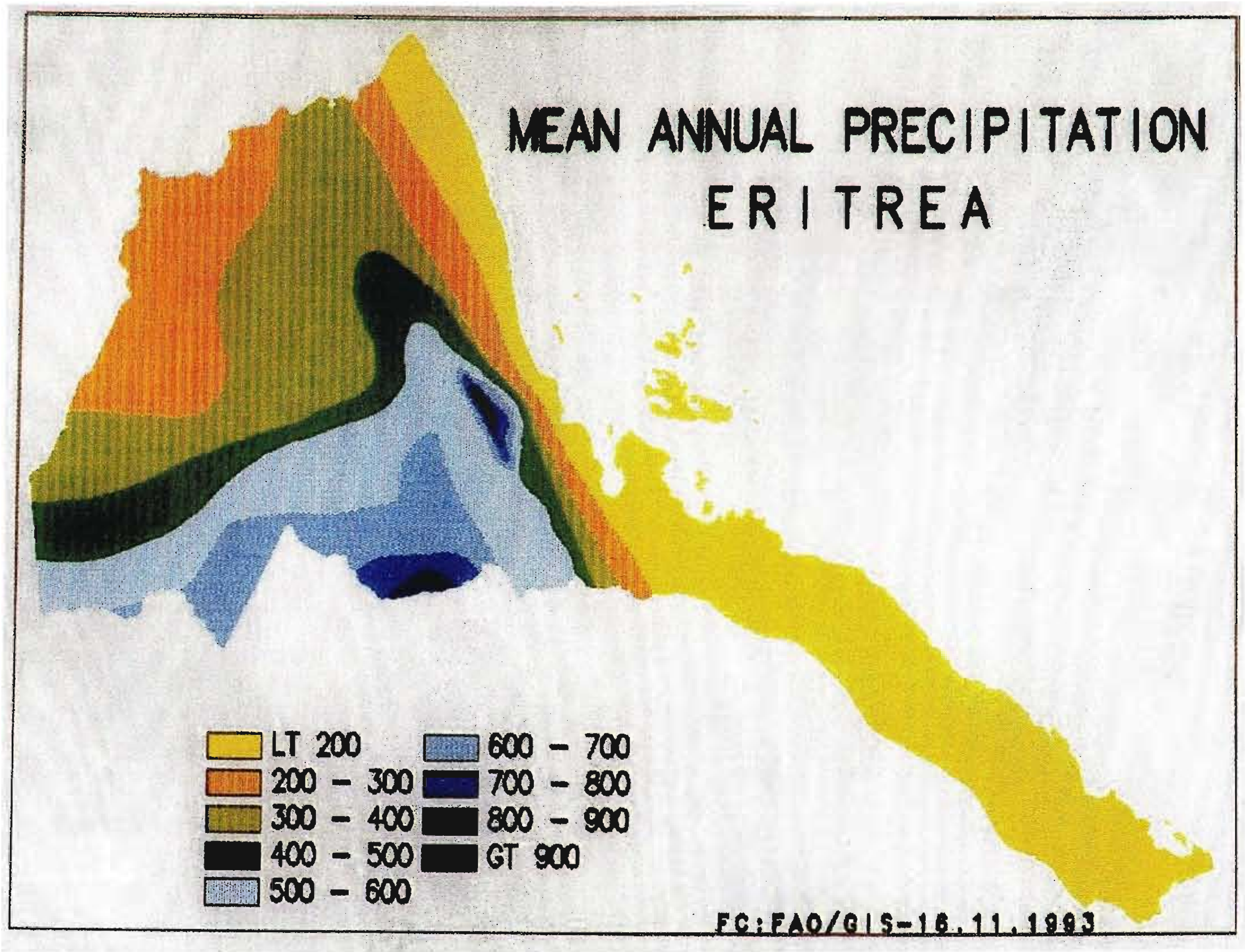

Figure 4.3 Distribution of mean annual precipitation in Eritrea (after FAO, 1994)

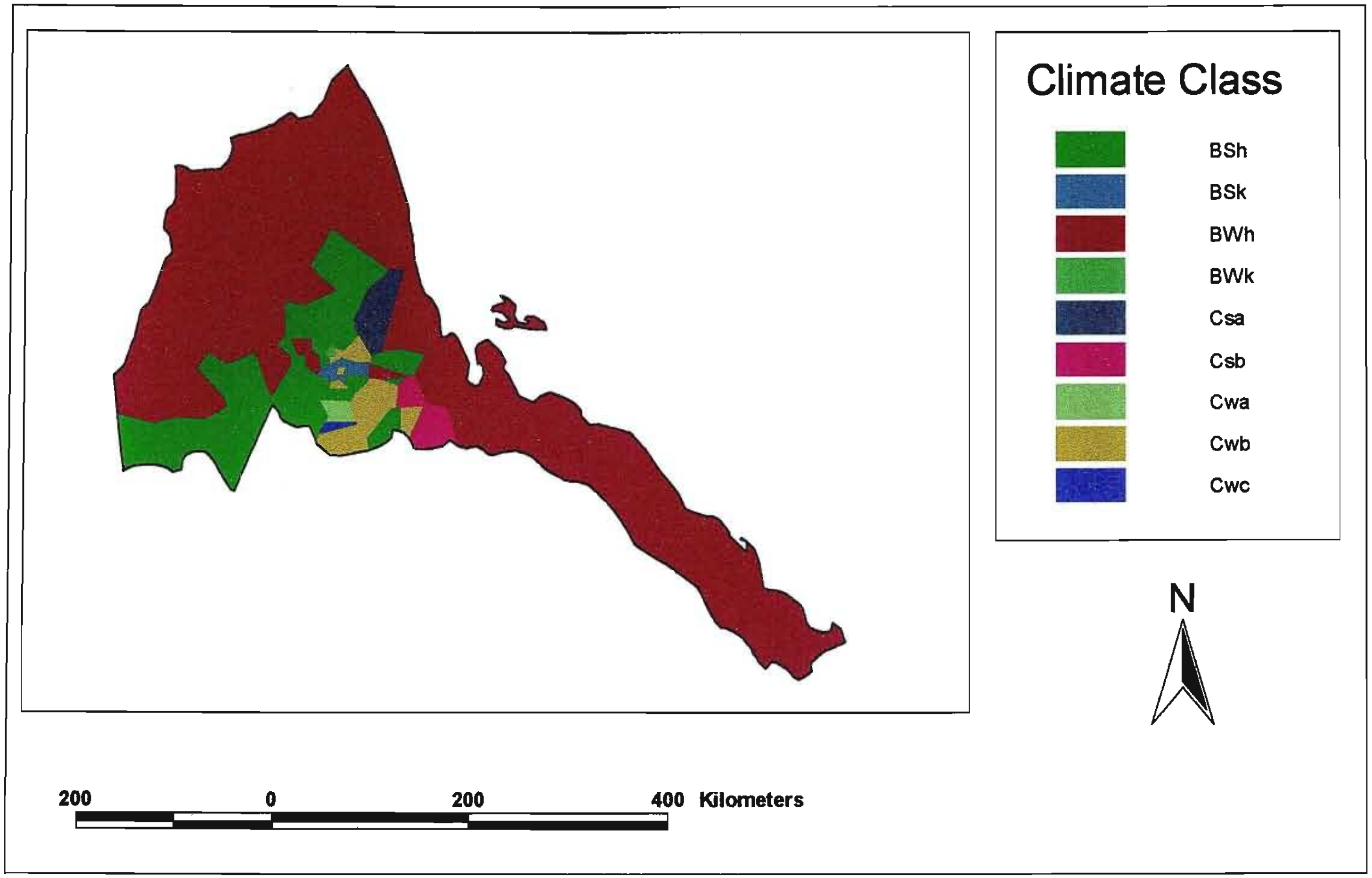

Figure 4.4 Köppen climate classes identified over Eritrea

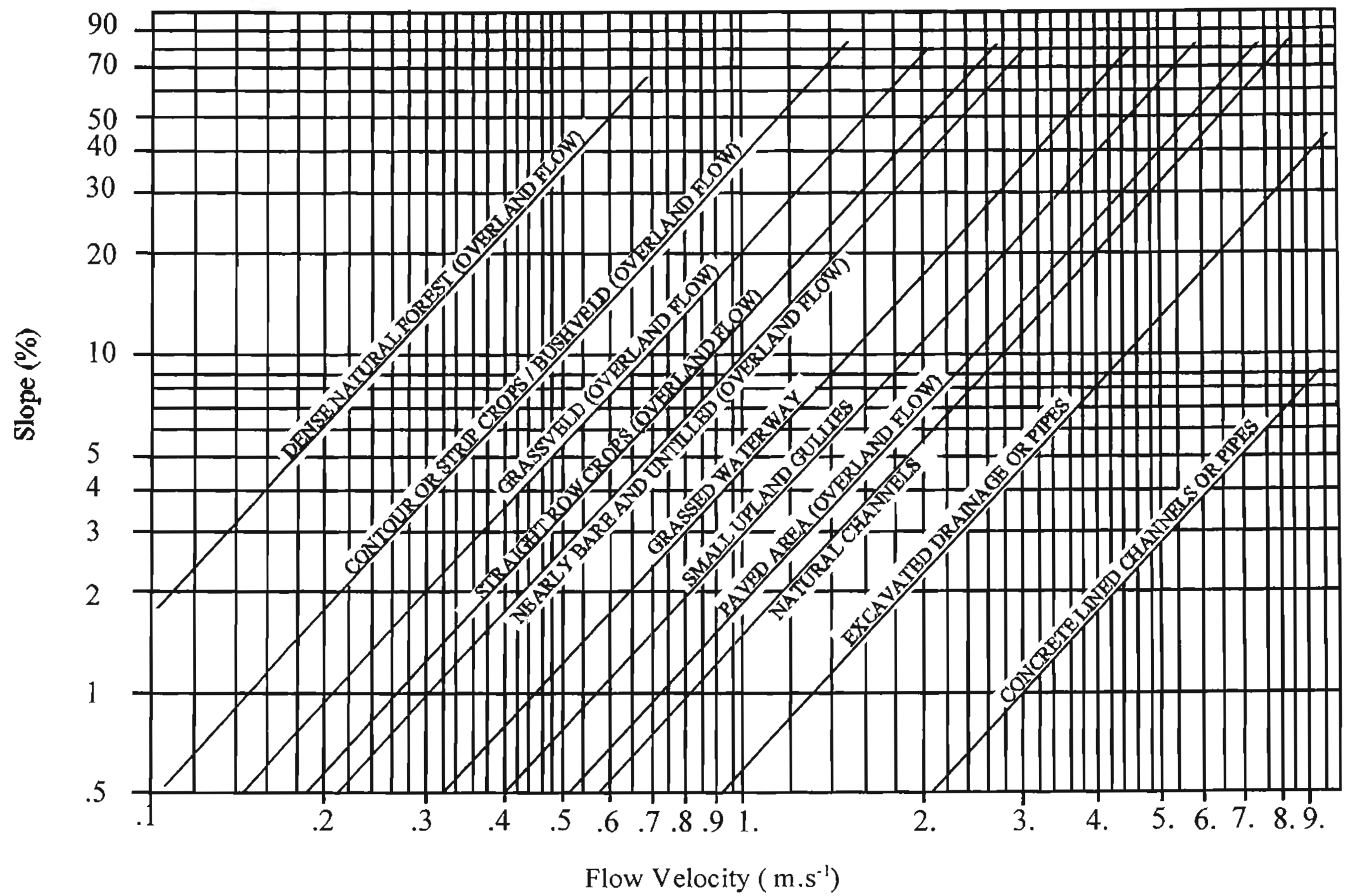

Figure 4.5 The Uplands nomograph for estimating flow velocities (after Schulze and Arnold, 1979)

Table 4.1 Initial Curve Numbers for the selected land cover and treatment classes, stormflow potentials and hydrological soil groups (after Schmidt and Schulze, 1987)

Land Cover Class	Land treatment/Practice/Description	Stormflow Potential	Hydrological Soil Group						
			A	A/B	B	B/C	C	C/D	D
Fallow	Straight row		77	82	86	89	91	93	94
	Straight row + conservation tillage	High	75	80	84	87	89	91	92
	Straight row + conservation tillage	Low	74	79	83	85	87	89	90
Row Crops	Straight row	High	72	77	81	85	88	90	91
	Straight row	Low	67	73	78	82	85	87	89
	Straight row + conservation tillage	High	71	75	79	83	86	88	89
	Straight row + conservation tillage	Low	64	70	75	79	82	84	85
	Planted on contour	High	70	75	79	82	84	86	88
	Planted on contour	Low	65	69	75	79	82	84	86
	Planted on contour + conservation tillage	High	69	74	78	81	83	85	87
	Planted on contour + conservation tillage	Low	64	70	74	78	80	82	84
	Conservation structures	High	66	70	74	77	80	82	82
	Conservation structures	Low	62	67	71	75	78	80	81
	Conservation structures + conservation tillage	High	65	70	73	76	79	80	81
	Conservation structures + conservation tillage	Low	61	66	70	73	76	78	79
Garden Crops	Straight row	High	45	56	66	72	77	80	83
	Straight row	Low	68	71	75	79	81	83	84
Small Grain	Straight row	High	65	71	76	80	84	86	88
	Straight row	Low	63	69	75	79	83	85	87
	Straight row + conservation tillage	High	64	70	74	78	82	84	86
	Straight row + conservation tillage	Low	60	67	72	76	80	82	84
	Planted on contour	High	63	69	74	79	82	84	85
	Planted on contour	Low	61	67	73	78	81	83	84
	Planted on contour + conservation tillage	High	62	68	73	77	81	83	84
	Planted on contour + conservation tillage	Low	60	66	72	76	79	81	82
	Planted on contour – winter rainfall region	Low	63	66	70	75	78	80	81
	Conservation structures	High	61	67	72	76	79	81	82
	Conservation structures	Low	59	65	70	75	78	80	81
	Conservation structures + conservation tillage	High	60	67	71	75	78	80	81
	Conservation structures + conservation tillage	Low	58	64	69	73	76	78	79
Closed Seeded Legumes or Rotational Meadow	Straight row	High	66	72	77	81	85	87	89
	Straight row	Low	58	65	72	75	81	84	85
	Planted on contour	High	64	70	75	80	83	84	85
	Planted on contour	Low	55	63	69	74	78	81	83
	Conservation structures	High	63	68	73	77	80	82	83
	Conservation structures	Low	51	60	67	72	76	78	80
Sugarcane	Straight row: trash burnt		43	55	65	72	77	80	82
	Straight row: trash mulch		45	56	66	72	77	80	83
	Straight row: limited cover		67	73	78	82	85	87	89
	Straight row: partial cover		49	60	69	73	79	82	84
	Straight row: complete cover		39	50	61	68	74	78	80
	Conservation structures: limited cover		65	70	75	79	82	84	86
	Conservation structures: partial cover		25	46	59	67	75	80	83
	Conservation structures: complete cover		6	14	35	59	70	75	79

Table 4.1 (Continued)

Land Cover Class	Land treatment/Practice/Description	Stormflow Potential	Hydrological Soil Group						
			A	A/B	B	B/C	C	C/D	D
Veld and Pasture	Veld/pasture in poor condition	High	68	74	79	83	86	88	89
	Veld/pasture in fair condition	Moderate	49	61	69	75	79	82	84
	Veld/pasture in good condition	Low	39	51	61	68	74	78	80
	Pasture planted on contour	High	47	57	67	75	81	85	88
	Pasture planted on contour	Moderate	25	46	59	67	75	80	83
	Pasture planted on contour	Low	6	14	35	59	70	75	79
Irrigated Pasture		Low	35	41	48	57	65	68	70
Meadow		Low	30	45	58	65	71	75	81
Woods and Scrub	Woods	High	45	56	66	72	77	80	83
	Woods	Moderate	36	49	60	68	73	77	79
	Woods	Low	25	47	55	64	70	74	77
	Brush – winter rainfall region	Low	28	36	44	53	60	64	66
Orchards	winter rainfall region understory of crop cover		39	44	53	61	66	69	71
Forests and Plantations	Humus depth 25 mm; compacted		52	62	72	77	82	85	87
	Humus depth 25 mm; moderately compacted		48	58	68	73	78	82	85
	Humus depth 25 mm; loose/friable		37	49	60	66	71	74	77
	Humus depth 50 mm; compacted		48	58	68	73	78	82	85
	Humus depth 50 mm; moderately compacted		42	54	65	70	75	78	81
	Humus depth 50 mm; loose/friable		32	45	57	62	67	71	74
	Humus depth 100 mm; compacted		41	53	64	69	74	77	80
	Humus depth 100 mm; moderately compacted		34	47	59	64	69	72	75
	Humus depth 100 mm; loose/friable		23	37	50	56	61	64	67
	Humus depth 150 mm; compacted		37	49	60	66	71	74	77
	Humus depth 150 mm; moderately compacted		30	43	56	61	66	69	72
	Humus depth 150 mm; loose/friable		18	33	47	52	57	61	65
Urban/Sub-urban land uses	Open spaces, parks, cemeteries, 75% grass cover		39	51	61	68	74	78	80
	Open spaces, parks, cemeteries, 75% grass cover		49	61	69	75	79	82	84
	Commercial/ business areas, 85% impervious		89	91	92	93	94	95	95
	Industrial districts, 72% impervious		81	85	88	90	91	92	93
	Residential: lot size 500 m^2, 65% impervious		77	81	85	88	90	91	92
	Residential: lot size 1000 m^2, 65% impervious		61	69	75	80	83	85	87
	Residential: lot size 1350 m^2, 65% impervious		57	65	72	77	81	84	86
	Residential: lot size 2000 m^2, 65% impervious		54	63	70	76	80	83	85
	Residential: lot size 4000 m^2, 65% impervious		51	61	68	75	78	82	84
	Paved parking lots, roofs, etc.		98	98	98	98	98	98	98
	Streets/roads: tarred, with storm sewers, curbs		98	98	98	98	98	98	98
	Streets/roads: gravel		76	81	85	88	89	90	91
	Streets/roads: dirt		72	77	82	85	87	88	89
	Streets/roads: dirt-hard surface		74	79	84	88	90	91	92

Table 4.2 Major Köppen (1931) climate classes and their detailed climatic characteristics (after Ahrens, 1994)

Table of Köppen's Climatic Classification System

Letter symbol 1	2	3	Climate characteristics	Criteria
A	-	-	Humid tropical	All months have an average temperature >18°C
	f	-	Tropical wet (rain forest)	Wet all seasons; all months have at least 60 mm of rainfall
	w	-	Tropical wet and dry (savanna)	Winter dry season; rainfall in driest month is < 60 mm and < than 100P/25
	m	-	Tropical monsoon	Short dry season; rainfall in driest month is < 60 mm but equal to or > 100P/25
B	-	-	Dry	P<20(t+14) when 70% or more of rain falls in warmer 6 months (dry winter) P<20t when 70% or more of rain falls in cooler 6 months (dry summer) P<20(t+7) when neither half of the year has 70% or more of the annual rain
	S	-	Semi-arid (steppe)	10(t+14) < P<20(t+14) when 70% or more of rain falls in warmer 6 months (dry winter) 10t <P< 20t when 70% or more of rain falls in cooler 6 months (dry summer) 10(t+7) <P <20(t+7) when neither half of the year has 70% or more of the annual rain
	W	-	Arid (desert)	P <10(t+14) when 70% or more of rain falls in warmer 6 months (dry winter) P< 10t when 70% or more of rain falls in warmer 6 months (dry winter) P <10(t+7) when neither half year has 70% or more of the annual rain
	-	h	Hot and dry	Mean annual temperature is 18°C or higher
	-	k	Cool and dry	Mean annual temperature is below 18°C
C	-	-	Moist with mild winters	Average temperature of coolest month is < 18°C and > -3°C
	w	-	Dry winters	Average rainfall of wettest month at least 10 times as much as in driest winter month
	s	-	Dry summers	Average rainfall of wettest winter month at least 3 times as much as in driest summer month
	f	-	Wet all seasons	Criteria for w and s cannot be met
	-	a	Summers long and hot	Average temperature of warmest month > 22°C
	-	b	Summers long and cool	Average temperature of all months < 22°C; at least 4 months with average > 10°C
	-	c	Summers short and cool	Average temperature of all months < 22°C; 1 - 3 months with average > 10°C
D	-	-	Moist with cold winters	Average temperature of coldest month is < -3°C; average temp of warmest month is > 10°C
	w	-	Dry winters	Same as under Cw
	s	-	Dry summers	Same as under Cs
	f	-	Wet at all seasons	Same as under Cf
	-	a	Summers long and hot	Same as under Cfa
	-	b	Summers long and cool	Same as under Cfb
	-	c	Summers short and cool	Same as under Cfc
	-	d	Summers short and cool; Winters severe	Average temperature of coldest month is < -3°C and warmest month >10°C
E	-	-	Polar climates	Average temperature of warmest month is <10°C
	T	-	Tundra	Average temperature of warmest month is >0°C but < 10°C
	F	-	Ice cap	Average temperature of warmest month is 0°C or below

"P" is the mean annual precipitation (mm) and "t" the mean annual temperature (°C)

Table 4.3 Regression equations developed from hydrological zones having similar Köppen climate classes in southern Africa, for a combination of three soil depth categories, three soil texture classes and three vegetation cover conditions

BWh

Soil Depth	Soil Texture	Vegetation Cover	Regression Equation
Shallow	Sand	Sparse	$y = 0.0393x - 10.26$
		Intermediate	$y = 0.0012x - 9.4665$
		Dense	$y = 3E\text{-}16x - 9.3$
	Loam	Sparse	$y = 0.0168x - 12.754$
		Intermediate	$y = 0.0054x - 18.691$
		Dense	$y = 0.0012x - 18.566$
	Clay	Sparse	$y = 0.0116x - 11.872$
		Intermediate	$y = 0.0031x - 17.70$
		Dense	$y = 0.0012x - 17.866$
Intermediate	Sand	Sparse	$y = 0.0246x - 13.259$
		Intermediate	$y = 0.0098x - 22.397$
		Dense	$y = 0.0023x - 23.433$
	Loam	Sparse	$y = 0.0222x - 21.468$
		Intermediate	$y = 0.0197x - 38.103$
		Dense	$y = 0.0167x - 46.103$
	Clay	Sparse	$y = 0.0196x - 21.086$
		Intermediate	$y = 0.0169x - 37.07$
		Dense	$y = 0.0126x - 44.088$
Deep	Sand	Sparse	$y = 0.0247x - 15.917$
		Intermediate	$y = 0.0132x - 29.004$
		Dense	$y = 0.0074x - 34.106$
	Loam	Sparse	$y = 0.0271x - 26.567$
		Intermediate	$y = 0.0249x - 46.826$
		Dense	$y = 0.0248x - 62.234$
	Clay	Sparse	$y = 0.0244x - 26.127$
		Intermediate	$y = 0.0278x - 46.933$
		Dense	$y = 0.0224x - 60.343$

BWk

Soil Depth	Soil Texture	Vegetation Cover	Regression Equation
Shallow	Sand	Sparse	$y = 0.0094x - 6.2283$
		Intermediate	$y = 0.0008x - 9.3032$
		Dense	$y = -2E\text{-}16x - 9.3$
	Loam	Sparse	$y = 0.0075x - 11.159$
		Intermediate	$y = 0.0048x - 18.122$
		Dense	$y = 0.0002x - 18.409$
	Clay	Sparse	$y = 0.0046x - 10.636$
		Intermediate	$y = 0.0035x - 17.368$
		Dense	$y = 0.0005x - 17.732$
Intermediate	Sand	Sparse	$y = 0.0084x - 10.721$
		Intermediate	$y = 0.0107x - 21.132$
		Dense	$y = 0.0031x - 23.27$
	Loam	Sparse	$y = 0.0132x - 19.427$
		Intermediate	$y = 0.0188x - 35.179$
		Dense	$y = 0.0125x - 43.653$
	Clay	Sparse	$y = 0.0134x - 19.34$
		Intermediate	$y = 0.0166x - 34.318$
		Dense	$y = 0.0121x - 42.333$
Deep	Sand	Sparse	$y = 0.0109x - 13.525$
		Intermediate	$y = 0.0167x - 27.289$
		Dense	$y = 0.0089x - 33.254$
	Loam	Sparse	$y = 0.0183x - 23.995$
		Intermediate	$y = 0.0264x - 42.889$
		Dense	$y = 0.0232x - 57.815$
	Clay	Sparse	$y = 0.0188x - 24.023$
		Intermediate	$y = 0.0230x - 42.0$
		Dense	$y = 0.0224x - 60.343$

BSh

Soil Depth	Soil Texture	Vegetation Cover	Regression Equation
Shallow	Sand	Sparse	$y = 0.0091x - 3.8345$
		Intermediate	$y = 0.0132x - 12.994$
		Dense	$y = 0.0049x - 11.111$
	Loam	Sparse	$y = 0.0326x - 16.792$
		Intermediate	$y = 0.0206x - 23.594$
		Dense	$y = 0.0117x - 21.879$
	Clay	Sparse	$y = 0.0222x - 15.236$
		Intermediate	$y = 0.0115x - 20.417$
		Dense	$y = 0.0087x - 20.284$
Intermediate	Sand	Sparse	$y = 0.0418x - 16.119$
		Intermediate	$y = 0.0398x - 31.789$
		Dense	$y = 0.0182x - 28.494$
	Loam	Sparse	$y = 0.0573x - 32.252$
		Intermediate	$y = 0.0403x - 45.157$
		Dense	$y = 0.0300x - 51.321$
	Clay	Sparse	$y = 0.0359x - 25.82$
		Intermediate	$y = 0.0269x - 40.425$
		Dense	$y = 0.0208x - 47.07$
Deep	Sand	Sparse	$y = 0.0449x - 20.702$
		Intermediate	$y = 0.0473x - 39.748$
		Dense	$y = 0.0289x - 41.255$
	Loam	Sparse	$y = 0.0627x - 37.402$
		Intermediate	$y = 0.0467x - 53.743$
		Dense	$y = 0.0370x - 66.44$
	Clay	Sparse	$y = 0.0436x - 31.589$
		Intermediate	$y = 0.0345x - 49.557$
		Dense	$y = 0.0291x - 62.703$

BSk

Soil Depth	Soil Texture	Vegetation Cover	Regression Equation
Shallow	Sand	Sparse	$y = 0.0115x - 4.6845$
		Intermediate	$y = 0.0102x - 11.807$
		Dense	$y = 0.0034x - 10.361$
	Loam	Sparse	$y = 0.0265x - 15.088$
		Intermediate	$y = 0.0140x - 20.942$
		Dense	$y = 0.0092x - 20.757$
	Clay	Sparse	$y = 0.0175x - 13.507$
		Intermediate	$y = 0.0095x - 19.296$
		Dense	$y = 0.0071x - 19.497$
Intermediate	Sand	Sparse	$y = 0.0369x - 15.832$
		Intermediate	$y = 0.0204x - 24.547$
		Dense	$y = 0.0111x - 25.672$
	Loam	Sparse	$y = 0.0359x - 24.666$
		Intermediate	$y = 0.0230x - 38.209$
		Dense	$y = 0.0178x - 46.215$
	Clay	Sparse	$y = 0.0267x - 22.538$
		Intermediate	$y = 0.0178x - 36.416$
		Dense	$y = 0.0150x - 44.277$
Deep	Sand	Sparse	$y = 0.0370x - 12.768$
		Intermediate	$y = 0.0509x - 43.089$
		Dense	$y = 0.0399x - 48.941$
	Loam	Sparse	$y = 0.0758x - 45.915$
		Intermediate	$y = 0.0684x - 67.614$
		Dense	$y = 0.0600x - 80.872$
	Clay	Sparse	$y = 0.0525x - 37.445$
		Intermediate	$y = 0.0486x - 58.56$
		Dense	$y = 0.0443x - 72.31$

Table 4.3 Continued

Cfa				*Cfb*			
Soil Depth	Soil Texture	Vegetation Cover	Regression Equation	Soil Depth	Soil Texture	Vegetation Cover	Regression Equation
Shallow	Sand	Sparse	y = 0.0089x - 2.8016	Shallow	Sand	Sparse	y = 0.0102x - 4.3135
		Intermediate	y = 0.0130x - 12.905			Intermediate	y = 0.0116x - 11.951
		Dense	y = 0.0130x - 16.603			Dense	y = 0.0078x - 12.252
	Loam	Sparse	y = 0.0192x - 9.1206		Loam	Sparse	y = 0.0223x - 12.462
		Intermediate	y = 0.0241x - 25.386			Intermediate	y = 0.0180x - 21.448
		Dense	y = 0.0209x - 28.496			Dense	y = 0.0129x - 22.05
	Clay	Sparse	y = 0.0189x - 13.146		Clay	Sparse	y = 0.0176x - 12.904
		Intermediate	y = 0.0161x - 22.373			Intermediate	y = 0.0127x - 19.966
		Dense	y = 0.0127x - 22.603			Dense	y = 0.0099x - 20.481
Intermediate	Sand	Sparse	y = 0.0189x - 3.8681	Intermediate	Sand	Sparse	y = 0.0264x - 11.031
		Intermediate	y = 0.0286x - 25.523			Intermediate	y = 0.0267x - 25.871
		Dense	y = 0.0278x - 35.462			Dense	y = 0.0163x - 26.879
	Loam	Sparse	y = 0.0509x - 30.526		Loam	Sparse	y = 0.0431x - 27.128
		Intermediate	y = 0.0531x - 53.902			Intermediate	y = 0.0308x - 38.302
		Dense	y = 0.0438x - 60.617			Dense	y = 0.0235x - 45.56
	Clay	Sparse	y = 0.0385x - 28.438		Clay	Sparse	y = 0.0298x - 22.597
		Intermediate	y = 0.0335x - 42.643			Intermediate	y = 0.0221x - 34.756
		Dense	y = 0.0306x - 52.172			Dense	y = 0.0179x - 42.661
Deep	Sand	Sparse	y = 0.0279x - 7.0184	Deep	Sand	Sparse	y = 0.0179x - 42.661
		Intermediate	y = 0.0413x - 35.957			Intermediate	y = 0.0327x - 32.425
		Dense	y = 0.0409x - 50.838			Dense	y = 0.0220x - 36.926
	Loam	Sparse	y = 0.0696x - 46.501		Loam	Sparse	y = 0.0482x - 31.873
		Intermediate	y = 0.0626x - 64.184			Intermediate	y = 0.0352x - 44.535
		Dense	y = 0.0552x - 76.232			Dense	y = 0.0287x - 56.623
	Clay	Sparse	y = 0.0450x - 33.355		Clay	Sparse	y = 0.0359x - 27.789
		Intermediate	y = 0.0418x - 51.417			Intermediate	y = 0.0267x - 41.238
		Dense	y = 0.0398x - 66.262			Dense	y = 0.0230x - 53.98
Other Köppen Climates				***Csb***			
Soil Depth	Soil Texture	Vegetation Cover	Regression Equation	Soil Depth	Soil Texture	Vegetation Cover	Regression Equation
Shallow	Sand	Sparse	y = 0.0117x - 4.9618	Shallow	Sand	Sparse	y = 8.6335Ln(x) - 49.818
		Intermediate	y = 0.0141x - 12.879			Intermediate	y = 12.807Ln(x) - 81.739
		Dense	y = 0.0104x - 13.093			Dense	y = 15.285Ln(x) - 101.59
	Loam	Sparse	y = 0.0259x - 13.781		Loam	Sparse	y = 13.709Ln(x) - 76.658
		Intermediate	y = 0.026x - 25.936			Intermediate	y = 21.911Ln(x) - 139.59
		Dense	y = 0.0192x - 24.457			Dense	y = 26.468Ln(x) - 176.25
	Clay	Sparse	y = 0.0216x - 14.4		Clay	Sparse	y = 13.782Ln(x) - 80.905
		Intermediate	y = 0.0174x - 22.117			Intermediate	y = 18.710Ln(x) - 123.7
		Dense	y = 0.0137x - 21.933			Dense	y = 18.747Ln(x) - 129
Intermediate	Sand	Sparse	y = 0.0289x - 11.201	Intermediate	Sand	Sparse	y = 13.228Ln(x) - 69.559
		Intermediate	y = 0.0333x - 28.154			Intermediate	y = 23.839Ln(x) - 148.45
		Dense	y = 0.0257x - 30.955			Dense	y = 31.778Ln(x) - 210.16
	Loam	Sparse	y = 0.0532x - 29.367		Loam	Sparse	y = 35.365Ln(x) - 206.72
		Intermediate	y = 0.0494x - 47.487			Intermediate	y = 49.453Ln(x) - 316.73
		Dense	y = 0.0422x - 55.335			Dense	y = 54.200Ln(x) - 362
	Clay	Sparse	y = 0.0397x - 26.55		Clay	Sparse	y = 32.203Ln(x) - 195.22
		Intermediate	y = 0.036x - 42.882			Intermediate	y = 36.288Ln(x) - 238.24
		Dense	y = 0.0309x - 50.145			Dense	y = 34.896Ln(x) - 240.84
Deep	Sand	Sparse	y = 0.0422x - 17.87	Deep	Sand	Sparse	y = 19.953Ln(x) - 107.29
		Intermediate	y = 0.0445x - 37.183			Intermediate	y = 34.333Ln(x) - 214.94
		Dense	y = 0.0364x - 43.563			Dense	y = 43.822Ln(x) - 289.72
	Loam	Sparse	y = 0.0653x - 37.306		Loam	Sparse	y = 55.389Ln(x) - 335.05
		Intermediate	y = 0.0598x - 57.544			Intermediate	y = 65.618Ln(x) - 422.58
		Dense	y = 0.0555x - 72.435			Dense	y = 68.330Ln(x) - 456.73
	Clay	Sparse	y = 0.048x - 32.592		Clay	Sparse	y = 41.283Ln(x) - 252.89
		Intermediate	y = 0.0449x - 52.248			Intermediate	y = 43.400Ln(x) - 284.51
		Dense	y = 0.0424x - 66.541			Dense	y = 42.777Ln(x) - 294.55

Table 4.3 Continued

Cwa				*Cwb*			
Soil Depth	Soil Texture	Vegetation Cover	Regression Equation	Soil Depth	Soil Texture	Vegetation Cover	Regression Equation
Shallow	Sand	Sparse	y = 0.0101x - 4.3382	Shallow	Sand	Sparse	y = 0.0091x - 3.1872
		Intermediate	y = 0.0137x - 13.262			Intermediate	y = 0.0117x - 11.621
		Dense	y = 0.0106x - 14.444			Dense	y = 0.0101x - 13.932
	Loam	Sparse	y = 0.0238x - 12.552		Loam	Sparse	y = 0.0193x - 8.5652
		Intermediate	y = 0.0427x - 40.61			Intermediate	y = 0.0245x - 25.846
		Dense	y = 0.0188x - 25.886			Dense	y = 0.0182x - 25.453
	Clay	Sparse	y = 0.0215x - 15.115		Clay	Sparse	y = 0.0197x - 13.58
		Intermediate	y = 0.0172x - 23.579			Intermediate	y = 0.0160x - 22.641
		Dense	y = 0.0127x - 22.574			Dense	y = 0.0121x - 21.985
Intermediate	Sand	Sparse	y = 0.0212x - 5.0492	Intermediate	Sand	Sparse	y = 0.0187x - 3.0646
		Intermediate	y = 0.0360x - 30.992			Intermediate	y = 0.0315x - 28.042
		Dense	y = 0.0273x - 34.132			Dense	y = 0.0254x - 33.07
	Loam	Sparse	y = 0.0597x - 34.506		Loam	Sparse	y = 0.0552x - 31.615
		Intermediate	y = 0.0564x - 55.68			Intermediate	y = 0.0534x - 54.28
		Dense	y = 0.0447x - 60.911			Dense	y = 0.0417x - 59.491
	Clay	Sparse	y = 0.0431x - 30.378		Clay	Sparse	y = 0.0419x - 29.51
		Intermediate	y = 0.0386x - 47.786			Intermediate	y = 0.0334x - 44.224
		Dense	y = 0.0308x - 53.252			Dense	y = 0.0270x - 50.716
Deep	Sand	Sparse	y = 0.0370x - 12.768	Deep	Sand	Sparse	y = 0.0336x - 10.46
		Intermediate	y = 0.0509x - 43.089			Intermediate	y = 0.0452x - 39.923
		Dense	y = 0.0399x - 48.941			Dense	y = 0.0365x - 47.284
	Loam	Sparse	y = 0.0758x - 45.915		Loam	Sparse	y = 0.0724x - 44.369
		Intermediate	y = 0.0684x - 67.614			Intermediate	y = 0.0645x - 65.942
		Dense	y = 0.0600x - 80.872			Dense	y = 0.0534x - 77.213
	Clay	Sparse	y = 0.0525x - 37.445		Clay	Sparse	y = 0.0507x - 36.003
		Intermediate	y = 0.0486x - 58.56			Intermediate	y = 0.0425x - 54.362
		Dense	y = 0.0443x - 72.31			Dense	y = 0.0366x - 67.11

Table 4.4 D-hour to one-day ratios and range of ratios (bracketed) for the four synthetic rainfall distributions (after Schulze, 1984)

Duration (hours)	Ratios and ranges of ratios for storm rainfall distributions			
	Type 1	Type 2	Type 3	Type 4
0.083	0.083 (0 - 0.108)	0.134 (0.108 – 0.153)	0.173 (0.153 – 0.191)	0.209 (0.191 – 1.000)
0.167	0.126 (0 - 0.165)	0.024 (0.165 – 0.242)	0.281 (0.242 – 0.314)	0.347 (0.314 – 1.000)
0.250	0.155 (0 - 0.202)	0.249 (0.202 – 0.302)	0.355 (0.302 – 0.399)	0.444 (0.399 – 1.000)
0.333	0.178 (0 - 0.230)	0.283 (0.230 – 0.346)	0.410 (0.346 – 0.463)	0.517 (0.463 – 1.000)
0.500	0.215 (0 - 0.273)	0.332 (0.273 – 0.409)	0.487 (0.409 – 0.552)	0.618 (0.552 – 1.000)
0.750	0.256 (0 - 0.320)	0.384 (0.320 – 0.472)	0.561 (0.472 – 0.635)	0.710 (0.635– 1.000)
1.000	0.289 (0 - 0.355)	0.422 (0.355 - 0.515)	0.609 (0.515 – 0.688)	0.768 (0.688 – 1.000)
1.500	0.341 (0 - 0.409)	0.478 (0.409 – 0.575)	0.672 (0.575 – 0.753)	0.835 (0.753 – 1.000)
2.000	0.383 (0 - 0.451)	0.520 (0.451 – 0.616)	0.713 (0.616 – 0.793)	0.873 (0.793 – 1.000)
3.000	0.449 (0 - 0.515)	0.582 (0.515 – 0.674)	0.767 (0.674 – 0.841)	0.916 (0.841 – 1.000)

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APPENDIX B A program to determine the Köppen climates over southern Africa (after Maharaj, 2003)

```
 dimension tx(12),ti(12),tm(12),rfl(12)
    character climate*1(3),ccc*3

    write(6,*)'What data are you using?'
    write(6,*)' 1 = South African '
    write(6,*)' '
    write(6,*)' 2 = Iritrean'
    read(5,*)ians1

    if(ians1.eq.1)then
c     open(10,file='test.maxt')
c     open(11,file='test.mint')
c     open(12,file='test.medmean')
c     open(13,file='test.rain')
     open(10,file='/u23/maharaj/sag/sag96.maxt')
     open(11,file='/u23/maharaj/sag/sag96.mint')

open(12,file='/u23/maharaj/sag/sag95.medmean')
     open(13,file='/u23/maharaj/sag/sag96.rain')
     open(20,file='Köppen.output')
    endif

    if(ians1.eq.2)then
     open(12,file='area.map')
     open(13,file='area.rain')
     open(14,file='area.meant')
     open(20,file='area.output')
    endif

    write(6,*)'Enter start of winter month'
    write(6,*)'    4 or 10'
    read(5,*)ians2

c   write(6,*)'Enter lat & long of point for a
closer look'
c   read(5,*)lach,loch

    do 1 i=1,1000000
     if(ians1.eq.1)then
      read(10,10,end=99)la,lo,(tx(j),j=1,12)
      read(11,11,end=99)la,lo,(ti(jj),jj=1,12)
      read(12,12,end=99)la,lo,rmed,rmap
      read(13,13,end=99)la,lo,(rfl(jjj),jjj=1,12)
     endif
     if(ians1.eq.2)then
      read(14,10,end=99)la,lo,(tm(j),j=1,12)
      read(12,12,end=99)la,lo,rmed,rmap
      read(13,13,end=99)la,lo,(rfl(jjj),jjj=1,12)
     endif

10    format(2i4,1x,12f3.0)
11    format(2i4,1x,12f4.0)
12    format(2i4,1x,2f6.1)
13    format(2i4,1x,12f6.1)
```

```
c -------------------------------------------------
c ----- VARIABLES
c       ---------
c       avt : mean annual temperature
c       rmap : mean annual rainfall
c       rfl(12) : monthly rainfall
c       tm(12) : mean monthly temperature
c       wsm : wettest summer month
c       dwm : driest winter month
c       wwm : wettest winter month
c       dsm : driest summer month
c       rdw : rainfall distribution of warmest 6
months
c       rdc : rainfall distribution of coldest 6
months
c -------------------------------------------------
      avt = 0
      tc = 99.9
      tw = -99.9
      do 2 k=1,12
        if(ians1.eq.1)then
          tx(k) = tx(k)/10.
          ti(k) = ti(k)/10.
          tm(k) = (tx(k) + ti(k))/2.
          else
          tm(k) = tm(k)/10.
        endif
        avt = avt + tm(k)
        if(tm(k).lt.tc)then
          mc = k
          tc = tm(k)
        endif
        if(tm(k).gt.tw)then
          mw = k
          tw = tm(k)
        endif
2     continue
      avt = avt/12.

c -------------------------------------------------
      climate(1) = '_'
      climate(2) = '_'
      climate(3) = '_'
      if(rmap.gt.(20*(avt + 14.)))then
        if(tm(mc).ge.18.)climate(1) = 'A'
        if((tm(mc).gt.-
3.).and.(tm(mc).lt.18.).and.(tm(mw).ge.10.))
    &   climate(1)='C'
        if((tm(mc).le.-
3.).and.(tm(mw).ge.10.))climate(1) = 'D'
        if(tm(mw).lt.10.)climate(1) = 'E'
      endif
```

```
c ----- RAINFALL DISTRIBUTION

     rdw = 0
     rdc = 0
     rdt = 0
     dwm = 9999.9
     wsm = -9999.9
     wwm = -9999.9
     dsm = 9999.9

     do 3 mth=1,12
      if((mth.ge.4).and.(mth.le.9))then
       if(ians2.eq.4)then
c -----       WINTER MONTHS
       rdc = rdc + rfl(mth)
       rdt = rdt + rfl(mth)
       if(rfl(mth).lt.dwm)dwm = rfl(mth)
       if(rfl(mth).gt.wwm)wwm = rfl(mth)
       else
c -----       SUMMER MONTHS
       rdw = rdw + rfl(mth)
       rdt = rdt + rfl(mth)
       if(rfl(mth).gt.wsm)wsm = rfl(mth)
       if(rfl(mth).lt.dsm)dsm = rfl(mth)
       endif
      else
c -----       SUMMER MONTHS
       if(ians2.eq.4)then
       rdw = rdw + rfl(mth)
       rdt = rdt + rfl(mth)
       if(rfl(mth).gt.wsm)wsm = rfl(mth)
       if(rfl(mth).lt.dsm)dsm = rfl(mth)
       else
c -----       WINTER MONTHS
       rdc = rdc + rfl(mth)
       rdt = rdt + rfl(mth)
       if(rfl(mth).lt.dwm)dwm = rfl(mth)
       if(rfl(mth).gt.wwm)wwm = rfl(mth)
       endif
      endif
3    continue
     rdc = (rdc/rdt)*100.
     rdw = (rdw/rdt)*100.

CCC   if(climate(1).eq.'B')then

c ----- 70% of rainfall in warmest 6 months (Oct-
Mar)
     if(rdw.ge.70.)then
      rlow = 10*(avt+14.)
      rhig = 20*(avt+14.)
      if(rmap.ge.rhig)then
       if(tm(mc).ge.18.)climate(1) = 'A'
       if((tm(mc).gt.-
3.).and.(tm(mc).lt.18.).and.(tm(mw).ge.10.))
    &    climate(1)='C'
       if((tm(mc).le.-
3.).and.(tm(mw).ge.10.))climate(1) = 'D'
       if(tm(mw).lt.10.)climate(1) = 'E'
      endif
      if((rmap.lt.rhig).and.(rmap.gt.rlow))then
       climate(1) = 'B'
       climate(2) = 'S'
      endif
      if(rmap.le.rlow)then
       climate(1) = 'B'
       climate(2) = 'W'
       else
      endif
     endif

c ----- 70% of rainfall in coldest 6 months (Apr-
Sep)
     if(rdc.ge.70.)then
      rlow = 10*avt
      rhig = 20*avt
      if(rmap.ge.rhig)then
       if(tm(mc).ge.18.)climate(1) = 'A'
       if((tm(mc).gt.-
3.).and.(tm(mc).lt.18.).and.(tm(mw).ge.10.))
    &    climate(1)='C'
       if((tm(mc).le.-
3.).and.(tm(mw).ge.10.))climate(1) = 'D'
       if(tm(mw).lt.10.)climate(1) = 'E'
      endif
      if((rmap.lt.rhig).and.(rmap.gt.rlow))then
       climate(1) = 'B'
       climate(2) = 'S'
      endif
      if(rmap.le.rlow)then
       climate(1) = 'B'
       climate(2) = 'W'
      endif
     endif

c ----- Even rainfall distribution (neither of the
above)
     if((rdw.lt.70.).or.(rdc.lt.70.))then
      rda = (rdw + rdc)/2.
      rlow = 10*(avt+7)
      rhig = 20*(avt+7)
      if(rmap.ge.rhig)then
       if(tm(mc).ge.18.)climate(1) = 'A'
       if((tm(mc).gt.-
3.).and.(tm(mc).lt.18.).and.(tm(mw).ge.10.))
    &    climate(1)='C'
       if((tm(mc).le.-
3.).and.(tm(mw).ge.10.))climate(1) = 'D'
       if(tm(mw).lt.10.)climate(1) = 'E'
      endif
      if((rmap.lt.rhig).and.(rmap.gt.rlow))then
       climate(1) = 'B'
       climate(2) = 'S'
       else
      endif
      if(rmap.le.rlow)then
       climate(1) = 'B'
```

```
      endif
     endif
CCC   endif

c -----------------------------------------------------------
c ----- A climate
c -----------------------------------------------------------
     if(climate(1).eq.'A')then
      rdry = 9999.9
      climate(2) = 'w'
      do 4 mn=1,12
       if(rfl(mn).lt.rdry)rdry = rfl(mn)
4     continue
      if(rdyr.ge.60.)climate(2) = 'f'
      rlim = 100 - rmap/25.
      if((rdry.lt.60.).and.(rdry.gt.rlim))climate(2) =
'm'
     endif

c -----------------------------------------------------------
c ----- B climate
c -----------------------------------------------------------
     if(climate(1).eq.'B')then
      if(avt.ge.18.)then
       climate(3) = 'h'
       else
       climate(3) = 'k'
      endif
     endif

c -----------------------------------------------------------
c ----- C climate
c -----------------------------------------------------------
     if(climate(1).eq.'C')then
      climate(2)='f'
      if(wsm.ge.(10*dwm))climate(2) = 'w'
      if(wwm.ge.(3*dsm))climate(2) = 's'
     endif
c -----------------------------------------------------------
c ----- D climate
c -----------------------------------------------------------
     if(climate(1).eq.'D')then
      climate(2)='f'
      if(wsm.ge.(10*dwm))climate(2) = 'w'
      if(wwm.ge.(3*dsm))climate(2) = 's'
     endif
c -----------------------------------------------------------
c ----- E climate
c -----------------------------------------------------------
     if(climate(1).eq.'E')then

if((tm(mw).ge.0.).and.(tm(mw).le.10.))climate(2)
= 'T'
      if(tm(mw).lt.0.)climate(2) = 'F'
       climate(2) = 'W'
c ----- DETERMINATION OF THIRD LETTER
c -----------------------------------------------------------

if((climate(1).eq.'C').or.(climate(1).eq.'D'))then
      nom = 0
      do 7 in=1,12
       if(tm(in).gt.10.)nom = nom + 1
7      continue
      if(tm(mw).ge.22.)then
       climate(3) = 'a'
       else
       if(nom.ge.4)then
        climate(3) = 'b'
        else
        climate(3) = 'c'
       endif
      endif
      if(tm(mc).lt.-38.)climate(3) = 'd'
     endif
c -----------------------------------------------------------

     write(20,20)la,lo,climate
20    format(2i4,1x,3a1)

     if(ians1.eq.2)then
      write(66,66)i,la,lo,(tm(l),l=1,12)
      write(66,67)(rfl(l),l=1,12)
      write(66,68)rmap,avt,rdc,rdw,climate
66     format(i2,1x,i4,1x,i4,1x,12f6.2)
67     format(1x,' Rain ',6x,12f6.2)
68     format(1x,' rmap = ',f6.1,' avt = ',f6.1,' rdc =
',f6.1,
    &     ' rdw = ',f6.1,' CLIMATE =',3a1)
     endif

1    continue
     endif
c -----------------------------------------------------------
99   stop
     end
```