ACRU;
BACKGROUND, CONCEPTS AND THEORY

By R E SCHULZE

WRC REPORT No 154 /1/89

ACRU : BACKGROUND, CONCEPTS AND THEORY

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AGRICULTURAL CATCHMENTS RESEARCH UNIT
REPORT 35, 1989

Contribution towards a final Report to the Water Research Commission on the Project "Applied Hydrological Process and Modelling Studies for the Determination of Water and Sediment Yield". Financial support for this project was also received from Natal Town and Regional Planning Commission.

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ACRU : BACKGROUND, CONCEPTS AND THEORY

FOREWORD

BACKGROUND

The Water Research Commission (WRC) has funded three successive research projects into small catchments hydrology in the Department of Agricultural Engineering at the University of Natal, Pietermaritzburg. Valuable hydrological experience has been gained from these projects, which have focussed research effort towards the development, improvement and adaptation of applied hydrological models for southern African conditions.

The research project which has now been completed, entitled "Applied Hydrological Process and Modelling Studies for the Determination of Water and Sediment Yield", had as its major objective the development, adaptation and testing of lumped and distributed hydrological models, at user level, for application in southern Africa, to provide output for decision makers in terms of runoff, sediment yield, soil water content and water utilization by different land uses.

Much of the fieldwork associated with the model development and the data used for model verification was obtained from research catchments at DeHoek/Ntabamhlope and Cedara. The project's final report was by way of four separate documents, viz.

* a review of data, information and research associated with the DeHoek/Ntabamhlope hydrological research catchments, (published as a Department of Agricultural Engineering internal report), similarly
* a review of data, information and research associated with the Cedara research catchments, (also published as an internal report),
* a volume documenting the background, concepts and theory of the *ACRU* agrohydrological modelling system (i.e. this volume) and its companion volume,
* the User Manual on the *ACRU* modelling system.

SUMMARY

As the title implies, this volume comprising 18 chapters provides the user of the *ACRU* agrohydrological modelling system with the necessary background, concepts and theory in order to understand what they are doing and why, when applying the model or when making input decisions with the *ACRU* User Manual. In Chapter 1 the *aims and philosophies* of agrohydrological modelling are outlined, with particular attention paid to considerations and philosophies in developing the *ACRU* system. The modelling system's *concepts* as well as water budget and modular *structure* are presented in Chapter 2, with emphasis on features of *ACRU* as a distributed model, on the *ACRU* Menubuilder and the model's computerised decision support systems. In essence *ACRU* is a

* multipurpose and
* multilevel (i.e. able to operate at different levels of sophistication according to available input or required output)
* daily soil water budgeting modelling system
* developed as an aid to objective water resources related planning, along
* deterministic (i.e. non parameter optimising) lines and which can be
* used at a point or on lumped or on distributed (heterogeneous) catchments,
* simulating, with risk analysis
* various elements of
  - streamflow and peak discharge
  - reservoir yield
  - sediment loss and reservoir siltation
  - irrigation water supply and demand
  - crop yield analyses and
  - impacts resulting from changes in land use/management as well as changes in climate

  and
* all of this in a user friendly mode through an interactive Menubuilder which contains different options and pathways, with default values available and built-in "error traps".

Components of the agrohydrological system are outlined in the next nine chapters. Chapter 3, on *rainfall*, highlights the importance of accurate point and areal rainfall estimation in hydrological studies, stressing the dilemma of short data sets, approaches to infilling missing rainfall information, the pros and cons of using synthetic daily rainfall and the role of the Computing Centre for Water Research in providing rainfall data for southern Africa.

In the chapter on *potential evaporation* (PE), reasons, problems, surrogates and *ACRU*'s procedures in estimating daily A-pan equivalent PE are given, followed by the description of the various equations for PE available within *ACRU*. As for rainfall, sources of information on PE estimation for southern Africa are provided.

Chapter 5 outlines *hydrological aspects of soils*, with descriptions of the decisions and procedures in *ACRU* regarding soils input, for both adequate and inadequate soils information being available to the modeller. In the section on soils information in southern Africa, the binomial soil classification, soil parameter equations and the application of Land Type information are discussed.

Since a major influence on hydrological response occurs through *vegetation and land use*, Chapter 6 examines the various options in *ACRU* of estimating canopy interception and estimating maximum evaporation from a crop by direct and indirect as well as simple and more complex means, before focussing on routines involving soil water extraction by plant roots. The *reduction of maximum evaporation* by plant stress, either because of water deficiency or because of excess water, is under the spotlight in Chapter 7.

Chapters 8, 10 and 11 discuss, respectively, the techniques employed in *ACRU* of estimating *streamflow* (stormflow and baseflow), simulating *peak discharge* and modelling *sediment yield*, all on a day by day, storm event by event basis with the emphasis on soil water budgeting as the driving force of runoff and associated peak discharge and sediment responses.

Chapter 9 is devoted to describing the computational sequences of the soil water budget processes and interactions.

The two chapters, 12 and 13 elaborate on the irrigation routines available in *ACRU*, with *irrigation water demand* modelling procedures and options, including the different modes of scheduling available, being described in Chapter 12. The *irrigation water supply* aspects incorporated in the model are described in Chapter 13. These aspects include options for modelling irrigation water supply for design purposes, as well as via abstractions from a reservoir or from streamflow or from a combination of the two or from outside sources, with the model accounting also for conveyance, storage, field application and return flow losses, and furthermore, containing routines for more complex inter- and intra-catchment water transfers.

Since irrigation (and other) water supply presupposes water stored in a dam, Chapter 14 describes the daily *reservoir yield routines* imbedded in *ACRU*. The model considers the standard reservoir yield analysis components such as evaporation losses, inflows, transfers, abstractions, normal flow and seepage, but additionally, contains an option for a surface area to capacity relationship being computed internally when no reservoir basin survey results are available, and also a reservoir sedimentation routine by which the capacity of the dam can be reduced on an event by event basis.

With *ACRU* being "driven" by daily soil water budgeting, this forms the foundation for including options in the model for *estimating crop yield* on a season by season basis. Imbedded within *ACRU* at present (Chapter 15) are phenology based submodels for primary productivity, maize, winter wheat and sugarcane yield estimation. Like the irrigation water demand routines, these are products of another WRC funded project, but already reported here.

In order to assess the performance of a model, it has to contain appropriate statistical routines and to use it for design and planning, various types of *risk analyses* have to be undertaken. The theoretical backgrounds to these are presented in Chapter 16. A multipurpose model such as *ACRU* can only be used with confidence if it is known that its output is realistic. For this reason Chapter 17 is devoted to a series of *verification studies* ranging from those on "internal" components of the model (such as canopy interception and the soil water budget) to "external" output of streamflow volume from lumped and distributed catchments and peak discharge, as well as verification studies on modelling the impact of an actively growing forest on a streamflow time series.

Finally, chapter 18 consists of a detailed *sensitivity analysis* of output from *ACRU* to input into the model, pointing the way to those components in *ACRU* requiring further research in future because hydrological responses may be highly sensitive to these variables.

ACKNOWLEDGEMENTS

Undertaking the task of producing a modelling system such as *ACRU* with its support documentation can only be achieved as a team effort. On behalf of my co-contributors to this volume I therefore wish to thank, in particular, the following members of the Department of Agricultural Engineering at the University of Natal for their assistance in preparing this document :

Mesdames Kay Temple
Jacquie Whyte
Cynthia O'Mahoney
Penny Emslie, and
Manju Maharaj,

as well as

Peter Shepherd.

The Computing Centre for Water Research's role in providing the necessary computing facilities and expertise is acknowledged gratefully.

Finally, members of the Water Research Commission Steering Committee on this project are thanked for their support of this project :

Mr H Maaren	(Water Research Commission and Chairman)
Mr D W H Cousens	(formerly Water Research Commission and Chairman)
Mr H C Chapman	(Water Research Commission)
Prof P Meiring	(University of Natal)
Mr A M Little	(Natal Town and Regional Planning Commission)
Prof D A Hughes	(Rhodes University)
Mr B J Middleton	(Steffen, Robertson & Kirsten)
Mr J M Bosch	(Department of Environment Affairs)
Dr C S James	(University of the Witwatersrand)
Mr A J Muller	(Department of Water Affairs)
Mr P W Weideman	(Water Research Commission, Committee Secretary)

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March 23, 1990

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CHAPTER 1

HYDROLOGICAL MODELLING AND *ACRU* : AIMS AND PHILOSOPHY

R.E. Schulze

1.1 HYDROLOGY AND AGROHYDROLOGY

Hydrology, according to the World Meteorological Organisation (WMO, 1974), is the science which deals with the processes governing the replenishment and depletion of the water resources of the land areas of the earth. As such, hydrology revolves around understanding and describing rigorously the various components of the terrestrial hydrological system with the objective of producing sufficient information in the proper form for rational decisions in planning, design and operation of water resources developments (Yevjevitch, 1969).

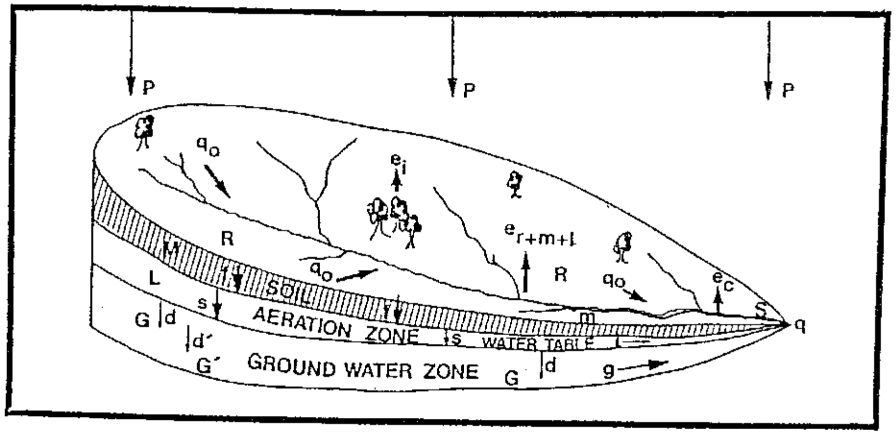
Agrohydrology, on the other hand, seeks to evaluate the influence of available water on the agricultural potential, with the objective of promoting a high efficiency for the use of the water. This available water may, on the one hand, be the precipitation which falls and is utilised *in situ* for dryland (rainfed) agriculture, in which major objectives would be a maximisation of infiltration and a minimisation of runoff and attendant soil loss through sound agricultural management practices. On the other hand, the available water may be that catchment runoff stored in reservoirs or rivers and utilised by irrigators practising total, supplementary or deficit irrigation as an insurance towards higher and less variable production.

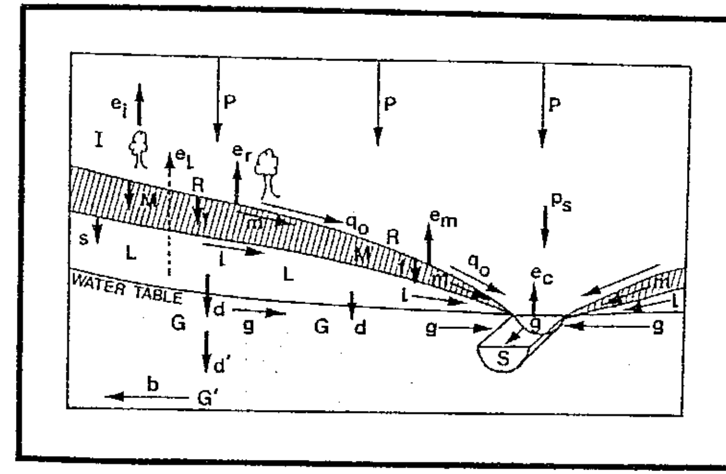
As such, agrohydrology should be seen not merely as a branch, but rather as an extension of the terrestrial hydrological system, when it comes to production information for planning and management of water resources in the broader sense.

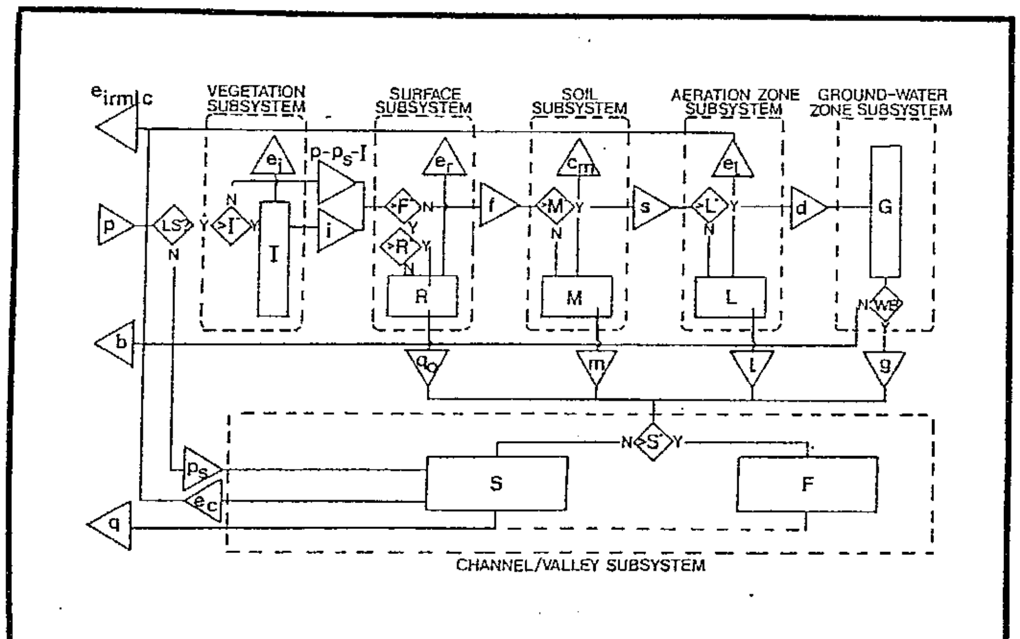
ACRU is an agrohydrological modelling system, in which the more conventional field of hydrology is integrated and interlinked with agrohydrology in terms of the forcing functions and responses of the various components which make up the terrestrial hydrological system.

1.2 THE TERRESTRIAL HYDROLOGICAL SYSTEM

The terrestrial hydrological system, within which the agricultural component of plant water utilisation also belongs, falls into the category Dooge (1986) terms a "complex" system with some "degree of organisation". The major components of this system may be depicted diagrammatically as a catchment system in plan and cross-sectional view and also as a canonical, cascading series of interrelated subsystems (Figure 1.2.1). The "organised complexity" in Figure 1.2.1 is both the basis and the source of our problems in hydrology and agro-hydrology, for we are dealing with a system characterised by large temporal and spatial fluctuations, irregularities and discrepancies which occur more or less regularly through a series of dynamic, non-linearly lagged responses with feedbacks in the subsystems. Agrohydrological processes can be analysed on the basis of equations







p	= precipitation	s	= percolatioon in aeration zone
p_s	= precipitation on streamflow/lake	L'	= storage capacity
e_i	= evaporation - transpiration	L	= aeration zone capacity
e_r	= evaporation - surface storage	l	= interflow
e_m	= evaporation - soil zone	d	= deep percolation
e_l	= evaporation - aeration zone	G	= groundwater storage
e_c	= evaporation - from wet surfaces	WB	= watertightness
I	= interception storage	g	= groundwater flow
i	= throughfall	S'	= channel capacity
R'	= surface detention	F	= floodplain storage
R	= surface storage	S	= channel storage
F'	= infiltration capacity	q	= streamflow
f	= infiltration below surface	q_o	= surface runoff into channels
M'	= field moisture capacity	q_b	= bankfall discharge
M	= soil moisture storage	b	= outflow to other catchments
m	= throughflow		

<u>DISPOSITION OF THE CATCHMENT HYDROLOGICAL SYSTEM</u>

$$P = \underbrace{i + e_i + e_r + e_m + e_l + e_c}_{\text{consumptive use by vegetation}} + \underbrace{\Delta R + \Delta S + \Delta F}_{\text{changes in surface storage}} + \underbrace{\Delta M + \Delta L + \Delta G}_{\text{changes in subsurface storage}} + \underbrace{q_o + m + l + g}_{\text{"surface" runoff}} + b$$

Figure 1.2.1 Diagrammatical depiction of the catchment hydrological system (after Moore, 1969) of soil physics, plant physiological response and hydraulics, but the high degree of spatial variability in a field or catchment of any size poses serious questions of parameter specifications. Indeed, one concurs readily with Dooge (1986), that elements of Murphy's Law are evident in the (agro)hydrological system, viz. if it can go wrong, it will! This complex system, which forms the foundation of agrohydrological modelling, has important characteristics worthy of note, which are listed below.

* The system attempts to produce *insights* rather than specific *solutions*.

* The system is too complex to take the narrow, utilitarian perspective that the (agro)hydrological cycle is "one big hydraulic machine where all water is driven by forces of gravity or friction" and whatever does not fit into this framework is treated "cavalierly" as "losses" or as errors "settled by assumptions" or fudged (perhaps an appropriate term for calibration by curve fitting?) "to give reasonable results" (Klemes, 1986).

* The serious agrohydrological practitioner should consider the system in its entirety and not become bogged down by some isolated detail within the system.

* The system is more complex than we can observe, measure or make assumptions about, with any discrepancy "corrected" (Klemes, 1986) in one place likely to show up in another.

* There are no "quickfix" solutions to agrohydrological modelling of this system if our modelling is taken seriously.

1.3 AGROHYDROLOGICAL SIMULATION MODELLING : WHAT IS IT?

* An agrohydrological simulation model provides a way of transferring knowledge from a measured or study area to an area where objective decisions and information are needed for planning, management and design.

* It provides a quantitative expression of that which is being *observed*, *analysed* or *predicted*.

* A model can be any calculation scheme to provide needed technical information.

* Models can therefore range from simple formulae to complex digital computer programmes which may require many years of effort in assembling data for effective use.

* A model behaves like the prototype system, in this case the agrohydrological system, with regard to certain selected variables and can be used to predict probable responses when some of the system parameters or input functions, e.g. those related to land use or management, are altered.

1.4 REASONS FOR MODELLING THE AGROHYDROLOGICAL SYSTEM

The types of technical hydrological and agrohydrological information needed for water resources management and utilisation include

* volume of water available from a catchment area,

* quality of water in terms of sediment yield,

* distribution of water in time and space in terms of quality and quantity,

* correct sizing of reservoirs, e.g. for irrigation purposes,

* the rates of siltation of the reservoirs,

* peak discharge estimates,

* response of the various agrohydrological systems to changes such as upstream afforestation or irrigation or construction of reservoirs,

* estimation of crop yields under dryland (rainfed) or irrigated conditions or improved tillage practice,

* selection of the most appropriate mode of irrigation scheduling, or

* risk analysis associated with the above.

With such a wide range of agrohydrological information needs, modelling not only assists in "solving" problems in terms of water resource and agricultural production management but helps, *inter alia*, to

* identify areas in which information is lacking, both in the model itself and in the agrohydrological system,

* stimulate new ideas in modelling which can lead to improving the model's efficiency,

* conveniently synthesise large amount of data (although this does not necessarily mean a more accurate model is produced),

* make better use of existing data sets which can yield required planning information and thereby conserve finance associated with the high expense of obtaining good quality data today,

* allow prediction of events, including "extreme" events such as flood or drought magnitudes or plant stress durations/severities, to enable better decisions to be made,

* possibly lead to a better understanding of the system,

* enhance the research methods used to improve the level of water use efficiency,

* instigate research into alternative water and agricultural resources,

* estimate the effect water or agricultural resources management upstream has on the users downstream, or

* deliver results in a less technical way for laymen and decision-makers to understand (James and Burges, 1981).

1.5 CONSIDERATIONS IN THE DEVELOPMENT OF THE *ACRU* MODELLING SYSTEM

Having established that an agrohydrological model is an excellent tool for assisting in objective management decisions, but that it has to simplify a highly complex natural system, the points below list considerations and philosophies which went towards the development of the *ACRU* modelling system. The philosophies reflect largely on the experience and background of *ACRU*'s developers and, as such, an element of subjectivity is inevitably evident. The points discussed were not all preconceived - in fact, a number of considerations crystallised when the model had already been under development for several years.

* The model should be *process oriented*, i.e. it should explain cause and effect in sequential, non-linear terms for both the above-ground and below-ground agrohydrological processes.

* Most rainfall (91% in southern Africa's case) manifests itself as evaporation from and through the soil and major differences in runoff, irrigation demand and crop yield response to rainfall are influenced, and to some extent even controlled, by soil water status. The model should therefore simulate the *soil water budgeting* and *total evaporation* (i.e. "actual evapotranspiration") processes realistically, since these processes may be considered the "heart" of the agrohydrological system (Kovacs, 1986).

* By implication an agrohydrological model should be what Eagleson (1983) terms a *physical conceptual* model; conceptual, e.g., in that it conceives of a one, two or even three dimensional system in which important processes and couplings are idealised, and physical to the degree that, for example, the ability of the soil to store and transmit water is represented explicitly and that vegetation water use, for example, is simulated using variables which would be observable if the agrohydrological system met the idealisations made.

* This, in turn, implies that such a model not be a parameter fitting/optimising model but that parameters should be replaced rather by *variables*, ideally *estimated* entirely *from physical features* of the catchment. Model calibration by parameter optimisation and parameter transfer from nearby catchments or agricultural research sites may be an unfortunate modelling necessity, but it remains a dangerous agrohydrological practice since, *inter alia*, apparent similarities in climate, soils, vegetation or agricultural practice do not necessarily imply similar parameter values. Also, the length of calibration record is crucial to parameter stability. Furthermore, catchment or regional scaling problems and variations can play havoc with parameter values often derived at a point or from a small area and agrohydrological extrapolation of event magnitudes or conditions beyond the range of those used in parameter determination may lead to questionable results. Klemes (1986) states that the assumptions in assigning parameter values sometimes "borders on arrogance", and if a model has many parameters one may as well "guess the answer".

* Objective functions in model *verification* should include conservation of means and deviations and goodness of fit around the 1:1 relationship between observed and simulated data, not only of the *end product* of a simulation (usually runoff or irrigation water demand or crop yield), but also of the *various internal state variables*, i.e. the components of the model simulated en route to the "final" estimations. These include interception losses, soil water status and total evaporation (i.e."actual evapotranspiration") under varying conditions. Models should be verified for a *wide range of agrohydrological regimes*, including humid areas, sub-humid and arid areas with a variety of land uses, for normally expected as well as for more extreme conditions important in agrohydrological design.

* The model should keep *multiple regression functions*, to a minimum, for these are artefacts of the data from which they were developed and may obscure cause and effect, and can give acceptable answers sometimes for the wrong reasons and cannot be used in extrapolative mode.

* Such a model as conceived in the above points has to have been developed in accordance with *systems theory* in that one initially has to disintegrate (decompose) the agrohydrological system into its component subsystems (e.g. atmosphere, land surface, vegetative, unsaturated and saturated zones) and then has to aggregate (recompose) the subsystems by reconstructing "broken" interconnections. The agrohydrological modeller must, by necessity, interface with scientists from neighbouring disciplines, including process hydrologists, engineers, agriculturalists and systems experts.

* By implication a complex agrohydrological modelling system is beyond the field of expertise of any one scientist. A *team approach* to model development is therefore vital, with different members of the team specialising in different aspects/components of the model construction processes.

* The model, while having to make simplifying assumptions, must reflect realistically the complexities of the agrohydrological system. *Simple models* have often been shown to give answers as successful as those given by *complex models* under "average" agrohydrological conditions. When extrapolating to "new" situations a complex model is, however, more likely to give realistic simulations. Models which are conceptually too simplistic are unlikely, therefore, to be satisfactory to use for land use related hydrological prediction.

* Model *users need to be trained.* Complex models, like large passenger jets, are "flown by the trained pilot, not by the passengers who merely want to arrive at a destination". Untrained model users are considered a "dangerous species" and through their sometimes cavalier use of input, and lack of understanding of agrohydrological principles, can bring discredit to a model.

* The model developer, while of necessity having to make his model accessible to a wide range of users, must, however, not fall into the trap of necessarily wanting to *oversimplify* the usability of a complex model, from which multi-million dollar decisions may be made, to the extent that anyone can play hydrological scenario games with it without proper interpretation of output.

* The model should, however, be structured such that it does not remain the elitist domain of its developers but that it can be used by other trained scientists in the fields of hydrology and water resources by rendering the model input *user friendly*, particularly by use of front end *input menus* which include input screening defaults to prevent subsequent misinterpretation (N.B.: "garbage in gives garbage out"). The advent of agrohydrological model development along the lines of *expert systems* is exciting.

* User oriented models should ideally be applied by a range of users. Many users, however, tend to change components of a model or add routines often without verifying output against observation, and frequently "violating" basic tenets/ philosophies upon which the model was founded. For this reason users should be *accredited* as

such, should keep in touch with the model developers, but only the model developers should effect changes to the model.

* The many subroutines which make up a modelling system should have *compatible levels of complexity*, since it must be remembered that in any systems chain its strength depends on the weakest link. A modelling system of the 1980s and 1990s invariably "borrows" many ideas and even entire subroutines from other models. The procedure of "*mixing and matching*" hydrological subroutines should be approached with due circumspection, however.

* Model structure must be *modular*, so that improved or new subroutines can be "hooked on" without major structural repercussions throughout the main program.

* *User models* (in contrast to more purely research models) must be developed to *maximise* the use of *available input data*. In southern Africa, for example, data are readily available from over 9000 rainfall stations with daily values but fewer than 100 recording raingauge stations have "clean" record of long duration. The aim should therefore be for user models to basically use daily rather than monthly or hourly time steps.

* Input data, particularly in the 3rd world situation where today most agrohydrological decisions are needed, frequently restrict a model's usability because of the high level of sophistication of data required by conceptually sound models. The model should therefore be able to accommodate various *options of model input* according to data availability, with *alternative pathways* provided depending on the detail of input information available (e.g. on soils, canopy characteristics, peak discharge formulations, potential evaporation, planting dates, crop growth curves or lengths of phenological periods) and the complexity of the problem to be solved.

* The production of a *user manual* for a model should not signify the end-product of a piece of research, but rather the beginning of a fruitful interaction with users, who, with both feet planted firmly in the real world of practical decision-making, eventually are the ones who will make most useful suggestions for improvements, refinements and additions. A major modelling effort must therefore be an *ongoing process*, with periodic *model updates* and continuing contact through, for example, update bulletins with all accredited users of the model.

* Hydrological impact of land use and management is *dynamic* in nature, in that an area's land use may change over time - either gradually over several years (e.g. as a forest grows) or intra-annually (e.g. when seasonal crops are grown) or abruptly (e.g. with the clearfelling of a forest, construction of a reservoir or an irrigation scheme). A sound model must accommodate dynamic change by incorporation of input information describing the changing nature of land use or management over time, or alternatively changing levels of sophistication of climatic input data.

* A soundly conceived model should have the option of simulating agrohydrological response either at a *point*, or over a catchment with relatively homogeneous characteristics; i.e. as a *lumped* model, or over a heterogeneous area in which the areal variations in characteristics (e.g. soil types, land use, slope or rainfall) are accounted for in *distributed models*, in which

case the area is subdivided into relatively homogeneous and hydraulically linked cells each with their unique non-linear responses.

* Agrohydrological responses to land use/ management are multi-facetted. The model should therefore also be *multipurpose and versatile* with options for, and relevant combinations of, a variety of output such as daily or monthly or annual water and sediment yield, irrigation demand/supply, soil water status, transpiration losses, reservoir yield, plant stress, crop yield, etc.

* While it goes without saying that a multipurpose modelling system is usually developed in a single country (the SHE system is a notable exception) and is probably used most frequently in the country of its development, a model should be structured for *application universally*, in both hemispheres for a range of agrohydrological conditions. Routines should therefore be *generic* rather than location specific.

* The model becomes a better decision-making tool still if it includes *risk analyses*, be they probability distributions or frequency analyses.

* The model must be applicable as an advanced, structured, *teaching tool* for students who become the next generation of agrohydrological decision-makers.

* * * * *

It is upon the above considerations that the *ACRU* agrohydrological modelling system, the concepts and structure of which are described in the next chapter, was developed.

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CHAPTER 2

ACRU : CONCEPTS AND STRUCTURE

R.E. Schulze, G.R. Angus and W.J. George

2.1 HISTORICAL PERSPECTIVE

The *ACRU* model has its hydrological origins in a distributed catchment evapotranspiration-based study in the Natal Drakensberg (Schulze, 1975). The acronym *ACRU* is derived from the *A*gricultural *C*atchments *R*esearch *U*nit within the Department of Agricultural Engineering of the University of Natal in Pietermaritzburg. The agrohydrological component of *ACRU* first came to the fore during research on an agrohydrological and agroclimatological atlas for Natal (Schulze, 1983). Since then the model has developed, through co-operation of colleagues and graduate students, and through generous funding of the Water Research Commission, to its present status.

The first user documentation was published in 1984 (Schulze, 1984) and subsequent to that a series of papers and reports applying constantly updated and more sophisticated versions of the model have been published in the international and southern African literature, the major papers on developmental aspects being an overview by Schulze (1986), a paper on its application as a dynamic simulator of afforestation effects on runoff (Schulze and George, 1987) and a synthesis on its current status by Schulze (1988). Other than in southern African countries the model has been lectured on in the UK, USA, Canada, Chile, Hungary, Portugal and Switzerland. Model output has been verified widely on observed data from southern Africa and the USA (Chapter 17). *ACRU* has been used extensively for decision-making in southern Africa and to date the model has been used internationally in research and applications in Namibia, the USA, Swaziland, Lesotho, Botswana and in Chile.

2.2 CONCEPTS OF THE *ACRU* MODEL

Based on the philosophies and considerations outlined in Chapter 1 the *ACRU* agrohydrological modelling system (Schulze, 1984; 1986; 1988) is centred around the following aims (Figures 2.2.1 and 2.2.2) :

* It is a so-called *"physical conceptual"* model.

* It is a *multi-purpose* model, outputting (with risk analysis) either
  - runoff elements (e.g. stormflow, baseflow, peak discharge at daily, monthly or annual level),
  - reservoir yield analysis (overflow, reservoir status, abstractions, transfers),
  - sediment yield analysis (daily, monthly, annual; reservoir deposition),
  - soil water status and total evaporation (i.e. "actual evapotranspiration"),
  - irrigation water demand (for different crops, scheme efficiencies, modes of scheduling),
  - irrigation water supply (from streams, reservoirs and combinations),
  - effects of land use changes (gradual or

abrupt), or

- seasonal crop yields (maize, sugarcane, winter wheat - dryland or irrigated).

* The model uses *daily time steps* and thus daily climatic data, thereby making optimal use of available data. Certain more cyclic, conservative and less sensitive variables (e.g. temperature, crop coefficients) which may have to be input at monthly level are reduced to daily values in *ACRU* by Fourier Analysis. More sensitive intra-daily variables may be input at daily level and disaggregated synthetically in the model.

* The *ACRU* model revolves around daily *multi-layer soil water budgeting* and the model has been developed essentially into a versatile total evaporation model (Figure 2.2.2). It has therefore been structured to be highly sensitive to land use changes on the soil water and runoff regimes, to effects of supplementary watering by irrigation and to the onset/degree of plant stress.

* *ACRU* has been designed as a *multi-level* model, with either multiple options or alternative pathways, (or a hierarchy of pathways) available in many of its routines depending on level of sophistication of available input data for the type of output required. Thus, for example, potential evaporation, interception losses, soil water retention constants, maximum (i.e. "potential") as well as total evaporation ("actual evapotranspiration"), leaf area index, peak discharge equations, reservoir storage:area relationships or the length of phenological periods in crop growth, all may be estimated by various methods according to the level of input data at hand (an example of a decision path which may be followed when selecting the method for estimating potential evaporation is given in Chapter 4).

* An important option in areas of complex land uses and soils is that *ACRU* can operate either at a *point* or as a *lumped* or as a *semi-distributed* cell-type model. In distributed mode each cell can generate individually requested and different output (Section 2.5).

* The model includes a *dynamic input option* to facilitate land use or management changes over time, be they long term/gradual changes (e.g. forest growth, urbanisation, expansion of irrigation scheme) or abrupt changes (e.g. clearfelling, fire, construction of dam/irrigation scheme, or land management strategies, such as new tillage practices), changes of an intra-annual nature (e.g. crops with non-annual cycles) or changes in the nature of climatic input data. A dynamic input file is then accessed each year with the new variable inputs, e.g. crop coefficients, root mass distribution, planting dates, soils properties (for new tillage practices). An example of the application of the dynamic input option is given in the *ACRU* User Manual (Schulze and George, 1989).

* *ACRU* can be operated with the *ACRU* Menubuilder, which prompts the user with unambiguous questions, leading the user into inputting, for example, complex distributed catchment information easily and containing alternative decision paths as well as preprogrammed *decision support systems*. These features facilitate rapid and simple input to complex land use interactions, and include built-in *default values* and *error traps*. The *ACRU* Menubuilder (Section 2.6) is thus structured along the lines of an *expert system*. A flowchart example of a small section of the

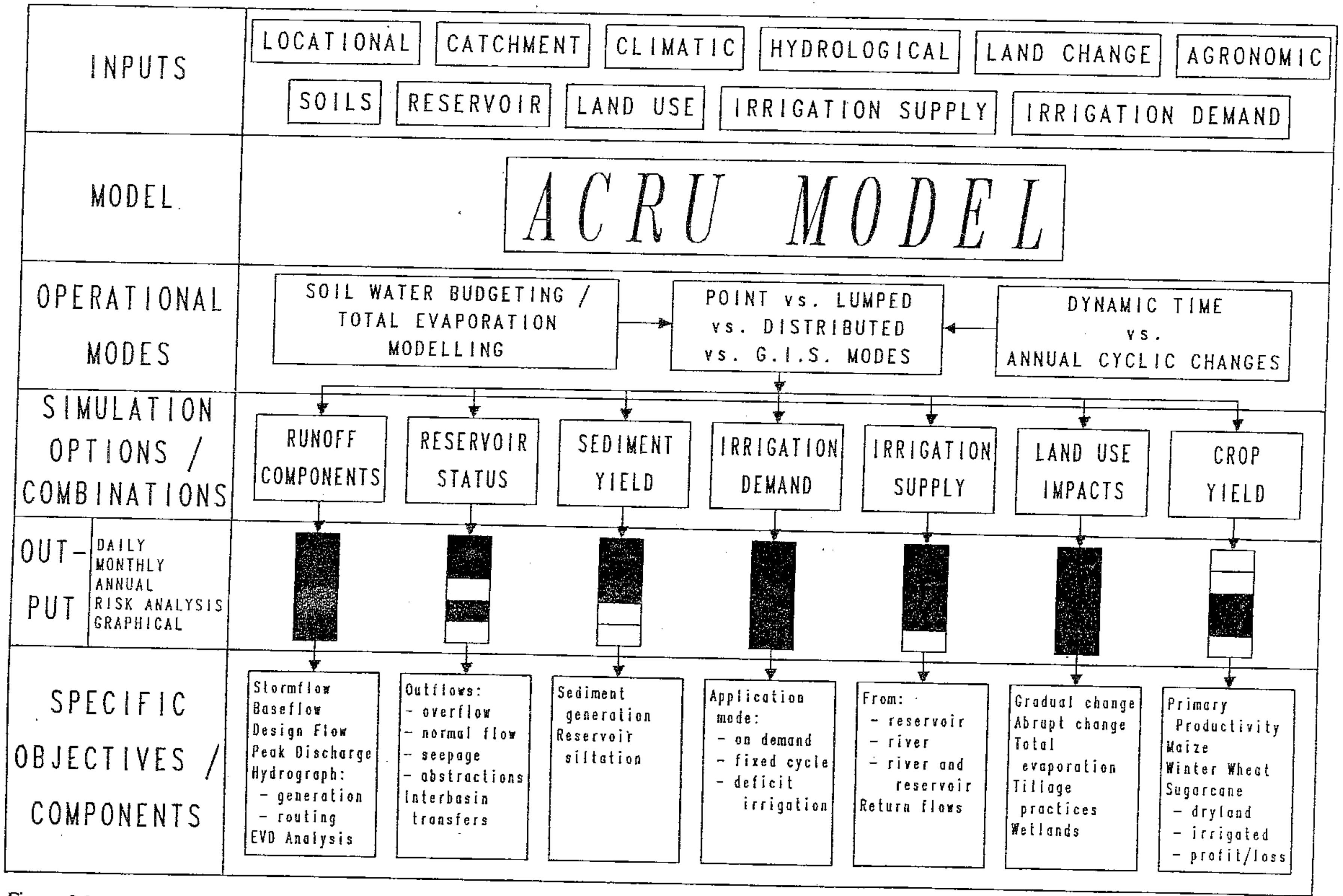

Figure 2.2.1 The *ACRU* agrohydrological modelling system : Concepts

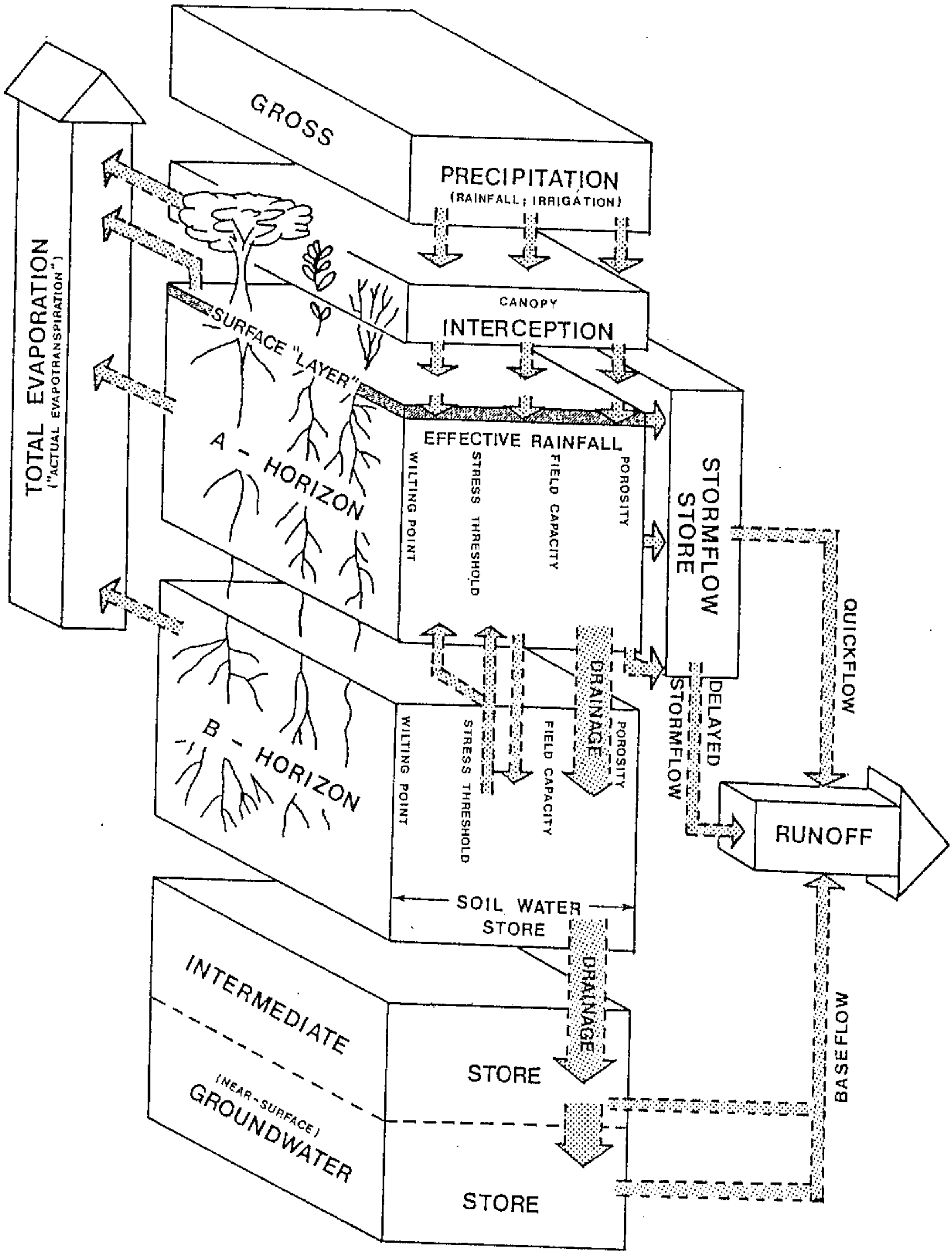

Figure 2.2.2 The *ACRU* agrohydrological modelling system : General structure

Menubuilder in Chapter 5 illustrates the methods by which soils information may be input in a distributed catchment, part of which has adequate (i.e. detailed enough) soils information and a part of which does not.

2.3 GENERAL STRUCTURE OF *ACRU* FOR WATER BUDGETING

Budgeting by partitioning and redistribution of soil water is depicted in Figure 2.2.2. That rainfall and/or irrigation application not abstracted as interception or as stormflow (quickflow or delayed), first enters and "resides" in the topsoil horizon. When that is "filled" to beyond field capacity the remaining water percolates into the subsoil horizon(s) as saturated drainage at a rate depending on soil texture and horizonation properties. Should the soil water content of the bottom subsoil horizon of the plant root zone exceed field capacity, saturated vertical drainage/irrigation recharge into the intermediate/groundwater store occurs, from which baseflow is generated. Unsaturated soil water redistribution, both upward and downward, also occurs but at a considerably slower rate than water movement under saturated conditions dependent, *inter alia*, on the relative wetnesses of adjacent soil horizons in the root zone. Evaporation takes place from previously intercepted water as well as from various soil horizons simultaneously, either separately as soil evaporation (from the topsoil only) and as plant transpiration (from all soil horizons in the root zone) or combined, as total evaporation. Evaporative demand on the plant is estimated, *inter alia*, according to its stage of growth and the roots are assumed to absorb the water from the soil water in proportion to the distribution of root mass density within the respective soil horizons, except when conditions of low soil water content prevail. Under such conditions the relatively wetter horizons provide higher proportions of soil water to the plant in order to obviate plant stress as long as possible.

It is vital in land use and crop yield modelling to determine at what point, in the depletion of the plant available water reservoir, plant stress may be assumed to actually set in, since stress implies the necessity to irrigate and also may imply a reduction in crop yield. In modelling terms, the onset of stress may be expressed as the critical soil water content at which total evaporation, E, is reduced to below the vegetation's atmospheric demand, i.e. its maximum evaporation, E_m, formerly termed "potential evapotranspiration".

Experimental evidence shows that E may be approximated to E_m until a certain fraction of maximum (profile) available soil water to the plant, PAW, is exhausted below which a reduction of E sets in.

Recent research (reviewed, for example, by Slabbers, 1980) shows that this fraction of available soil water varies according to atmospheric demand and the critical leaf water potential of the respective vegetation, the latter being an index of the resilience of the vegetation to stress situations. The implications of stress setting in at such different levels of soil water content are significant in terms of total crop evaporation and crop production modelling.

The generation of stormflow in *ACRU* is based on the premise that, after initial abstractions, the runoff produced from rainfall is a function of the soil water deficit from a critical response depth of the soil. The soil water deficit antecedent to a rainfall event is simulated by multi-layer soil water budgeting. The critical response depth has been found to depend, *inter alia*, on the dominant runoff-producing mechanism. This depth is therefore generally shallow in more arid areas characterised by eutrophic (i.e. poorly leached and drained) soils and high intensity storms which would produce predominantly surface runoff, and deeper in high rainfall areas with dystrophic (highly leached, well-drained) soils where interflow and "push-through" runoff mechanisms predominate. Not all the stormflow that is generated is same day response; stormflow is therefore split into quickflow (i.e. same day response) and delayed stormflow (Figure 2.2.2), with this "lag" is dependent, *inter alia*, on soil properties, catchment size and the drainage density.

2.4 *ACRU* AS A DISTRIBUTED MODEL

Being a daily time step model, *ACRU* does not account for the temporal variability within individual storm events; however, the distributed version of the *ACRU* model has the ability to take account of the spatial variability not only of rainfall, but also of land uses and soils to provide a more accurate representation of where, within the catchments, the hydrological responses are occurring and with what magnitude.

2.4.1 Catchment Discretisation

ACRU makes use of a cell-type discretisation to subdivide the catchment, where each cell is a subcatchment. Cell boundaries are defined by making use of large scale orthophotos or topographical maps. If the effect of land use changes on outflow from a catchment is to be investigated, then the cell boundaries should be so defined as to obtain a high degree of homogeneity of vegetation type. However, this may then often be achieved at the expense of, say, homogeneity of soil type. Likewise, if the cell outlet is selected at a point where hydrological information is required, e.g. at the inflow or outflow of a reservoir, then this information is likely to be obtained at the expense of (say) vegetation homogeneity, because in such a case the cell boundary would be defined uniquely by the selection of the location of the cell outlet, irrespective of the subcatchment's soil and vegetation characteristics. The process of delineating cell boundaries is thus largely subjective and dependent on the particular purpose of the modelling exercise.

Cell models are semi-distributed models in the way in which the catchment is depicted as an assembly of interconnected units of area. Each such unit is represented in the model by a cell, which is a lumped representation of that area. The interconnected layout of cells within a hypothetical catchment can be represented by an inter-cell flow diagram as in Figure 2.4.1, which reflects the major stream pattern of the catchment.

Two types of cells can be identified from Figure 2.4.1, viz. exterior cells and interior cells. An exterior cell has a portion of its boundary as a common boundary with the main catchment and the outflow from an exterior cell is assumed to be independent of all the other cells. An interior cell has one or more upstream cells and the outflow from an interior cell may include contributions from upstream cells.

When analysing interior cells it is important that the runoff contributions from upstream cells have been determined previously and are available for consideration in runoff determination of internal

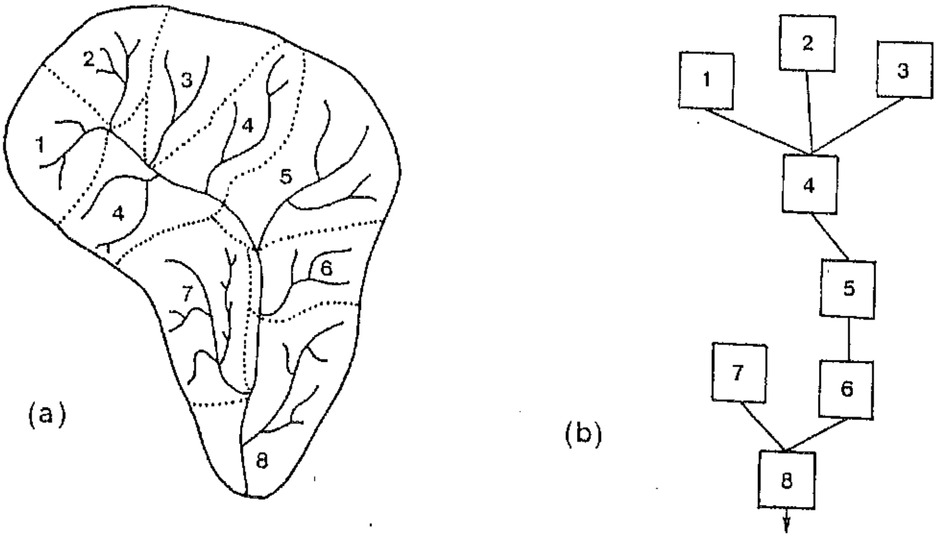

Figure 2.4.1 Cell-type discretisation of hypothetical catchment for the distributed version of the *ACRU* model: (a) Delineation of cell boundaries (b) Layout of cells (Angus, 1987)

cells. It is therefore important that the sequence in which cells are analysed is defined accurately. By applying a simple numbering system to the cell layout in Figure 2.4.1, each cell is allocated a number greater than that allocated to any of the cells upstream of its position. The model analyses each cell in ascending numerical order, thereby ensuring that outflow information from upstream cells is always available when analysing any internal cell downstream. This information is conveyed to the model by means of a menu, i.e. a file containing input information for the model.

2.4.2 Inter-Subcatchment Runoff

The lumped model's soil water budgeting routine is performed on a point scale with all units expressed in mm. Stormflow and baseflow, which together make up streamflow, are thus also expressed in mm. In order to direct outflow to downstream cells, the streamflow depth calculated by the model has to be converted to a volume (m^3) because each subcatchment may have a different area.

The presence or absence and the identity of upstream subcatchments are determined by interrogation of the menu. The method of directing streamflow between cells is illustrated in Figure 2.4.2. An explanation of the abbreviations follows:

* A_1 represents the area of Cell 1 (km^2),

* q_1 represents the streamflow depth generated with Cell 1 (mm),

* q_1^{1} represents the equivalent depth of streamflow distributed over that entire portion of the catchment upstream of the outlet to Cell i (mm), and

* Q_1 represents the total volume of streamflow leaving Cell 1 (m^3).

Daily streamflow depths (q_1) are calculated for each cell and should upstream cells exist, then q_1 is converted to a volume by multiplying by the catchment area A_1. This value is added to the upstream streamflow volumes and becomes

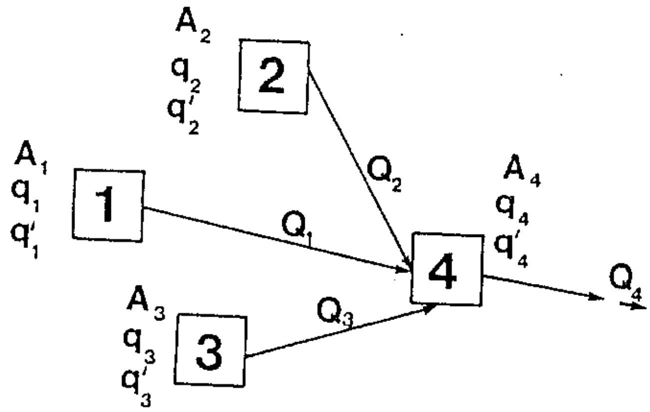

Figure 2.4.2 Method of directing streamflow to downstream cells in *ACRU* (Angus, 1987)

outflow Q_1 from the cell, or should a reservoir exist, first becomes inflow to the reservoir and after a reservoir yield analysis, then becomes outflow Q_1. Q_1 can also be expressed as an equivalent depth of streamflow (q_1') over the entire catchment upstream of the outlet to Cell 1.

Equivalent streamflow depth is a useful method of expressing streamflow since high or low streamflow producing regions can be identified within a catchment. As rainfall is also expressed in mm the proportion of rainfall that becomes streamflow is easily determinable.

2.4.3 Other Features Of *ACRU* As A Distributed Model

* A feature of the *ACRU* distributed model is that each subcatchment, while nested within other up- and downstream subcatchments in transmitting water, also operates as a unique, individual catchment. Therefore individually requested input information pathways can be used on different subcatchments and individual and different output can be requested for each subcatchment. Thus, for example, one could request crop yield and sediment yield from Cell 1 with only a risk analysis of monthly streamflow, whilst requesting an irrigation requirement analysis, reservoir yield risk analysis and daily water budget printout from the next subcatchment.

* In a series of re-runs of the *ACRU* distributed model, which may become very computer time consuming, changes may occur or sensitivity tests may be required for only certain subcatchments, without necessitating re-runs of all cells in the entire catchment. This facility exists in *ACRU* and is explained in the *ACRU* User Manual (Schulze and George, 1989).

* In, for example, a series of complex multi-irrigated subcatchments, irrigation water may all have been abstracted by upstream users, requiring downstream irrigation users to "invoke" water releases from an upstream reservoir as draft - a "fact" which the simulation only "finds out" after having cascaded through a number of

subcatchments downstream. For such cases a "loopback" option can be operated in *ACRU*, by which complex transfers of water (other than natural streamflow) between subcatchments are handled.

* Distributed modelling makes high demands on data inputting. To this end a menubuilder, incorporating Decision Support Systems, has been developed for *ACRU*. This is described in Section 2.6.

2.5 THE *ACRU* MENUBUILDER

Distributed models require intensive soils, vegetation and climatic data and the collection and inputting of these data is both time consuming and laborious. Once the data have been collected, the information must be assigned to each cell on an area-weighted basis. The need has thus been identified for a system which automatically weights these data for each cell according to their relative proportions within each cell.

It is to this end that the *ACRU* Menubuilder has been developed. The *ACRU* Menubuilder operates in an interactive mode as a "front-end" program to *ACRU* with prompts guiding the user. The first-time or inexperienced user can select the optional HELP facilities available. The input information is entered directly into a file ready for input to *ACRU*.

The Menubuilder can automatically extract pre-programmed soils and vegetation "look up" information in the form of default values, should detailed information on these variables not be available. For most of the more important soil or vegetation input variables to which values are being assigned to a cell, the user then has the option of selecting either default values or entering sub-catchment-derived values.

A series of screening tests (error traps) has been included in the *ACRU* Menubuilder which check input data for validity and authenticity. Depending on the severity of the input error either a warning or an error message will be issued. If a warning message is issued, the program will continue running; the user is merely made aware of the fact that the input data should be checked. However, when an error message is issued the program requests that the data be re-entered until such time as the input data are deemed acceptable.

The Menubuilder program and various information bases form part of the *ACRU* Decision Support System which is discussed in the following section.

2.6 COMPUTERISED DECISION SUPPORT SYSTEMS

2.6.1 Background

One of the major problems facing hydrologists simulating runoff on catchments with complex land use patterns or with distributed models is the extensive input information base required for the execution of the models. Hill, Singh and Aminion (1987) state that the two basic data acquisition problems experienced in hydrological simulation are that

* existing information cannot generally be used in the format in which they were acquired, and

* existing information are rarely sufficient.

This sentiment was echoed by Arnold and Sammons (1988) and resulted in their formulation of the concept of Decision Support Systems (DSS) to aid in selecting inputs to distributed hydrological models at large catchment scale. Besides the obvious advantage of reducing the time spent on collecting, analysing and adapting information to the format required by the respective models, they also believed that the development of a more user-friendly interaction between the model and its user could reduce the gaps between model availability and model use.

With the development of a distributed version of the *ACRU* model for use on either large or complex catchments and the resultant increase in bulk information requirements the same philosophy as expressed by Hill *et al.* (1987) and Arnold and Sammons (1988) has been employed in the development of computerised DSS with regard to land use and soils information for *ACRU*.

2.6.2 Structures Of A Decision Support System : The Example Of The Land Use DSS In *ACRU*

The land use information base is an integral component of the *ACRU* modelling system, various components of which are illustrated in Figure 2.6.1. The *ACRU* Menubuilder provides for an interactive data and information input system which prompts the user for information, gives instructive explanation via a HELP facility, supplies default values where required, screens parameters according to pre-defined limits and finally outputs the information in an *ACRU* format menu which forms part of the input data base to the *ACRU* model. The Menubuilder has the ability to function in both lumped and distributed mode and it is when employed in the latter mode on large catchments with many sub-catchments that the data entry system is most useful.

The ACRU land use information base for use in southern Africa, to date, contains relevant information (from various sources) on over 50 land uses on a month-by-month basis. This information has been collated from practical applications of the model in research studies and represents some of the more common land uses encountered. Each land use is numbered and it is on the basis of this number that the Menubuilder interrogates the land use information file, encounters the required land use number and retrieves the relevant information to assign representative values to each sub-catchment on an area-weighted basis. The land uses are not confined to only one set of values per crop type. For example, from Table 2.6.1 it can be seen that the data base contains input information on maize for different planting dates, lengths of growing season and locality. Although this is still far from a complete data set, it is easy enough to update the information therein merely by the model developers' appending additional information to the land use data base.

In addition to input information on various crop types, the information base also contains defaulted input values on natural vegetation such as grasses, wetlands, exotic tree species, indigenous forests, pastures and urban and peri-urban land uses. However, with regard to urban and peri-urban land uses it must be cautioned that *ACRU* is, at its present status, essentially a catchment model for rural land uses and its application should be restricted to catchments where urban settlements represent only a small area, less than, say, 20% of the total catchment. From Table 2.6.1 it is evident that up to four types of vegetation input information may be specified for each land use type. These are the crop coefficient, Leaf Area Index, interception loss (mm per rainday) and fraction of root mass density in the topsoil horizon, all input variables of land use used by *ACRU* and which are described in Chapter 6. If information on one of these input variables is not available for a specific land use this is flagged with -1.00 in the first column of the monthly values. This code is a signal to the Menubuilder that the information should be derived by alternative means within the Menubuilder. For example, if the information base does not contain Leaf Area Index for that particular land use but it does have information on the crop coefficient then *ACRU* would contain an internal mechanism to derive the values of the former from the latter (Chapter 6). The monthly vegetative information on crop coefficient and/or LAI, read in direct or derived internally, is subsequently transformed into appropriate daily values within *ACRU* by Fourier Analysis.

The land use information base as a component of the DSS has as a primary objective the decrease in time and money spent during model input preparation by improving the effectiveness of user/model interface and technology transfer. Hopefully this will serve ultimately as an aid to bridge the gap between model developers and practising engineers and hydrologists, the eventual model users.

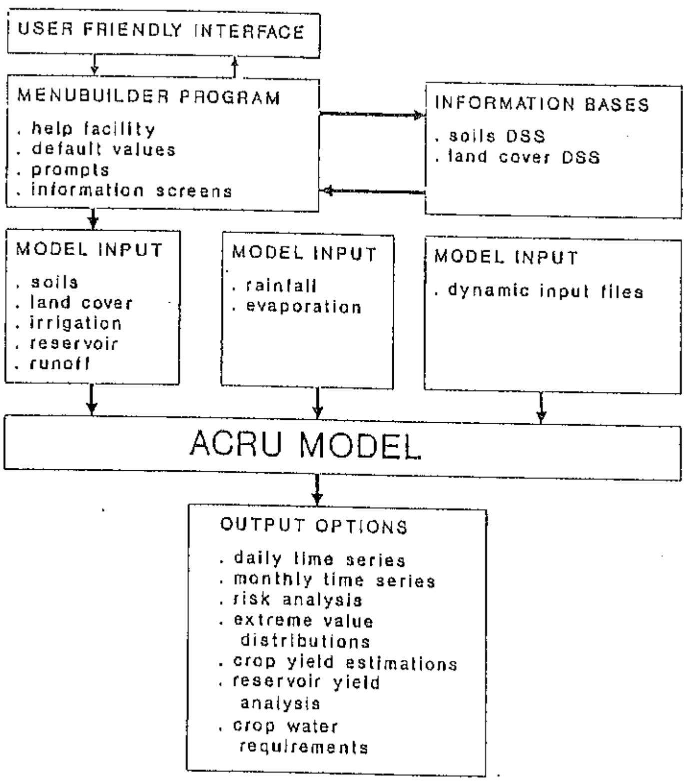

Figure 2.6.1 Components of the *ACRU* Decision Support System and their relationships in the *ACRU* modelling system

Table 2.6.1 Extract of selected examples from the land use information base

Land Use Number	Land Use Description Locality, Planting Date, Length of Growing Season	Vegetative Information	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2	Maize - all areas	Crop Coefficient	1.10	0.95	0.46	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.49	0.98
	Planting Date = Nov 1	Leaf Area Index	3.50	5.10	1.80	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.20	0.70
	Growing Season = 140 days	Interception Loss (mm.rainday^{-1})	-1.00											
		Root Fraction, A-horizon	0.74	0.78	0.91	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.92	0.79
4	Maize - all areas	Crop Coefficient	0.89	1.10	0.96	0.46	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.50
	PD = Dec 1	Leaf Area Index	3.00	5.25	2.50	0.10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.25
	GS = 120 days	Interception Loss (mm.rainday^{-1})	-1.00											
		Root Fraction, A-horizon	0.79	0.74	0.78	0.91	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.92
6	Wheat - E. Tvl, Pongola	Crop Coefficient	0.20	0.20	0.20	0.20	0.30	0.79	1.00	0.52	0.20	0.20	0.20	0.20
	PD = May 15	Leaf Area Index	0.00	0.00	0.00	0.00	0.35	1.70	2.90	4.80	0.15	0.00	0.00	0.00
	GS = 110 days	Interception Loss (mm.rainday^{-1})	-1.00											
		Root Fraction, A-horizon	1.00	1.00	1.00	1.00	0.92	0.75	0.65	0.55	1.00	1.00	1.00	1.00
7	Wheat - Tvl. Middleveld	Crop Coefficient	0.20	0.20	0.20	0.20	0.20	0.30	0.60	0.97	0.94	0.44	0.20	0.20
	PD = Jun 1	Leaf Area Index	0.00	0.00	0.00	0.00	0.00	1.00	1.80	2.90	5.70	1.20	0.00	0.00
	GS = 140 days	Interception Loss (mm.rainday^{-1})	-1.00											
		Root Fraction, A-horizon	1.00	1.00	1.00	1.00	1.00	0.92	0.75	0.65	0.55	1.00	1.00	1.00
18	Sucarcane - N. Coast	Crop Coefficient	0.81	0.84	0.85	0.86	0.87	0.85	0.82	0.78	0.77	0.78	0.81	0.82
		Leaf Area Index	-1.00											
		Interception Loss (mm.rainday^{-1})	-1.00											
		Root Fraction, A-horizon	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60
23	Cotton - Marginal areas	Crop Coefficient	0.69	0.82	0.62	0.40	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.29
	PD = Nov 1	Leaf Area Index	1.89	2.91	2.96	2.10	0.46	0.00	0.00	0.00	0.00	0.00	0.12	0.44
	GS = 160 days	Interception Loss (mm.rainday^{-1})	-1.00											
		Root Fraction, A-horizon	0.65	0.55	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.92	0.75
26	Citrus - Tvl and Natal	Crop Coefficient	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67
		Leaf Area Index	-1.00											
		Interception Loss (mm.rainday^{-1})	-1.00											
		Root Fraction, A-horizon	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40
38	Poplar Plantation	Crop Coefficient	0.95	0.95	0.95	0.80	0.20	0.20	0.20	0.20	0.40	0.80	0.90	0.95
		Leaf Area Index	4.00	4.00	4.00	4.00	3.50	3.00	3.00	3.00	3.00	3.50	4.00	4.00
		Interception Loss (mm.rainday^{-1})	-1.00											
		Root Fraction, A-horizon	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40

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CHAPTER 3

RAINFALL

R.E. Schulze, M.C. Dent and N.W. Schäfer

Rainfall is the fundamental driving force and pulsar input behind most hydrological processes and, because it is the most variable hydrological element (Hamlin, 1983), an accurate estimate of areal rainfall is the basic input to catchment rainfall-runoff models (for example, Hall and Barclay, 1975; Corradini, 1985). Rainfall-runoff models are particularly sensitive to the rainfall input and errors in rainfall estimates are amplified in runoff simulations. This implies that the success of hydrological simulation studies depends to a large extent on the precision with which the rainfall data are observed and processed in a model.

Hydrological models such as *ACRU* have become increasingly more complex and have reached a high level of performance in that the physical processes can be portrayed realistically. However, the same does not apply to the sampling and processing of the rainfall data that drive the model.

Because of the sensitivity of runoff to rainfall this chapter therefore discusses those aspects of rainfall to which important consideration has to be given when applying *ACRU* and expecting realistic results. Aspects discussed are

* the effects of rainfall variation on runoff,
* problems associated with rainfall estimation at a point,
* considerations regarding the spatial distribution of rainfall over a catchment,
* the dilemma of appropriate rainfall record length,
* the pros and cons of applying synthetic rainfall in agrohydrological simulations, and
* sources of rainfall data in southern Africa.

3.1 EFFECTS OF RAINFALL VARIATION ON RUNOFF

According to Hamlin (1983), rainfall is the most variable hydrological element and has a fundamental effect both on the catchment response and the catchment processes themselves. The rainfall-runoff process is non-linear. Hence, errors in the rainfall input to a model will limit the possible accuracy of the simulation results. The effect of rainfall input on rainfall-runoff modelling has been researched extensively. Results of the work in the USA by Lumb (1969) show that an increase of 10% in the rainfall input to some hydrological models produced an increase of 35% to the streamflow. The literature abounds with such examples. While an in-depth sensitivity analysis of input : output relationships in *ACRU* is made in Chapter 18, Figure 3.1.1 shows that for a research catchment under current land uses at Cedara in Natal a 20% underestimation of rainfall may lead to a 41% decrease in simulated runoff, while for a 20%

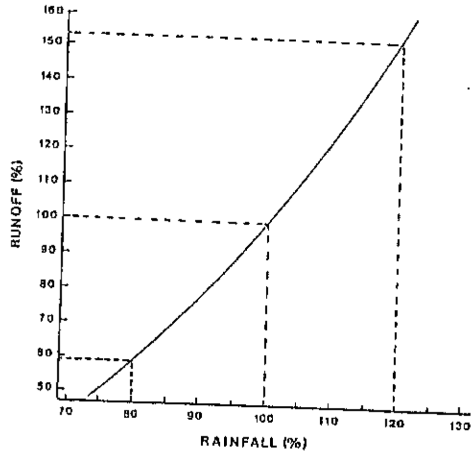

Figure 3.1.1 The variation in mean annual runoff using various incremental changes of actual rainfall data as input to the *ACRU* model for Cedara catchment U2M16

overestimation simulated runoff may be out by over 50%.

Considerable deficiencies in raingauge measurement can occur (c.f. 3.2.2) and point underestimations of 20% occur frequently (Boughton, 1981). The conversion of point to areal rainfall can also result in errors of between 10% and 20%, increasing to 60% in mountainous catchments (Hall and Barclay, 1975). The fact that a majority of gauges is usually found at lower elevations of a catchment generally leads to an under-estimation of the areal rainfall; hence these errors are likely to compound rather than cancel each other. In order to stress the importance of the rainfall input into the *ACRU* modelling system, the accuracy of point measurement of rainfall is therefore considered next.

3.2 PROBLEMS ASSOCIATED WITH RAINFALL ESTIMATION AT A POINT

ACRU, in attempting to maximise critical data available for hydrological modelling, uses daily rainfall input. Rainfall data recorded daily in southern Africa, for example, are obtainable from the Computing Centre for Water Research (Section 3.7) for in excess of 9 000 stations. While this suggests a highly adequate network, several factors need to be borne in mind.

3.2.1 Sample Size

The actual sample of measured rainfall is minute. A standard 127 mm diameter raingauge, for example, takes a 0.00000001267 sample per km^2 and, except in very few (usually research) areas, raingauge networks of that density do not exist. What is therefore being sampled as the primary input into *ACRU* is a minute fraction of the catchment's rainfall represented by the sample, which, in addition, may not even be an accurate measure of rainfall at that point.

3.2.2 Accuracy Of Point Rainfall Measurement

A raingauge is essentially an obstacle to windflow. It is therefore incorrect to assume that a gauge reading represents the actual rainfall at the site since rainfall is usually associated with a wind component. Point rainfall amounts are therefore essentially only indices of the true rainfall, due to catch deficiencies caused by the aerodynamic interaction of rainfall, wind, the gauge itself and local/regional topography. Not only are there systematic errors in the sampling accuracy of the gauges, but oversights also occur due to misreading the gauged amounts, faulty instrumentation and to the particular measuring technique adopted. The main factors that may affect the accuracy of the rainfall estimation at a point are depicted in Figure 3.2.1. The quantity of rainfall reaching level ground is thus invariably greater than that recorded by the gauge - an inherent error in gauge sampling which is generally ignored. Wind is the primary cause of inaccurate sampling (Helvey and Patric, 1983) and under-catch is a result of the wind flow causing turbulent eddies around the gauge orifice which deflect the rain drops. Allerup and Madsen (1980) estimated that wind accounted for about a 15% deficiency from an exposed gauge and this aerodynamic catchment deficiency has been found by Larson and Peck (1974) to be approximately 0.6%.km^{-1} windspeed.

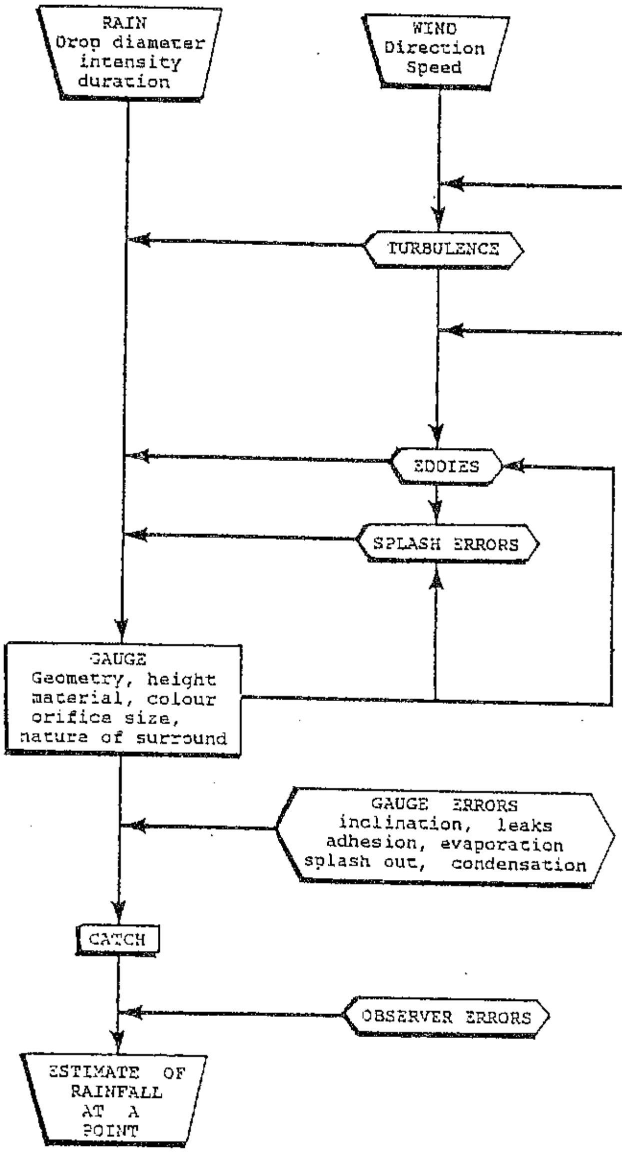

Figure 3.2.1 Factors giving rise to catch deficiencies in point rainfall measurements (after Rodda, 1967)

Allerup and Madsen (1980) found that surface adhesion of the water either in the funnel or receptacle and subsequent evaporation amounted to about 4% of annual rainfall, these losses varying from 0.2 mm to 0.4 mm per rainday; errors small enough *per se*, but nevertheless tending to accumulate.

Catch deficiency could be reduced, by shielding, and Schulze (1975) has found that at Cathedral Peak in the Natal Drakensberg, a Nipher-type windshield decreases catch deficiency by an average of 9.2%. Placement of the raingauge closer to the ground than the standard orifice height of 1.22 m in order to reduce turbulence is not seen as a viable proposition in southern Africa, which is characterised in many regions by largely convective rainfall producing mechanisms which could cause insplash. Using again Cathedral Peak as an example, Schulze (1975) showed that catch deficiency of the standard gauge decreased by 7.3% on average when the gauge orifice height was only at 0.3 m, but the greater rain catch difference when compared with an adjacent standard gauge in summer, must be attributed largely to insplash associated with large raindrops from convective storms. The classic South African study on influences of gauge elevation, protection and inclination probably remains that of De Villiers' (1980), who showed catch differences due to gauging techniques of up to 31.9% for different gauges at one meteorological site.

Furthermore, the rainfall received on the ground not only depends on the angle of incidence of the falling drops, shown by Schultz (1981) to be a function of wind speed and drop diameter, but also on the slope and aspect of the ground surface. Thus the discrepancy between "meteorological" rain catch (i.e. measured by a vertical raingauge) and "hydrological" rain catch (i.e. with the raingauge perpendicular to the slope face) may be as high as 4-11% on different aspects when rainfall is associated with storms moving in predominant wind directions, as Schultz (1981) has shown for the eastern Orange Free State, for example.

While *ACRU* contains the facility to apply month by month correction factors to gauged rainfall, the model does *not* account *per se* for the problems of unrepresentative rain catch, as outlined above. It neither contains a corrective equation for "true" rainfall as a function of meteorologically measured rainfall, slope gradient and aspect, average storm direction and angle of inclination of rainfall. This section has merely highlighted that the primary input in a hydrological model is already a poorly sampled point index rather than an absolute value, and that before the spatial representation of rainfall over a catchment has even been considered.

3.3 CONSIDERATIONS REGARDING THE SPATIAL DISTRIBUTION OF RAINFALL OVER A CATCHMENT

The problems associated with the spatial variation in rainfall and errors in calculating areal averages and their effect on simulated runoff have been considered by many researchers. In South Africa, for example, Hughes and Beater (1987) have compared the performance of a lumped and a semi-distributed model. Their results indicated that a lumped model performs as well as a semi-distributed model when the rainfall input is relatively uniform spatially; however, the semi-distributed model was superior when the rainfall was areally heterogeneous.

Dawdy and Bergmann (1969) indicated that the use of a single rainfall record as a lumped input can at best predict the peak discharge of a catchment with a standard error of the order of 20%. The use of a non-representative set of raingauges can also result in poor runoff predictions as Beven and Hornberger (1982) have shown conclusively. These points and results highlight the importance of preserving the spatial rainfall input and incorporating ideally some sort of distributed rainfall input into models like *ACRU* to lead to accurate runoff simulation, even when the total rainfall depth at a gauge is considered not to be in serious error.

The most important considerations in determining areal rainfall rely on the quantification of the factors which influence the spatial distribution of rainfall, especially with physiographic characteristics of a catchment. Mountain ranges, local topography and other physiographic features, as well as the prevailing synoptic conditions influence the occurrence and the spatial distribution of rainfall. The variations of rainfall with altitude, slope, aspect, exposure, steepness or areal location have been investigated widely, particularly using multiple regression techniques, and for southern Africa have been documented, *inter alia*, by Whitmore (1972), Schulze (1979), Hughes (1982) and Dent, Lynch and Schulze (1988).

Rainfall over an area may vary considerably due to even relatively small differences in altitude. Boughton (1981), for example, found a rainfall gradient of some 310 mm per 100 m rise in altitude occurring near Brisbane, Australia. Whitmore (1972) stressed that elevation with respect to a base level rather than altitude would give a better indication of the role that relief plays in the distribution of rainfall. The escalation in rainfall with rising altitude was explained by Duckstein, Fogel and Thames (1973) to be the result of an increase in the volume per event as well as an increase in the number of events which become rain-bearing.

Even small terrain features may play an important role in enhancing rainfall. According to Storebo (1976), relatively small hills of the order of 50 m above the general ground level may cause an increase of 25% to 50% in rainfall amounts by causing the formation of low level feeder clouds with droplets too small for independent rainfall, but large enough to be coalesced by rain falling from above. Thus, an appreciable variation in rainfall especially under frontal systems over relatively small areas may occur.

Continentality, i.e. a measure of the distance inland from a coast or the position of a site with respect to the source of moisture, was found by Whitmore (1972) to account for 22% of the variation in MAP in the southwestern Cape. The further inland a moisture laden air mass must travel, the more likely it is that the precipitable water will be reduced due to the orographic effect of previous upliftings. The bias in the areal distribution of the rainfall on windward and leeward slopes is illustrated well by Schulze (1979) in Figure 3.3.1 for the Natal Drakensberg.

Another important consideration in the spatial distribution of rainfall is aspect, particularly in association with direction of rain bearing wind. Furthermore, because of the marked seasonal variation in rainfall type in southern Africa, with predominantly frontal systems occurring in winter and convective storms in summer (Whitmore, 1972), it must be stressed that these two systems will not necessarily be affected by the same topographic and meteorological conditions. Frontal systems are far

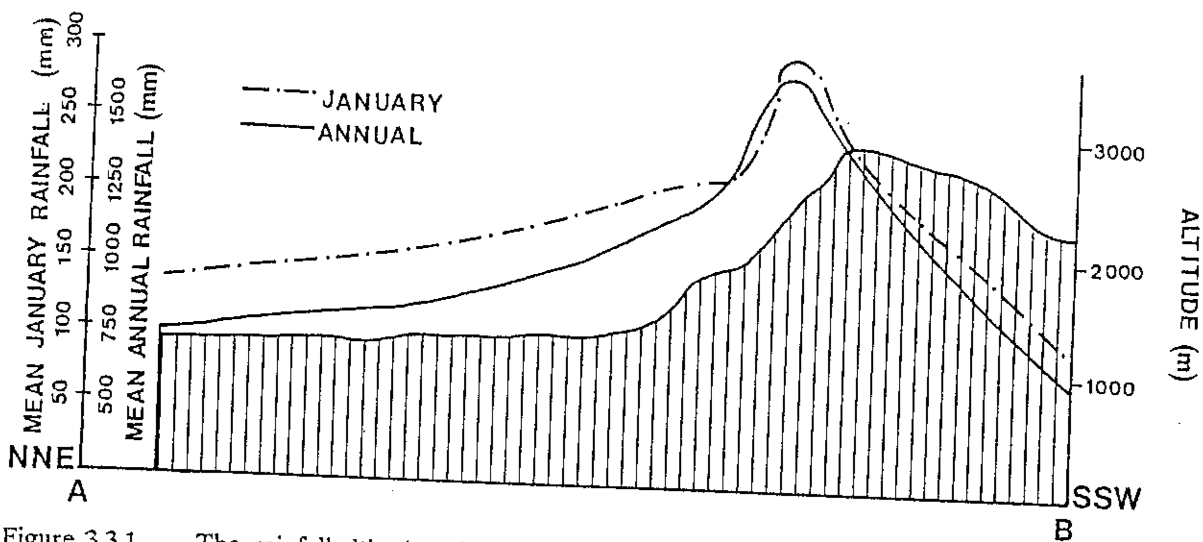

Figure 3.3.1 The rainfall:altitude relationship along a cross section of the Natal Drakensberg (after Schulze, 1979)

more extensive and uniform than the isolated convectional systems. Hence, rainfall type is another factor influencing the areal distribution of rainfall.

It is aspects such as the above that require careful forethought in data preparation when applying *ACRU*, particularly in a physiographically heterogeneous catchment, or when using the distributed version of the model or when using rainfall data non-representative of the *true* catchment's rainfall. The latter may be either because the gauge is located non-representatively, or the network is distorted, or the record lengths of daily rainfall are not long enough and possibly from a non-representative time series.

3.4 THE DILEMMA OF MINIMUM RAINFALL RECORD LENGTH FOR HYDROLOGICAL MODELLING

3.4.1 How Long Is Long Enough?

This vexing question is a crucial one modellers ask themselves in the context of hydrological risk analysis and planning, even more so when using a multipurpose daily model such as *ACRU* where, for example, in irrigation or crop yield or reservoir analyses it is intra-monthly rainfall distributions (i.e. daily rainfall totals and their interactions with the soil and plant environments) rather than merely monthly totals of rainfall that are important.

Little research has been undertaken on "how long is long enough" regarding *daily* rainfall data sets used in hydrological risk modelling (Knisel, Renard and Lane, 1979). Considerable work has, however, been published on suggested minimum length of record regarding statistical stability of annual and monthly rainfall totals, and that may be taken as a guideline to minimum record lengths appropriate for use with the *ACRU* model.

If, for example, a minimum 40 year annual rainfall record were selected for an *ACRU* simulation run, that duration would at the same time

* satisfy any bias which could be induced by short (say 10 years) record lengths being

influenced unduly by a particularly wet or dry spell of years especially where, for example, in southern Africa "quasi" periodic fluctuations with approximately 20 year oscillations have been reported by many researchers (see review by Tyson, 1987), because a 40 year period would then encompass at least two such "cycles". A 40 year record length would, furthermore,

* satisfy the international agreement of using a minimum base period of 30 years, as discussed by Dunne and Leopold (1978).

Figure 3.4.1 illustrates the distribution of rainfall stations in southern Africa with record lengths exceeding 40 years. Most regions within southern Africa appear to have an adequate network of stations with long records. It is in certain critical areas such as Lesotho (a major source of future water resources for South Africa) and the Independent and National States (where rural development schemes require planning) that there appears a dearth of stations with long records.

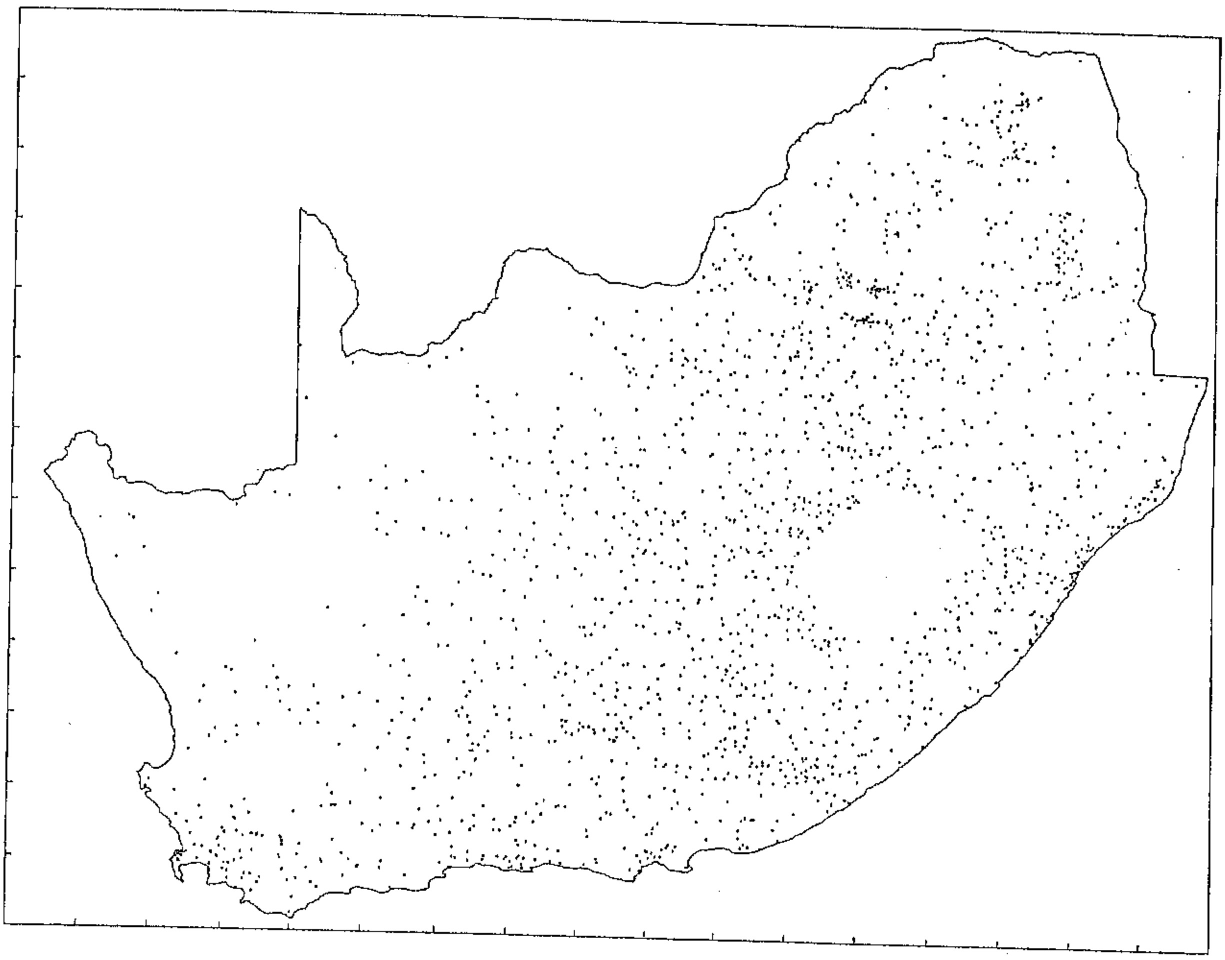

Figure 3.4.1 The distribution of rainfall stations in southern Africa with record lengths exceeding 40 years of observed data (Source : Computing Centre for Water Research)

However, the minimum usable record length will also vary regionally within southern Africa. On the premise that variability of rainfall is generally higher in areas of low rainfall (Schulze, 1983) and that the use of short term records can bias estimates of MAP significantly, semi-arid areas are likely to require longer record lengths for hydrological risk analysis than wetter areas.

In order to establish regional minimum record lengths of MAP in southern Africa, Dent, Lynch and Schulze (1988) produced a map with 24 regions in which record lengths required to ensure that the mean of annual rainfall estimates were within 10% of a long term mean in 90% of years. A method of "moving windows" at 5 year intervals to a 40 year period was used. This is described in Dent Lynch and Schulze, (1988). Figure 3.4.2 shows the eastern parts of southern Africa to require a minimum of 15 years' record for a relatively "stable" MAP while parts of the semi-arid regions in the west require a minimum of 30 and up to 35 years' record for meaningful estimates of MAP.

It is surmised that for a *daily model* such as *ACRU* the *ideal minimum record lengths* required be double those for MAP as given in Figure 3.4.2, with a 50 year record being acceptable in those regions where a suggested minimum record length for MAP is 25 years and over. Where stations with shorter records than the suggested minimum are used with *ACRU* for expediency sake, a sensitivity test of output should ideally be undertaken using the closest appropriate station of acceptable length and relevant interpretation be made.

However, the question as to whether or not length of record is crucial depends also on the problem to be solved by the simulation, as the case study below illustrates.

3.4.2 <u>On The Sensitivity Of Output From Simulated Irrigation Water Demand To Rainfall Record Length</u> : <u>A Case Study With Apparently Anomalous Results</u>

A case has been made in Section 3.4.1 for the use of relatively longer rainfall records in more arid areas. This is certainly the case when using a model such as *ACRU* to provide (say) realistic risk analysis of monthly summations of daily simulated flows or design values of annual maximum daily stormflows using extreme value distributions.

Furniss (1988) has, however, shown that in the analysis of irrigation water demand shorter records may give relatively more accurate simulations in semi-arid areas than in more humid areas when compared with simulations from long duration rainfall records. He compared the following with long record lengths in simulations of irrigation demand, viz.

* a 10 year daily rainfall record (which is the minimum length Green in 1985 had recommended for use in irrigation demand analyses) and

* a five year daily rainfall record (since about 40% of stations in southern Africa have fewer than 10 years' record). Monthly rather than seasonal values of irrigation requirements were selected because within a season there may be periods of high or low irrigation demand which may dictate the design of an irrigation project (Furniss, 1988).

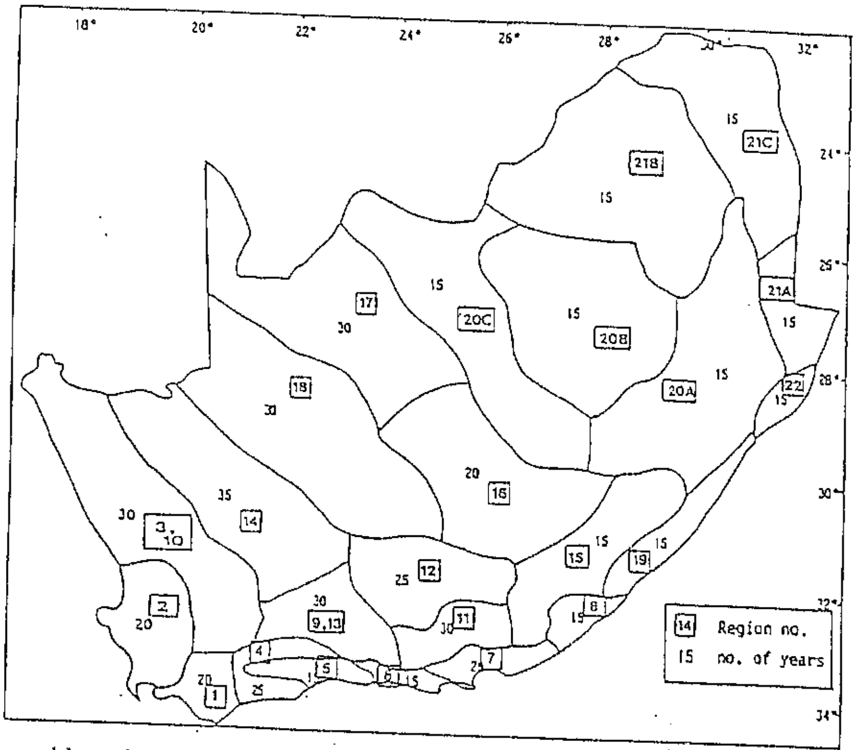

Figure 3.4.2 Record lengths required to ensure that the mean of annual rainfall are within 10% of the long term mean in 90% of years (Dent, Lynch and Schulze, 1988)

Results for irrigated maize from Robertson (33 ° 50'S; 19 ° 54'E, MAP 254 mm) and Cedara (29 ° 32'S; 30 ° 17'E, MAP 839 mm) indicate clearly that in higher rainfall areas, where supplementary rather than total irrigation is practised, long rainfall records are needed in order for a planner to attain a higher measure of certainty in water use (Figure 3.4.3, c.f. Cedara). In areas of lower rainfall, where virtually total irrigation is practised, it is not as necessary to obtain rainfall records as long and a shorter period would simulate irrigation demand with nearly the same degree of certainty as would the longer records (Figure 3.4.3, c.f. Robertson).

This case study illustrates an apparent anomaly and shows length of record to be a criterion dependent on the use to which a simulation is to be put.

3.4.3 Other Problems Of Importance To Hydrological Modelling Associated With Rainfall Records

Apart from errors of rainfall measurement at a point and over an area and those induced by using short records, users of *ACRU* must be made aware of the following problems:

* The *standard rainfall day* begins and ends at nationally determined times, in southern Africa it is 08:00. In recording the previous day's rainfall at 08:00, many characteristics of individual storm events which may be occurring at that time may be lost for non-recording gauges read daily. This may lead to misinterpretations and under-simulations, particularly of the more crucial "extreme" events and in long duration events.

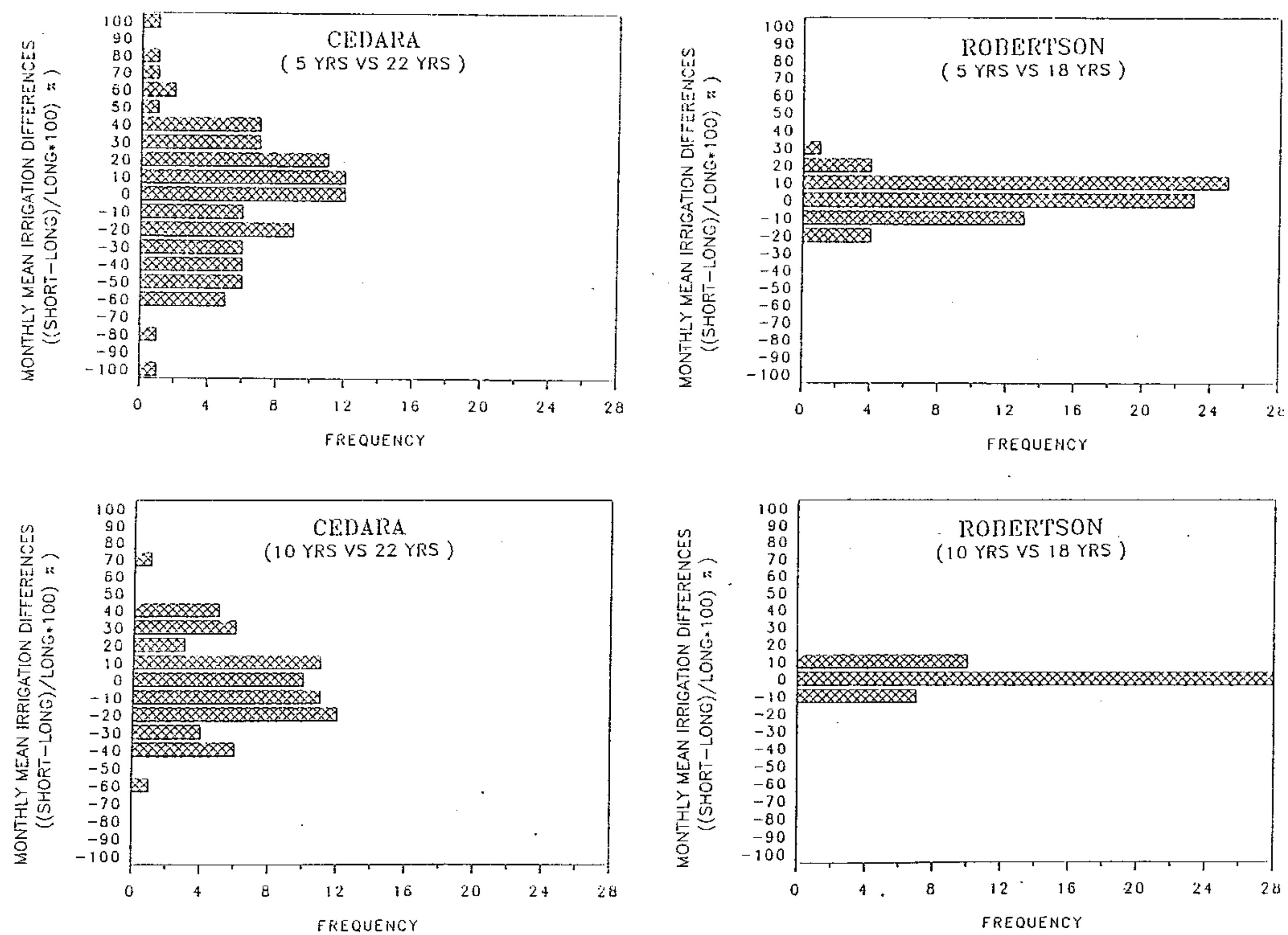

Figure 3.4.3. Histograms of the deviations from long term mean monthly irrigation requirements for maize resulting from the use of short vs long rainfall records (after Furniss, 1988)

* The vast majority of rainfall stations are run by volunteers and it is possible for *human errors* to occur in reading and recording rainfall. There is no objective means of checking for such errors. Schulze (1979) found that at certain stations in the Drakensberg, for example, it became quite obvious by careful manual perusal of the rainfall records when the operators' annual leave was taken.

* *Errors in transposing data* into computer compatible form also occur. The South African Weather Bureau, for example, cautions against such errors and it claimed 95-98% accuracy in the data acquired from them (Schulze, 1979).

* *Extreme events* are of primary concern in hydrological modelling. In an analysis of events in southern Africa recording in excess of 200 mm per day, Dent, Lynch and Schulze (1988) found that of 3500 such events on the official data files only 1300 could be accepted beyond any doubt when careful checking was undertaken against concurrent daily rainfall at nearby stations, and the remaining 2200 so-called extreme events had to be considered as being suspect, often the result of a keying-in gremlin.

* In many high lying areas *fog* may play a major role in hydrological response. Fog contributions are not recorded by standard raingauges. Schulze (1979) reviews the contribution of fog measurements by special fog interceptors, and reports that in many areas so-called fog catch may in fact exceed total rainfall recorded.

3.5 MISSING RAINFALL RECORDS AND APPROACHES TO INFILLING MISSING DATA

A major problem in the application of daily rainfall driven models such as *ACRU* remains that of missing data for a station's records. For continuous daily water budgeting it is desirable to have an unbroken daily rainfall record for *ACRU* individual years have to be "complete".

3.5.1 How Serious Is The Missing Data Problem?

Dent, Schulze and Angus (1988), in analysing daily rainfall data from 712 southern African stations with long records, conducted a study to ascertain what fraction of the total daily rainfall record at those stations was missing, and in addition how many of those missing data occurred in short sequences of less than 4 consecutive days (Table 3.5.1).

Results show that all stations in this particular analysis had some missing data. The missing data problem is thus a serious one. Ninety-five percent of stations had less than 14% data missing, but less than 2% of the missing data occurred in short sequences. It is disconcerting to note that 50% of the stations had as much as 4% missing data, invariably in longer sequences.

Methods of infilling daily rainfall data thus have to become part of the armoury of using a model such as *ACRU* effectively and some methods available are discussed below. Further details of the application of the methods are given in the *ACRU* User Manual (Schulze and George, 1989).

Table 3.5.1 Amount of missing daily rainfall at 712 stations in southern Africa in a study by Dent, Schulze and Angus (1988)

Percentage of Stations	100	95	90	75	50	25	5
Any length sequence of missing data (%)	48	14	10	6	4	3	1
Short sequences (<4 days) of missing data (%)	41	2	0	0	0	0	0

3.5.2 Methods Of Infilling Missing Data For *ACRU* When Using Southern African Data Bases

Other than manual infilling of missing data from nearby stations, two automated methods are available through the CCWR for users in southern Africa for infilling gaps in the daily rainfall record at stations on the CCWR's southern African data files.

* The more sophisticated and scientifically correct method developed by Adamson (1987) involves the use of observed concurrent daily data from five automatically scanned/selected nearby stations in order to synthesise records where they are missing. These synthetic records, which are weighted by an inverse distance technique, preserve the sequence of wet and dry days and therefore compare realistically with the records at nearby stations for the same day.

* A second method makes use of a 12-parameter synthetic rainfall generator developed by Zucchini and Adamson (1984), with parameters available for 2550 daily rainfall stations for southern Africa. In this method the synthesis of missing data proceeded as follows (Dent, Schulze and Angus, 1988) :

(i) A complete year of synthetic daily rainfall data was generated using the technique developed by Zucchini and Adamson (1984).

(ii) The observed daily rainfall record was then scanned for missing data and the appropriate day of year from the year of synthetic daily data in (i) was used to replace any missing daily value.

(iii) Once used, that day of the year in the synthetic record was labelled as such.

(iv) If such a "used" day of year was required again at the station under consideration then a complete new year of synthetic daily rainfall data was generated (so as not to re-use any particular synthetic rainfall value) and steps (ii) and (iii) repeated.

This method, which was used by Dent, Schulze and Angus (1988) in a study determining crop water requirements for irrigation planning in South Africa, does not account for correct probability of wet:wet, wet:dry or dry:dry sequences in the case of a single day's missing record. However, in replacing missing data by this technique the record for the first day of the synthetic sequence does not take cognizance of the previous day's rainfall.

3.6 ON THE USE OF SYNTHETIC DAILY RAINFALL DATA IN *ACRU*

The 12-parameter synthetic daily rainfall generator developed for 2550 stations in southern Africa by Zucchini and Adamson (1984) has been mentioned above. For users of the model in southern Africa these parameters are available through the CCWR.

3.6.1 Advantages Of Using Synthetic Rainfall Information In Models Such As *ACRU*

A major advantage of using synthetic rainfall information is that the parameter sets for an entire region or subcontinent and the techniques to automate its application in models such as *ACRU*, are suitable for use on micro-computers. Daily soil water budgeting and hydrological modelling for *planning* purposes is thus now possible, for example in southern Africa, without the need to store and maintain a large and cumbersome observed daily data base. The daily rainfall records may be generated as and when required. The problems of missing data and short data sets are also not present when using generated data. This removes two of the largest obstacles in the path of the widespread adoption of daily water budget modelling techniques for a range of applications.

3.6.2 Comparison Of Output From Observed vs Synthetic Daily Rainfall Using *ACRU* : A Case Study

Dent, Schulze and Angus (1988) conducted tests at 17 stations in southern Africa with widely diverging climates to ascertain the effect on simulated total evaporation (i.e. "actual evapotranspiration") and runoff by employing an entirely synthetic daily rainfall set versus observed rainfall data both using the *ACRU* model. Selected output from four rainfall stations, viz. Nieweberg (winter rainfall region), Diepdrif (arid Karoo region), Durban (summer rainfall, coastal region) and Karina (summer rainfall, interior region) is shown in Table 3.6.1.

Results display close association between statistics of total evaporation and runoff from *ACRU* simulations when using observed vs synthetic daily rainfall for a range of soils and land uses at the stations, with results generally diverging only at the 95 percentile (approximation the 1:20 year event). Application of synthetic rainfall is thus seen to hold considerable potential for use in agrohydrological planning exercises, circumventing many of the problems associated with observed daily rainfall data sets.

3.6.3 A Note Of Caution On The Application Of Synthetic Daily Rainfall In Models

The potential for using synthetic rainfall sequences with the *ACRU* model having been indicated, it is necessary to sound a strong note of caution that synthetic daily rainfall is not the panacea to the hydrologist's data problems. Synthetic data sets, when re-used, are not unique, cannot reproduce discrete or extreme events as an historical time series, nor can they mimic short or longer term (secular) sequences of wet or dry periods. Their main application is thus restricted to producing sets of statistics useful to long term planning and decision making only, and not to mimicking historical sequences and their hydrological responses.

Table 3.6.1 Comparison of selected output from the *ACRU* model when using observed and synthetic daily rainfall (after Dent, Schulze and Angus, 1988)

Station	Length of Record (yrs)	Crop	Soil	Rain	Monthly Total Evaporation (mm)							Monthly Runoff (mm)						
					Mean	Std Dev	Skew-ness	Kurt-osis	Percentiles 95	90	75	Mean	Std Dev	Skew-ness	Kurt-osis	Percentiles 95	90	75
1. <u>Nieweberg</u> Zone 9 Lat. Long. 34 04' 19 03' Alt. MAP. 564 m 1605.9	57	Wheat	Clay	obs	23.6	10.1	1.3	1.0	46.0	2.2	25.7	97.8	107.5	2.1	5.1	320.9	233.6	142.1
				syn	23.4	10.1	1.2	0.9	45.0	1.6	25.6	98.3	94.3	1.7	3.8	285.1	234.0	144.9
		Wheat	Sand	obs	22.2	10.3	1.2	0.9	44.6	1.5	24.5	99.1	84.1	1.8	4.5	257.1	207.5	137.2
				syn	22.1	10.2	1.1	0.7	43.9	0.6	24.0	99.5	74.0	1.3	2.7	248.3	198.1	139.4
6. <u>Diepdrif</u> Zone 208 Lat. Long. 31 34' 20 18' Alt. MAP. 1039 m 129.1 mm	49	Sparse Veld	Clay	obs	8.0	10.3	2.0	4.7	30.6	1.9	11.8	1.1	4.5	6.1	43.3	6.4	1.5	0.0
				syn	8.4	10.7	1.9	4.2	30.3	4.9	12.8	1.0	4.5	9.0	100.9	5.1	2.3	0.1
		Sparse Veld	Sand	obs	8.5	10.2	1.8	3.6	30.0	2.2	12.8	0.6	2.4	6.7	52.5	3.0	0.8	0.0
				syn	8.9	10.3	1.7	3.4	30.1	3.9	13.9	0.5	2.6	8.4	76.7	2.2	0.3	0.0
10. <u>Bergville</u> Zone 377 Lat. Long. 28 44' 29 21' Alt. MAP. 1130 m 740.9 mm	46	Maize	Clay	obs	39.4	35.2	1.0	0.1	109.7	89.0	63.0	12.3	22.0	2.9	10.6	58.3	37.0	14.2
				syn	38.9	34.9	1.0	0.0	111.0	92.1	62.4	10.7	18.5	2.7	8.8	49.9	33.5	13.9
		Maize	Sand	obs	38.8	38.3	1.1	0.3	120.1	99.4	62.6	12.7	15.9	2.5	7.6	41.8	33.0	16.5
				syn	38.9	38.4	1.1	0.2	121.5	103.6	61.3	10.6	12.1	1.8	3.4	35.9	27.1	15.1
14. <u>Karina</u> Zone 518 Lat. Long. 26 05' 29 50' Alt. MAP. 1648 m 645.1 mm	67	Maize	Clay	obs	33.5	33.2	1.2	0.3	108.6	91.2	53.5	11.5	21.8	2.9	10.5	60.3	36.4	13.1
				syn	35.5	32.6	1.0	0.0	106.6	88.8	59.1	11.1	18.8	2.8	12.0	51.2	37.1	15.2
		Maize	Sand	obs	31.6	32.7	1.1	0.2	103.1	89.1	50.8	13.3	17.2	2.1	5.7	49.0	36.5	18.6
				syn	33.9	33.0	1.0	0.1	104.2	90.2	55.7	12.7	14.3	1.9	4.4	41.8	1.7	18.6

3.7 SOURCES OF RAINFALL DATA FOR USE IN SOUTHERN AFRICA

3.7.1 The Computing Centre For Water Research

The most readily accessible source of daily rainfall data for southern Africa is the Computing Centre for Water Research (CCWR). The CCWR was established jointly by the Water Research Commission, ISM (Pty) Ltd (formerly IBM) and the University of Natal and is located at the University of Natal's Pietermaritzburg campus. It acts as an information dissemination system for *bona fide* users in the broad field of water related subjects. Researchers can request data remotely through one of several national computer networking facilities. One of the major aims of the CCWR is to link researchers to available data banks in southern Africa. In order to become a CCWR user, contact should be made with :

The Manager, CCWR,
P O Box 375,
Pietermaritzburg 3200,
South Africa.

3.7.2 Daily Rainfall Data

The CCWR collates daily rainfall data files from several primary sources throughout southern Africa, for example, the South African Weather Bureau (which operates the major regional raingauge network), the State Departments of Agriculture and of Environment Affairs, the South African Sugar Association and private individuals. CCWR's function is that of updating data files periodically, i.e. it does not operate as a data bank *per se*. Daily rainfall may be requested in an *ACRU* format for observed or synthetic data sets. Details are given in the *ACRU* User Manual (Schulze and George, 1989).

3.7.3 Maps/Images Of Mean Annual And Median Monthly Rainfall For Southern Africa

In order to make appropriate corrections from point to areal (catchment) rainfall, long term spatial distributions of rainfall need to be known. For southern Africa these distributions have been determined by the Department of Agricultural Engineering in a comprehensive study of rainfall statistics by Dent, Lynch and Schulze (1988). For any specified catchment area, either maps at any requested scale of MAP and/or Median Monthly Rainfall or gridded point values at 1 minute of a degree latitude/longitude may be obtained through the CCWR. Their detailed application to making decisions regarding rainfall input to *ACRU* is explained in the *ACRU* User Manual (Schulze and George, 1989).

3.8 CONCLUSIONS

Rainfall is the major driving force to responses in the agrohydrological system. This chapter has therefore highlighted the importance of accurate rainfall input to *ACRU* by examining the problems inherent in obtaining realistic daily rainfall estimates under the premises that

* one should not accept rainfall data with blind faith at face value

* in a model "garbage in" results in "garbage out"

* agrohydrological response is probably more sensitive to rainfall than to any other input (c.f. Chapter 18).

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CHAPTER 4

POTENTIAL EVAPORATION

R.E. Schulze

4.1 THE CONCEPT OF POTENTIAL EVAPORATION

In the discussion of the basic concepts of the *ACRU* agrohydrological modelling system, it was described as being essentially a total evaporation (i.e. "actual evapotranspiration") -based model (c.f. Chapters 1 and 2). Total evaporation, E, is "driven" by maximum evaporation, E_m (i.e. "potential evapotranspiration"), the forcing function of which is, in turn, potential evaporation, E_p. Since evaporation is by definition the conversion of liquid water to vapour at an evaporating surface and the vertical transport of vapour into the atmospheric boundary layer (Ward, 1975), E_p may be considered an "atmospheric demand", determined by climatic variables such as net radiation, wind and vapour pressure deficits, or their surrogates. The accurate estimation of daily E_p is viewed as vital in the *ACRU* model, particularly when simulations are performed in regions such as southern Africa, where an estimated 91% of MAP is returned to the atmosphere by total evaporation (Whitmore, 1971), as against a global average of 65-70% (Ward, 1975).

4.2 THE DAILY A-PAN EQUIVALENT AS REFERENCE POTENTIAL EVAPORATION IN *ACRU*

4.2.1 Reasons For Selecting The A-Pan As A Reference For Potential Evaporation Estimates

There are many methods of estimating E_p, ranging from complex physically-based equations to simple measurements and even simpler surrogates based on single variables such as temperature. These methods all yield different answers under different climatic conditions, and a reference potential evaporation, E_r, (with its inherent advantages and defects) therefore has to be selected as that potential evaporation against which all other methods must be adjusted appropriately.

For the *ACRU* model the daily American Class A evaporation pan amount has been selected as reference potential evaporation. Reasons for its selection are as follows :

* The American Class A evaporation pan is, universally, the most common evaporation pan in usage, having been adopted as the standard evaporation pan since the International Geophysical Year 1957/8.

* When operated properly it is accepted as a reasonably reliable, inexpensive integrator of the E_p process over time and it is used commonly as a reference for potential evaporation (Green, 1985).

* In southern Africa, where to date the *ACRU* model has been used most frequently, crop coefficients, relating consumptive water use of the plant/soil continuum under different growth stages to a reference potential evaporation, have been tried and tested most widely against the A-pan.

* Physically elegant methods of estimating E_p, such as the universally accepted Penman-based methods (e.g. Penman, 1948), make high demands on input data, including net radiation, wind and vapour pressure deficits). These data are not yet available from many stations in southern Africa, particularly not in developing areas. On the other hand there is often at least a rudimentary, if physiographically biased, network of A-pans. Physically-based equations such as Penman's can thus only be used where relevant data are available, and at those locations should, in fact, be used in preference to A-pan data.

4.2.2 Problems Associated With A-Pan Data

Use of the A-pan as a reference for potential evaporation estimations is not without its problems. Some problems are listed below :

* The spatial distribution of A-pans in southern Africa, for example, is such that they are found generally at dams, existing irrigation schemes or in areas of low relative relief where commercial agriculture is carried out. These sites are not always representative either of areas where water resources assessments are required (i.e. in higher altitude areas, where runoff production may be a prime concern) or of developing areas in the third world.

* According to Smith (1975) the extrapolation of evaporation pan data from its measurement at a site to other locations is a "very hazardous procedure". Green (1985) also discusses errors which could be incurred when extrapolating A-pan data and at the University of Zululand's hydrological research catchments a dense network of pans has yielded inexplicably variable results (Hope and Mulder, 1979) due to influences of local climate.

* Research by Bosman (1987) has highlighted proper pan installation and micro site-conditions, both of which can cause readings from adjacent A-pans to vary significantly by over 20% in the long term.

* A-pans may or may not be screened (to prevent, for example, animals drinking from the pans). Screening suppresses evaporation losses from the pan by 5-15%, the suppression depending on the mesh size of the screen (Bosman, 1988). Public records of pan evaporation seldom indicate whether or not the pan is screened.

* Other errors may be due to possible accumulation of dirt/algae in the pans or to advection.

* Pan data are nowadays usually assumed to be those from a Class A-pan, whereas they may have been derived from other evaporation tanks with different physical properties (e.g. the Symon's tank), thus requiring a regional and seasonal dependent conversion to A-pan equivalents (c.f. Section 4.4).

* The A-pan's physical dimensions and exposure to the atmosphere render its readings to often be unrepresentative of atmospheric demand, due to heat storage in the water contained in the pan.

It becomes evident from the above discussion on problems associated with the A-pan that not all data obtained through existing networks are necessarily accurate. Great care should therefore be taken in checking the A-pan data for reliability, and if need be many pans' data may have to be rejected (Clemence, 1986). It is therefore necessary to consider surrogates of A-pan evaporation, which when calibrated against pan data under experimental conditions, may yield equivalent evaporation information which may, in fact, be extrapolated with greater confidence to locations where no evaporation measurements are available than poor A-pan data could have been.

4.2.3 The Use Of Temperature Information As A Surrogate For Estimating Potential Evaporation

A number of reasons may be advanced for using temperature information as a surrogate for estimating daily A-pan equivalent evaporation :

* Temperature, while closely associated with the solar energy forcing function in the evaporation process, is less susceptible than pans to measurement errors or effects of local anomalies in micro-climate.

* There are, in southern Africa, more than twice as many temperature stations as evaporation stations. The distribution of temperature stations is, furthermore, more even spatially and the network covers a wider range of altitudes and physiographic zones than that of A-pans (Schulze, 1985).

* Temperature information may be extrapolated to unmeasured locations more readily than evaporation pan information by use of multivariate techniques, including, for example, trend surface analysis (Schulze, 1982) and regional lapse rate-based equations (Schulze and Schäfer, 1989), because of the close association of temperature with altitude and other physiographic factors.

A problem which then remains is the selection of appropriate temperature-based equations for a given problem or region, should A-pan data not be available or be deemed unreliable.

4.3 DECISIONS AND PROCEDURES IN *ACRU* REGARDING POTENTIAL EVAPORATION ESTIMATES

ACRU, being a multilevel model designed to accommodate different levels of available climatic input, contains options for a number of methods, using both daily and monthly input, to estimate the daily A-pan equivalent, E_p. A decision chart of an illustrative (rather than computationally sequential) nature on potential evaporation estimation techniques for *ACRU* is depicted in Figure 4.3.1.

In this essentially self-explanatory diagram it may be seen that where only monthly mean climate or temperature information is available, the monthly mean equivalent evaporation is converted by Fourier Analysis to daily mean pan equivalents, which are corrected to yield mean daily A-pan equivalents. These generated mean daily values are, in turn, "perturbed" to give a more realistic actual daily estimate of A-pan equivalent by adjusting according to whether or not it was a rainy day (suppression to 0.8 of value) or a "rainless" day (enhancement to 1.05 of the mean value). Verification of the 0.8 and 1.05 adjustment coefficients is discussed in Chapter 17.

4.4 METHODS FOR ESTIMATING A-PAN EQUIVALENT POTENTIAL EVAPORATION

A number of methods are available in *ACRU* to estimate potential evaporation, as illustrated in Figure 4.3.1. These methods are discussed in this section.

4.4.1 The Penman (1948) Equation

The Penman equation, of which there are many variants, is a physically-based combination equation (i.e. combining energy budget and turbulent transfer approaches).

Over 40 years after its origin it remains a most elegant equation and is, universally, the most widely verified and cited standard E_p equation. The version of the Penman equation as used in *ACRU*, E_p ($mm.day^{-1}$) is given by

$$E_p = (\Delta/\gamma\, R_n + E_a)/(\Delta/\gamma + 1)$$

in which

R_n = net radiation (in mm equivalents)
= $R_{se} - R_l$

where

R_{se} = effective shortwave radiation
= $(1 - r).R_s$

with

r = reflected shortwave radiation (usually 0.05 to 0.08 for an evaporation pan)

and

R_s = incoming shortwave radiation.

ACRU contains two options for calculating R_s. If locally observed radiant flux densities (i.e. R_o in $MJ.m^{-2}$) are available these are used, with the $MJ.m^{-2}$ converted to mm equivalents of water, i.e.

$$R_s = 0.3979166\, R_o.$$

Where radiant flux densities are not measured, R_s has to be estimated by an Angström-type equation using

R_a = extraterrestrial radiation,
= computed in *ACRU* in mm equivalent by equations combining latitude and declination (the latter as a function of the date within a year)

and observed sunshine duration, such that

$$R_s = R_a\,(a + b.n/N)$$

with

n = actual (observed) sunshine duration

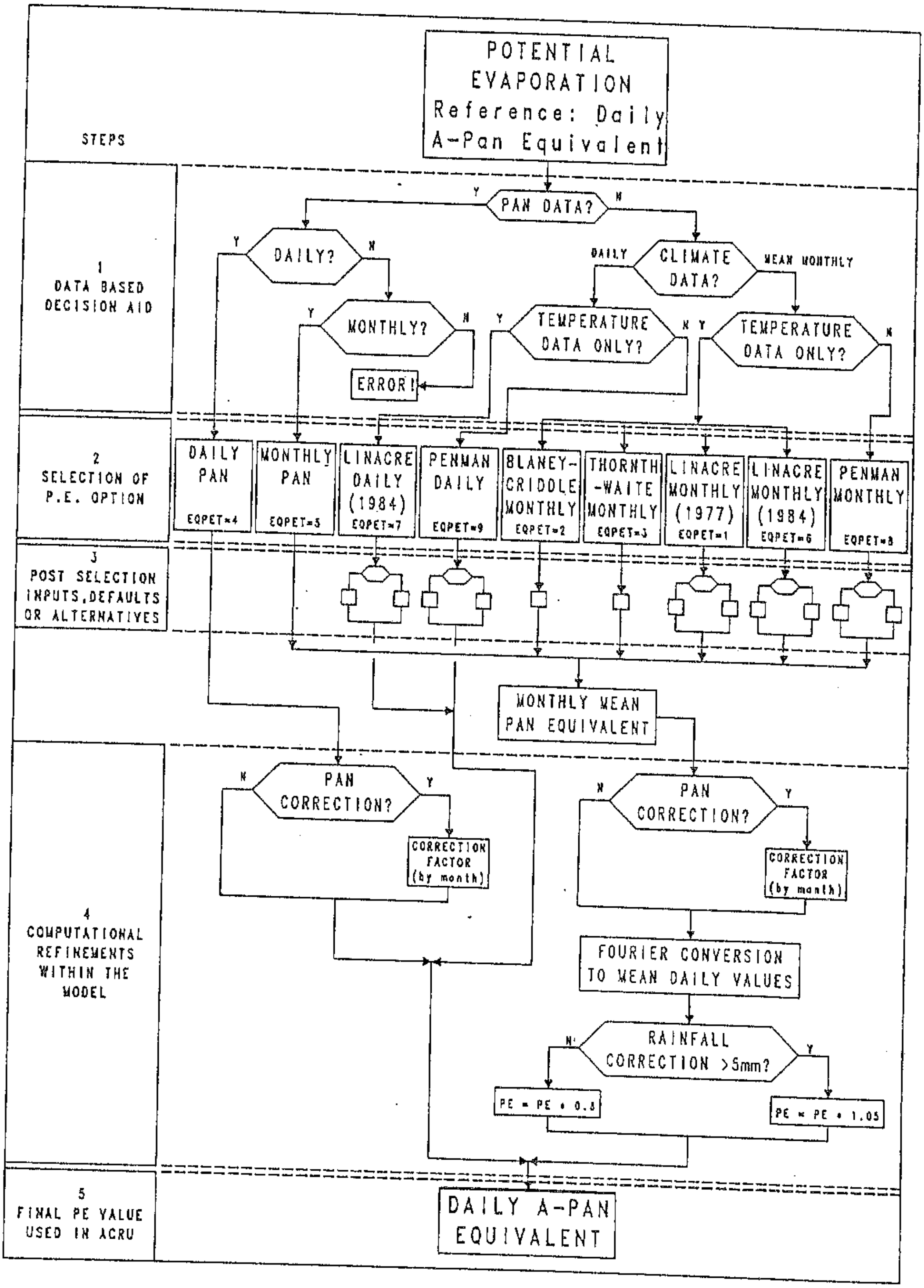

Figure 4.3.1 Decisions and procedures in *ACRU* regarding potential evaporation estimates

(h) for the day or

N = maximum hours of sunshine on a completely cloudless day, and input month by month into *ACRU* for a given latitude using tables provided in the *ACRU* User Manual (Schulze and George, 1989)

a and b = coefficients relating to atmospheric transmissivity, including cloudiness, with typical values provided in the User Manual, but

a = 0.24, if defaulted in *ACRU*

and

b = 0.53, if defaulted in *ACRU*.

Net longwave radiation, R_l, is estimated from a Brunt-type equation by

$$R_l = (0.98)(8.17 \times 10^{-11})(T_a + 273.16)^4 (0.56 - 0.08e_d^{0.5})(0.1 + 0.9\, n/N)/(59.73 - 0.057T_a)$$

in which the first bracketed term represents longwave emissivity, the second and third terms the Stefan-Boltzmann constant, the fourth term absorption by water vapour, with

T_a = mean (daily or monthly) air temperature (°C)

and

e_d = actual vapour pressure (hPa)

and the fifth term denoting backscattering by clouds. The sixth bracketed term (the divisor) converts the equation to mm equivalents evaporation.

Actual vapour pressure e_d is expressed as

$$e_d = e_a.RH/100$$

where

e_a = saturated vapour pressure (hPa), calculated by Tetens' equation as $6.11 \times 10^{(7.5\, T_a/(237.3 + T_a))}$

while

RH = mean relative humidity (daily or monthly), per cent

= defaulted to 50% if unknown.

The E_a term is the turbulent transfer term, in which

$$E_a = 0.35\, V_d\, (1 + 0.1\, u/1.609)$$

in which

V_d = vapour pressure deficit

= $0.75\, (e_a - e_d)$ and

u = windrun at 2 m height ($km.day^{-1}$).

The term Δ/γ is the ratio of the psychrometric constant and the slope of the saturated vapour pressure curve, and is a dimensionless weighting factor used in the Penman equation, expressed by Schulze (1975) as

$$\Delta/\gamma = 0.00223136\, T_a^2 + 0.0281431T_a + 0.704861.$$

ACRU contains two options for running the Penman equation, viz. a daily and a monthly option, depending on the availability of input data.

4.4.2 The Linacre (1977;1984) Equations

Clemence and Schulze (1982) compared six commonly used temperature based equations for the estimation of potential evaporation, including the Thornthwaite and Blaney-Criddle equations, and found from lysimeter studies undertaken under diverse climatic conditions that for maize, wheat, sugarcane and soybeans, the equation proposed by Linacre (1977) proved to be superior to the others. This equation is a function of temperature, locational variables and parameters, yet it contains, according to Linacre (1977), much of the generality and universality of the Penman (1948) equation. Linacre (1977) approximated the Penman (1948) equation by "disaggregating" it and relating its components to temperature variables or replacing them with equivalent expressions or approximations involving temperature values alone. The outcome is an empirical formula, simple to use, but with a basis which is physical enough to be of general use, "with sufficient accuracy for many practical problems and unusually modest demands as regards input data" (Linacre, 1977; p. 410).

For pan equivalent evaporation ($mm.day^{-1}$) Linacre's (1977) equation gives the potential evaporation rate as

$$E_p = \frac{700\ T_m/(100-\phi) + u_1(T_a-T_d)}{(80 - Ta)}$$

where

T_m = $T_a + 0.006\ A_m$, with

T_a = mean air temperature (°C)

= $(T_{max} + T_{min})/2$

A_m = altitude (m)

ϕ = latitude (degrees) and

u_l = wind factor (with a default value of 15, regional adjustments to this wind factor being discussed in the next section)

(T_a-T_d) = difference between air and dew point temperature, approximated by = $0.0023A_m + 0.37T_a + 0.53R_m + 0.35R_{hc} - 10.9$ in °C for $(T_a-T_d) >$ 4°C

in which

R_m = the mean daily or monthly range of temperature (°C) and

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

Apart from the altitude, latitude and the regional wind function applicable to a location, all the variables in the equation are obtained from maximum and minimum temperatures. The equation has been tested with temperature and pan evaporation data from 24 widely scattered stations in Natal by Schulze (1983) and found to yield markedly more reliable simulations of A-pan values in all months of the year when compared with other temperature-based equations commonly in use, viz. Thornthwaite (1948) and Blaney and Criddle (1950).

The 1977 version of the Linacre equation was based on the assumptions that the net radiation is half the global radiation and in its original form it incorporated an average windspeed function (expressed through the factor u_l). Linacre (1984) therefore revised his equation, claiming greater accuracy for open water surfaces with the equation as follows :

$$Ep = [650\ .\ T_m/(85-\phi) - 56 + (5+4.u_{ms}).(T_a-T_d)] / (80 - T_a)$$

where

u_{ms} = average daily windspeed ($m.s^{-1}$) and defaulted in *ACRU* to 1.5 $m.s^{-1}$.

For unknown local windspeeds (in which case defaulted to 1.5 $m.s^{-1}$), the 1984 version of the Linacre equation was found to yield better simulations of A-pan equivalent evaporation than the 1977 version.

In the *ACRU* model the 1977 version of the Linacre equation, while expressed as $mm.day^{-1}$ in the equation, can be used only with mean monthly temperature data. The value of pan equivalent evaporation is thus first multiplied by the number of days in the respective month before further adjustments are made by Fourier Analysis to reconvert to a daily value taking cognizance of different lengths of months. The 1984 version can be invoked either as a direct daily estimator when daily temperature values are known, or an indirect daily estimator, via the mean monthly temperature/Fourier Analysis route.

4.4.3 The Linacre (1977) Equation Modified For Use In Southern Africa

Despite simulating daily A-pan evaporation better than other temperature-based equations, estimates by both Linacre equations were not considered to be sufficiently accurate enough for general usage in southern Africa and the need for local calibration was recognised. Such a need for local calibration has been reported by many eminent researchers and Dent, Schulze and Angus (1988) review their ideas. Thus, for example, Cuenca (1982) maintains that poor prediction may be expected from temperature based methods in certain climatic zones if regional calibration is not made and that this holds true for every commonly used method.

In a study by Dent, Schulze and Angus (1988) it was decided to adjust the equation using two variables which are meaningful physically, viz. daylength and windspeed. A daylength correction was applied to the radiation related term as indicated in the Linacre (1977) equation, that it became

$$D_l(700\ T_m)/(100 - \phi)$$

where

D_l = daylight hours/12.

This daylength correction resulted in a marked improvement in the seasonal distribution of mean daily A-pan evaporation values.

The wind factor u_l (*ACRU* variable name LINWIN), which was given a default value of 15 by Linacre (1977) and for which Schulze (1983) had already made regional and seasonal adjustments for Natal, was adjusted by Dent, Schulze and Angus (1988) for more generalised use in southern Africa. Initial adjustments were made according to the monthly mean wind velocities for each month at stations within or near the major wind regions depicted in Figure 4.4.1. These regions were delimited by considering proximity to the coast and major topographic features.

The monthly mean wind velocities for Cape Town, Durban, Kimberley, Middelburg (Cape Province), Germiston, Pretoria and Piet Retief obtained from SAWB (1965) were used initially to generate monthly values of u_l.

The monthly wind velocities in each region were then adjusted, within acceptable physical limits, until the mean and median of the residuals as well as the kurtosis of the frequency distributions of residuals in each month and for each region were considered acceptable. In most instances, the general seasonal wind patterns presented by SAWB (1965) remained largely unaltered; however, the scale of the adjustment from these

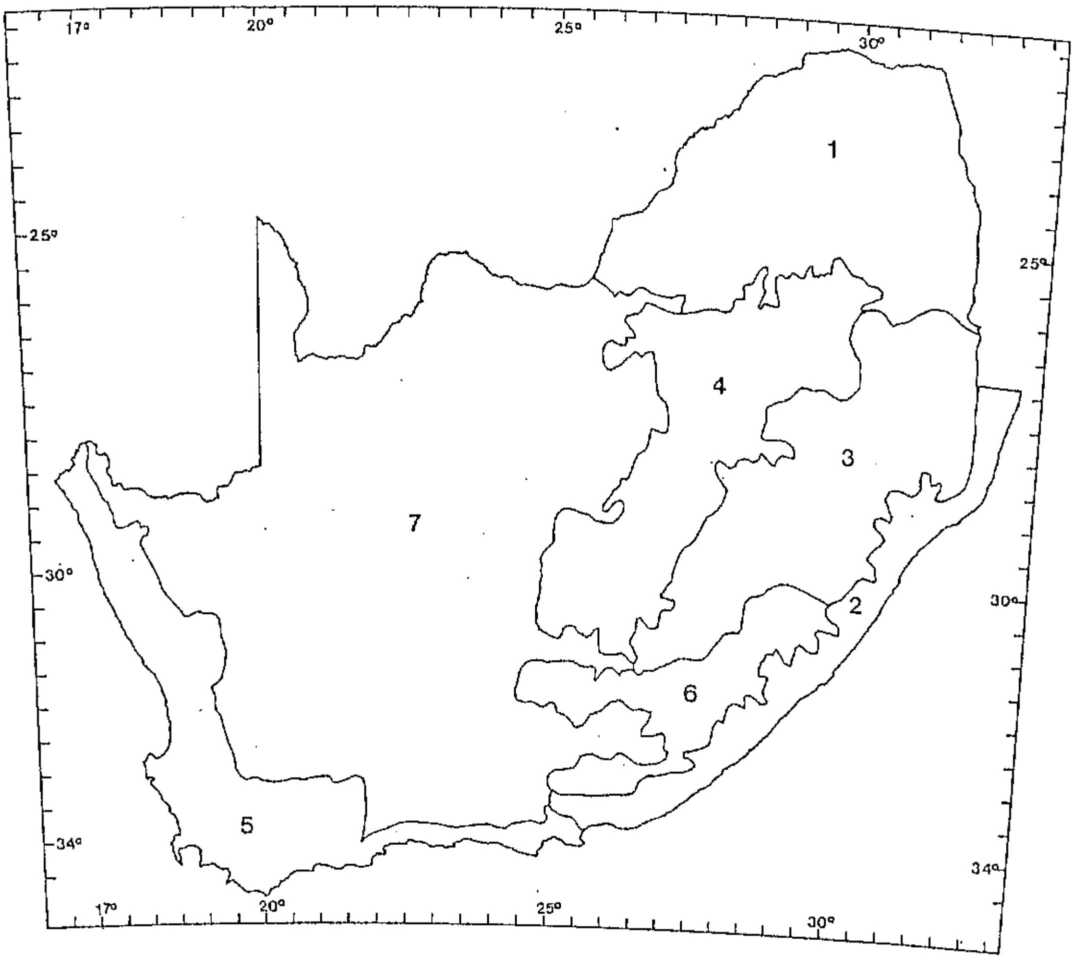

Figure 4.4.1 Delimitation of major wind regions in southern Africa (after Dent, Schulze and Angus, 1988)

Table 4.4.1 Monthly values of the Linacre (1977) wind factor, u_l for seven wind regions in southern Africa (after Dent, Schulze and Angus, 1988)

Wind Region	Wind Factors for the Wind Regions											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	10.2	9.7	9.5	9.0	8.9	8.7	9.0	11.4	13.4	13.8	12.8	10.8
2	17.0	13.7	13.1	12.4	12.2	12.1	15.0	19.4	20.8	21.1	21.0	19.2
3	10.9	9.7	9.5	9.2	8.9	8.9	10.2	11.6	14.1	14.3	13.1	11.6
4	12.4	11.2	10.5	9.7	9.7	10.2	11.2	13.5	15.6	15.7	15.3	15.0
5	27.0	26.5	21.9	20.0	18.9	18.2	17.7	19.7	22.6	25.8	27.3	27.0
6	17.3	16.0	4.3	13.4	14.6	16.8	18.2	19.0	18.9	18.5	18.5	18.8
7	16.0	14.6	14.4	13.8	13.8	14.3	14.6	16.0	18.5	20.0	20.4	17.5

patterns did vary from region to region. Table 4.4.1 gives the values of u_l which were estimated by the above procedures. In the *ACRU* model these values are in a data statement and they are invoked by the variable LINWIN, which has a value identical to that of the region in Figure 4.4.1.

The application of these wind factors resulted in the pan equivalent evaporation residuals from more than 70 per cent of the evaporation stations used in the study by Dent, Schulze and Angus (1988) to lie between $\pm$ 1 mm.day^{-1} for almost all of the 84 region months contained in the analyses.

In addition to net radiation and a wind function potential evaporation is furthermore sensitive to vapour pressure deficit. The term $(T_a - T_d)$ in the Linacre equations provides an index of vapour pressure deficit and hence any adjustment to the u_l factor should be considered an adjustment to the vapour pressure deficit as well, because the two terms are multiplicative. Hence the u_l factor is, in strict terms, a pseudo wind function adjustment.

It is recognised that the wind regions depicted in Figure 4.4.1 are rather broad and that further refinement of these boundaries and the consequent further adjustment to the wind factor, both temporally and spatially, is possible. The possibilities in this direction for future more detailed research are interesting. One of the reasons for not pursuing the investigation during the study by Dent, Schulze and Angus (1988) was the thought that some of the stations produced a poor fit because the Class A-pan evaporation data were not good or that local anomalies existed. Hence, it was deemed undesirable for finer adjustment to take place until the evaporation data had been investigated further.

4.4.4 The Thornthwaite (1948) Equation

This universally applied procedure, which has been found generally to underestimate E_p in southern Africa (Clemence and Schulze, 1982), equates

$$E_p = 16(10.T_a/A_{hi})^A.D_t \quad (\text{mm.mo}^{-1})$$

in which

T_a = monthly mean air temperature (°C),

A_{hi} = annual heat index, calculated by summing the 12 monthly mean temperatures as

$$= \sum_{i=1}^{12} (T_a/5)^{1.514}$$

A = $0.49 + 0.0179\, A_{hi} - 0.000077\, A_{hi}^2 + 0.000000675\, A_{hi}^3$

D_t = daylength correction factor to adjust for latitude and month in the Thornthwaite equation.

The 12 values of D_t are input into the *ACRU* model. Monthly values for various latitudes are given in the *ACRU* User Manual (Schulze and George, 1989).

4.4.5 The Blaney and Criddle (1950) Equation

This standard method, particularly useful with irrigation scheduling, yields fair to good estimates of potential evaporation in southern Africa (Clemence and Schulze, 1982). In this simple equation

$$E_p = (0.142T_a + 1.095)(T_a + 17.8) \ . \ D_{bc} \quad (\text{mm.mo}^{-1})$$

where

D_{bc} = daylength correction factor for the Blaney and Criddle equation to adjust for latitude and month.

Again, monthly values of D_{bc} for respective latitudes are given in the *ACRU* User Manual by Schulze and George (1989).

4.4.6 The Evaporation Pan Options

The evaporation pan input to *ACRU* may be read in as monthly values, in which case data are read in through the dynamic input file or as daily data. Three notes of caution on evaporation pan data are sounded.

* The evaporation pan may be screened. This has to be determined, and if it is screened the appropriate correction factor according to the screen's mesh size has to be applied, as outlined in the *ACRU* User Manual (Schulze and George, 1989) and illustrated in Figure 4.4.2.

* The original pan data may be from a non A-pan. This would usually be the Symon's(S) tank, which was the evaporimeter used as the original standard in southern Africa. Typical seasonal adjustments from S- to A-pan equivalents are illustrated for southern African zones in Figure 4.4.3, with the zones depicted in Figure 4.4.4.

* Daily pan evaporation data from various institutions and networks need to be checked carefully before use. Experience has shown data to contain many gaps, for which daily means from the "good" days of a respective month may be substituted, and also accumulations of pan data over two or more days, usually weekends, which would then have to be disaggregated into realistic daily values.

4.5 THE IMPORTANCE OF ACCURATE POTENTIAL EVAPORATION INPUT IN *ACRU*

In arguing the case for accurate estimation of potential evaporation in soil water budgeting models, it is often stated that E_p is a conservative climatic parameter. Dent, Schulze and Angus (1988), for example, analysed over 100 000 daily pan evaporation values in southern Africa and found that 67% of the ratios of four day means to monthly means of pan evaporation were within 20% of unity. Many authors argue that errors incurred in soil water budget studies result from poor estimates of rainfall, stormflow or drainage beneath the root zone, and not from poor E_p input and that

> "in view of this and of the appreciable uncertainties in measuring rainfall it is obviously inappropriate to strive for high accuracy in determining the amount of evaporation" (Linacre and Till, 1969 p. 180).

This hypothesis gained credibility in a study by Calder, Harding and Rosier (1983) who showed that the inclusion of sophisticated evaporation equations such as those by Priestley-Taylor, Penman or Thom-Oliver gave no improvement in the estimation of soil water deficit under dryland conditions when compared with the monthly mean evaporation or a simple sinusoidal distribution. Further, Johns and Smith (1975) tested the accuracy of size published functions for deriving potential evaporation and found that computed deficits in a soil water budget

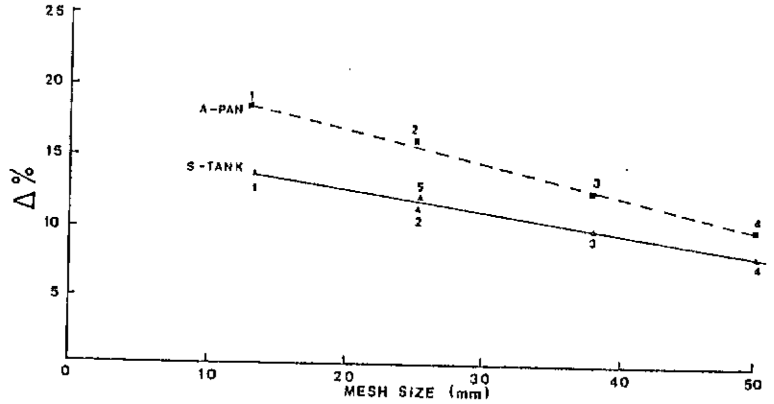

Figure 4.4.2 Pan correction (Δ%):mesh size (mm) relationship (after Bosman, 1988)

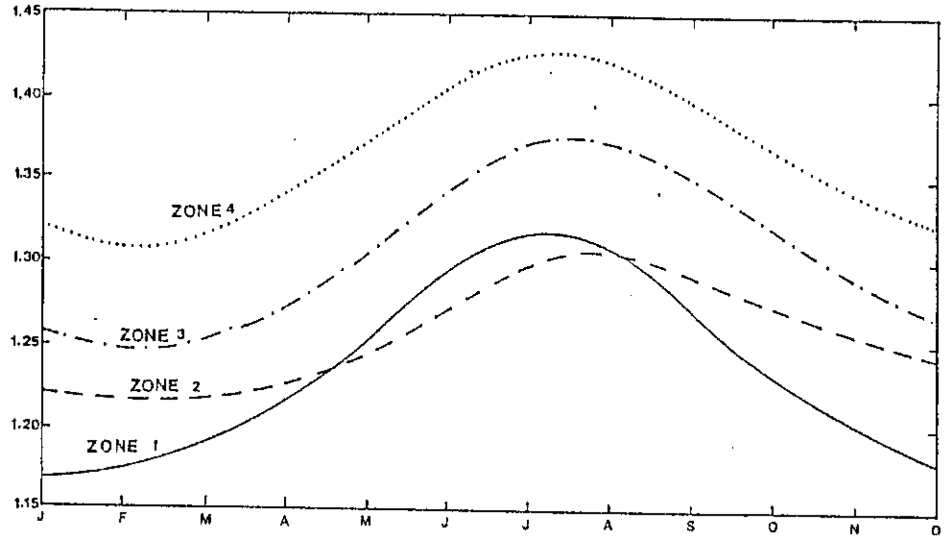

Figure 4.4.3 Smoothed mean monthly S-tank:A-pan evaporation ratios for southern Africa (after Louw, 1966)

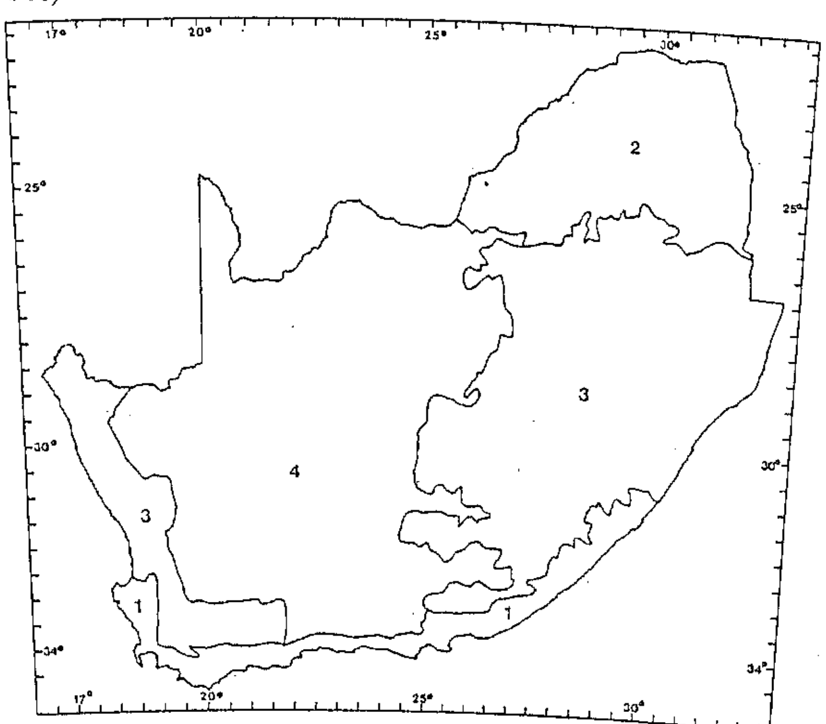

Figure 4.4.4 Zones of similar S-tank:A-pan relationships

were very similar, despite the wide range in values of the E_p functions used. They ascribed this to what they termed "strong negative feedback influences" existing in soil water systems, i.e. an over-estimation of potential evaporation (under dryland conditions) will produce an overestimation of soil water deficit on that day. However, this will result in a partially compensating decrease in estimated total evaporation from the plant-soil system for the following day, thereby reducing the total estimated soil water deficit. This partially compensating effect will also work in the reverse direction.

Contrary to the above arguments, the illustrations of Figure 4.5.1 indicate clearly, however, the necessity for accurate estimates of the daily A-pan evaporation equivalents. In comparing monthly totals of E for dryland conditions using the unmodified Linacre (1977) equation for potential evaporation in *ACRU*, to E estimated using observed daily A-pan values, it may be seen that comparisons of E output are close in semi-arid areas such as Vaalharts but differ markedly by approximately 30% for Cedara. Such differences due to systematic error in potential evaporation estimates by, for example, the Linacre (1977) approach are significant and signal the necessity to estimate E_p as accurately as possible, particularly in more humid areas, when simulating crop yields and also when simulating soil water budgets under irrigated conditions, where negative feedback mechanisms are not, as a rule, operational.

4.6 DETERMINATION OF TEMPERATURE VALUES FOR SURROGATE A-PAN ESTIMATES

Experience with the *ACRU* model shows that the number of occasions that simulations have to estimate daily potential evaporation using temperature-based methods necessitates accurate estimates of maximum, minimum and mean temperatures at points where they are not measured.

4.6.1 Sources Of Temperature Information In Southern Africa

* Daily values as well as monthly means of maximum and minimum temperatures are available for over 1200 stations throughout southern Africa from the CCWR. It should be noted that a number of the stations have short records and, because of the physiographic uniqueness at some of the stations (e.g. exposed or in deep valleys), the temperature records may appear anomalous in a regional context.

* Schulze, Maharaj and Lynch (1989) have recently completed a major study of monthly means of daily maximum and minimum temperatures for southern Africa. The subcontinent was divided into 11 temperature regions and for each region and month stepwise multiple regression equations of mean, maximum and minimum temperature were developed using altitude, latitude, longitude, distance from coast and a physiographic valley index (with cross-products) as variables. Temperature information on a month by month basis for means, maxima and minima is stored as gridded images covering southern Africa, with the temperature estimates available at 1 minute of a degree latitude/longitude resolution. This information may be obtained from the Department of Agricultural Engineering at the University of Natal, Pietermaritzburg, through the CCWR.

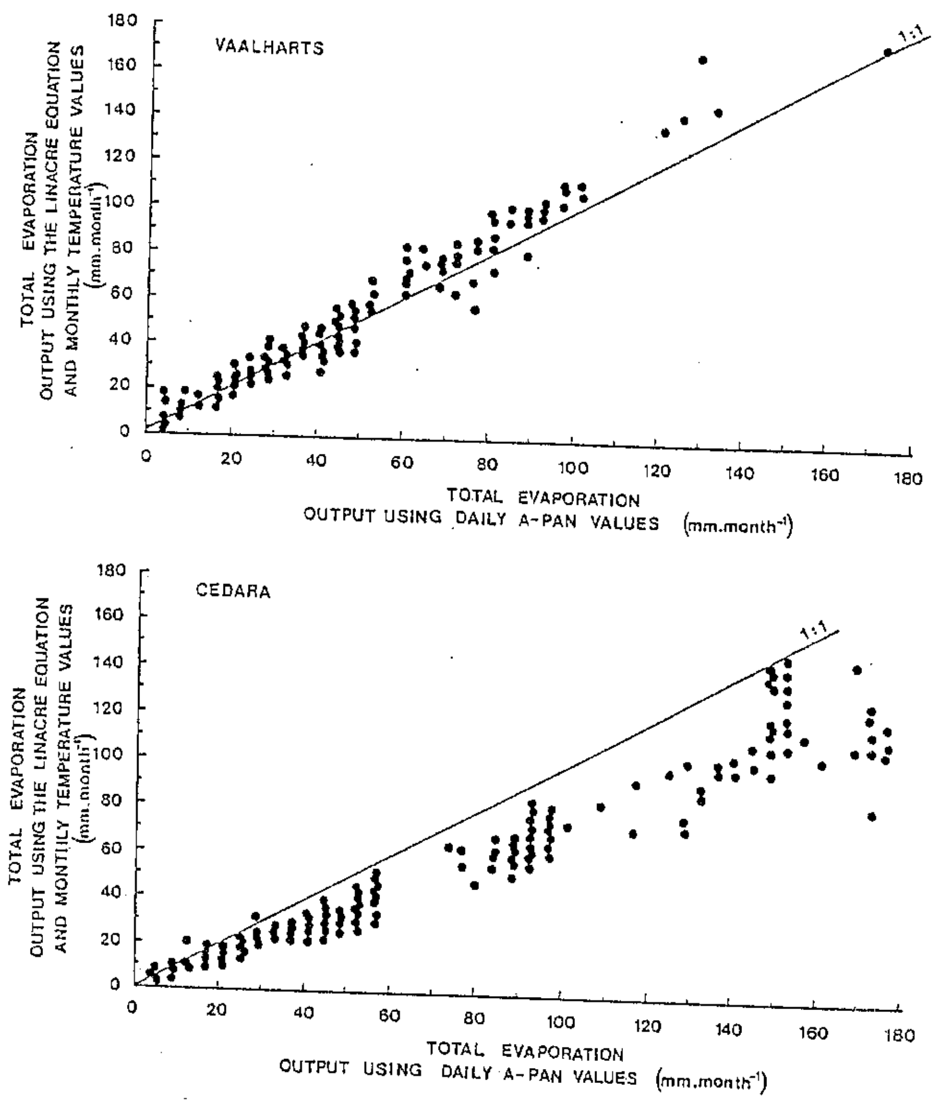

Figure 4.5.1 Monthly estimates of total evaporation, E, using the unmodified Linacre (1977) equation for potental evaporation vs monthly E summations using observed daily A-pan values at Vaalharts and Cedara (after Dent, Schulze and Angus, 1988)

4.6.2 Temperature Corrections For Altitude

The dependence of temperature on altitude is well documented, and for southern Africa has been reviewed by Schulze and Schafer (1989). Table 4.6.1 shows that in southern Africa temperature lapse rates (-°C/1000 m) vary regionally as well as intra-annually and also between maximum and minimum values (Schulze and Maharaj, 1989). The regions referred to are illustrated in Figure 4.6.1.

In order to accommodate such variable temperature : altitude relationships and to estimate a catchment's temperatures from values at a nearby station, the following equations are

Table 4.6.1 Regional lapse rates in southern Africa for monthly means of daily maximum and minimum temperatures (Schulze and Maharaj, 1989)

Lapse Rate Region	Adiabatic lapse rate for mean monthly maximum temperatures (°C.1000m^{-1})													
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean	SDEV
1	-4.90	-5.10	-4.98	-5.64	-5.59	-6.12	-5.79	-5.32	-4.39	-3.96	-4.48	-4.97	-5.10	0.63
2	-2.95	-3.26	-3.11	-3.33	-3.46	-3.19	-3.48	-2.53	-1.41	-1.82	-2.37	-2.55	-2.85	0.73
3	-3.87	-3.99	-4.42	-4.58	-5.26	-5.52	-5.59	-4.88	-4.13	-3.62	-3.83	-3.81	-4.46	0.70
4	-8.63	-8.62	-6.89	-6.20	-5.34	-4.71	-4.55	-4.37	-5.61	-6.29	-7.17	-8.10	-6.37	1.53
5	-0.07	-0.55	-0.77	-1.27	-2.52	-2.50	-2.40	0.79	0.58	0.51	0.00	-0.72	-0.74	1.21
6	-0.99	-1.25	-1.50	-4.31	-4.63	-5.27	-4.11	-3.71	-3.33	-2.74	-1.83	-1.18	-2.90	1.52
7	-1.92	-2.94	-2.90	-3.67	-4.51	-4.46	-4.20	-3.26	-2.74	-2.01	-2.34	-1.46	-3.03	1.02
8	-3.86	-4.08	-4.16	-3.70	-3.39	-3.47	-3.04	-2.25	-2.18	-1.82	-2.43	-3.11	-3.12	0.79
9	-5.82	-8.46	-7.10	-5.50	-7.26	-6.94	-7.26	-6.54	-6.14	-4.94	-5.82	-6.22	-6.50	0.96
10	0.20	2.49	2.10	-2.13	1.95	-4.31	-3.35	-1.68	-1.09	0.06	0.17	0.72	-0.41	2.16
11	3.77	0.86	0.80	-1.91	-1.27	-4.65	-3.26	-2.58	-1.07	0.90	1.17	0.53	-0.56	2.33
Lapse Rate Region	Adiabatic lapse rate for mean monthly minimum temperatures (°C.1000m^{-1})													
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean	SDEV
1	-4.68	-4.72	-4.86	-4.87	-4.55	-4.15	-4.30	-4.28	-4.22	-4.26	-4.45	-4.48	-4.48	0.25
2	-4.96	-5.19	-5.39	-5.83	-5.99	-6.18	-5.66	-5.46	-5.23	-5.30	-5.43	-5.27	-5.49	0.36
3	-4.86	-5.07	-5.24	-5.52	-5.68	-5.59	-5.48	-5.59	-5.30	-4.86	-4.99	-4.91	-5.26	0.31
4	-4.54	-4.70	-3.57	-2.14	-1.33	-1.26	-1.90	-1.57	-1.05	-2.66	-3.74	-4.74	-2.77	1.42
5	-4.11	-4.04	-3.60	-4.47	-6.15	-4.80	-4.45	-3.87	-4.05	-3.88	3.82	-3.97	-4.27	0.68
6	-2.95	-2.02	-2.62	-3.03	-3.46	-4.25	-4.11	-3.62	-3.25	-3.53	-2.74	-2.45	-3.17	0.67
7	-3.66	-3.96	-4.00	-3.96	-5.22	-4.45	-5.53	-4.71	-3.76	-3.32	-3.36	-3.07	-4.08	0.76
8	-2.27	-2.51	-2.57	-3.41	-3.31	-3.31	-3.49	-2.96	-2.01	-1.59	-1.64	-1.97	-2.59	0.70
9	-7.66	-6.56	-8.18	-8.18	-5.23	-9.18	-4.25	-6.33	-5.48	-2.16	-7.66	-7.42	-6.52	1.98
10	-6.25	-4.63	-4.90	-5.29	-3.92	-4.43	-5.58	-5.37	-5.30	-5.36	-4.94	-5.22	-5.10	0.60
11	-2.62	-1.05	-0.70	-2.75	-3.60	-4.32	-4.14	-3.41	-3.70	-3.16	-3.16	-2.29	-2.91	1.12

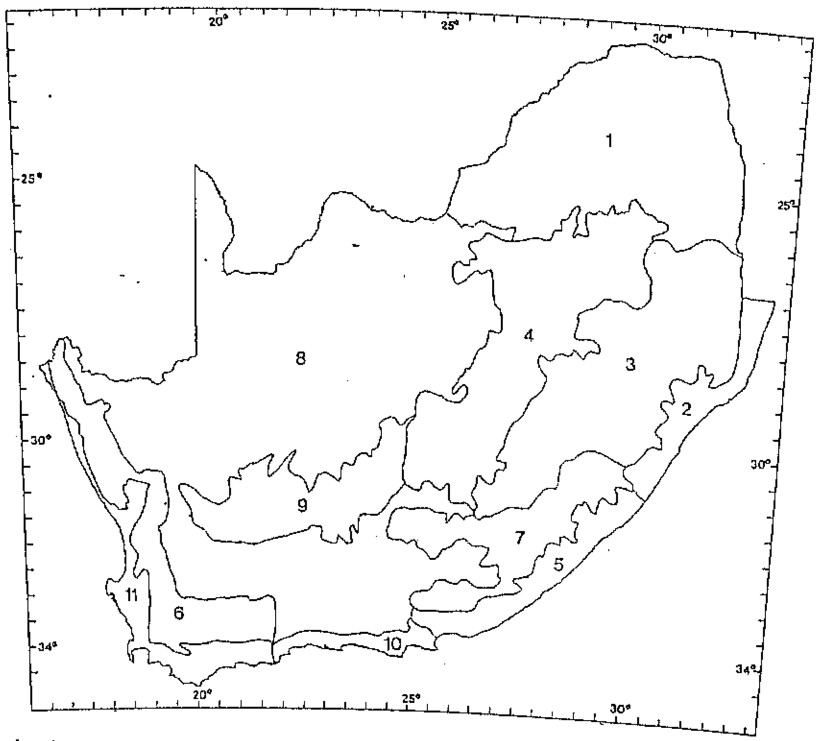

Figure 4.6.1 Delimitation of temperature lapse rate regions in southern Africa (Schulze and Maharaj, 1989)

used in *ACRU* :

$$T_{mxc} = T_{mx} + L_{mx}(A_{mc} - A_{mm})/1000$$

and

$$T_{mnc} = T_{mn} + L_{mn}(A_{mc} - A_{mm})/1000$$

in which

T_{mxc} and

T_{mnc} = monthly mean estimates of daily maximum and minimum temperatures (°C) for the mean altitude of a catchment,

T_{mxc} and

T_{mnc} = monthly means of daily maximum and minimum temperatures (°C) for a nearby control temperature station,

A_{mc} = altitude (m) of the control temperature station,

A_{mm} = mean altitude (m) of the catchment for which temperature is to be estimated from the control station,

L_{mx} = regional dry adiabatic lapse rate for maximum temperature, defaulted to -6.5°C (per 1000 m) in the absence of regional values, and

L_{mn} = regional dry adiabatic lapse rate for minimum temperature (default input -6.5°C).

4.7 CONCLUSIONS

In a total evaporation-based modelling system such as *ACRU* the need for accurate estimates of the forcing function, potential evaporation, are required. This chapter introduced the daily A-pan value as the reference E_p for use in *ACRU*. However, problems with frequent lack of A-pan data necessitate a variety of other methods for estimating A-pan equivalents to be used, and different methods and levels of sophistication are described. Since many of the A-pan surrogate estimates of E_p are temperature based, sources of temperature information are also discussed.

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CHAPTER 5

SOILS

R.E. Schulze

5.1 THE ROLE OF SOIL PROPERTIES IN HYDROLOGICAL MODELLING

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

- absorb
- retain and
- release/redistribute

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

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

Soils information relevant to hydrological modelling is, however, not always readily available at the detail required; it may have to be implied or derived from non-hydrologically based soil classifications. This chapter, after outlining which soils variables are required by the present version of *ACRU* and describing procedures/decisions to be followed in inputting soils information into the model, therefore, also focusses on the availability of directly or indirectly derived soils information, with particular reference to southern Africa.

5.2 SOILS INPUT REQUIRED FOR THE *ACRU* MODELLING SYSTEM

In regard to soils input requirements, the user is reminded that *ACRU* operates for general use (in the present version) with two "active" horizons in which rooting development and hence soil water extraction through evaporation and transpiration can take place. Amounts of soil water at three critical soil water retention constants, viz. at

- porosity, PO,
- field capacity, FC and
- permanent wilting point, WP,

have either to be known or be inferred for each of the two active soil horizons (i.e. PO1, PO2...). These soil water retention constants (with units $m.m^{-1}$ by volume) may be defined as follows :

- *Porosity*, PO, is the percentage soil volume occupied by voids, and as such contains the maximum possible soil water storage. At PO soil is therefore saturated. The matric potential at saturation is 0 kPa.

* *Field Capacity*, FC, is the soil water condition reached when water has been allowed to percolate naturally from the soil until drainage ceases and the water remaining is held by capillary forces that are great enough to resist gravity. FC is often described as being the wet limit of the soil water available freely to plants. This theoretical definition has drawbacks when applied to soils in a natural environment and FC can be described as the soil water content below which the hydraulic conductivity is sufficiently small for redistribution of moisture due to hydraulic head to be ignored. A definition in terms of matric potential is difficult owing to the fact that FC may vary with texture, but it is traditionally taken to fall somewhere between -5 and -33 kPa. In this document a value of -10 kPa is used as the matric potential representing FC.

* *Permanent Wilting Point*, WP, is taken as the dry, i.e. lower, limit of water available to plants. At the stage of permanent wilting point, WP, the hydraulic conductivity is so low that water cannot move to the roots fast enough, even over short distances, and no water is available for transpiration. As such WP is assumed to be a soil parameter which it is not strictly, as it depends also on the plant as well as on the depth of the root system at which the plant is trying to extract soil water. In this document the matric potential at WP is taken to be -1 500 kPa.

Using these definitions one can define plant available water, PAW ($m.m^{-1}$), as

$$PAW = FC - WP.$$

Amounts of soil water are, for modelling purposes, functions of, *inter alia*, soil texture and respective horizon depths. What are therefore further required are

* the texture class (of which 11 are used in *ACRU*) of the soil (variable name ITEXT),

* the depth (in m) of the topsoil horizon (designated by DEPAHO in *ACRU*) and

* the depth (in m) of the subsoil horizon (DEPBHO).

Soil water amounts in excess of WP value are available to plants for transpiration and hence growth processes. Soil water amounts in excess of FC are available for so-called "saturated" drainage, the daily rates of drainage being dependent on a response fraction of the excess water

* from the top- to the subsoil horizon, designated ABRESP in *ACRU*, and

* from the subsoil out of the active root zone, given variable name BFRESP in *ACRU*.

These response fractions depend, *inter alia*, on textural conditions. Soil water between FC and WP may be redistributed (as so-called "unsaturated" drainage) upwards or downwards, at rates depending, *inter alia*, on soil water gradients. The ensuing section of this chapter expounds on where and how these input variables are derived.

Hydrologically the concept of a multi-layered soil system is sound, as quickflow responses are considered in *ACRU* as being highly dependent on physical properties and soil water status of mainly the topsoil horizon (or part of it), while the bulk of the active soil water store and also the release of water for baseflow are dependent on properties and soil water status of the active subsoil horizon(s).

5.3 DECISIONS AND PROCEDURES IN *ACRU* REGARDING SOILS INFORMATION

ACRU having been designed as a *multi-level* model, one of the inputs where multiple pathways are available (depending on the level of sophistication of available input data) is soils information. Decisions and procedures in *ACRU* regarding soil textural and depth input is best illustrated by way of an example, illustrated in Figure 5.3.1. The first soils related decision to be taken is on the so-called "adequacy" or "inadequacy" of available soils information.

5.3.1 Decisions And Procedures In *ACRU* With Inadequate Soil Texture And Depth Information

If soils information is sketchy or considered "inadequate", only three items will be requested of the user by the *ACRU* Menubuilder (Figure 5.3.1, left hand option).

* The first is the *number of different soil texture classes* identified within the catchment (or subcatchment if *ACRU* is run in distributed mode). Zones of identical texture class within the catchment need not be contiguous, and should be grouped together, as only the number of *different* classes, and not the total number of zones is required.

* Secondly, for each of the number of classes present, the *texture class* is designated and the *percentage* of the catchment's area that class covers, is given (NB. Percentages must add up to 100%!). For each of the 11 major soil texture classes *ACRU* contains preprogrammed default (i.e. typical) values for the soil water retention constants used in the model, viz. WP, FC and PO.

These constants and the percentages covered are then used in a Decision Support System of the Menubuilder to prepare an area-weighted set of soil water retention values for the soils of that catchment. The default soil water retention constants are given in Table 5.3.1. For example, in Figure 5.3.1 the catchment would contain

Clay : 38%, i.e. texture class no. 1
Sandy loam : 52%, i.e. texture class no. 5
Loam : 10%, i.e. texture class no. 2.

It should be noted that when the "inadequate" soil information option is invoked, no distinction is made between soil water retention values at PO, FC and WP of the top- and subsoil horizons.

* The third requirement relates to the *number of different soil depth classes* found in the (sub) catchment, whereupon each *depth class* present has to be designated together with the percentage of the catchment's area it covers. Thus, for example, in Figure 5.3.1, two depth classes were identified, viz.

Depth class 1 : i.e. very deep soils, 90%
5 : i.e very shallow soils, 10%.

These default depth classes refer to the top-and subsoil horizon depths, and the values preprogrammed into *ACRU* are given in Table 5.3.2.

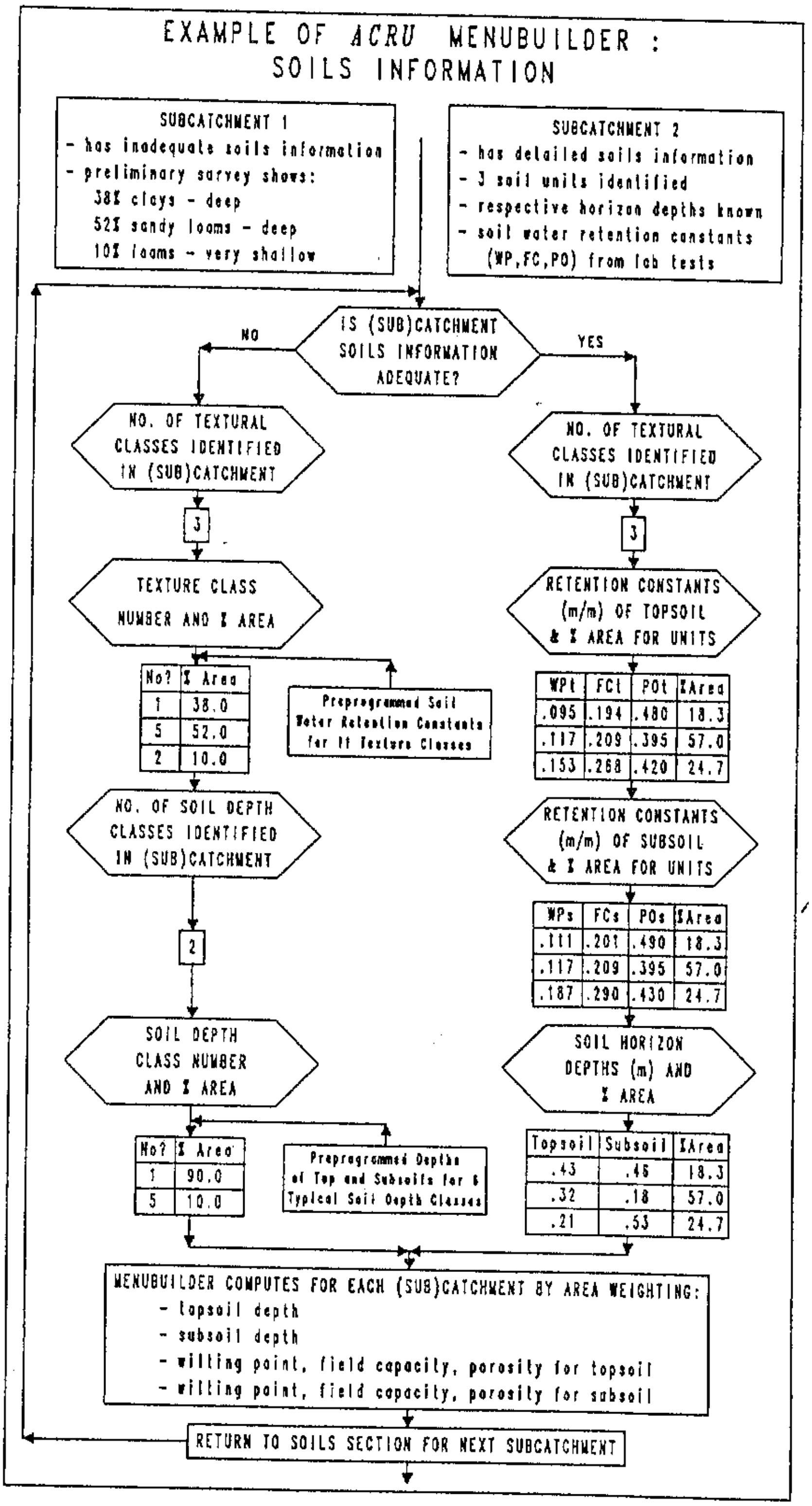


Figure 5.3.1 Decisions and procedures in *ACRU* regarding soils input

Table 5.3.1 Default soil water retention constants preprogrammed in *ACRU*

Texture Class Number	Texture Class	WP ($m.m^{-1}$)	FC ($m.m^{-1}$)	PO ($m.m^{-1}$)
1	Clay	.298	.416	.482
2	Loam	.128	.251	.464
3	Sand	.050	.112	.430
4	Loamy sand	.068	.143	.432
5	Sandy loam	.093	.189	.448
6	Silty loam	.121	.272	.495
7	Sandy clay loam	.159	.254	.402
8	Clay loam	.195	.312	.468
9	Silty clay loam	.190	.335	.473
10	Sandy clay	.228	.323	.423
11	Silty clay	.253	.390	.480

Table 5.3.2 Default soil depth values preprogrammed in *ACRU*

Soil Depth Number	Soil Depth Class	Depth (m) of Horizon	
		Topsoil	Subsoil
1	Very deep	0.30	0.80
2	Deep	0.25	0.50
3	Moderately shallow	0.20	0.20
4	Shallow	0.15	0.15
5	Very shallow	0.10	0.10
6	Impervious (e.g. rock)	0.02	0.02

5.3.2 Decisions And Procedures In *ACRU* With Adequate Soil Texture And Depth Information

The term "adequate" is a relative one when referring to soils information. In the context of the structure of *ACRU* it implies that for both the upper and lower horizons respective soil depth and values of retention constants need to be known. An example is provided by the right hand option in Figure 5.3.1. Effects of gradual or abrupt textural change with a soil profile can thus be accounted for. The various methods of deriving "adequate" input for *ACRU* from soil maps and published pedological information is described in the next major section.

5.3.3 Area-Weighting The Soil Texture And Depth Information

Once the Menubuilder has been provided with its requested input, internal computations are performed for either "inadequate" or "adequate" information to give, from each of the subcatchments within the catchment, area-weighted values of

* topsoil depth
* subsoil depth
* WP, FC, PO for the topsoil and
* WP, FC, PO for the subsoil

which are used in subsequent water budget computations.

5.4 SOURCES OF SOILS INFORMATION IN SOUTHERN AFRICA FOR USE IN *ACRU*

In order for *ACRU* to simulate the major agrohydrological processes occurring within the soil profile, accurate estimates of the soil water retention constants PO, FC and WP, particularly the latter two, are required. This section provides the background and methods to these estimates. Since much of the hydrological soils information in southern Africa derives from the current "official" soil classification, this is first described briefly but from a hydrological perspective.

5.4.1 The Southern African Binomial System Of Soil Classification Into Forms and Series

Soil, as the medium in which hydrological processes occur, has a heterogeneous character by virtue of its horizonation, which controls rates of water redistribution, both vertically and laterally. Horizons formed under given genetic conditions tend to be reproduced over and over again, with their organization resulting in generalized master horizons (MacVicar *et al.*, 1977). This concept is illustrated in Figure 5.4.1.

The specific properties of master horizons led to the recognition in the southern African binomial system of soil classification (MacVicar *et al.*, 1977) of diagnostic horizons (Figure 5.4.2). In the diagnostic horizon concept a grouping of pedological features is recognised. For example, organic carbon content, colour, structure, thickness or expansive properties distinguish the five diagnostic topsoil horizons. On the other hand, eluviation, gleying, colour variegations, concretions, redistribution of clay materials, differential weathering, podzolisation or lack of development are used to categorize the 15 subsoil diagnostic horizons recognized in southern Africa (MacVicar *et al.*, 1977).

The grouping of specific kinds and sequences of diagnostic horizons has resulted in the concept of the soil form, of which 41 have been described to date. These soil forms have been further subdivided into 501 soil series (MacVicar *et al.*, 1977), thus giving a two-level naming of the soil into form and series; hence the *binomial* classification. Criteria used to distinguish series within forms include soil texture (clay content, sand grading), base status in terms of leaching, calcareousness, soil reaction (pH), surface physical properties, colour of the B horizon, consistence of the B horizon, surface wetness and topography. An example of the binomial system with selected *ACRU*-related information is given in Table 5.4.1.

At series level no depth limits of the various horizons are set. Depth of horizons, or the slope or topographic position of the series and other local properties, which are most important to hydrological response, cannot be generalized but must be determined *in situ* and added as a further descriptor of the soil series, namely, the soil phase. Figure 5.4.3 illustrates the above concepts.

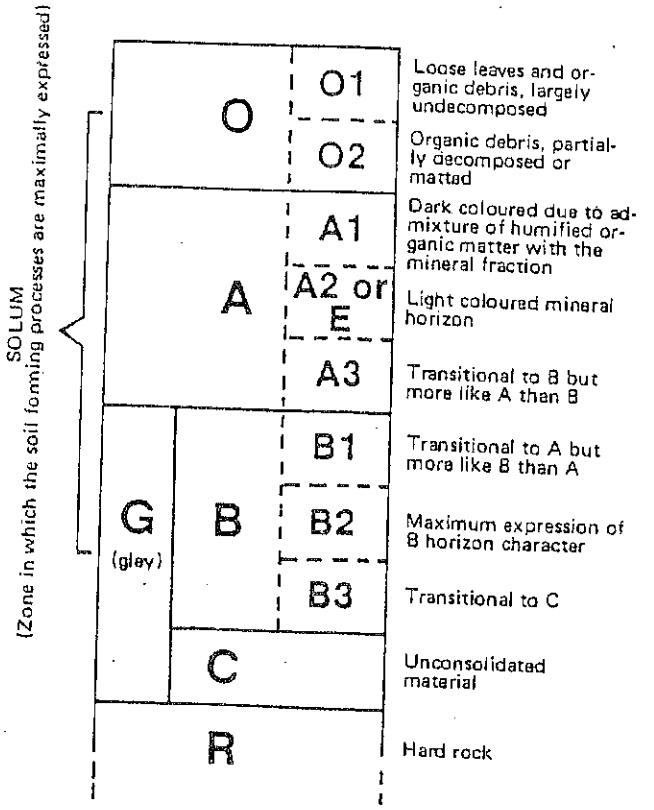


Figure 5.4.1 The arrangement of master horizons (MacVicar *et al.*, 1977)

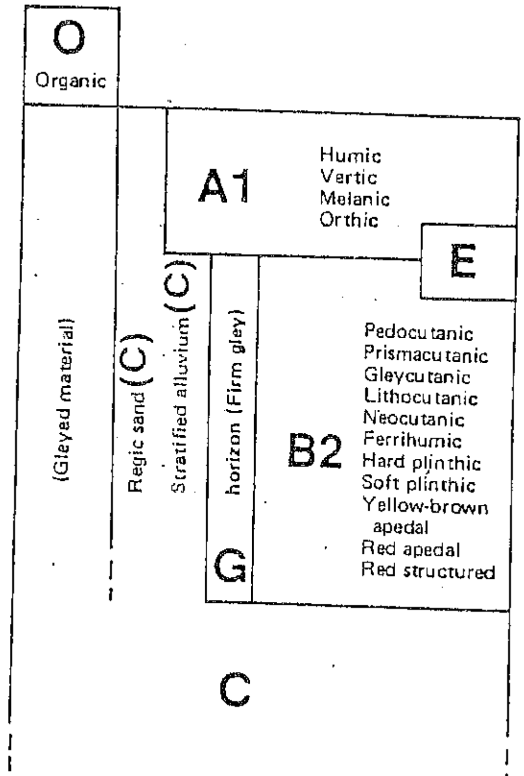


Figure 5.4.2 Diagnostic horizons (MacVicar *et al.*, 1977)

Hydrologically, the division of soils into diagnostic horizons, with their attendant properties and subdivisions, is important. This is so because they constitute the vital heterogeneous soil stores within, between and along which important hydrological processes can take place (arrows in Figure 5.4.3).

5.4.2 Estimation Of Wilting Point And Field Capacity When Soil Form And Series Information Is Available

In southern Africa soil classification in the field is by soil form and series, or by groupings/ associations of form and series. This subsection outlines the background to estimating WP and FC from form and series.

Percentage clay and hence its distribution within a soil profile is a major determinand in estimating soil water retention constants. Schulze, Hutson and Cass (1985) identified five clay distribution models for southern Africa. From Figure 5.4.4 it may be gleaned that clay distribution

* Model 1 displays an increase in percentage of a clay down the soil profile (e.g. Avalon, Shortlands forms),

* Model 2 has clay content remaining constant with depth (e.g. Dundee, Mispah forms),

* Model 3 shows an abrupt and increasing clay content transition, which can occur in three degrees of abruptness (e.g. Estcourt, Sterkspruit forms),

* Model 4 reveals an indented clay content distribution with depth, and

* Model 5 represents the mirror image of Model 3 (e.g. Nomanci, Glenrosa forms).

Details of soil genesis and other characteristics of these clay distribution models are provided by Schulze *et al.* (1985).

These models refer only to the distribution, with depth, of clay, and not to the percentage of clay present in the soil. To each clay distribution model Standard Binomial System *classes* of clay content of the B2 horizon (Figure 5.4.2) were therefore assigned, such that typically (i.e. except for Model 3, see Schulze *et al.*, 1985) clay class

* a = 0- 6% clay
* b = 6-15% clay
* c = 15-35% clay
* d = 35-55% clay
* e = >55% clay

Each of the 501 soil series of the 41 soil forms found in southern Africa was then classified by clay distribution model/class as outlined above (e.g. clay distribution model/class 1e or 5a, etc.). This is illustrated by way of the examples given in Table 5.4.1. The complete table with relevant hydrological information for all 501 soils series appears in the *ACRU* User Manual (Schulze and George, 1989).

By assigning clay percentages to topsoil and subsoil horizons using certain criteria and assumptions (which are detailed by Schulze *et al.*, 1985) for each clay distribution model/class and utilising equations developed by Hutson (1984) and Schulze *et al.* (1985), estimates of soil

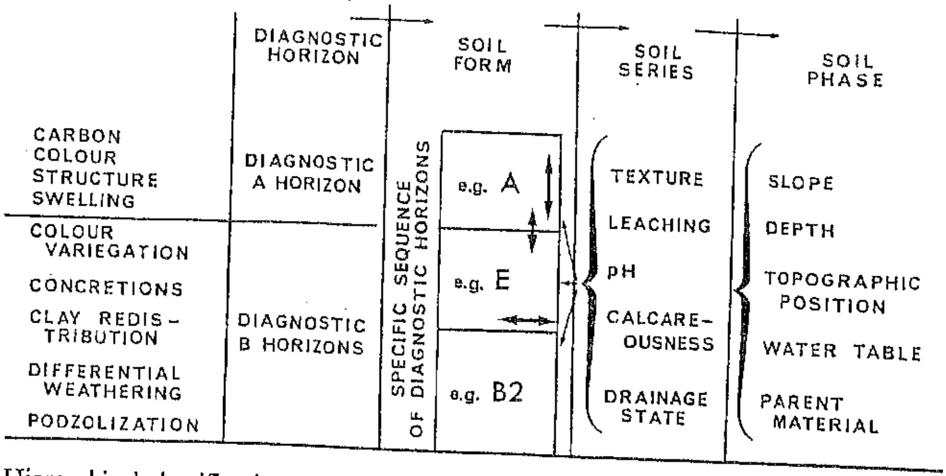


Figure 5.4.3 Hierarchical classification of soils for hydrological application in southern Africa (Schulze, 1984)

Table 5.4.1 Example of hydrological classification of soils for use with *ACRU*

Soil Form	Code	Soil Series	Clay Distribution Model/Class	Typical Textural Class	SCS Interflow Potential	Soil Grouping
KROON-STAD	Kd 14	Mkambati	3e	SLm/SClLm	XX	C/D
	Kd 10	Rocklands	3b	LmS/SLm	XX	C/D
	Kd 15	Slangkop	3e	LmS/SClLm	XX	C/D
	Kd 12	Swellengift	3b	S/SLm	XX	C
	Kd 18	Uitspan	3h	SClLm/SCl	XX	C/D
	Kd 21	Umtentweni	3c	LmS/SClLm	XX	C/D
	Kd 11	Velddrif	3b	LmS/SLm	XX	C/D
	Kd 19	Volksrust	3k	SCl/CL	XX	D
LAMOTTE	Lt 10	Alsace	2a	LmS	X	A/B
	Lt 21	Burgundy	2a	LmS	XX	B
	Lt 14	Chamond	2b	SLm	X	A/B
	Lt 22	Franschhoek	2a	LmS	XX	B
	Lt 25	Hooghalen	2b	SLm	XX	B
	Lt 12	Lamotte	2a	LmS	X	A/B
	Lt 11	Laparis	2a	LmS	X	A/B
LONG-LANDS	Lo 30	Tayside	1a	S	XX	C
	Lo 31	Vaalsand	1b	SLm	XX	C
	Lo 20	Vasi	1a	LmS	XX	C
	Lo 11	Waaisand	1b	SLm	XX	C
	Lo 12	Waldene	1c	SClLm	XX	C/D
	Lo 13	Winterton	1d	SCl	XX	C
MAGWA	Ma 12	Frazer	1e	Cl	O	A/B
	Ma 11	Magwa	1d	SCl	O	A/B
	Ma 10	Milford	1c	SClLm	O	A
MAYO	My 10	Mayo	5c	SClLm	O/X	C
	My 11	Msinsini	5d	SCl	O/X	C/D
	My 21	Pafuri	5d	SCl	O/X	C/D
	My 20	Tshipise	5c	SCl	O/X	C

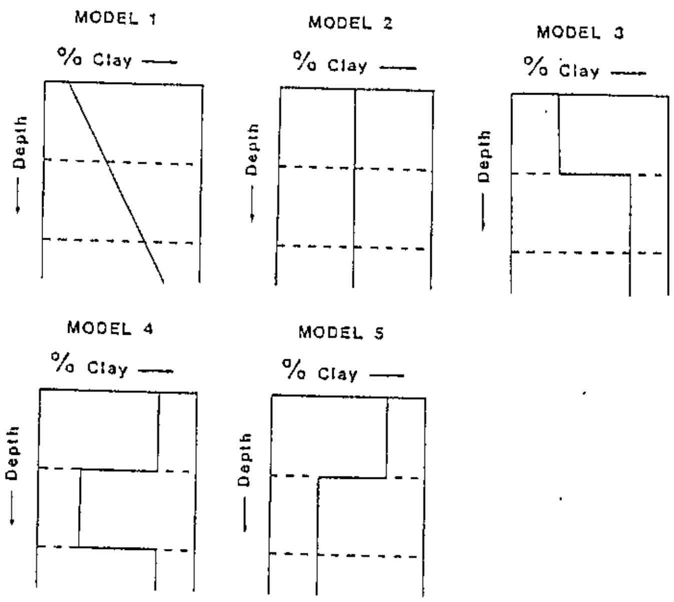


Figure 5.4.4 Clay distribution models for southern Africa (Schulze, Hutson and Cass, 1985)

Table 5.4.2 Estimates of soil water content (Θ) at WP and FC by clay distribution model and class (after Schulze *et al.*, 1985)

Clay Distribution Model/Class	Θ at Wilting Point, WP ($m.m^{-1}$)		Θ at Field Capacity, FC($m.m^{-1}$)	
	Topsoil WP1	Subsoil WP2	Topsoil FC1	Subsoil FC2
1a	.064	.065	.158	.171
b	.083	.091	.180	.201
c	.112(.127)	.158(.211)	.213	.277
d	.173(.226)	.226(.320)	.282	.354
e	.231(.320)	.265(.383)	.348	.398
2a	.067	.062	.162	.168
b	.089	.084	.187	.193
c	.138(.169)	.133(.169)	.242	.248
d	.202(.273)	.197(.273)	.315	.321
e	.250(.352)	.245(.352)	.370	.376
3a	.067	.084	.162	.193
b	.067(.054)	.110(.132)	.162	.222
c	.067(.054)	.142(.185)	.162	.259
e	.089(.091)	.133(.169)	.187	.248
h	.138(.169)	.181(.247)	.242	.303
k	.202(.273)	.245(.352)	.315	.376
5a	.067	.057	.162	.156
b	.089	.068	.187	.175
c	.138	.092	.242	.202
d	.202	.124	.315	.239

( ) Bracketed values refer to unstable soils. Distribution model 4 is not found in southern Africa water content (Θ) at FC and WP were made for each clay distribution model/class. Table 5.4.2 summarises this information.

When deriving FC and WP for *ACRU* by this method the following steps are therefore involved:

* From fieldwork or soil maps, determine soil form and series.

* Obtain the clay distribution model and class for the soil form/series from the table in the *ACRU* User Manual.

* Read off Θ at WP and FC values ($m.m^{-1}$) for topsoil and subsoil horizons from Table 5.4.2 (also given in the *ACRU* User Manual).

* Where unstable soils are encountered (i.e. soils with vertic, prisma-, pedo- and gleycutanic horizons, as in Figure 5.4.2) the bracketed values in Table 5.4.2 are used.

5.4.3 Texture Classes Of Southern African Soil Series

Generalised values of retention constants are frequently given for soil texture classes and the "inadequate" soils information option in *ACRU* makes use of this premise (Section 5.3.1). Since a silt content around 10% may be assumed for most of southern African soils (Hutson, 1984), and since the binomial system of soil classification groups soil series by classes of clay content, each soil series may be grouped, in general terms, into a texture class, if the middle value of the clay class is assumed to be representative. By this approach the 501 soil series identified in southern Africa were placed in texture classes, using the South African texture triangle given in MacVicar *et al.* (1977), on the following basis:

Series in the 0-6% clay class : loamy sands, except those with coarse sand fraction designated sands, then

6-15% clay class	:	sandy loams
15-35% clay class	:	sandy clay loams
35-55% clay class	:	sandy clays
>55% clay class	:	clays

The texture classes of the 501 soil series are listed in the *ACRU* User Manual (Schulze and George, 1989) and selected examples are given in Table 5.4.1.

5.4.4 Estimation Of Wilting Point And Field Capacity When Laboratory Analysis Of Soil Is Available

Particle size analysis in a laboratory divides the soil fraction into

* per cent clay, Cl (<2μm diameter)
* per cent silt, Si (2-20μm diameter)
* per cent sand, S (>20μm diameter)

while further analysis may give

* per cent organic carbon, C
* division of the sand fraction into coarse, medium and fine classes and
* bulk density, ρ_b ($Mg.m^{-3}$).

Research by Hutson (1984) from a large southern African data base provides the user of *ACRU* with the following equations for estimating Θ at WP and FC from laboratory analysis of soils :

(a) For stable soils :

$$\Theta_{WP} = 0.0602 + 0.00322 \text{ Cl} + 0.00308 \text{ Si} - 0.0260 \rho_b$$

$$\Theta_{FC} = 0.0558 + 0.00365 \text{ Cl} + 0.00554 \text{ Si} + 0.0303 \rho_b$$

(b) For unstable soils, water retention at WP (only) changes

* for vertic soils :

$$\Theta_{WP} = 0.0293 + 0.00606 \text{ Cl} + 0.00285 \text{ Si} + 0.0384 \text{ C}$$

* for prisma-, pedo- and gleycutanic soils

$$\Theta_{WP} = 0.01616 + 0.0052 \text{ Cl} + 0.00222 \text{ Si}$$

Further details on these regression equations are in Schulze *et al.* (1985).

5.4.5 Estimation Of Wilting Point And Field Capacity When Only Clay Percentage Is Available

If any single one of the soil fractions from laboratory analysis were the only one known, it would be the clay percentage of a soil. Since clay content is also the primary characteristic used in the binomial soil classification (MacVicar *et al.*, 1977) a number of regression equations for the estimation of soil water retention constants have thus been developed based on percentage of clay only. Schulze *et al.* (1985), following intensive laboratory analysis by Hutson (1984), made a number of quantitatively based simplifications on silt percentage, bulk density and organic carbon characteristics, and expressed the equations given in Section 5.4.4 to the following, based only on clay as the dependent variable :

(a) For stable topsoils :

$$\Theta_{WP} = 0.0572 + 0.00322 \text{ Cl}$$

$$\Theta_{FC} = 0.1506 + 0.00365 \text{ Cl}$$

(b) For stable subsoils :

$$\Theta_{WP} = 0.0520 + 0.00322 \text{ Cl}$$

$$\Theta_{FC} = 0.1567 + 0.00365 \text{ Cl}$$

(c) For unstable soils water retention at WP (only) changes

* for vertic soils

$$\Theta_{WP} = 0.1077 + 0.00606 \text{ Cl}$$

* for prisma-, pedo- and gleycutanic soils

$$\Theta_{WP} = 0.0384 + 0.00522 \text{ Cl}$$

5.4.6 Estimation Of Porosity Values

Soil water content at so-called "porosity", i.e. at saturation (PO) is highly variable within a given soil texture class (Hutson, 1984). The southern African data base on PO values is, furthermore, not extensive (Hutson, 1984). For this reason literature derived values of PO by texture class are suggested for use in *ACRU*. These have already been tabulated in Table 5.3.1. By implication, no distinction is made in this version of *ACRU* between the soil water content of topsoils and subsoils at PO, i.e. PO1 = PO2.

5.4.7 On The Application Of "Land Type" Information In *ACRU*

In South Africa the Soil and Irrigation Research Institute (SIRI) of the Department of Agriculture and Water Supply, in endeavouring to inventorise natural factors that determine agricultural potential systematically, initiated the *Land Type* surveys (SIRI, 1987) with the aims of

* delineating relatively uniform terrain form/soil pattern/climate areas, known as Land Types, at 1:2500 000 scale (NB. with fieldwork at 1:50 000)

* defining each Land Type and

* analysing, in-depth, soil profiles within Land Types.

Results of this survey, which eventually will cover all of South Africa, are published as analyses for different regions and are completed as

* a memoir containing tabulated Land Type information, accompanied by

* a Land Type map (with explanations).

An example of part of a Land Type map is illustrated in Figure 5.4.5.

The tabulation for each mapped Land Type contains information, *inter alia*, on

* climate parameters (rainfall, evaporation, temperature, frost)

* area, slope, slope length, slope form and mechanical limitations of the crests, scarps, midslopes, footslopes and valley floors which are present

* soil forms/series and land classes present, including soil depth, their positions in the landscape and their proportions they occupy.

A page of typical tabulated Land Type information is illustrated in Table 5.4.3.

While not intended as a hydrological data inventory, the Land Type series nevertheless has tremendous potential for hydrological decision making through models such as *ACRU*.

What remains to be done by the user of *ACRU* is to be able to "translate" this information to *ACRU* required and compatible input. In doing so, the following steps are followed (use Tables 5.4.3 and 5.4.4 as a guide)

* With reference to the percentages given in the "total" column, all groups of soil series (including rocks) covering more than 5% of the Land Type are identified (Table 5.4.3) and listed (Table 5.4.4). Soil series <5% of the area are lumped and their most typical characteristics used in the next steps.

* Also listed are typical texture class and the percentage area covered by each series, or groups of series (Table 5.4.4 columns 2,3).

* From tables and suggested input values described in this chapter and given in the *ACRU* User Manual, clay distribution model and class, PO, FC for top- and subsoil, WP for top- and subsoil and saturated response fractions ABRESP and BFRESP (Section 5.5 of this Chapter) are assigned to each series. In entering values for BFRESP,, cognizance must be taken of the information given under the last column of the Land Type table, viz. "Depth limiting material" (Table 5.4.3).

* A median total depth for each series may be inferred from the soil profile's "depth" column. This is then split into a topsoil and subsoil depth, a topsoil depth of 0.3 m being

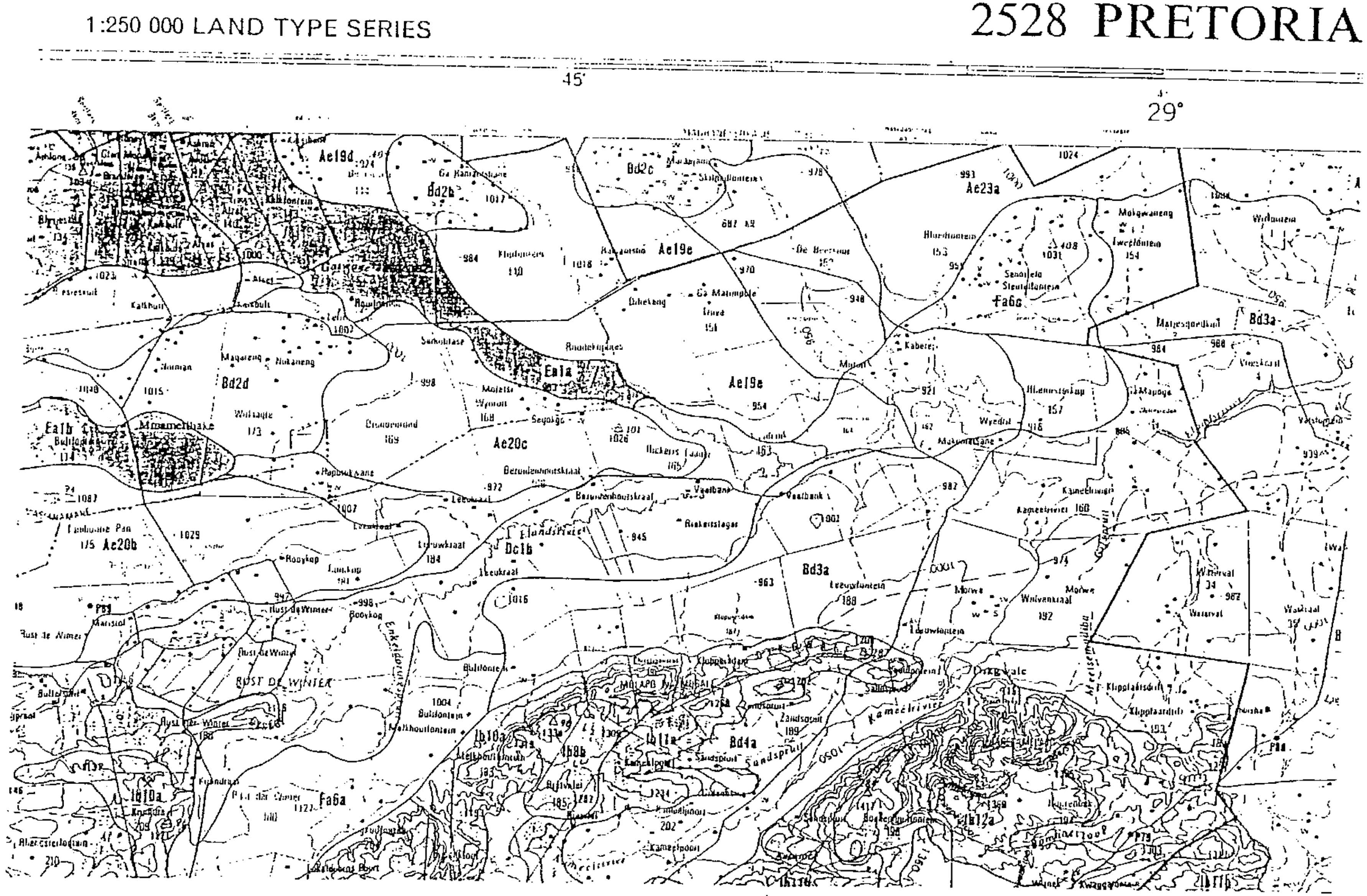


Figure 5.4.5 An example of part of a Land Type map (after SIRI, 1987)

Table 5.4.3 An example of tabulated Land Type information (SIRI, 1987)

LANDTIPE/LAND TYPE : Ae23
KLIMAATSONE/CLIMATE ZONE : 585S
Oppervlakte/Area : 17320ha
Beraamde oppervlakte onbeskikbaar vir landbou
Estimated area unavailable for agriculture : 100ha

Voorkoms(kaarte) en oppervlaktes/Occurrence (maps) and areas:
2528 Pretoria(8100ha) 2428 Nylstroom(9220ha)

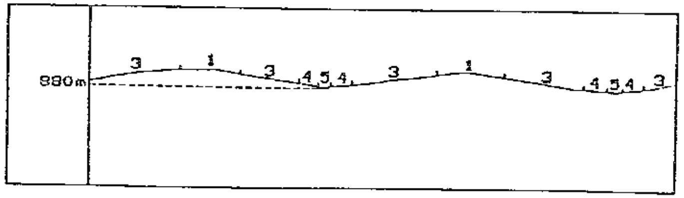
Inventaris deur/Inventory by : J L Schoeman
Modale profiele/Modal profiles P1380

Terreineenheid/Terrain unit		1		3		4		5	
% van landtipe/% of land type	:	30		50		15		5	
Oppervlakte/Area(ha)	:	5196		8660		2598		866	
Helling/Slope (%)	:	0-2		1-3		0-1		0-1	
Hellingslengte/Slope length (m)	:	500-1000		600-2000		100-300		30-200	
Hellingsvorm/Slope shape	:	Y		Y		X		X	
M00,MB1 (ha)	:	3637		6495		1949		867	
MB2-MB4 (ha)	:	1559		2165		650		0	

Totaal/Total: S>12% 0; S<12% 12946; 4374

Grondseries of landklasse / Soil series or land classes	Diepte / Depth (mm)	MB	1: %	1: ha	3: %	3: ha	4: %	4: ha	5: %	5: ha	Totaal/Total: ha	Totaal/Total: %	Klei-inhoud / Clay content (%): A	E	B21	Hor	Tekstuur / Texture: Klas / Class	Diepte-beperkende materiaal / Depth limiting material
Rots/Rock		4	5	260	5	433	5	130			823	4.7						
Shorrocks Hu36	450-1200+	0	40	2078	40	3464	30	779			6322	36.5	12-25		15-30	B	fi/coSaLm-SaClLm	so;ka;R
Portsmouth Hu35, Mangano Hu33	600-1200+	0	30	1559	20	1732					3291	19.0	10-15		10-15	B	Lmfi/coSa-SaLm	so;R
Mispah Ms10, Klipfontein Ms11, Trevanian Os17	200- 350	3	25	1299	20	1732	20	520			3551	20.5	10-20			A	Lmfi/coSa-SaLm	R;hp;lc
Lindley Va41, Swartland Sw31	200- 400	0			10	866	15	390	30	260	1516	8.8	15-30		35-50	B	meSaCl,ClLm,Cl	vp
Jozini Oa36, Leeufontein Oa16	> 900	0			5	433	15	390	30	260	1083	6.3	20-30		20-35	B	fi/meSaClLm	R;ka
Sibasa We13	300- 450	0					15	390	10	87	476	2.8	15-20		35-45	A	me/coSaLm	sp
Weenen Bo40, Bonheim Bo41	> 900	0							30	260	260	1.5	30-45		30-45	A	meSaClLm-SaCl	so

Terreintipe/Terrain type : A2
Terreinvormskets/Terrain form sketch



Ter verduideliking van hierdie tabel kyk LANDTIPE-INVENTARIS (inhoudsopgawe)
For an explanation of this table, consult LAND TYPE INVENTORY (table of contents)

Geologie: Skalie, grintsteen en sandsteen van die Groep Ecca; sliksteen, sandsteen en skalie van die Formasie Irrigasie, Opeenvolging Karoo; Nebograniet (Suite Lebowa).

Geology: Shale, grit and sandstone of the Ecca Group; siltstone, sandstone and shale of the Irrigasie Formation, Karoo Sequence; Nebo granite (Lebowa Suite).

Table 5.4.4 Translation of Land Type information into *ACRU* compatible input : An example (Ae23, Land Type map 2528 Pretoria)

Soil Series	Texture Class	Area %	Clay Model	Porosity	Soil Water Retention Constants (m.m^{-1}) Field Capacity Topsoil	Field Capacity Subsoil	Wilting Point Topsoil	Wilting Point Subsoil	Depth (m) Topsoil	Depth (m) Subsoil	Saturated Response Top- to Subsoil	Saturated Response Subsoil to Groundwater
				PO	FC1	FC2	WP1	WP2	DEPAHO	DEPBHO	ABRESP	BFRESP
Hu36	SClLm	36.4	1c	402	213	277	64	65	0.300	0.525	0.50	0.40
Hu35,Hu33	SLm	19.0	1b	448	180	201	83	91	0.300	0.600	0.65	0.55
Ms10,Ms11,Gs17	SClLm	20.5	2c	402	242	248	138	133	0.100	0.125	0.50	0.10
Va42,Sw31	SCl	8.8	1d	423	282	354	173	266	0.100	0.200	0.40	0.30
Oa36,Oa16	SClLm	6.3	1c	402	213	277	64	65	0.300	0.750	0.50	0.40
We13	SCl	2.8	1d	423	282	354	173	226	0.150	0.225	0.40	0.30
Bo40,Bo41	SClLm	1.5	2c	402	242	248	138	133	0.300	0.750	0.50	0.50
Rock	SClLm	4.7	-	402	254	254	159	159	0.050	0.050	0.50	0.10
Area-weighted input				413	223	264	101	108	0.225	0.415	0.52	0.43

suggested for all profile median depths >0.6 m. Where total depth is given as >1.2 m, use 1.2 m. For rocks the respective horizon depths may be taken as 0.05 m.

* The soils variables required as input into *ACRU* are then area-weighted (Table 5.4.4).

* Should a catchment or point at which simulation is undertaken fall distinctly into a particular terrain type (e.g. midslope or valley floor, etc.), the procedures described in the previous five steps above are followed using information in the column for that particular terrain type and not for the "total" column.

* If a catchment is comprised of a number of Land Types, the procedures above are repeated, and a final area-weighting by percentage areas of Land Types present is undertaken.

A computer program is available from the Department of Agricultural Engineering whereby only the soil series codes (e.g. Hu26 for Hutton Msinga) and their percentage areas are entered from the Land Type tables and all the *ACRU* input plus area-weighting is computed automatically for the catchment. This program is available on request from the Department.

5.5 SOIL WATER REDISTRIBUTION

Soil water redistribution in *ACRU* takes place both under so-called saturated and unsaturated conditions.

5.5.1 Saturated Soil Water Redistribution

"Saturated" soil water redistribution takes place

* from the top- to the subsoil horizon when the topsoil horizon's soil water content exceeds FC, the daily redistribution rate being a response fraction, ABRESP, of the remaining "excess" water (thus functioning as a decay function) and

* from the subsoil out of the active root depth zone into the intermediate groundwater zone, at a redistribution fraction BFRESP.

The redistribution fractions depend largely on soil texture and the following are suggested as default values for use in *ACRU* :

clay	: 0.25	sandy clay loam	: 0.50
loam	: 0.50	clay loam	: 0.40
sand	: 0.80	silty clay loam	: 0.35
loamy sand	: 0.70	sandy clay	: 0.40
sandy loam	: 0.65	silty clay	: 0.35
silty loam	: 0.45		

Southern African soils are hydrologically complex, and are characterised by hydraulic discontinuities because of their heterogeneous horizonation. Where gradual or abrupt changes toward finer textures take place between the top- and subsoil horizons, therefore, for example in clay distribution Models 1 and 3, BFRESP should be reduced. Similarly, where stonelines clay- or other hardpan layers occur in a soil profile, ABRESP and/or BFRESP should be reduced accordingly. The "Interflow Potential" column of Table 5.4.1 (and in the *ACRU* User Manual, for all series) provides a good guide to ABRESP and BFRESP reductions, with no reduction "no interflow potential" and substantial reductions for "high interflow potential" soil series. Poor subsurface drainage (i.e. low BFRESP) can result in waterlogging, which will cause a reduction in crop yield.

5.5.2 Unsaturated Soil Water Redistribution

Unsaturated soil water redistribution *downwards* can take place slowly from the top- to the subsoil horizon at soil water content below FC on the condition that the topsoil horizon is relatively wetter than the subsoil horizon. Redistribution is dependent on the soil water gradient between the top- and subsoil horizon and the "head" of water (i.e. amount of water in the topsoil horizon). The rate of downward redistribution in *ACRU* is set at the product of 2% of topsoil horizon soil water content and the gradient, the latter being expressed as the fractional difference between the percentages of soil water content in the top- and subsoil horizon.

The magnitude of redistribution on a given day, D_{ab} (mm) is thus expressed as follows in *ACRU*:

$$D_{ab} = 0.02\,\Theta_{1v}(\Theta_{1v}/\Theta_{fc1} - \Theta_{2v}/\Theta_{fc2})$$

in which

Θ_{1v},Θ_{2v} = volumetric soil water contents (mm) of topsoil and subsoil horizons on a given day

$\Theta_{fc1},\Theta_{fc2}$ = soil water contents of top- and subsoil horizons (mm) at their respective field capacities.

Upward redistribution, which may be likened to a capillary movement, takes place when the subsoil horizon contains a higher relative soil water fraction than the topsoil. The driving forces for upward redistribution are the same as for downward redistribution, but the rate of movement against gravity is reduced in *ACRU* to 1% of the subsoil horizon soil water content in calculations. Thus the magnitude of upward redistribution on a given day, D_{ba} (mm), is expressed as follows in *ACRU* :

$$D_{ba} = 0.01\,\Theta_{2v}(\Theta_{2v}/\Theta_{fc2} - \Theta_{1v}/\Theta_{fc1}).$$

The values used in the above equations have been derived from the literature (for example, Knisel, Baird and Hartman, 1969; Stone, Horton and Olson, 1973).

5.6 CONCLUSIONS

* In regard to southern Africa the binomial system (MacVicar *et al.*, 1977) is the "official" soil classification at the present stage. It is imperative, therefore, that modellers using *ACRU* in southern Africa not only acquaint themselves, but in fact become fully conversant with this detailed classification as it also forms a basis on which Land Type information may be used in *ACRU*. (Research on a revised soil classification for southern Africa is under way, but the binomial system will remain the working basis for some years to come).

* The information on texture classes, clay distribution models and of soil water retention constants derived by the methods described in this chapter is not absolute. It will be revised as field experience is gained or further laboratory analyses on soils are undertaken.

* This chapter gives generalized information on soils. *In situ examination* of soils properties in the catchment and attendant laboratory analysis, both necessary for in-depth understanding of the spatial and temporal variations of agrohydrological processes on a catchment or irrigated field, remain very necessary for the modeller wishing to use *ACRU* successfully.
* For southern African users derivation of information for input into *ACRU* has its roots in three seminal documents, viz. the binomial soil classification by MacVicar *et al.* (1977), the estimation of hydrological soil properties of South African soils by Hutson (1984) and the Land Type memoirs/maps under the general editorship of MacVicar. Grateful acknowledgement is expressed to these two eminent soil scientists and their teams of collaborators for having supplied the sound basis upon which soil hydrological decisions can now be made for the *ACRU* model.

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CHAPTER 6

VEGETATION AND LAND USE

R.E. Schulze, W.J. George and G.R. Angus

6.1 COMPONENTS OF VEGETATION AND LAND USE IN HYDROLOGICAL MODELLING

Vegetation (designating, in this chapter, natural vegetative cover) and land use (implying anthropogenic influence through cropping, including plantations, as well as agricultural practices such as irrigation and tillage operations) play a significant and dynamic role in the plant and soil evaporation processes. This is particularly true in the case of agricultural crops, which are sown following land preparation, may be irrigated then grow, may suffer water deficiencies and finally are harvested, all with considerable variation temporally and geographically to water usage (Schulze, 1984). Research in the past two decades has therefore placed far more emphasis than before on evaporative losses with incomplete canopies or limited water supply. With regard to hydrological modelling vegetation and land use process may be grouped functionally into

(a) *above ground factors*, concerned with

* canopy interception losses
* consumptive water use by plants
* shading of the soil, thereby separating total evaporation into
  - evaporation from the soil and
  - transpiration from the plant
* protection by the plant/litter cover against erosion, and

(b) *below ground factors*, concerned with

* plant root distribution
* root water uptake, and
* the onset of plant stress.

This chapter elaborates on the first three factors of above ground factors (the fourth factor being discussed in Chapter 11) and the first two of the below ground factors (the third factor being the theme of Chapter 7). General background is provided in each section of the chapter and detail is then focussed on the manner in which *ACRU* routines apply the principles involved.

6.2 CANOPY INTERCEPTION LOSSES

6.2.1 Canopy Interception Processes

Interception, I, is the process by which precipitation is "caught" by the vegetative canopy, stored temporarily on the canopy surfaces as interception *storage*, I_s, and then redistributed. Important to hydrological modelling is the interception *loss*, I_l, i.e. the portion of the precipitation which, after interception, does not reach the ground because it is retained by the aerial portion of the vegetation to be either absorbed by it or returned to the atmosphere by evaporation, E_i. Interception loss may be viewed as the difference between gross and net precipitation (P_g and P_n respectively), i.e.

$$I_l = P_g - P_n \quad \text{(all in mm)}$$

or, alternatively as the sum of interception storage and evaporation of intercepted water, i.e.

$$I_l = I_s + E_i.$$

After a day with rainfall, a portion of non-evaporated intercepted water which is stored on the canopy surface, I_s, may be approximated to I_l by

$$I_s = 0.5\, I_l$$

following experimental evidence by De Villiers (1975) and Rutter and Morton (1977).

A most important role in estimating interception loss, is that played by climatic parameters. Interception loss : gross rainfall relationships have been established frequently, in southern Africa, for example, by Schulze, Scott-Shaw and Nänni (1978) or by De Villiers (1982) (Figure 6.2.1). Equally important are evaporation rates during a rainfall event (for example, De Villiers, 1982) and the rainfall intensity and duration relationships to I_l which several researchers have reported. In Southern Africa both Schulze *et al.* (1978) and De Villiers (1982) have produced such relationships showing that higher rainfall intensities result in higher interception losses for a given duration; also that I_l increases with duration for any given intensity category. Such intensity : duration : interception relationships cannot at this stage be considered for *ACRU*, however, because *ACRU* uses daily totals of rainfall only.

Early researchers on the interception process (for example Horton, 1919) already relate I_l to canopy factors such as Leaf Area Index and for southern Africa De Villiers (1975) expressed interception loss per rainday in terms of a "density value" derived as the quotient of mean annual precipitation (MAP) to mean annual temperature (MAT). This density value (Figure 6.2.2) is analogous to an expression of interception being a function of biomass or vegetation density, in that for a given rainfall, interception loss is assumed to decrease with increasing temperature as aridity sets in; or increase with decreasing temperature until temperatures become so low that less biomass is produced and the I_l curve flattens or even reverses rather than continuing along the stippled line in Figure 6.2.2. Alternatively, for a given temperature, interception loss would increase with rainfall because a denser vegetal cover is assumed.

6.2.2 Rainday Interception Losses On A Month By Month Basis In *ACRU*

Initially the only method in *ACRU* of estimating interception loss values per rainday involved inputting typical values of I_l for each month of the year in order to account for differences in I_l with stage of growth or dormancy.

6.2.3 Rainday Interception Loss Estimates In *ACRU* By The Von Hoyningen-Huene Method

That a relationship between I_l and LAI exists has already been mentioned in Section 6.2.1. Von Hoyningen-Huene (1983) conducted extensive research with a number of agricultural crops (including maize, wheat, oats, sugarbeet) and their interception loss (mm.rainday) as associated with gross rainfall, P_g, and LAI. He developed

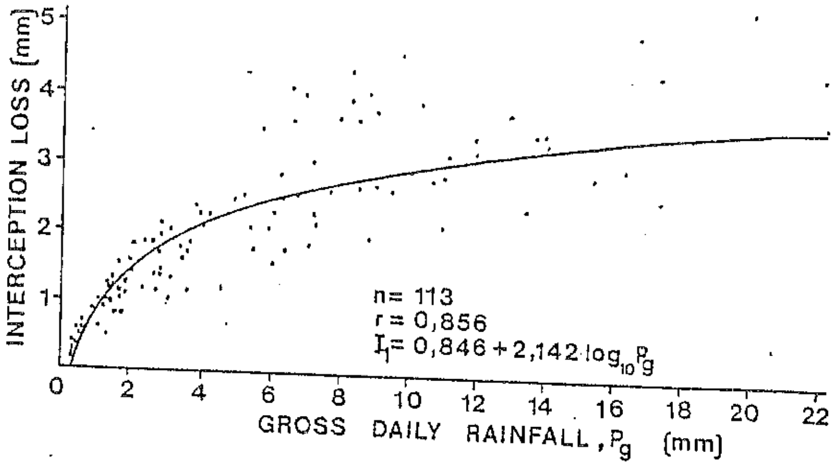

Figure 6.2.1 An interception loss : gross rainfall relationship for *Pinus patula* at Cathedral Peak, Natal (after Schulze, Scott-Shaw and Nänni, 1978)

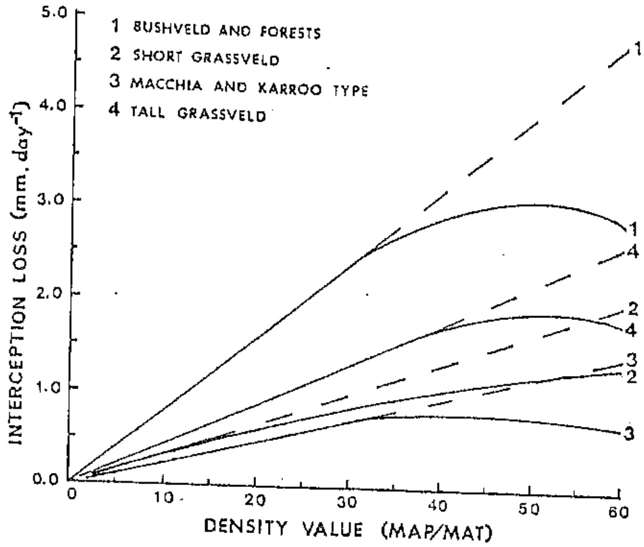

Figure 6.2.2 De Villiers' relationship between interception loss and climatic factors for different vegetation types (after De Villiers, 1975)

the following equation, viz.

$$I_l = 0.30 + 0.27P_g + 0.13LAI - 0.013P_g + 0.0285P_g.LAI - 0.007\ LAI^2$$

This equation is considered to give physically more realistic estimates of I_l than the monthly input method of Section 6.2.3. It can, however, only be used when LAI is known or estimated (Section 6.3). It has also been found that the equation is "stable" only for gross daily rainfall amounts up to 18 mm. When the equation is invoked in *ACRU*, any rainfalls exceeding that threshold are taken as 18 mm for the sake of I_l esimations.

While developed from data for agricultural crops, this equation has been found to perform well on *Pinus patula* (Chapter 17) and as such it may be deduced that the Von Hoyningen-Heune approach has potentially widespread application. It is, therefore, encouraged as the I_l estimator in *ACRU*.

6.2.4 Enhanced Wet Canopy Evaporation From Forests

Intercepted water stored on the plant canopy from a previous day's rainfall is evaporated back to the atmosphere using up the energy available from potential evaporation (E_p) first, before the remaining E_p is used in PET and AET processes. In the case of forests this stored water is evaporated at rates well in excess of available net radiation and potential evaporation, *inter alia*, because of advection (Calder, 1982) and low aero-dynamic resistances (Rutter, 1967) of wet forest canopies. The literature provides a range of values of the rates by which wet canopy evaporation exceeds the potential rate, usually around 1.5 - 2.0, but increasing with forest growth to values of 3 and higher (Holmes and Wronski, 1981; Calder, 1982). The following (conservative) estimate of enhanced wet canopy evaporation rate, E_w, has therefore been incorporated when *ACRU* is simulating evaporation processes under forest conditions, viz.

$$E_w = E_r (0.267LAI + 0.33) \text{ for } LAI > 2.7$$

where

E_r = A-pan equivalent reference evaporation (mm)

LAI = leaf area index

implying wet canopy evaporation to proceed, for example, at 1.67 times potential evaporation for LAI = 5.

On a day following a wet day the remaining potential evaporation, remaining after wet canopy evaporation has taken place, is then available for the transpiration process from the dry canopy.

6.2.5 Sources Of Information On Interception Loss Values For Use In Southern Africa

The major source of interception loss information for use with *ACRU* under southern African conditions derives from the seminal work on interception by De Villiers (1975). Table 6.2.1 summarises suggested interception loss values for agricultural crops and veld types by stage of growth, and respective values would then be assigned to a given month of the year when used in *ACRU*. Estimates of interception loss per rainday for natural vegetation have been derived by Schulze (1981) from information extracted from De Villiers. On a regional basis these I_l estimates are shown for southern Africa in Figure 6.2.3. The *ACRU* User Manual gives a further and more detailed tabulation of I_l values for natural vegetation based on Acocks'(1975) vegetation classification.

6.3 MAXIMUM EVAPORATION FROM A CROP ("POTENTIAL EVAPOTRANSPIRATION")

6.3.1 Evaporation From Vegetated Surfaces: Concepts And Terminology

Terminology on evaporation from vegetated surfaces is frequently used loosely or maybe misinterpreted. This subsection on concepts and terminology follows closely on recent proposals by Monteith (1985), Wright (1985), De Jager, Van Zyl, Kelbe and Singels (1987). All units are in mm.day^{-1}.

Table 6.2.1 Selected values of crop and grass interception losses for use in southern Africa (after De Villiers, 1978; 1980)

Stage of Growth	Maize	Wheat	Sunflowers	Sugarcane Erect	Sugarcane Waste layer	*Themeda triandra*	*Hyparrhenia hirta*	*Aristida congesta*
Early vegetative	0.30		0.30					
Late vegetative	0.40	0.30	0.60					
Culm/Piping		1.00						
Flowering	0.80	1.40	0.80					
Seed development	1.30	1.40	1.40			2.20	1.40	1.00
Complete ripe	1.10	1.50	1.30			1.60	1.60	0.80
Dry	1.20		0.40	1.60	2.00			

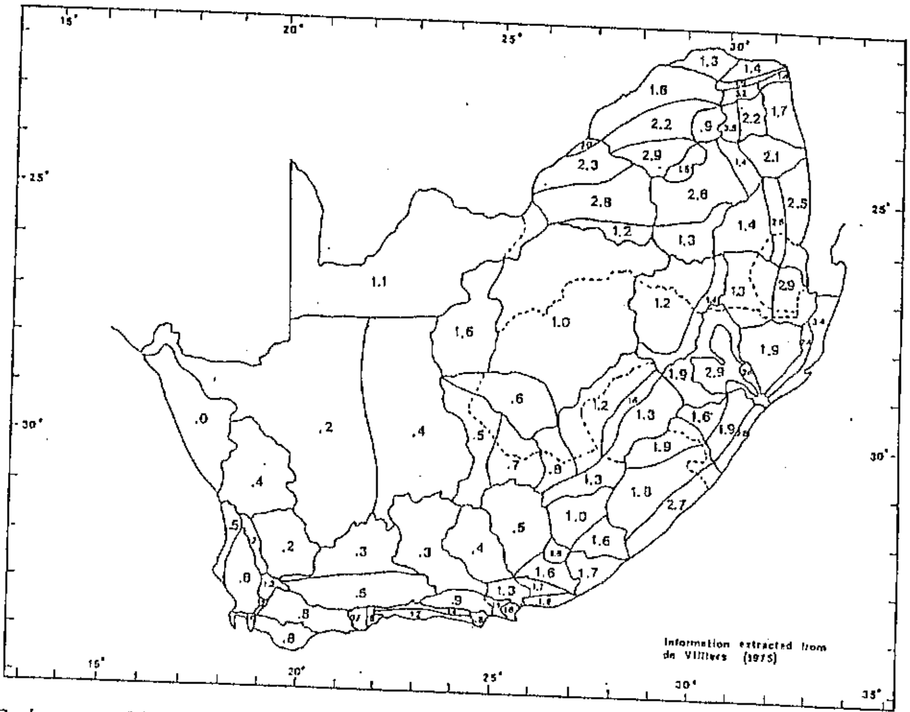

Figure 6.2.3 Estimates of interception loss (mm per rainday) for natural vegetation in southern Africa (Schulze, 1981)

* *Total Evaporation*. The total evaporation, E, from a natural vegetative surface is defined as

$$E = E_t + E_s$$

with

E_t = evaporation from the sub-stomatal cavities of leaves = transpriation

and

E_s = evaporation from the surface of the soil.

The term "total evaporation" is synonymous with the term "actual evapotranspiration". By implication neither E_t nor E_s need to be at their maximum rate.

* *Maximum Evaporation from a Given Crop.* This term replaces the commonly used term "potential evapotranspiration". It occurs from a specific crop surface in a given growth stage when soil water is capable of meeting atmospheric demand of the day.

$$E_m = E_{tm} + E_{sm}$$

with

E_{tm} = maximum (previously "potential") transpiration when soil water is capable of meeting atmospheric demand, and

E_{sm} = maximum (previously "potential") soil evaporation, again when the soil water is capable of meeting atmospheric demand.

Under such conditions of soil water status E_m may also be expressed as

$$E_m = E_r.K_{cm}$$

where

E_r = a reference evaporation

K_{cm} = a dimensionless mean crop coefficient for a particular crop growing in its various stages, under conditions of no soil water limitations with soil surface conditions at an average wetness.

* *Reference Maximum Evaporation, E_r.* Reference evaporation has been defined in several ways, for example, as the maximum evaporation from a short grass surface (De Jager *et al.*, 1987; Doorenbos and Pruitt, 1977) or the evaporation from alfalfa (Wright, 1982), in both cases lysimeter based and supplied with adequate water, covering an extensive area growing actively and completely shading the ground. In *ACRU* the selected reference evaporation is the daily A-pan equivalent evaporation.

Problems arise in applying literature derived values of the crop coefficient to a pan-based E_r to give realistic values of E_m, because E_r from alfalfa, grass and A-pans are different. From a diagram by Wright (1985) it has been calculated that

$$E_r(\text{pan}) \sim 1.103\ E_r\ (\text{alfalfa})$$
$$E_r(\text{pan}) \sim 1.190\ E_r\ (\text{FAO - Doorenbos and Pruitt, 1977})$$

In *ACRU* there is thus a need for great caution when using mean crop coefficients from the literature. Because A-pan reference evaporation is used in *ACRU*, K_{cm} values based on an alfalfa reference will have to be divided by 1.10 and K_{cm} values taken, for example, from a standard reference by Doorenbos and Pruitt (1977) will have to be divided by 1.19 to approximate an A-pan based maximum evaporation (i.e. "potential evapotranspiration").

6.3.2 The Crop Coefficient, K_{cm}

The K_{cm} provides the dependent relationship of maximum evaporation for a given stage of plant growth and phenology under conditions when soil water is capable of meeting atmospheric demand and surface wetness of the soil is "average". One can re-arrange the equation for "maximum evaporation", given previously, to express K_{cm} as

$$K_{cm} = E_m/E_r$$

which gives the ratio of maximum evaporation of a crop at a given stage of growth to reference evaporation.

If reference is made to Figure 6.3.1 and to Wright (1985) it may be seen that K_{cm} comprises of the mean of a

* basal crop coefficient, K_{cb},

* of a crop coefficient at a given soil water condition which may be very wet (and immediately following a day with rainfall or irrigation) or soil water limited, viz. K_c and

* of K_a and K_s, relative coefficients related respectively to relative soil water and surface soil wetness.

From its definition and from Figure 6.3.1, it can be implied that K_{cm} applies when transpiration and soil evaporation are treated as one entity and not as separate components. This option is designated EVTR=1 in *ACRU*. When transpiration and soil evaporation are split and computed separately (Section 6.3.1) the pathway in *ACRU* is via EVTR=2 (Schulze and George, 1989).

6.3.3 Determination Of Values Of Crop Coefficients For Southern Africa

In the frequently cited international literature on crop coefficients (e.g., Doorenbos and Pruitt, 1977) K_{cm} is given either

* for percentiles of a growing season
* for calendar months
* for intervals of calendar days

or * for clearly defined growth stages.

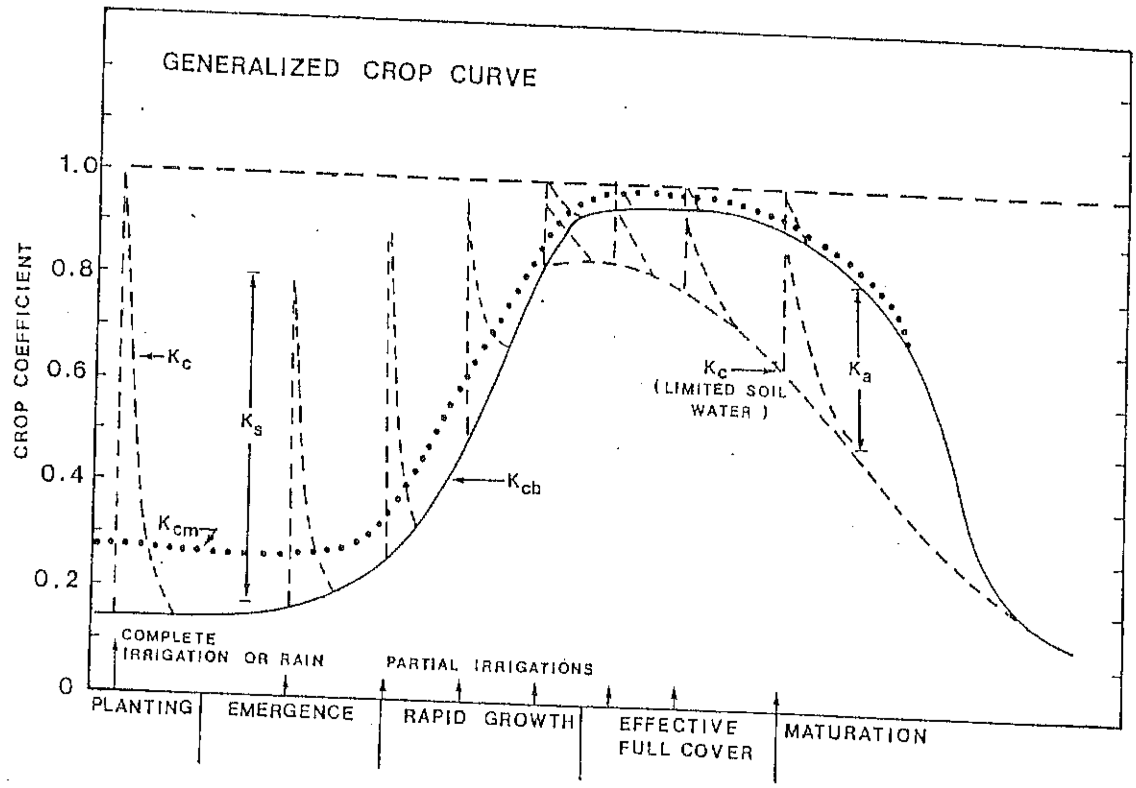

Figure 6.3.1 Generalised crop coefficient curves (after Wright, 1985)

(a) In southern Africa, the generic international FAO model by Doorenbos and Pruitt (1977), shown diagrammatically in Figure 6.3.2, may be used to estimate crop coefficients for seasonal crops. For this model

* reference K_{cm} values for the initial growth stage, the mid-season stage and at harvest/maturity are given, as are, furthermore,

* the durations (in days) of the initial, crop development, mid-season and late stages of growth (obtainable from local tables or from tables in Doorenbos and Pruitt, 1977).

* When used in *ACRU* the values of K_{cm} from Doorenbos and Pruitt (1977) will have to be divided by 1.19 to equate them to A-pan equivalent reference PE.

(b) The most common source of K_{cm} information for southern Africa is, however, Green (1985). He tabulates (either by calendar day interval, or as percentiles of the growing season, or by calendar month) K_{cm} values derived for use with the A-pan reference evaporation for different crops, planting dates and regions in southern Africa. An example tabulation is shown in Table 6.3.1; the *ACRU* User Manual (Schulze and George, 1989) gives a more complete tabulation of K_{cm} information for southern Africa taken mainly from Green.

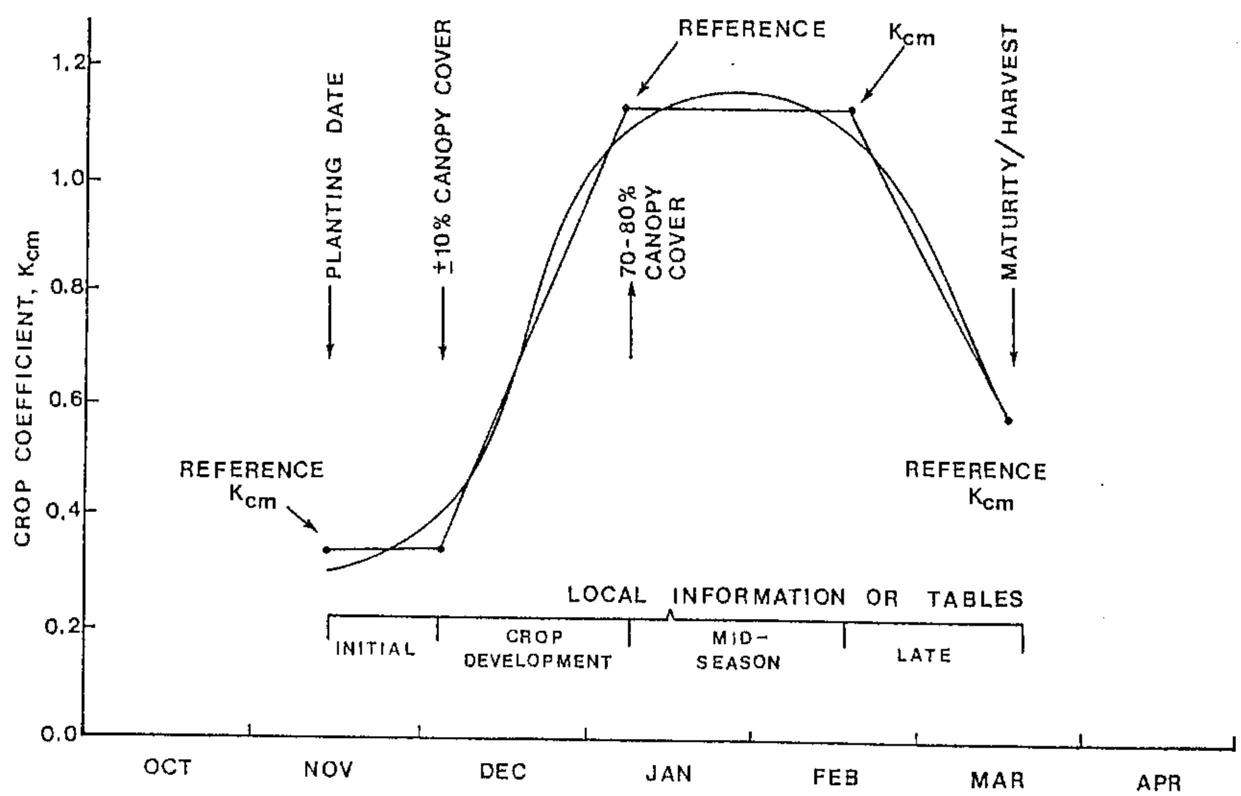

Figure 6.3.2 The FAO generic method for estimating crop coefficients (after Doorenbos and Pruitt, 1977)

Table 6.3.1 An example of A-pan referenced crop coefficients derived for use in southern Africa (after Green, 1985)

Crop : Beans

Region and Planting Date	Length of Growing Season	Days after Planting	Crop Coefficient
Orange Free State; November 1	140 days	0 - 35 36 - 65 66 - 90 91 - 140	0.3 0.7 0.6 0.5
Transvaal: W,S and Middleveld October 15	150 days	0 - 30 31 - 60 61 - 90 91 - 150	0.3 0.7 0.6 0.5

6.3.4 Problems Associated With The Crop Coefficient Concept

* The major shortcoming of the use of K_{cm} in estimations of evaporation is the lack of K_{cm} information on natural vegetative surfaces such as grasslands, macchia and bushveld, which often cover large tracts of catchments. Use then has to be made of those few lysimeter-based values derived by Snyman, Opperman and van den Berg (1980) for different succession stadia of veld.

* The assignment of K_{cm} by intervals of calendar days is common. Despite regionalization of K_{cm} to account for climatic differences (for example, Green, 1985; Dorrenbos and Pruitt, 1977; Table 6.3.1), this does not account for local climatic variations and differences between seasons for any one locality. Therefore a conceptually sounder and more accurate method of determining K_{cm}, based on a measure of that part of the climatic environment which is largely responsible for variations of numbers of calendar days within growth periods, viz. temperature, is being developed more and more with the growing degree day (GDD) concept. Such a GDD:K_{cm} relationship, for example, has been developed lysimetrically for use in *ACRU* with sugarcane (Hughes, 1989; Figure 6.3.3). The *ACRU* maize yield model (Chapter 14) therefore also has its K_{cm} not specified by time period, but rather it is generated from year to year and location to location by a generic relationship between K_{cm} and GDD (Domleo, 1989; also Chapter 15). Such refinements to K_{cm} variations are not yet routine in this documentation of *ACRU* at this stage other than for maize.

6.3.5 Relationships Between Crop Coefficient And Leaf Area Index

Leaf Area Index may be defined as the planimetric area of the plant leaves relative to the soil surface area, the LAI as a determinand of consumptive water use by plants as well as of shading of the soil, protection of soil from erosive raindrop impact and interception (c.f.

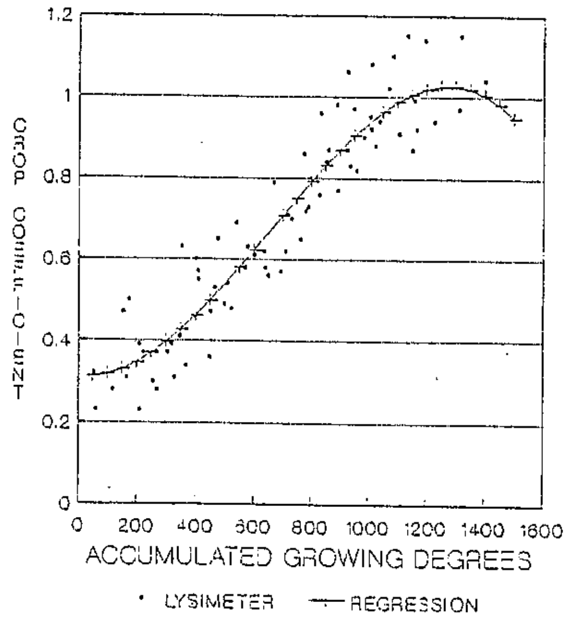

Figure 6.3.3 A K_{cm} : growing degree day relationship for sugarcane (Hughes, 1989)

the Von Hoyningen-Huene LAI : P_g : I_l relationship in Section 6.2.4) is conceptually sound. LAI information is, however, not as common as K_{cm} information. A number of researchers have, however, related K_{cm} to LAI. Thus Ritchie (1972), for example, developed the relationship

$$K_{cm} = 0.71 \, LAI^{0.5} - 0.2 \quad \text{for } LAI < 3.0.$$

Research by Kristensen (1974), for example, has shown that K_{cm} approaches 1.0 as LAI approaches 3. This is illustrated in Figure 6.3.4.

Since K_{cm} values are frequently known, but *ACRU* requires LAI values, for example, for estimations of interception on an event basis and transpiration (when the option EVTR = 2 is used, which splits transpiration and soil evaporation), LAI is estimated from the Kristensen (1974) relationship in Figure 6.3.4 as

$$LAI = \frac{\ln\left((K_{cm} - 1.0932)/-0.07947 \right)}{-0.6513}$$

This equation was derived by Angus (1987) from information given by Kristensen (1974). While this equation is considered generally applicable to all crops, a word of caution must be noted, since it was developed only from grasses, barley and sugar beets. As such, the above equation should be used with caution on other vegetation types. In applying the above equation in *ACRU* a maximum K_{cm} of 1.05 is assumed because Kristensen's (1974) graph is asymtotic to the line representing K_{cm} = 1.07 and the above equation becomes unreliable in that region (Angus, 1987); furthermore the lower limit of K_{cm} estimated by this equation in ACRU is 0.2.

6.3.6 Estimation Of Total Evaporation In *ACRU* By Considering Transpiration And Soil Evaporation Separately, Using LAI

ACRU uses an adaptation of the Ritchie (1972) submodel when computing transpiration and soil evaporation separately. While this section considers maximum evaporation (i.e. "potential evapotranspiration") the discussion which follows

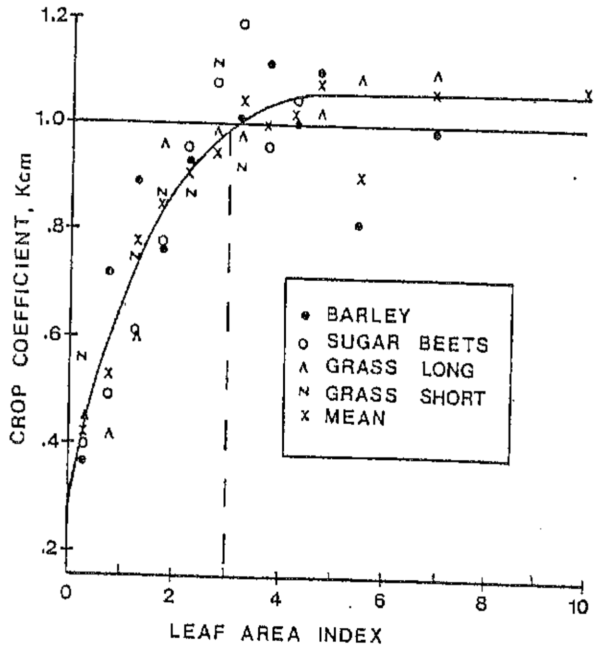

Figure 6.3.4 Relationships between K_{cm} and Leaf Area Index (after Kristensen, 1974)

in this particular sub-section also describes equations of Ritchie's (1972) for estimation of total evaporation (i.e. "actual evapotranspiration"). In *ACRU* the energy available for the soil evaporation and transpiration processes is taken as the daily A-pan equivalent evaporation minus that energy used up first by the evaporating previously intercepted water.

(a) Following a minimum threshold of rainfall, maximum ("potential") soil evaporation is given by Ritchie (1972) as

$$E_{sm} = E_{ri}\, e^{-0.4LAI} \quad (\text{mm.day}^{-1})$$

where

E_{ri} = residual A-pan equivalent evaporation (mm.day^{-1}), after evaporation of previously intercepted water

"Actual" soil evaporation, E_s, is calculated in two stages. In the first stage soil evaporation is limited only by the energy available at the surface, and is thus equal to maximum ("potential") soil evaporation, i.e.

$$E_s = E_{sm}$$

When the accumulated soil evaporation exceeds the stage one upper limit, the stage two evaporative process commences. Stage one upper limit is estimated with

$$UL_1 = 9(\alpha_s - 3)^{0.42}$$

where

UL_1 = stage one upper limit (mm)

α_s = soil evaporation parameter dependent on soil water transmission characteristics (with values of α_s related to texture class, which are preprogrammed in *ACRU*).

Stage two soil evaporation, E_s(mm.day^{-1}) is predicted by

$$E_s = \alpha_s\ t^{0.5} - (t-1)^{0.5}$$

with

t = number of days since stage two soil evaporation began.

Effectively, once stage two is reached, soil evaporation thus declines very rapidly.

(b) Maximum (i.e. "potential") plant evaporation, i.e. transpiration, is computed in *ACRU* by the Ritchie (1972) subroutine as follows :

$E_{tm} = (E_{ri}.LAI)/3$ for $0<LAI<3$ and
$E_{tm} = E_{ri} - E_s$ for $LAI>3$

When soil water is limited

$E_t = E_{tm}.f(Soil\ Water\ Content)$
where
f(SWC) is discussed in Chapter 7.

The sum of transpiration and soil evaporation cannot exceed E_{ri} for a given day.

6.3.7 Procedures Utilizing Crop Coefficients And LAI In *ACRU*

Through the *ACRU* Menubuilder 12 monthly mean values of K_{cm} are input. These are converted internally in *ACRU* to 365 daily values by Fourier Analysis. The daily K_{cm} is then converted to a daily value of LAI by the Kristensen (1974) curve expressed as the equation by Angus (1987), as given in Section 6.3.5. The LAI can then be used in computations of transpiration, soil evaporation and interception loss, if so desired. Daily K_{cm} for a given crop at a given growth state is used to calculate maximum evaporation for that crop (i.e. its "potential evapotranspiration"). If the *ACRU* maize yield submodel is requested, K_{cm} is computed internally year by year according to daily temperature regimes by a K_{cm}:GDD relationship.

6.4 SOIL WATER EXTRACTION BY PLANT ROOTS

6.4.1 The Complexity Of Water Uptake By Roots

Root distribution within the soil profile and the processes of water uptake by roots are complex subjects, made more difficult, for example, by soil horizonation and layers which may be impermeable to root penetration. Roots development may be assumed to be linear with time, but the root mass may be distributed exponentially throughout the entire root zone at any time (De Jager, Van Zyl, Kelbe and Singels, 1987). At night water may move through the plant from roots which were in wet soil and exuded from roots which were in dry soil, to the extent that dry soil could supply a high proportion of its transpiration needs in this way (e.g. Baker and Van Bavel, 1986).

It has been hypothesised that roots in the topsoil may take up the water available to them first, until a stress level is reached in the topsoil, before soil water is withdrawn from the lower soil zones (e.g. Baier and Robertson, 1966) and also that the lower zone roots do not extract water down to the same water contents as in the case with the upper zone roots. In fact Ritchie, Burnett and Henderson (1972) contend that the lowest soil water content to which roots can dry the soil gradually increases with depth until finally the minimum soil water content at depth may be close to field capacity.

The distribution of roots, and hence its extraction patterns may be distorted by impermeable layers such as plough or other hard pans, the presence of water tables, and may be "controlled" by man, for example, with different tillage practices or by frequent shallow irrigations which concentrate root growth in the upper soil zone.
The result is that a range of complexities of root growth/distribution/extraction models exist (in Southern Africa, for instance, models by De Jager *et al.*, 1987 or Bennie *et al.*, 1988). However, Taylor's and Klepper's (1978 p. 120) conclusion still holds, viz. that

> "all models of water uptake by root systems contain assumptions that are not strictly valid for everyday field situations".

This is undoubtedly true; models such as *ACRU* therefore have to make a number of simplifying assumptions regarding its routines for root distribution and the uptake of water by roots.

6.4.2 Concepts Of Root Water Uptake Employed In *ACRU*

In the *ACRU* model, soil water extraction takes place simultaneously from both soil horizons and in proportion to the assumed active rooting masses within the respective horizons. In the present version of *ACRU* no extraction from the intermediate groundwater zone takes place because this zone is assumed in this model to be at greater depth than the active root zone. The variable ROOTA describes the fraction of active root mass in the topsoil horizon. It varies seasonally; hence 12 typical monthly values are required. The corresponding fraction of roots in the subsoil-horizon is (1 -ROOTA). The fraction of roots in any one horizon has to account for the effect of genetic and environment factors on transpiration, factors such as winter dormancy, senescence, spring regrowth, planting date, growth rates or impeding soil properties. Typical values of ROOTA taken from the literature are incorporated in the land use Decision Support System of *ACRU* (Chapter 2). When plants are not under stress, it is the fraction ROOTA which determines to a large extent at what rates differential drying of the soil takes place in the respective horizons. During periods of senescence or when no active root extraction takes place (for example, in bare fallow or ploughed situations), the ROOTA fraction is set at 1.00, designating that effectively soil evaporation from only the topsoil layer and not transpiration takes place.

On the premise that "roots look for water, water does not look for roots", a routine has been added to *ACRU* whereby if the subsoil horizon is not stressed, but the topsoil horizon is, the subsoil's contribution to total evaporation will be enhanced beyond that computed for its root mass fraction; similarly, if the subsoil horizon is stressed but the topsoil horizon not, the topsoil's contribution to E is enhanced. This routine is described more fully in Chapter 7.

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CHAPTER 7

TOTAL EVAPORATION
("ACTUAL EVAPOTRANSPIRATION")

R.E. Schulze

7.1 INTRODUCTION

In the introductory Chapter 1 which outlines considerations and philosophies upon which the *ACRU* modelling system was structured, it was already stated that most rainfall is transformed into evaporation either from the soil or through the plant. So dominant is total evaporation in the soil-plant-atmosphere continuum in southern Africa that Whitmore (1971) estimates 91% of rainfall to evaporate again. Major differences in runoff, irrigation demand and crop yield response are influenced, and to some extent even controlled, by soil water status. One of *ACRU*'s major aims is, therefore, to simulate the soil water budget by accounting realistically for the total evaporation processes, since these processes are the "heart" of the agrohydrological system (Kovacs, 1986).

Total evaporation (E) may equal or be less than the maximum evaporation (E_m, i.e. "potential evapotranspiration"). E can be less than E_m either when soil water has been depleted or when there is an excess of water in the soil profile. Total evaporation from a multi-layered soil also responds to self regulatory mechanisms when certain soil horizons are relatively wetter than others. The above-named aspects are discussed in this chapter in the context of routines in *ACRU* and many of the aspects involved revolve around the concepts embodied in Figure 7.1.1.

7.2 TOTAL EVAPORATION UNDER CONDITIONS OF WATER DEFICIENCY

When a plant experiences water stress $E < E_m$. The water status of a plant is dependent largely on the soil water content of the root zone and on atmospheric demand. The atmosphere places an evaporative demand on the plant and the roots absorb the water from the soil water reservoir. When the reservoir becomes depleted the roots cannot absorb the water at a rate sufficient to meet demand, plant stress sets in and the plant loses turgor. Subsequently, physiological and metabolic processes are affected (for example, leaf emergence, leaf extension, photosynthesis rates) and rates of plant growth are reduced. As a result the crop coefficient can reduce, as is shown in Wright's (1985) generalised diagram in Figure 6.3.1 as well as by Hughes' (1989) illustration for sugarcane (Figure 7.2.1).

It is vital in land use and crop yield modelling to determine at what point in the depletion of the plant available water reservoir (i.e. the soil water content between FC and WP) plant stress actually sets in, since stress implies the necessity to irrigate and also a reduction in crop yield. In modelling terms, this problem may be expressed as the critical soil water content below which total evaporation E is reduced to below the atmospheric demand, i.e. E_m.

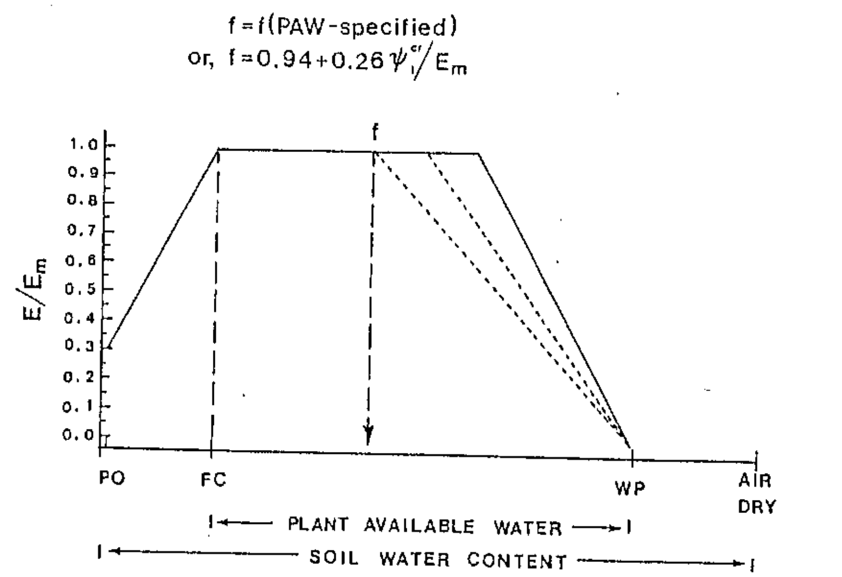

Figure 7.1.1 Generalised interrelationships used in *ACRU* between soil water content and the ratio of E : E_m

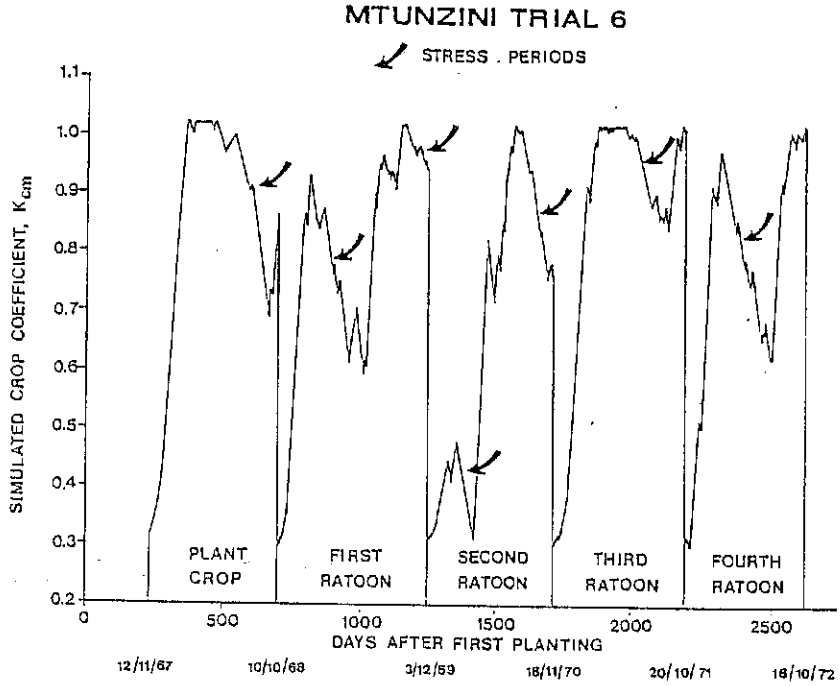

Figure 7.2.1 Simulated decreases of the crop coefficient of sugarcane under stressed conditions (after Hughes, 1989)

Experimental evidence shows that E equals E_m until a certain fraction, 'f', of maximum (profile) available soil water to the plant, PAW, is reached (Figure 7.1.1). Below this fraction the reduction of E depends, *inter alia*, on the remaining water and the atmospheric demand, E_m. Under natural conditions the reduction of E, from point 'f' to zero at WP, is curvilinear. Its representation as a linear reduction in Figure 7.1.1 is a simplification introduced into *ACRU* for computational simplicity. Furthermore, under natural conditions and only in a topsoil horizon with little vegetal cover, the reduction of E would not continue to zero at WP, but to an E/E_m ratio of approximately 0.2. The reason is that bare topsoil can "dry" to below the -1500 kPa generally associated with the lower level of root soil water extraction (WP).

The classical literature of the past two decades has frequently attributed differences in 'f' to soil texture properties. Authors (for example, Dunne and Leopold, 1978) would give the 'f'-value of clays around 0.9, that of loams at 0.5 and that for sandy soils around 0.2, implying that the high retention of soil water by clay caused "stress" at relatively high soil water contents already while sand evaporated at near maximum (atmospheric demand) rates until soil water content was close to WP.

Others, notably irrigation modellers, maintain simplistically that stress sets in at a more or less fixed soil water content irrespective of plant, soil or atmospheric demand. Usually it is suggested that under irrigation, soil water content should not be allowed to be depleted beyond f = 0.5 (for example, Green, 1985), particularly during the vegetative growth stage. In the grain filling stage a suggested value of 'f' would be 0.3, a value also found by Meyer and Green (1980) to be applicable to wheat in southern Africa. Schulze and George (1989) in the *ACRU* User Manual list 'f' values for certain crops, as specified by Green (1985) for different conditions/regions in southern Africa.

Recent research, reviewed by Slabbers (1980), shows that 'f' may vary according to atmospheric demand (E_m) and the critical leaf water potential, ψ_l^{cr}, of different crops, the latter being an index of the resilience of crops to stress situations. Many other authors had found similar relationships, *inter alia*, Denmead and Shaw (1962) in a classic study, Baier and Robertson (1966) and Eagleman (1971). Slabbers (1980) derived 'f' as

$$f = 0.94 + 0.26\ \psi_l^{cr}/E_m$$

where

ψ_l^{cr} = critical leaf water potential as given by Slabbers (1980) in negative bar (negative because of suction). One bar = 100 kPa.

Using the above equation with critical leaf water potentials for different crops, the wide variation of 'f', also for different E_m, is demonstrated in Table 7.2.1. The table illustrates clearly that more resilient plants (e.g. maize) can extract more soil water out of the profile than rapidly wilting plants (e.g. sunflowers) before they are in a water deficient stressed condition; also that on hotter days with higher E_m, stress will already occur at higher soil water contents. The implications of stress setting in at such different levels of soil water content are highly significant in terms of total evaporation and crop production modelling.

It should be noted that Slabbers' (1980) equation was derived empirically. Under certain conditions a negative value of 'f', which is a physically meaningless answer, may be obtained by the equation. Such negative answers are defaulted internally to 0.05 in *ACRU*.

A question frequently posed is how sensitive soil water and crop response are to accurate estimates of 'f'. Under dryland conditions the effect of a decreasing E/E_m ratio is to introduce an apparent conservatism into soil water budgeting. This conservatism is due largely to the negative feedback mechanism which begins to operate in a soil water budget model such as *ACRU* when $E/E_m < 1$. The

Table 7.2.1 The effects of critical leaf water potential and maximum evaporation on the fraction of available soil water, 'f', at which stress sets in

Crop	Critical Leaf Water Potential (-bar)	E_m ($mm.day^{-1}$)	f	E_m ($mm.day^{-1}$)	f
Maize	-17	6	0.20	4	0.00
Lucerne	-14	6	0.33	4	0.03
Grass	-10	6	0.51	4	0.29
Sunflowers	- 7.5	6	0.62	4	0.45

mechanism has been discussed, *inter alia*, by Johns and Smith (1975) and by Calder *et al.* (1983). When $E/E_m < 1$ the negative feedback mechanism ensures that, if E is overestimated in one period, then in the next period the soil water is underestimated, which in turn produces an underestimate of E/E_m and hence a reduction in the soil water depletion in that period. The mechanism also works in the reverse direction if an initial underestimation of E is made. The modelling mechanism is thus self compensating, i.e. it has a negative feedback.

In addition E is limited at the upper end by stomatal action and at the lower end by soil water being unavailable below WP. Johns and Smith (1975) found that when the appropriate value of 'f' was used then the simple linear decline of E/E_m, as illustrated in Figure 7.1.1, was generally as good or better than other more complex curvilinear functions for expressing the relative decrease of E.

The purpose of irrigation is to try and ensure that E does not decline below E_m by providing the correct quantities of water when it is needed. Considerable amount of water can, however, be saved by applying water at "correct" 'f' values under conditions of supplementary irrigation and deficit irrigation, and Ponnambalam and Adams (1985) cite water savings of up to 50% for this reason alone. In crop yield modelling realistic estimation of 'f' is also vital, particularly in those phenological periods when the plant's yield reduction is highly sensitive to stress (Chapter 15).

7.3 TOTAL EVAPORATION UNDER CONDITIONS OF EXCESS WATER

While considerable research has been conducted to determine the response of crops to deficient soil water levels, less has been done to gain a better understanding of plant responses to excessive soil water conditions. A routine for estimating this effect is included in *ACRU*. The problem of excessive soil water is one that centres around deficient aeration, i.e. annoxia. In *ACRU* reduced transpiration rates are only assumed as a result of excessive soil water if the soil water content remains above field capacity for a period exceeding one day. The one-day period is considered critical for maize, for example, by Ritter and De Beer (1969). The overall excess soil water stress relationship to be used in the *ACRU* modelling system is depicted in Figure 7.1.1. The linear relationship of the E/E_m decline between field capacity (FC) and porosity (PO) expresses the reduction in E, and hence yield, due to annoxia. This decline is set at a maximum of $E/E_m = 0.3$ when soil water content is at porosity, following Dijkhuis and Berliner (1988).

7.4 SOIL WATER STRESS RELATIONSHIPS WHEN SOIL EVAPORATION AND PLANT TRANSPIRATION ARE COMPUTED SEPARATELY

In Chapter 6 (Section 6.3.6) the Ritchie (1972) submodel, which splits soil evaporation and transpiration and models them separately, has already been described, also for conditions of $E<E_m$. The description will therefore not be repeated in this chapter.

7.5 ADJUSTMENTS TO TOTAL EVAPORATION FOR DIFFERENTIALLY WET SOIL HORIZONS

ACRU operates on the premise that "roots look for soil water, soil water does not look for roots". In the computational procedures, therefore, once soil water contents of the respective soil horizons have been adjusted, following evaporative extractions of the day, a further refinement to E is applied horizon by horizon when one of the horizons experiences water deficiency stress ($E<E_m$) while the other does not ($E = E_m$).

Under such conditions *ACRU* has been programmed for the unstressed horizon to contribute more to E than computed by its proportion of root mass available for transpiration (*ACRU* variable ROOTA), conditional upon the plant's being in a phase of active growth (i.e. a minimum of 10% of the roots are in that horizon). This "compensational", additional evaporation by the unstressed horizon is made up of 0.5 times the difference between E and E_m of the stressed horizon.

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CHAPTER 8

SIMULATION OF STREAMFLOW

R.E. Schulze

8.1 INTRODUCTION

In the *ACRU* model the generated streamflow (also designated runoff) comprises *baseflow* and *stormflow*, with the stormflow component consisting of a *quickflow* response (i.e. stormflow released into the stream on the day of the rainfall event) and a *delayed stormflow* response. Baseflow is derived from a groundwater store which is recharged by drainage out of the lower active soil horizon when its water content exceeds field capacity. In a purely diagrammatical depiction, these components are illustrated in Figure 2.2.2, to which reference should again be made while reading this chapter.

8.2 ESTIMATION OF STORMFLOW VOLUME

8.2.1 Estimation Of Stormflow Volume By The SCS Equation

The Soil Conservation Service (SCS) of the United States Department of Agriculture developed a procedure for estimating stormflow volumes from small catchments. This SCS procedure, designed to use daily rainfall input as the driving mechanism, has been adapted for use in southern Africa (Schulze, 1984; Schmidt and Schulze, 1987). The concept of the SCS stormflow routine is based on the principle that the runoff potential is, *inter alia*, an inverse function of the soil's relative wetness.

The Soil Conservation Service (United States Department of Agriculture, 1972) and Schmidt and Schulze (1987) derive the following stormflow equation from "initial" principles, viz.

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

where

Q = stormflow volume (mm)

P = daily rainfall amount (mm)

I_a = initial abstractions (mm) before stormflow commences, and consisting mainly of interception, infiltration and depression storages

S = potential maximum retention (mm), which is equated to the soil water deficit.

In order to eliminate the necessity of estimating both I_a and S, I_a may be expressed in terms of S by the empirical relationship

$$I_a = cS$$

where

c = coefficient of initial abstraction.

The stormflow equation thus becomes

$$Q = \frac{(P - cS)^2}{P + S(1 - c)}$$

8.2.2 Conceptual Deviations From And Refinements To The SCS Stormflow Equation In *ACRU*

Notable exceptions to the original SCS stormflow equation are made in *ACRU*.

* *Interception* as a store is abstracted separately before the commencement of potential runoff-producing rainfall, and is not part of the initial abstractions as in the SCS model.

* The *coefficient of initial abstraction* is a parameter which can change from month to month in *ACRU*, dependent on vegetation, site and management characteristics. The default value of the coefficient in *ACRU* is 0.2 and not 0.1, which was the value suggested by Schmidt and Schulze (1987) in a design manual for southern Africa, for which a conservative stormflow estimate was sought. The coefficient can increase to (say) 0.3 immediately after ploughing when surface roughness is high, or under forested conditions, and reduce to (say) .05 to 0.15 under conditions of soil compaction or in peri-urban situations. Schulze, George, Arnold and Mitchell (1984) related the coefficient 'c' to physiographic factors (catchment area, slope, stream order, drainage density) and climatic factors (rainfall amount, intensity, duration and antecedent soil water status) with multivariate equations. These gave regionally improved estimates of stormflow, but no universally applicable equation for 'c' was found; hence these equations are not presented here for general use.

* The *potential maximum retention* of the soil, S, is conceived as a soil water deficit, calculated by the multi-layer soil water budgeting techniques of *ACRU* (c.f. Chapter 9). The soil water deficit is taken as the difference between water retention at porosity and the actual soil water content just prior to the rainfall event, i.e. after total evaporation for the day has been abstracted. The assumption is made in *ACRU* that a rainfall event occurs at the end of a computational day and not at the beginning of the day.

* The *critical soil depth* for which the soil water deficit, S, is calculated for runoff generation is a variable in the *ACRU* model in order to attempt to account for different dominant runoff-producing mechanisms prevailing in catchments and for different infiltration rates. This variable is designated SMDDEP in *ACRU*. For example, a catchment with predominantly short vegetation which is shallow-rooted would use the soil water deficit equivalent to the topsoil-horizon depth in estimations of stormflow. On the other hand, on land use with a dense canopy cover which can dissipate the rainfall's energy and/or has deep litter/organic layers or highly leached soils, resulting in relatively high infiltratibility, the critical depth of the soil water deficit S may be deeper than the topsoil-horizon because stormflow on such catchments may be perceived as being produced more by a "push through" (translatory) mechanism. An example of the latter was found in simulations by Schulze and George (1987) at Cathedral Peak (MAP = 1400 mm) where a SMDDEP of 0.4 m gave best

results. In more arid areas, on the other hand, where soils are skeletal and may have developed salt crusts, Dunsmore, Schulze and Schmidt (1986) have shown SMDDEP = 0.1 m to give best results in simulations, the indication being that under such conditions overland flow would have been the dominant runoff-producing mechanism. Figure 8.2.1, based on experience with *ACRU* simulations, gives suggested values of SMDDEP according to climatic, vegetation and soils characteristics.

* The generated total *stormflow response* may be rapid (mainly same-day response) or slow (with the generated stormflow contribution spread over several days) at a catchment's outlet. Soils with a high interflow potential (c.f. *ACRU* User Manual, Chapter 7) would respond rapidly, as would small and/or steep catchments when compared with relatively larger ones and/or ones with gentler gradients. Similarly, catchments with dense vegetation are likely to respond slower than those with sparser vegetation, all else being equal. For this reason another deviation from standard SCS procedures is incorporated in the *ACRU* model, viz. the inclusion of a stormflow response coefficient (a fraction $\leq$ 1), expressed by the input parameter QFRESP, which controls the "lag" of the delayed stormflow by discharging on the specified fraction of stormflow on the day of the event. The remaining stormflow is "retained" to the next day, when again the fraction QFRESP of the remaining stormflow is discharged as streamflow. Please note that this parameter, which acts as a decay function, controls only the *timing* of stormflow over one or several days and not the amount of Q.

8.2.3 Estimation Of Baseflow In *ACRU*

In regard to baseflow generation, two response coefficients are applied in *ACRU*.

* The first relates to the *drainage rate* of water out of the bottom subsoil-horizon store, when its soil water content exceeds field capacity, into the intermediate/ groundwater store. While this response rate BFRESP (Chapter 5) is intuitively slower for heavy textured than for light textured soil, no readily available data are at hand as yet in southern Africa to propose definite response rates for different soil textures or degrees of imperviousness. Suggested values of BFRESP for soil texture classes are given by Schulze and George (1989) in the *ACRU* User Manual.

* The second response coefficient concerns the *baseflow release* of water from the intermediate/groundwater store into the stream. This coefficient is likely to depend on factors such as geology, topography and catchment size. No research has been undertaken with the model to date to determine the magnitude of this variable, COFRU, but from experience of simulations on many small catchments, 2-5% per day (i.e. COFRU = 0.02 - 0.05) are suggested as starting values. By implication baseflow "release" at a given percentage per day from the groundwater store acts as a decay constant.

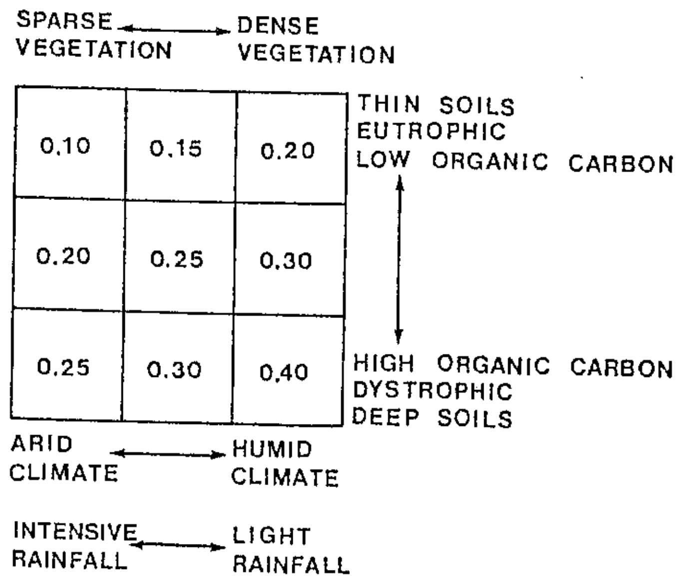

Figure 8.2.1 Suggested values of the critical stormflow response soil depth, SMDDEP (m), according to climatic, vegetation and soils characteristics

* Experience has shown that the baseflow release "decay" is not constant. Thus, when the groundwater store is large, i.e. exceeds 100 mm, COFRU is enhanced by a factor of 1.3 in *ACRU*, while when the groundwater store is low, i.e. less than 15 mm, COFRU is reduced to 0.8 of its impact value.

* * * * *

Computational procedures and sequences relating to runoff components are discussed in Chapter 9.

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CHAPTER 9

PROGRAM STRUCTURE AND SEQUENCE OF COMPUTATIONS IN *ACRU*

R.E. Schulze and W.J. George

9.1 PROGRAM STRUCTURE OF *ACRU*

The modular program structure and sequence of computations in ACRU are illustrated by way of a flowchart (Figure 9.1.1) .

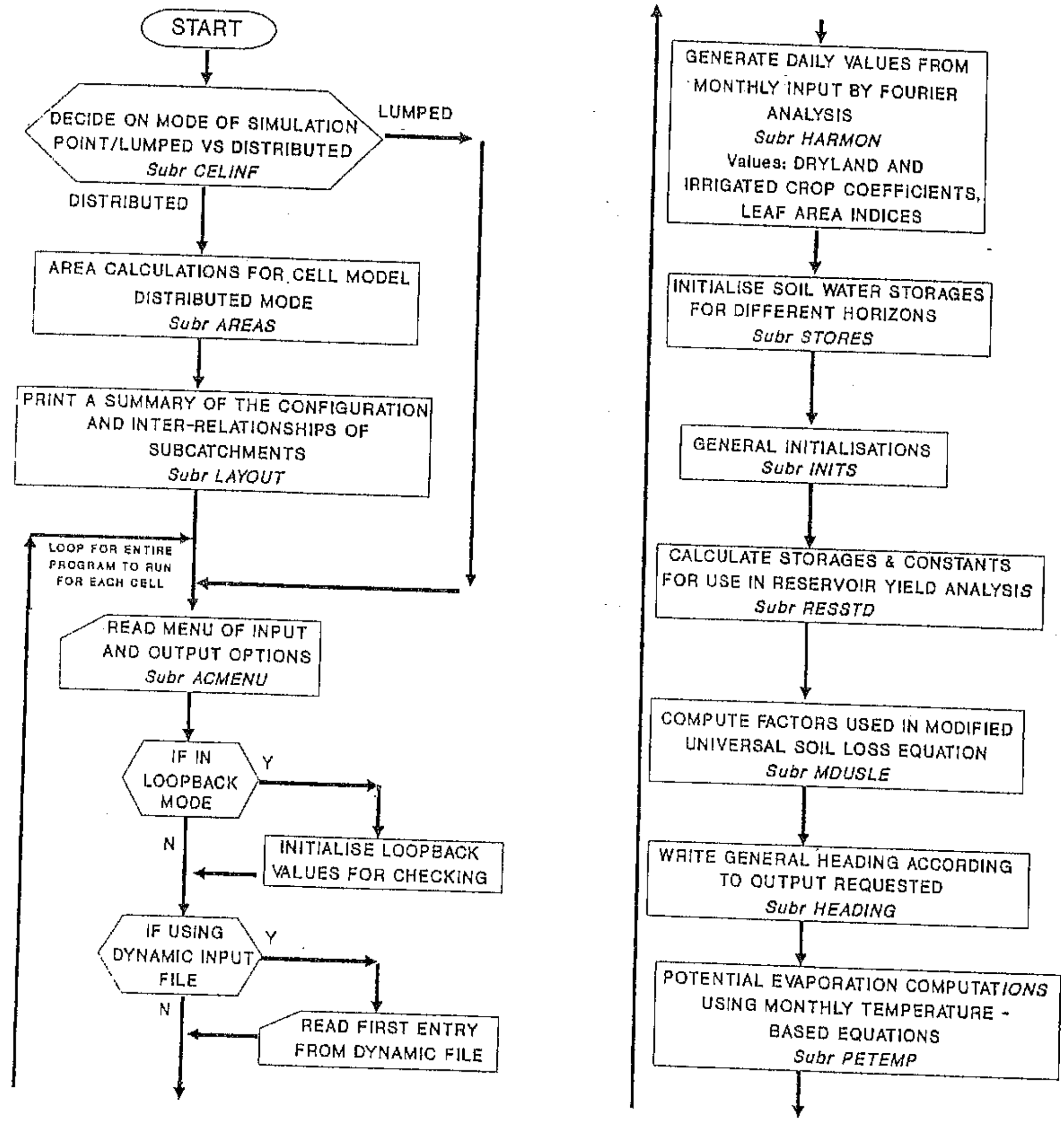

Figure 9.1.1 Program structure and sequences of computations in *ACRU*

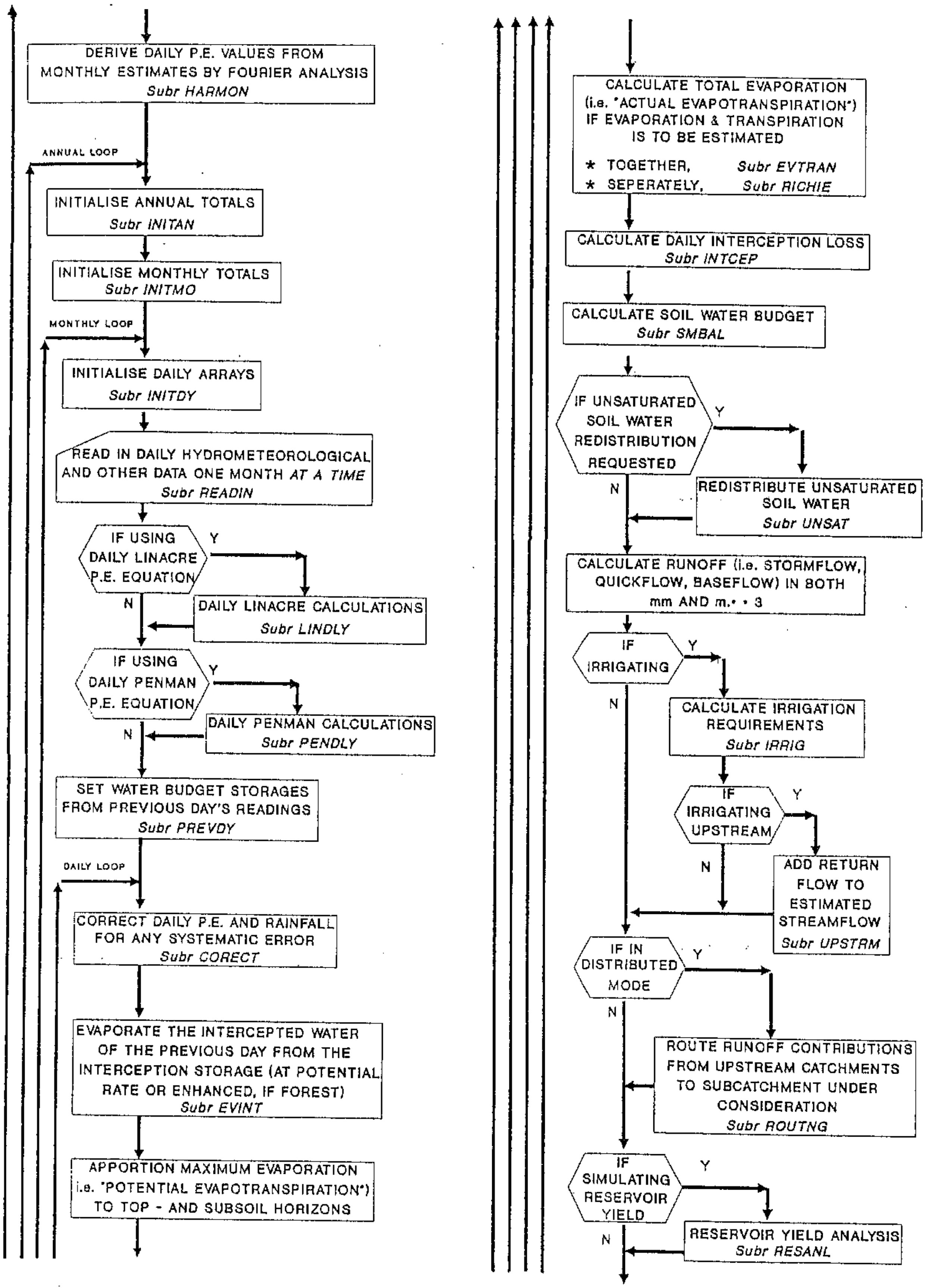

Figure 9.1.1 (continued)

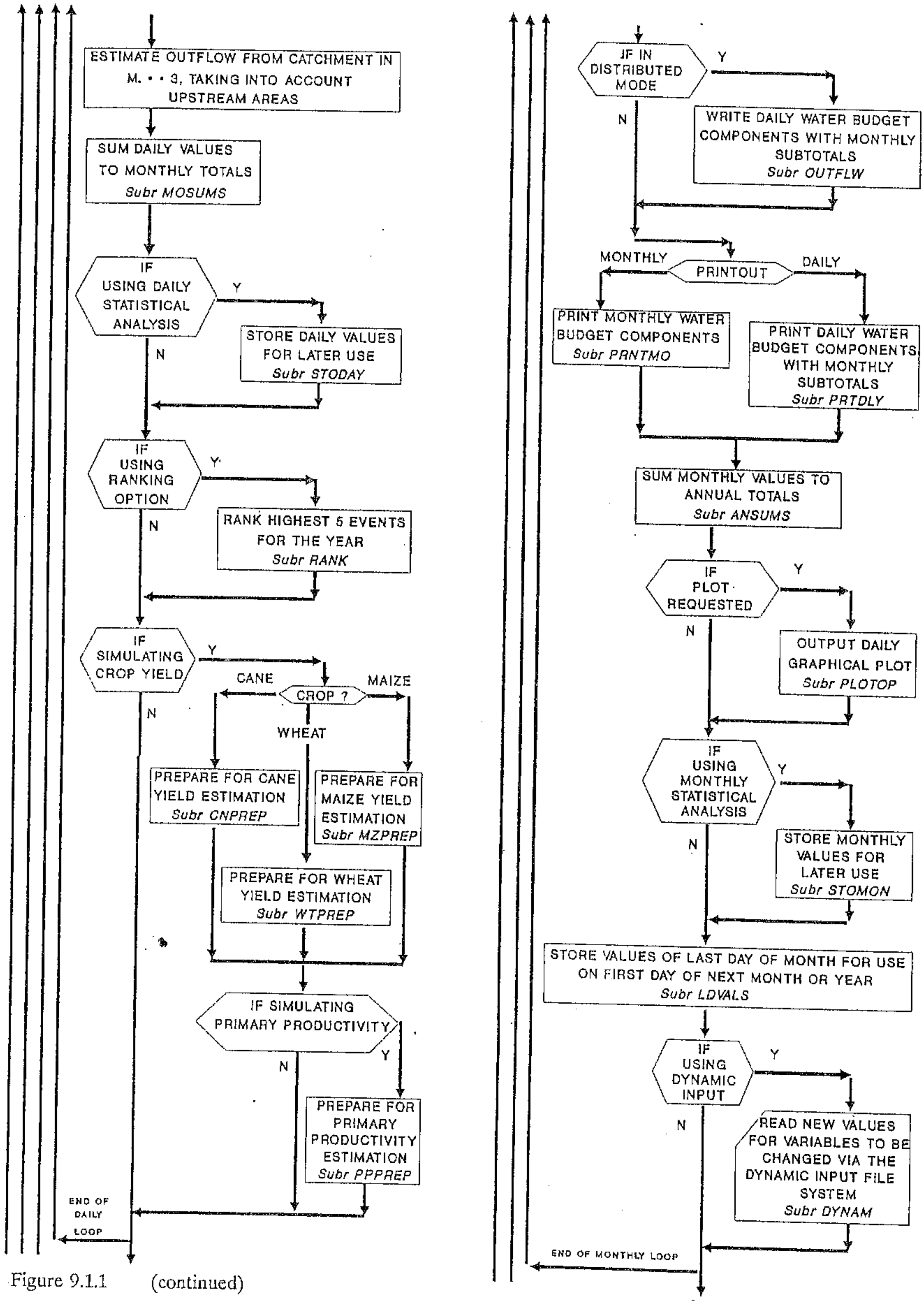

Figure 9.1.1 (continued)

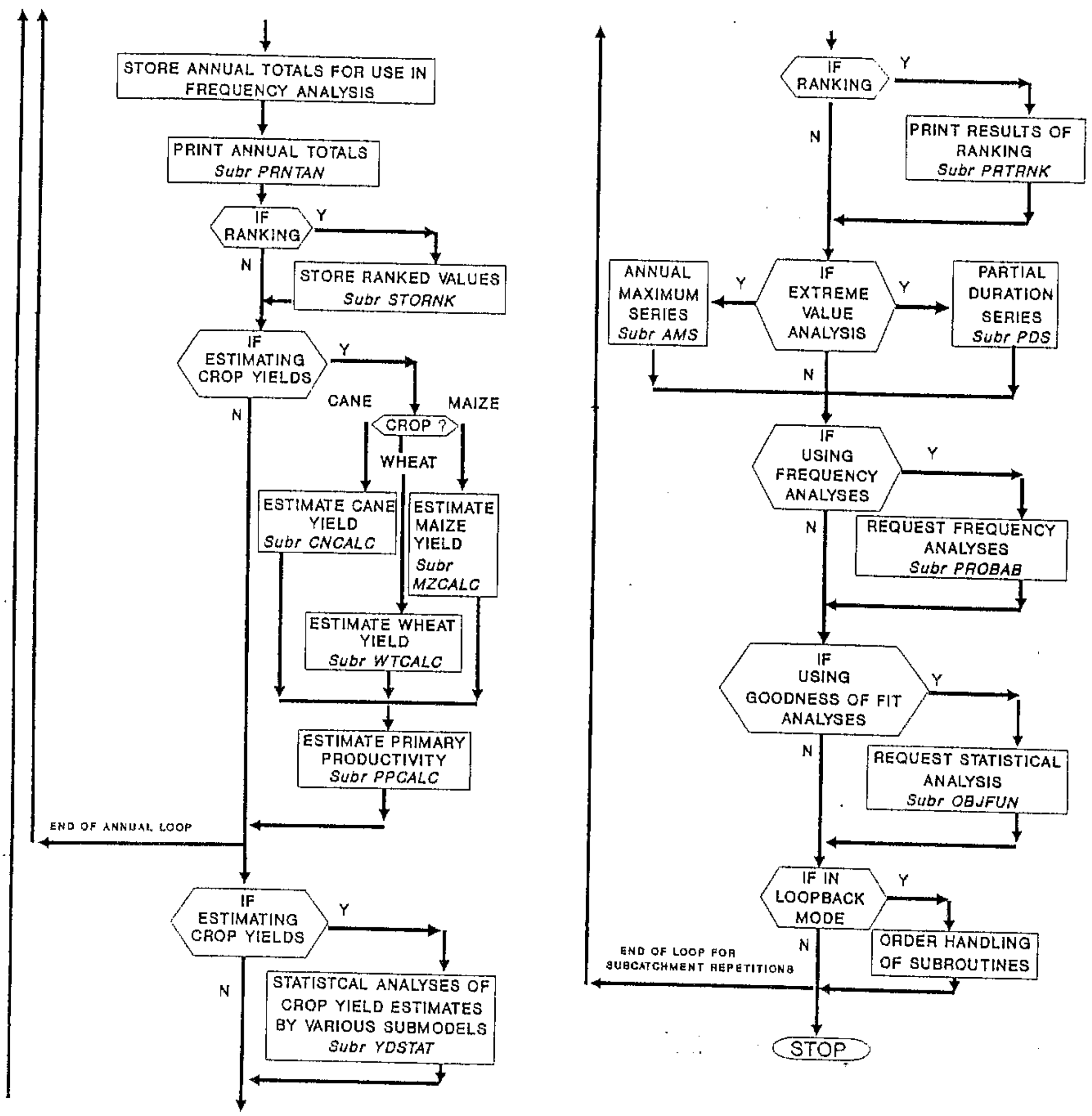

Figure 9.1.1 (continued)

9.2 COMPUTATIONAL SEQUENCES IN SOIL WATER AND RUNOFF RESPONSE BUDGETING

Soil water budgeting and runoff response lie at the core of the *ACRU* modelling system. The computational sequences involved in their routines are therefore detailed separately in this Section for a typical day with rainfall. The assumption is made that plant transpiration and soil evaporation are to be computed separately. Reference should be made to Figure 9.1.1.

* The plant intercepted water stored from the previous day, if it had rained, is first evaporated, *either* at potential rate (according to atmospheric demand) for most vegetation types/crops, *or* at an enhanced rate if the land use is forest. The remaining potential evaporation, E_{pr}, becomes available for soil water extraction.

* The maximum evaporation, E_m, i.e. the product of the reference daily A-pan equivalent evaporation and the crop coefficient for the day, is then apportioned to maximum soil evaporation (E_{sm}) and maximum plant transpiration (E_{tm}). The apportionment depends on the stage of development of the plant, which is a function of LAI. LAI, in turn, if not input directly either as a monthly mean or a daily value, is derived internally by equation from the daily crop coefficient, K_{cm}.

* The maximum evaporation available for plant transpiration, E_{tm}, is apportioned to the different soil layers in direct proportion to the root mass distributions of the respective soil layers.

* Soil evaporation, E_s, is computed from the topsoil horizon. E_s can either be occurring at maximum rate, i.e. E_{sm}, if a minimum threshold of rainfall had been measured previously and E_s occurs at "stage one" rate (Section 6.3.6), or below maximum rate once soil water content has dried to a "stage two" level, in which case E_s declines very rapidly with time.

* Plant transpiration, E_t, is calculated next, initially for the topsoil horizon.

  - First check whether the soil water content (Θ_{1i}), carried forward from the final soil water content of the previous day, is above or below the plant stress fraction, 'f'.
  - If above, $E_t = E_{tm}$ for that horizon.
  - If below, E_t is a fraction of E_{tm} for that horizon, depending on the degree of soil water stress and the value of 'f' (Section 7.2).
  - If the Θ_1 is above FC and this had been the case the previous day as well, i.e. for at least one day, then E_t is reduced to a fraction of E_{tm} depending on the amount of "excess" soil water, as illustrated in Figure 7.1.1.

* Θ_1 is reset, E_t having been abstracted.

* The above procedures are repeated for the subsoil horizon.

* The relative soil water contents of the topsoil and subsoil horizons are then compared, and if one horizon is under water deficit stress and the other is not, compensations are made by the E_t of the wet layer being enhanced (Section 7.3) if it exceeds a minimum threshold of actively growing roots.

* On a day with rainfall occurring, the stormflow-generating routines become operational.

- Soil water deficit for the critical soil depth related to stormflow response is determined either for the topsoil-horizon (if ACRU's default value is used) or for some input soil depth, as specified by variable SMDDEP (Section 8.2.2).
- Initial abstractions are computed as the product of the coefficient of initial abstraction and the soil water deficit, PO - Θ.
- If the net rainfall (observed rainfall minus interception loss) is less than the estimated initial abstractions, no stormflow is generated, the net rainfall is infiltrated into the soil and the delayed stormflow remaining from a previously generated stormflow is calculated.
- If net rainfall exceeds initial abstractions, stormflow is generated by an SCS-related equation (Section 8.2.1). This stormflow is added to the stormflow store from a previous event, quickflow is computed by applying the response coefficient QFRESP to the total stormflow store, subtracted from the stormflow store, which is then reset for the following day.

* Following stormflow abstractions Θ is reset by the addition of effective rainfall, i.e. gross rainfall minus interception minus stormflow (if net rainfall exceeds initial abstractions).

* Θ for the topsoil horizon is reassessed and if it is above FC1, a proportion of the excess water drains into the subsoil horizon, and Θ_1 is reset.

* The above is repeated for the subsoil horizon, where excess water from the A-horizon is added and if Θ_2 is above FC2, a fraction of the excess water drains to below the root zone and Θ_2 of the subsoil horizon is reset.

* Upward and downward unsaturated soil water redistribution procedures (as described in Chapter 5.5.2) are considered next and Θ_1 and Θ_2 stores are reset.

* Baseflow routines become operative next.

  - If no contribution is made to the baseflow store by drainage, baseflow release is calculated as the product of the previous day's groundwater store and the coefficient of baseflow response.
  - In computing baseflow release, the coefficient of baseflow response may be multiplied by a factor dependent on whether the store is "full" or relatively "empty" (Chapter 8).
  - The store's magnitude is then reset.
  - If a contribution is made to the baseflow store, in accordance with the amount of water available from the subsoil-horizon and its drainage coefficient (BFRESP), then this contribution is first added to the baseflow store before baseflow is released and the store is reset.

* Final values of soil water storage, evaporation and transpiration, stormflow, baseflow, quickflow and baseflow store amounts are stored, to be used as initial values the following day, and/or for daily/monthly/ other statistical output, and/or to be used in subsequent water budget related computations such as crop yield analyses.

CHAPTER 10

SIMULATION OF PEAK DISCHARGE

E.J. Schmidt and R.E. Schulze

10.1 INTRODUCTION

The estimation of peak discharge is an important component of the *ACRU* modelling system, especially with respect to the hydrological design of hydraulic structures. Actual measurements of peak discharge are rarely available at the location of concern, and estimations of design flood magnitude are normally based on the application of methods which represent the major processes affecting the runoff response of a catchment to rainfall. Peak discharge from small catchments is related closely to runoff volume, (Rogers, 1980; Schmidt and Schulze, 1984) and the accurate estimation of antecedent soil water status and hence runoff volume is of primary importance in determining peak discharge. Thus the use of a daily runoff model, such as *ACRU*, which simulates soil water status in a physical-conceptual manner, and hence accounts for the joint association between rainfall amount and soil water regime, allows for a realistic representation of daily runoff volume and hence peak discharge.

The *ACRU* model can be used to estimate the peak discharge associated with each day's runoff volume generated for the selected simulation period. The annual maximum or partial duration series of daily peak discharge can then be extracted and an extreme value distribution fitted to such events in order to quantify the expected magnitude of a flood of selected risk of non-exceedence. Schmidt, Schulze and Dunsmore (1985) and Dunsmore, Schulze and Schmidt (1986) provide verification of estimates of design runoff volume and peak discharge using the *ACRU* model and the verification is discussed in Chapter 17.

10.2 THE SCS PEAK DISCHARGE EQUATIONS

The *ACRU* model utilises the United States Department of Agriculture's Soil Conservation Service (SCS) unit hydrograph concepts in order to compute the peak discharge from the generated daily stormflow volume (United States Department of Agriculture, 1972). The SCS unit hydrograph, which is considered to be an average characteristic of small agricultural catchments, has a triangular shape with 37.5% of the total stormflow volume under the rising limb. Typically standard unit hydrograph convolution procedures are used to superimpose the unit hydrographs according to the effective rainfall intensity distribution. However, when using a daily model and in the absence of recording rainfall data, a uniform rainfall distribution has been assumed and hence in *ACRU* a single rather than an incremental unit hydrograph is used for peak discharge computation. Should recording rainfall data be available for use in runoff simulation, or alternatively should the complete hydrograph be desired for routing between subcatchments, the suite of programs discussed by Caldecott (1989), which utilise the *ACRU* modelling system, should be considered for use. An intensive review of the developments and application of the SCS procedures for southern Africa is given by

Schmidt and Schulze (1987). Assuming a single triangular hydrograph the equation for peak discharge, q_p, is expressed as

$$q_p = \frac{0.2083\ A\ Q}{\frac{D}{2} + L} \qquad \text{..... Eq. 10.2.1}$$

where

q_p = peak discharge ($m^3.s^{-1}$)
Q = runoff depth (mm)
A = catchment area (km^2)
L = catchment lag time (h) and
D = effective storm duration (h).

For design storms and in the absence of information for individual events the storm duration, D, is assumed equal to the catchment's time of concentration, T_c, which is related empirically to lag time, L, as $L = 0.6\ T_c$ (United States Department of Agriculture, 1972). The denominator in Equation 10.2.1 may thus be expressed as 1.83 L.

10.3 ESTIMATION OF CATCHMENT LAG TIME

The index of catchment response time, L, represents the weighted average of the time for runoff from each point of the catchment to reach the catchment outlet. It can be estimated from historical hydrographs as described by Schmidt and Schulze (1984) or from specific catchment characteristics such as catchment slope, hydraulic length and flow retardance using hydraulic principles, or by means of empirical equations.

10.3.1 Estimation Of Lag Time By Hydraulic Principles

The time of concentration, T_c, of a catchment is the time taken for runoff to travel from the hydraulically most distant part of a catchment to the point of reference. As indicated previously L is related to T_c by the equation :

$$L = 0.6\ T_c \qquad \text{..... Eq. 10.3.1}$$

Time of concentration may be computed by summing the flow travel times along the various reaches comprising the flow path of water from the hydraulically most distant point. The travel time in each flow reach is determined by dividing reach length (in m) by flow velocity as determined from uniform flow equations (e.g. Manning's equation) for full flow conditions. The time of concentration (in h) can then be calculated from the following equation :

$$T_c = \sum_{i=1}^{n} \frac{H_{li}}{v_i \times 3600}$$

where

H_{li} = hydraulic length of reach i (m),
v_i = flow velocity in reach i ($m.s^{-1}$), and
n = number of reaches.

Application of Equation 10.3.1 then provides an estimate of L. When the flow phases contributing to the hydraulically most distant point are not defined clearly, as is frequently the case for a catchment which does not have a well developed drainage system, one of the following two empirical equations can be applied.

10.3.2 The SCS Lag Equation

An empirical lag equation, which was developed by the United States Department of Agriculture (1972) to represent a broad set of land uses, for catchment areas of less than $10km^2$ is given as

$$L = \frac{H_l^{0.8} (S' + 25.4)^{0.7}}{7\,069\, S_{\%}^{0.5}} \quad \text{..... Eq. 10.3.2}$$

where

L = catchment lag time (h),

H_l = hydraulic length of catchment along the main channel (m),

$S_{\%}$ = average catchment slope (%), and

$S' = \frac{25\,400}{CNII} - 254$

with

CNII = retardance factor approximated by the runoff Curve Number for average catchment antecedent wetness.

Values for CNII are given in Table 10.3.1 for various land use/land treatment classes, hydrological soil groups and runoff potentials. The hydrological soil group is provided for each of the 501 series defined for southern Africa in the *ACRU* User Manual (Schulze and George, 1989). Runoff potential refers to the effects of management practices on runoff response. Thus a management practice such as uncontrolled grazing producing poor veld condition will result in high runoff potential while the use of conservation practices such as minimum tillage in cultivated lands will produce low runoff potential. It is recommended that where CNII is less than 50, a value of 50 be assumed and where it is greater than 95, a value of 95 be assumed.

The hydraulic length, H_l, of the catchment is the length of the main stream to the furthest catchment divide, as measured from a contour map. In the absence of a contour map H_l may be approximated by

$$H_l = 1\,738\, A^{0.6}$$

where

A = catchment area (km^2)

10.3.3 The Schmidt-Schulze Lag Equation

An alternative lag equation, using data from the USA and from southern Africa was developed by Schmidt and Schulze (1984) and is given as

$$L = \frac{A^{0.35}\, MAP^{1.1}}{41.67\, S_{\%}^{0.3}\, \bar{I}_{30}^{0.87}} \quad \text{..... Eq. 10.3.3}$$

where

L = catchment lag time (h),

A = catchment area (km^2),

MAP = mean annual precipitation (mm),

$S_{\%}$ = average catchment slope (%), and

$\bar{I}_{30}$ = 2-year return period 30-minute rainfall intensity ($mm.h^{-1}$).

Mean catchment slope, $S_{\%}$, may be determined from the equation given below :

$$S_{\%} = \frac{M\, N \times 10^{-4}}{A}$$

where

M = total length of all contour lines within the catchment (m), according to the scale of the map,

N = contour interval (m), and

A = catchment area (km^2).

Slope can alternatively be determined by covering a catchment contour map with a rectilinear grid and evaluating the slope, perpendicular to the contour lines at each grid intersection point. The mean catchment slope is then determined by averaging. It is recommended that at least 20 points be used to estimate mean catchment slope.

Table 10.3.1 Runoff Curve Numbers CNII for selected land use/treatment classes, hydrological soil groups and runoff potentials (after Schmidt and Schulze, 1987)

LAND USE	TREATMENT/PRACTICE/DESCRIPTION	RUNOFF POTENTIAL (page 12)	HYDROLOGICAL SOIL GROUP A	A/B	B	B/C	C	C/D	D
Fallow	Straight row	-	77	82	86	89	91	93	94
Row crops	Straight row	High	72	77	81	85	88	90	91
	Straight row	Low	67	73	78	82	85	87	89
	Planted on contour	High	70	75	79	82	84	86	88
	Planted on contour	Low	65	70	75	79	82	84	86
	Conservation structures	High	66	70	74	77	80	81	82
	Conservation structures	Low	62	67	71	75	78	80	81
Garden crops	-	-	45	56	66	72	77	80	83
Small grain	Straight row	High	65	71	76	80	84	86	88
	Straight row	Low	63	69	75	79	83	85	87
	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 - 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
Close 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 structure	High	63	68	73	77	80	82	83
	Conservation structure	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: < 50% cover	-	67	73	78	82	85	87	89
	Straight row	-	49	60	69	73	79	82	84
	Straight row: > 75% cover	-	39	50	61	68	74	78	80
	Planted on contour: < 50% cover	-	65	70	75	79	82	84	86
	Planted on contour	-	25	46	59	67	75	80	83
	Planted on contour: > 75% cover	-	6	14	35	59	70	75	79
Pasture or veld (range)	-	High	68	74	79	83	86	88	89
	-	Medium	49	61	69	75	79	82	84
	-	Low	39	51	61	68	74	78	80
	Planted on contour	High	47	57	67	75	81	85	88
	Planted on contour	Medium	25	46	59	67	75	80	83
	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
Natural forest		High	45	56	66	72	77	80	83
		Medium	36	49	60	68	73	77	79
		Low	25	47	55	64	70	74	77
Scrub	Brush - winter rainfall region	-	28	34	44	53	60	64	66
Orchards	Winter region, understory of crop cover	Low	39	44	53	61	66	69	71
Forests/plantations		High	52	62	72	77	82	85	87
		Medium	41	53	64	69	74	77	80
		Low	30	43	56	61	66	69	72
Urban/suburban land uses	Open spaces, parks, cemeteries	(75% + grass cover)	39	51	61	68	74	78	80
		(50-75% grass cover)	49	61	69	75	79	82	84
	Commerical/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 500m²	65% impervious	77	81	85	88	90	91	92
	1 000m²	38% impervious	61	69	75	80	83	85	87
	1 350m²	30% impervious	57	65	72	77	81	84	86
	2 000m²	25% impervious	54	63	70	76	80	83	85
	4 000m²	20% 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
	gravel		76	81	85	88	89	90	91
	dirt		72	77	82	85	87	88	89
	dirt-hard surface		74	79	84	88	90	91	92
	GENERALISED CURVE NUMBERS								
	Agriculture		63	66	69	74	77	79	82
	Open space		36	49	60	67	73	76	78
	Forest		25	47	55	64	70	74	77
	Disturbed land		72	77	82	85	88	89	90
	Residential		61	69	76	81	84	86	88
	Paved		98	98	98	98	98	98	98
	Commerical - Industrial		84	86	88	89	90	91	93

The 2-year return period 30-minute rainfall intensity, $\overline{I}_{30}$, is related to the rainfall intensity patterns occurring typically in a region. It may be computed for southern Africa by multiplying the 2-year return period one-day rainfall depth presented in Figure 10.3.1 by an intensity multiplication factor given in Table 10.3.2 for various rainfall distribution zones. The rainfall distribution zones as delimited for southern Africa are identified in Figure 10.3.2. Weddepohl (1988) describes the procedures used to delimit the rainfall distribution zones, while Schmidt and Schulze (1987) discuss in more detail the use of Equations 10.3.2 and 10.3.3.

10.3.4 On The Selection Of An Empirical Lag Equation

It is suggested that the use of the above empirical equations should be restricted to catchments where hydraulic calculations of flow velocity for various reaches cannot be made. The Schmidt-Schulze lag equation has been shown to generally give estimates of lag time which are longer than those obtained using the SCS equation. Verification studies have shown that the Schmidt-Schulze lag equation should be used in preference to the SCS equation on natural catchments with good surface cover and where stormflow response is comprised not only of surface runoff (e.g. in areas of high mean annual precipitation). The SCS lag equation appears more suited to more arid areas of limited vegetation cover and shallow soils.

10.4 SIMULATION OF PEAK DISCHARGE IN *ACRU*

In the *ACRU* model peak discharge refers to the highest instantaneous rate of runoff occurring during a given day from the *total* hydrograph. It is therefore comprised of the peak discharge in $m^3.s^{-1}$ calculated from the day's generated stormflow, as given by Equation 10.2.1, superimposed on the mean baseflow for the day in $m^3.s^{-1}$ and the carry-over for the day of mean quickflow from the previous day's stormflow, also in $m^3.s^{-1}$.

10.5 PROCEDURES FOR VERIFYING SIMULATIONS OF PEAK DISCHARGE IN *ACRU*

The *ACRU* model facilitates observed daily peak discharge rates to be read in via the hydrometeorological input data file when the variable IOBSPK is set equal to 1. Simulation of peak discharge, i.e. when the variable PEAK = 1, then enables verifications to be undertaken in *ACRU* of the peak discharge estimates for the various lag equation options. The goodness of fit statistics discussed in Chapter 16 can then be used to assess modelling errors and a comparison of peak discharge rates for various risks of non-exceedence can be made using extreme value distributions fitted to the observed and simulated annual maximum series (c.f. Section 16.4). Examples of the verification of peak discharge simulations by *ACRU* are given in Chapter 17.

Table 10.3.2 Multiplication factors used in the determination of $\overline{I}_{30}$

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

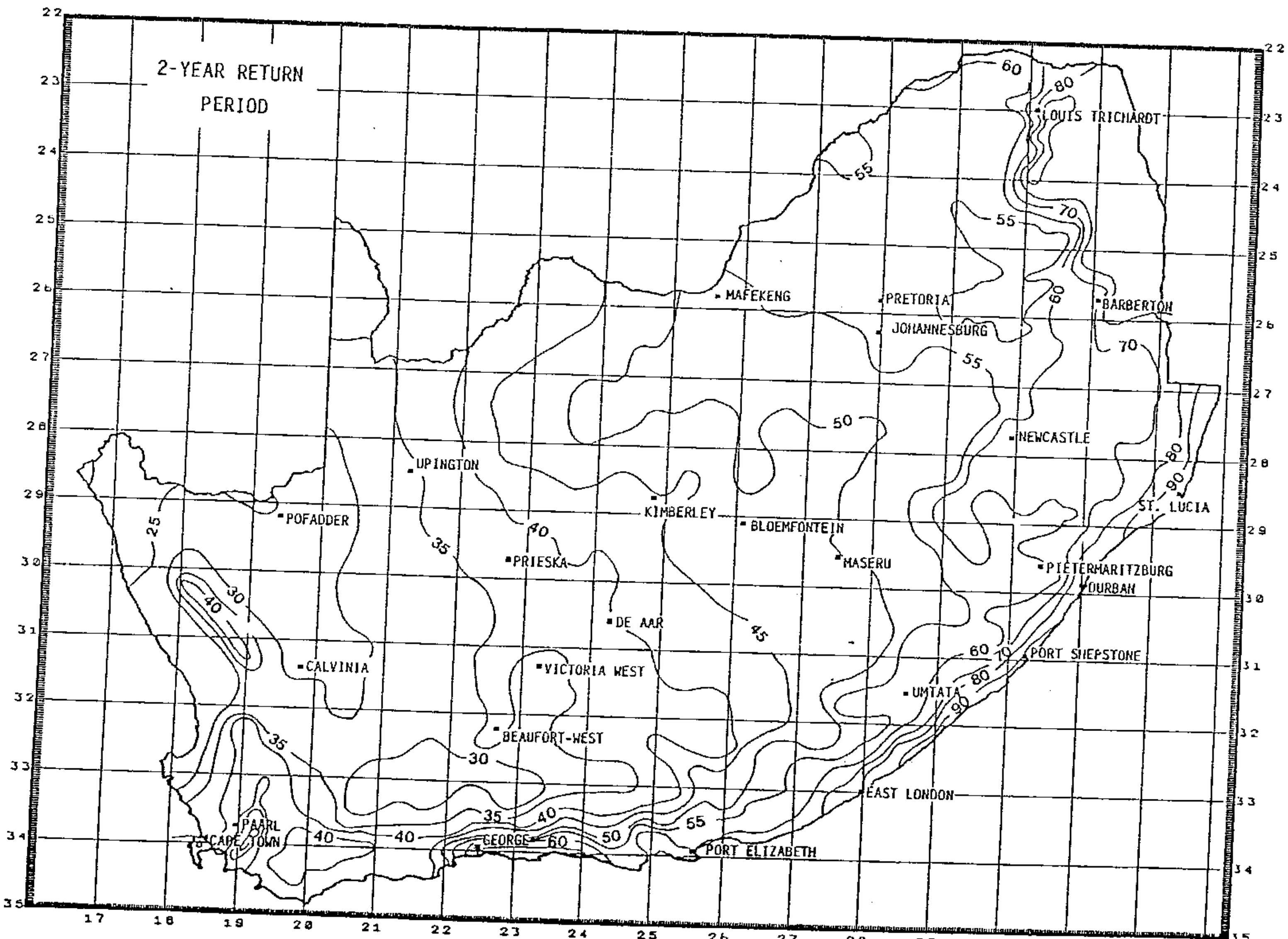

Figure 10.3.1 Expected maximum one-day rainfall in southern Africa for 2-year return periods (after Schmidt and Schulze, 1987)

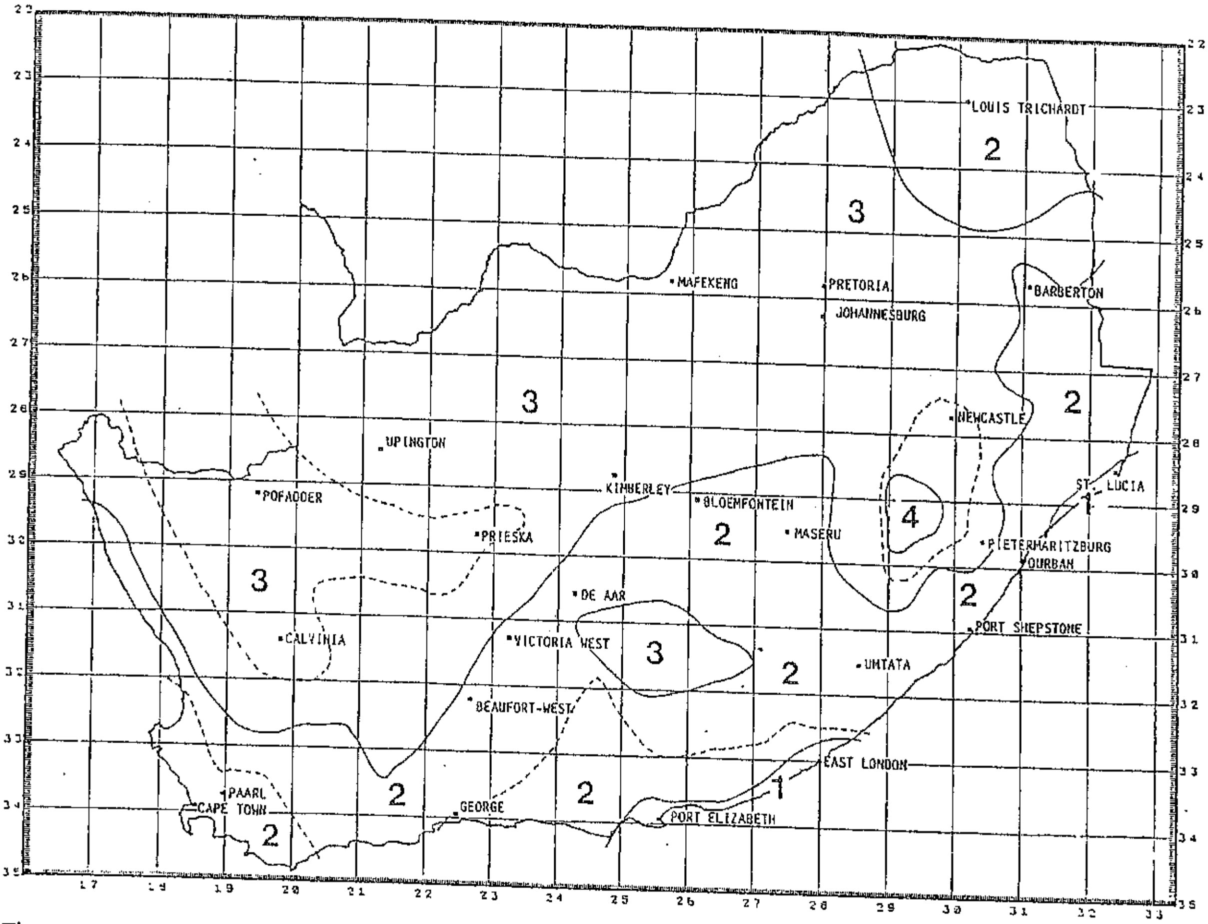

Figure 10.3.2 Regionalisation of rainfall distributions in southern Africa (after Weddepohl, 1988)

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CHAPTER 11

SIMULATION OF SEDIMENT YIELD

E.J. Schmidt

11.1 INTRODUCTION

Soil erosion in southern Africa is a serious problem due to one or a combination of

* arid climatic conditions,

* intense thundershower activity with inherent high rainfall erosivity,

* shallow erodible soils, and

* limited vegetation cover and poor conservation management techniques.

It has been estimated that the average annual sediment load carried by southern African rivers is approximately 100 - 150 million tonnes (Rooseboom, 1975). The loss of topsoil and attendant crop production potential reduction and the decrease in the storage capacity of reservoirs, together with the environmental degradation associated with soil erosion and sediment transportation, remain one of the major problems facing the development of the water resources of southern Africa.

There is as yet no simple procedure for predicting the sediment production from a catchment. Complex deterministic models representing erosion processes and sediment transport: deposition functions do exist. However, such models remain of limited practical value owing to the requirements for input parameters which are unobtainable other than from a research catchment, and the reliance of these models on calibration.

Simple empirical methods do, however, meet the requirements for initial planning and design and in the absence of gauged data, are the basis for most water resources decisions. The Universal Soil Loss Equation, USLE (Wischmeier and Smith, 1978), is the method that has received greatest recognition worldwide, has seen most application and is the foundation for many other empirical equations, including the Modified USLE (Williams, 1975). The USLE provides for an estimate of the long term average annual soil loss due to sheet and rill erosion. It thus excludes the soil loss due to concentrated flow and gulley formation and requires the inclusion of a separate term to represent the delivery ratio which accounts for the portion of eroded soil which leaves the catchment.

An advantage in the use of the USLE and MUSLE equations is that components of the equations have been researched extensively, also for southern African conditions. Smithen (1981), for example, investigated the areal distribution of rainfall erosivity and Smithen and Schulze (1982) presented equations to assist in its prediction at locations in southern Africa where recording rainfall data are not available. The State Directorate of Agricultural Engineering and Water Supply in South Africa have evaluated in the past, and continue to evaluate, the erodibility of southern African soils and the effects of conservation practices and crop cover conditions on soil loss (Crosby, Smithen and McPhee, 1981; McPhee, Smithen, Venter, Hartmann and Crosby, 1983). Furthermore, the South African Sugar Association's Experiment Station (Platford, 1982) and the Natal Parks Board (Venter, 1988) have undertaken research to improve the application of the USLE as a decision tool in sugarcane farming and in game management respectively.

11.2 ESTIMATION OF SEDIMENT YIELD BY THE 'MUSLE'

The USLE was developed empirically from a large data base and the component factors of the equation, while being physical determinants of soil loss, represent statistical and not strictly physical interrelationships. The equation, which is valid for estimating the long term average annual soil loss, is not directly applicable to determining soil loss estimates for individual storms. The USLE equation is given as

$$A = RKLSCP$$

where

- A = the computed long term average soil loss per unit area ($t.ha^{-1}.annum^{-1}$)
- R = an index of rainfall erosivity ($J.mm.1000^{-1}.m^{-2}.h^{-1}$)
- K = soil erodibility factor (dimensionless)
- LS = slope length and gradient factor (dimensionless)
- C = cover and management factor (dimensionless)
- P = support practice factor (dimensionless).

The rainfall erosivity factor, which is the long term average annual product of rainfall energy and its maximum 30 minute intensity (EI_{30}), may be determined in southern Africa from information presented by Smithen and Schulze (1982). The USLE was modified by Williams (1975), who replaced the rainfall erosivity factor with a runoff factor. This modification, termed the MUSLE, allows for the prediction of sediment yield directly, thereby eliminating the need for sediment delivery ratios, and is applicable for individual storm events (Williams and Berndt, 1977). The MUSLE is expressed as

$$Y_{sd} = 11.8\ (Q.q_p)^{0.56}\ KLSCP$$

where

- Y_{sd} = sediment yield from an individual event (tonne)
- Q = storm runoff volume for the event (m^3) and
- q_p = peak discharge for the event ($m^3.s^{-1}$).

The factors K, LS, C and P are taken directly from the USLE. In *ACRU*, estimates of Q and q_p, are obtained using the techniques described in Chapters 8 and 10. Although Q and q_p are highly correlated, Q is more related to the detachment process while q_p is associated with sediment transport (Williams and Berndt, 1977).

11.3 THE SOIL ERODIBILITY FACTOR

The soil erodibility factor, K (*ACRU* variable = SOIFAC), may be estimated from a nomograph developed by Wischmeier, Johnson and Cross (1971) with consideration given to per cent silt plus very fine sand, per cent sand, per cent organic matter, soil structure and permeability of the eroding land surface (Figure 11.3.1). With regard to southern African soils, K- values can be assigned on the basis of experience and field experimentation. Southern

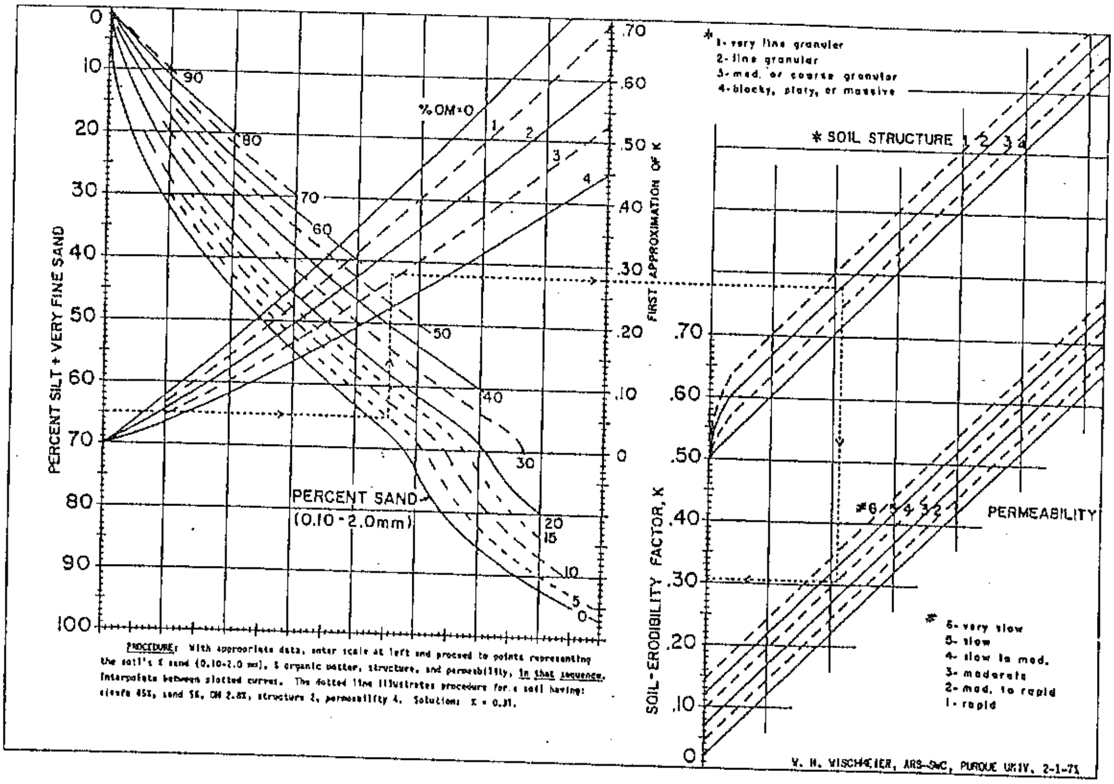

Figure 11.3.1 The soil erodibility nomograph to estimate K-values in the MUSLE (after Wischmeier *et al.*, 1971)

Table 11.3.1 Erodibility factors for various erodibility classes

Erodibility Class	K-value
Very high	> 0.70
High	0.50 - 0.70
Moderate	0.25 - 0.50
Low	0.13 - 0.25
Very low	< 0.25

African soils were rated according to their erodibility by the then Department of Agricultural Technical Services, DATS (DATS, 1976) and approximate K values can be allocated to each of the soil forms and series given in the *ACRU* User Manual (Schulze and George, 1989) in terms of the erodibility classes given in Table 11.3.1. Further information on measured soil erodibility factors is presented by McPhee *et al.* (1983). A weighted value of K can be determined for a catchment area from a suitable soils map depicting soil forms and series. The Land Type maps published by the Soils and Irrigation Research Institute, SIRI, of the Department of Agriculture and Water Supply, provide a useful source of information in this regard (SIRI, 1987).

11.4 THE SLOPE LENGTH FACTOR

The length of a slope of land and its gradient affect the rate of soil erosion by water substantially. Slope length is defined as the distance from the point of origin of overland flow to the point where either the slope gradient decreases sufficiently for deposition to take place or the runoff enters a well defined natural or artificially constructed channel. Thus in a contoured land the slope length, L, would be equal to the distance between contours. The slope length, expressed in m, is often difficult to estimate in the field, but can be related to slope gradient S (Williams and Berndt, 1977), and has been given by Schulze (1979) as

$$L = -3.0S_{\%} + 100 \qquad \text{for } S < 25\%$$

and

$$L = 25 \qquad \text{for } S \geq 25\%$$

where

$S_{\%}$ = slope gradient in per cent.

The slope gradient factor is expressed as the mean catchment slope (in per cent) and is obtained from topographic maps. In the MUSLE equation the two effects, L and S, are combined into a slope length factor, LS (*ACRU* variable = ELFACT), which may be determined using the following equation

$$LS = \left[\frac{L}{22.1}\right]^m \times \frac{(430\ S^2 + 30\ S + 0.43)}{6.613}$$

where

L = slope length (m), determined by equation or from field layout

S = slope of land expressed as a fraction (i.e. $S_{\%}/100$) and

m = 0.3 for slope <0.03
 = 0.4 for slope <0.05 and >0.03
 = 0.5 for slope >0.05.

11.5 THE COVER AND MANAGEMENT FACTOR

The Cover and Management factor, C (*ACRU* variable COVER), is possibly the most important factor in the MUSLE equation, due to its considerable range the difficulties in its estimation as well as its variation during the year. The C-factor is made up of three subfactors to account for the effect of canopy, surface vegetation or mulch cover, and residual effects, which are related to management. The C-factor is thus related to cropping history, management techniques as well as current vegetation cover. Furthermore, C varies during the year with cropping rotations and operations and the natural growth patterns brought about by the changes in season. The overall erosion reducing effectiveness of a crop therefore depends largely on the magnitude of the C-factor when rainfall produces large flood volumes and high peak discharges occur. In order to establish the magnitude of the C-factor for a given period the three subfactors of canopy cover, mulch cover and residual/management effects must be quantified.

11.5.1 Cultivated Crops

The effects of the first two subfactors, viz. canopy cover and mulch cover, are considered together and in the case of cultivated crops, values for a soil loss ratio, SR1, for any stage of growth are obtained from Figures 11.5.1 and 11.5.2 which combine canopy cover and mulch

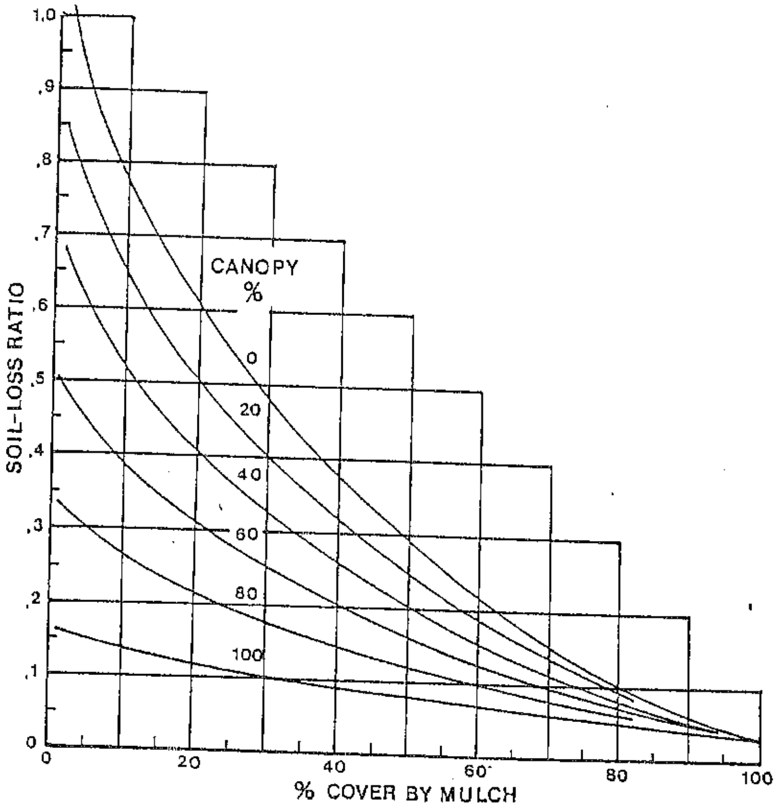

Figure 11.5.1 Combined mulch and canopy effects for cultivated crops when average fall distance of drops to the ground is about 0.5 m (after Wischmeier and Smith, 1978)

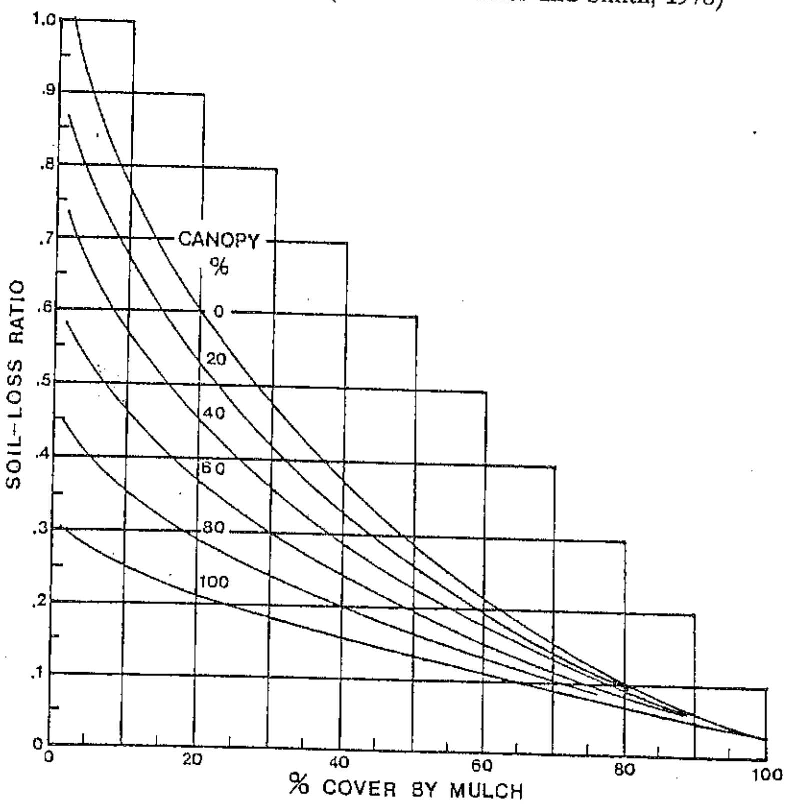

Figure 11.5.2 Combined mulch and canopy effects for cultivated crops when average fall distance of drops to the ground is about 1.0 m (after Wischmeier and Smith, 1978)

effects. It can be deduced from Figures 11.5.1 and 11.5.2 that mulch cover which is in contact with the ground provides a greater protection than a similar canopy cover, the effects of which are related to the average fall height between such canopy and the soil surface.

The third subfactor, accounting for residual/ management effects, is quantified using a second soil loss ratio, SR2, and is more difficult to assess. It is suggested that 0.5 be used for the second soil loss ratio for periods when the seedbed is either cloddy, ridged, compacted or for the first year after a grass crop has been ploughed in (Crosby, Smithen and McPhee, 1981). Each of these practices will have a combining effect on reducing soil loss and thus a seedbed prepared following a year of lucerne production (SR2=0.5) which is also ridged (SR2=0.5) will have a combined residual/management soil loss ratio of 0.5 x 0.5 or 0.25 (Crosby *et al.*, 1981). The cover and management factor, C, is the product of the two soil loss ratios (SR1 x SR2) and is computed for various stages of growth : input on a monthly or daily basis to the *ACRU* model. A more detailed account of the C-factor is presented by Wischmeier and Smith (1978).

11.5.2 Uncultivated Land

The approach to determine C in the cases of pastures, veld, bush and forests is far more direct. As a general rule under these land uses the protection afforded to the soil does not vary significantly throughout the year and residual effects are not marked. Wischmeier and Smith (1978) presented a table (Table 11.5.1) which can be used to derive average annual C-factors for permanent pasture, veld and woodland. Adjustments can be introduced to represent expected monthly variations on consideration of the protection afforded at different times of the year.

Table 11.5.2 should be used to estimate Cover factors for undisturbed forest land (Wischmeier and Smith, 1978).

Input of the crop management factor into the *ACRU* model will depend on the nature of the catchment land use. Monthly C-factors would commonly be determined using the methods described above. However, when the effects of cultivation, crop production or other practices (such as veld burning) are being evaluated during which marked variations of the C-factor will occur over a short period of time, daily C-factors can be included in the data files (for example, Everson, George and Schulze, 1989).

11.6 SUPPORT PRACTICE FACTOR

When sloping land is cultivated the protection afforded by the vegetation cover is frequently supported by conservation practices such as contour tillage and contour bank systems. Stabilised waterways are a necessary part of each of these practices. While minimum tillage practices, crop rotations and controlled seedbed preparation contribute to erosion reduction, these factors are considered in the crop and management factor. Cultivated land which is tilled directly up and downslope will have a P-factor (*ACRU* variable = PFACT) of unity. Tillage and planting on the contour reduces soil erosion, depending on the slope of the land. Maximum protection is afforded by slopes between 3 and 8 per cent. Table 11.6.1 provides P-values for contour tilled lands. Contour

Table 11.5.1 Cover factor, C, for permanent pasture, veld and woodland[1] (after Wischmeier and Smith, 1978)

Vegetative canopy		Cover that contacts the soil surface						
Type and height[2]	Per cent cover[3]	Type[4]	Per cent ground cover 0	20	40	60	80	95+
No appreciable canopy	25	G	.45	.20	.10	.042	.013	.003
		W	.45	.24	.15	.091	.043	.011
Grassland or short brush with average drop fall height of 0.5 m	25	G	.36	.17	.09	.038	.013	.003
		W	.36	.20	.13	.083	.041	.011
	50	G	.26	.13	.07	.035	.012	.003
		W	.26	.16	.11	.076	.039	.011
	75	G	.17	.10	.06	.032	.011	.003
		W	.17	.12	.09	.068	.038	.011
Appreciable brush or bushes, with average drop fall height of 2 m	25	G	.40	.18	.09	.040	.013	.003
		W	.40	.22	.14	.087	.042	.011
	50	G	.34	.16	.08	.038	.012	.003
		W	.34	.19	.13	.082	.041	.011
	75	G	.28	.14	.08	.036	.012	.003
		W	.28	.17	.12	.078	.040	.011
Trees, but no appreciable low brush. Average drop fall height of 4 m	25	G	.42	.19	.10	.041	.013	.003
		W	.42	.23	.14	.089	.042	.011
	50	G	.39	.18	.09	.040	.013	.003
		W	.39	.21	.14	.087	.042	.011
	75	G	.36	.17	.09	.039	.012	.003
		W	.36	.20	.13	.084	.041	.011

1 The listed C values assume that the vegetation and mulch are distributed randomly over the entire area.

2 Canopy height is measured as the average fall height of water drops falling from the canopy to the ground. Canopy effect is inversely proportional to drop fall height and is negligible if fall height exceeds 10 m.

3 Portion of total-area surface that would be hidden from view by canopy in a vertical projection (a bird's-eye view).

4 G:cover at surface is grass, grasslike plants, decaying compacted duff, or litter at least 50 mm deep. W:cover at surface is mostly broadleaf herbaceous plants (e.g. weeds with little lateral-root network near the surface) or undecayed residues or both.

banks are more effective than tillage on the contour without contour banks, since in the former instance the slope is divided into segments and substantial deposition occurs within the contour bank. Table 11.6.1 also provides the P-values for lands which include contour banks. For uncultivated lands the P-factor is generally assumed equal to unity.

Table 11.5.2 C-factor for undisturbed forest land (after Wischmeier and Smith, 1978)

Per cent of area covered by canopy of trees and undergrowth	Per cent of area covered by litter at least 50 mm deep	Cover Factor[1]
100 - 75	100 - 90	.0001 - .001
70 - 45	85 - 75	.002 - .004
40 - 20	70 - 40	.003 - .009

1 The ranges in listed C values are caused by the ranges in the specified forest litter and canopy covers and by variations in effective canopy heights.

Table 11.6.1 P-values for contour tilled lands and lands with contour banks (after Wischmeier and Smith, 1978)

Land slope (%)	Contour Tilled	Contour Banks with Grassed Waterways
1 - 2	0.60	0.12
3 - 8	0.50	0.10
9 - 12	0.60	0.12
13 - 16	0.70	0.14
17 - 20	0.80	0.16
21 - 25	0.90	0.18

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CHAPTER 12

IRRIGATION WATER DEMAND

R.E. Schulze and P.W. Furniss

12.1 BACKGROUND

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

* if the water consumption of the plant, i.e. its maximum evaporation, can be estimated for the period,
* if the amount of water from rainfall, which replenishes soil water, is known,
* if it is known how much water the soil can hold in the active root zone, and
* if it is known how much water can be withdrawn from the soil before plant stress sets in.

The *ACRU* irrigation requirements routines incorporate the above factors and, furthermore, also consider different modes of irrigation scheduling which may be appropriate to prevailing climatic and crop conditions, in a daily soil water budget option which runs parallel with the dryland catchment water budgeting routines of the model. In this version of the *ACRU* irrigation submodels a single soil layer of varying depth (according to crop type, growth stage and soil properties) is used in computations.

The various irrigation water demand considerations and options available in the *ACRU* modelling system are shown schematically in Figure 12.1.1

12.2 MODES OF SCHEDULING

Modes of irrigation scheduling depend, *inter alia*, on the irrigation system (i.e. equipment), the level of management, water availability, climatic conditions, the type of crop and its stage of growth. Four modes of scheduling (variable name = SCHED) are currently available in *ACRU* and the mode may be changed from one to another on a month by month basis in the course of a year, depending on crop and climatic demand or other irrigation constraints.

12.2.1 Irrigation To Field Capacity (SCHED=1)

Irrigation to field capacity, also referred to as "crop demand mode" irrigation, is considered a highly desirable scheduling strategy (Schulze, 1984) because it involves an irrigation application only when water is actually required. This occurs when the active root soil profile has reached a critical water content level at which plant stress is assumed to set in. The soil water store is then *recharged to field capacity and no more*. The interval between successive irrigation applications is therefore variable (according to demand) and is thus maximised.

This strategy of irrigation application is water efficient, with considerable savings being effected (when compared with, say, fixed amount/fixed cycle time irrigation), particularly in higher

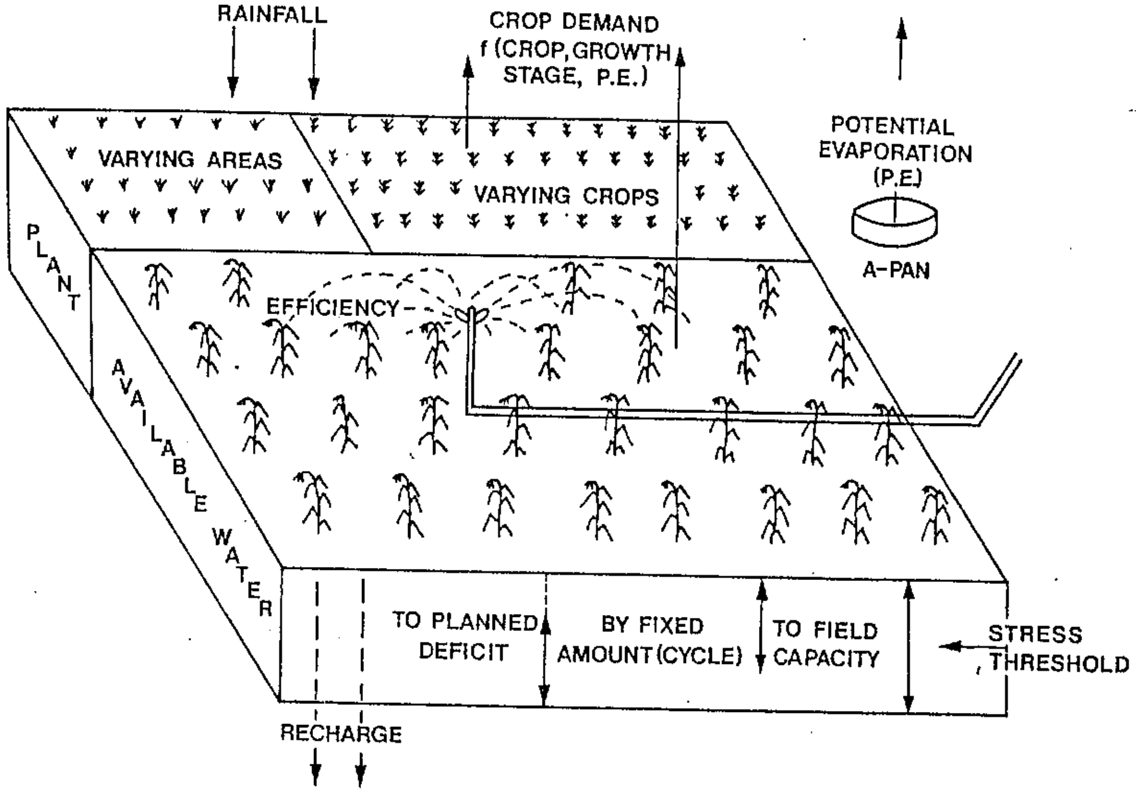

Figure 12.1.1 Irrigation water demand considerations and options available in *ACRU* (Schulze, 1985)

rainfall areas (Furniss, Schulze and Dent, 1988). However, high practical management inputs are required, first for the irrigator to acquire the additional/variable scheduling information and secondly, because of irregular movement of irrigation hardware in the field.

12.2.2 Irrigation To A Planned Deficit (SCHED=2)

Irrigating to a planned deficit is an application in which the root zone soil profile is recharged deliberately to below field capacity when in *ACRU* the irrigation threshold is reached. Irrigation amount is therefore planned to satisfy a specified fraction of plant available water. Assumptions in planned deficit scheduling strategies would be, *inter alia*, that irrigation is supplementary to rainfall in areas where there is a high probability of rains falling between application, or that there may be a finite amount of water available which has to be optimised such that maximum yields are attained.

Rainfall effectivity may then be maximised and runoff reduced. The fraction of plant available water to which irrigation is applied varies (*ACRU* variable fraction PLADEF) according to local climatic conditions.

Furniss (1988) has shown that this mode of simulation can result in water savings particularly when used as supplementary irrigation in the wet season of high rainfall areas with deep soils.

However, savings in water may possibly be offset by increased labour inputs, as irrigation in dry spells has to be applied more frequently than when irrigating to field capacity.

12.2.3 Irrigation By A Fixed Amount (SCHED=3)

Irrigation pumping capacity or other logistical constraints in practice (for example, labour, amount of piping available) sometimes enable only a fixed amount of irrigation water to be applied. In *ACRU*, when this mode of scheduling is invoked, the fixed amount (mm) is specified (variable amount = AMTIR, mm) and irrigation is triggered to take place "on demand", i.e. when the stress threshold of plant available water is reached.

12.2.4 Irrigation By A Fixed Cycle And Fixed Amount (SCHED=4)

In this mode of irrigation, commonly in use with centre pivot systems, either a preselected or otherwise predetermined amount of irrigation water is applied (AMTIR, mm) in a cycle length (ICYCLE, days) which is either fixed or selected. In *ACRU* this cycle is assumed to continue, regardless of smaller amounts of rainfall occurring, except that the entire cycle is interrupted and restarted when rainfall on a given day exceeds the predetermined irrigation amount, AMTIR.

In terms of judicious use of water, this common scheduling strategy tends to be wasteful of water in areas of high rainfall. However, in low rainfall areas, or in the dry season of high rainfall areas, where effectively the total crop's water requirement has to be met by irrigation, this method may be highly recommended because of low management inputs required (Furniss, 1988). Where this mode of irrigation is used in the wet season, particularly in higher rainfall areas, it is vital that appropriate cycle lengths and irrigation amounts be determined (optimised) for the specific location, as these have been shown to vary considerably with prevailing climatic condition (Furniss *et al.*, 1988). If these inputs are not optimised regionally, fixed cycle/amount irrigation is not efficient in terms of water usage and associated leaching of fertilisers may occur.

12.3 IRRIGATION SOILS INFORMATION

Concepts, techniques and constants related to soil information required by the *ACRU* modelling system have been outlined in detail in Chapter 5 and are not repeated in detail here except where irrigation soils information constitutes a special case or warrants particular attention.

* In this version of *ACRU* the irrigation routines assume the soil to comprise of a single, texturally uniform soil horizon in which root development and hence the water budget components interact.

* Soil water retention constants for irrigated soils, viz. porosity, field capacity and permanent wilting point, and associated profile plant available water, effects of excess or deficient water stress and "saturated" drainage rates, therefore all pertain to a single layer only.

* Depth of soil in irrigation routines relates to the maximum active rooting depth of the irrigated crop, which may be considerably less than the total depth of the top- and subsoil horizons measured in the field or assumed in *ACRU*'s

dryland soils routines (Chapter 5).

* Since a major purpose of irrigation is to attain high crop yields by obviating plant water stress the fraction 'f' of plant available water at which stress is assumed to set in generally errs on the conservative side, and a common value for 'f' in irrigation routines is 0.5 (Hensley and De Jager, 1980).

* As in dryland routines, there are input pathways for "adequate" and "inadequate" soil information in *ACRU*'s irrigation routines. Where, in the "inadequate" soils information option, total active rooting depth of the crop under irrigation is not known (*ACRU* variable name IRRDEP) three categories of soil depth may be used as defaults, viz.
  - deep irrigated soils, i.e. >1.0 m, and assumed 1.1 m deep,
  - shallow irrigated soils, i.e. <0.5 m., and defaulted to 0.4 m, and
  - intermediate depth soils, i.e. 0.5 - 1.0 m, and assumed 0.75 m deep.

12.4 IRRIGATION CROP INFORMATION

Crop coefficients and interception losses per rainday for irrigated crops are handled in the same way as for dryland routines, as are all crop default options and pathways. Details are given in Chapter 6 and in the *ACRU* User Manual (Schulze and George, 1989).

12.5 RAINFALL AND RUNOFF SPECIFICATIONS

12.5.1 Daily Rainfall Correction For Irrigation Areas

In *ACRU* the rainfall information used in the irrigation water budget is from the identical rainfall input file as that used for the entire catchment (or subcatchment) which would be supplying the irrigation water either from a reservoir or from streamflow, or the (sub)catchment within which the irrigation is being applied. However, the catchment's or subcatchment's rainfall input may not be representative of the specific location at which irrigation is being practised, for example, if the irrigation project is at one extremity of a catchment. An irrigation rainfall correction factor thus has be applied on a month by month basis to the daily rainfall read from the hydrometeorological data file to account for seasonal/systematic rainfall differences encountered at the site of irrigation. An example of the application of this correction factor is given in the *ACRU* Manual (Schulze and George, 1989).

12.5.2 Stormflow Generation

The same principles of stormflow simulation apply to irrigated areas as do to general catchment areas (Chapter 8), except that from irrigated lands the critical soil depth considered in stormflow generation is set at 0.3 m.

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CHAPTER 13

IRRIGATION WATER SUPPLY

R.E. Schulze and W.J. George

13.1 INTRODUCTION

In the *ACRU* modelling system water for irrigation application may be supplied from a number of sources, including reservoirs, streams, the combination of streams and reservoirs or it may be supplied from remote sources outside the catchment in question. In the real world of irrigation, design water supplies may be complicated further by intra-catchment water transfers to lands being irrigated either upstream or downstream of a source of water supply or even by transfers of water to areas outside the water supply area. The area being irrigated may vary seasonally according to the crop(s) being grown and, in certain months, no irrigation water whatever may be demanded. Irrigation supply losses to a system have to be accounted for, as do irrigation return flows into the system resulting from over- or untimely irrigation. Owing to complexities in the real world of irrigation water supply, such as those summarised above, *ACRU*'s water supply routines have been developed to allow for a large degree of flexibility in simulating real situations.

13.2 SOURCES OF WATER SUPPLY FOR IRRIGATION

Reference should be made to Figure 13.2.1, which depicts schematically some of the different sources of water supply available in *ACRU* to an irrigation scheme. In *ACRU* the variable name for the source of water supply for irrigation purposes is IRRAPL.

13.2.1 Irrigation Water Supply For Planning And Design Purposes

In the planning and design phase of an irrigation scheme the need may arise to determine how much water is required for the scheme in order to satisfy all crop water demands. For these purposes the planning option IRRAPL = 0 is invoked and an unlimited source of water is assumed. If the option is used to examine design water supply to a given irrigation scheme, realistic input values also have to be given, in preparing a simulation run, to irrigation supply losses such as conveyance, farm dam and field application efficiency losses (c.f. Section 13.4). This option would also be used in assessing optimum crop yield under irrigation.

13.2.2 Irrigation Water Supply From A Reservoir Only

If the catchment being simulated contains a reservoir (Chapter 14), the option IRRAPL = 0 is again invoked, but in tandem with a reservoir yield analysis (and all the specifications that have to be input for that). All irrigation demands by the crop, plus all supply losses (conveyance, etc), are then abstracted from the reservoir, subject to it's containing water, i.e. when dead storage levels are reached in the reservoir, no more irrigation is supplied to the fields and the crops may suffer yield losses due to plant stress.

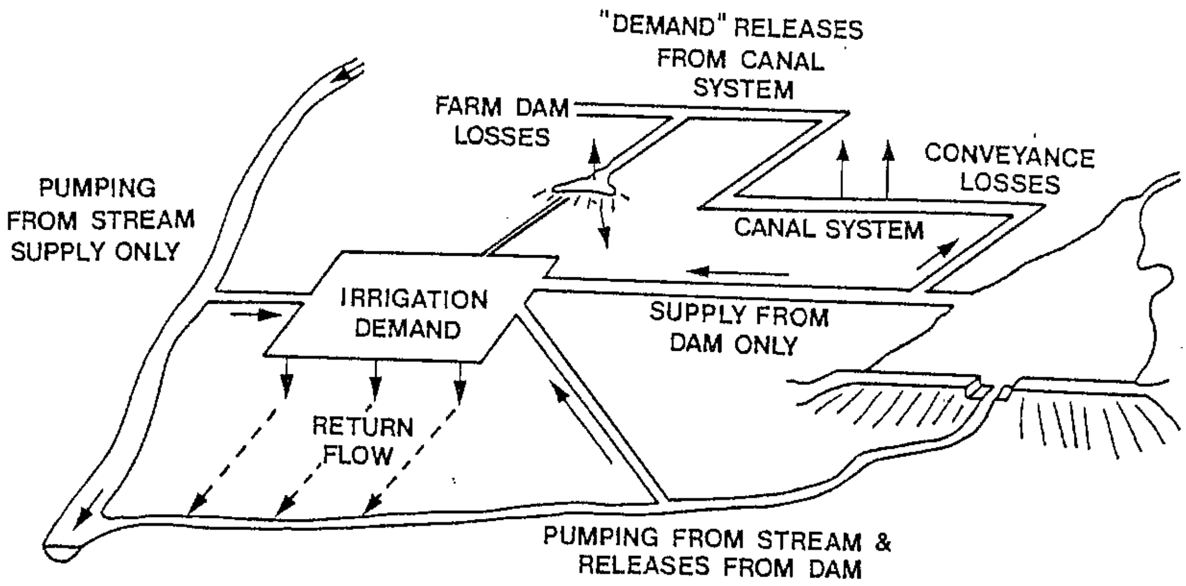

Figure 13.2.1 Simulating irrigation water supply - a schematic of options available in *ACRU*

13.2.3 Irrigation Water Supply Directly From A River

It is a common practice for irrigators to pump water directly out of a river onto their adjacent fields. When this option (IRRAPL = 3) is selected, it can satisfy only those irrigation water demands (crop plus losses) for which the stream has enough water at the point of abstraction. Daily streamflow downstream from that point is consequently reduced by the amount of daily irrigation requirements.

13.2.4 Irrigation Water Supply From A Combination Of Streamflow And Upstream Reservoir

When irrigation water is supplied directly out of a stream with a variable flow regime, a reservoir may be constructed upstream as a reserve or insurance against the stream's drying up or being pumped dry (IRRAPL = 2). In such a case *ACRU* assumes water to be supplied initially from the overflow of the reservoir to satisfy gross irrigation requirement. Once overflow is no longer sufficient for an irrigation scheme's demand, all excess requirements are released from the reservoir, again subject to there being water available in the reservoir.

13.2.5 Irrigation Water Supply From Outside Sources

Major schemes frequently supply water from remote sources, often hundreds of km from the point of irrigation water demand. The irrigation demand is estimated by the farmer or group of farmers and a regulated amount of water is released as a "slug" of water on a given day via canal systems direct to the fields or into smaller balancing dams (for redistribution by the farmer himself). *ACRU* accounts for such schemes (IRRAPL = 1, e.g. the Vaalharts Scheme) by assuming there to be no reservoir in the catchment under consideration. The regulated irrigation releases are read via the daily hydrometeorological data file.

13.3 RECONCILING IRRIGATION WATER SUPPLY WITH DEMAND

13.3.1 Routines Involving More Complex Irrigation Supplies By Inter- and Intra-Catchment-Water Transfers

In southern Africa a substantial number of irrigation schemes have evolved along river frontages, where along a length of river water is abstracted by pumping by a series of farmers. A consequence is that the farmers on the downstream end of the river often cannot irrigate to full demand because the upstream farmers have used up all the streamflow for their own irrigation demands. It is then often necessary that inter-subcatchment transfers of water have to take place by transferring water from a dam within the system to supply irrigation demands either upstream or downstream of that subcatchment containing the reservoir. In *ACRU* this is known as the "loopback" option, which can be invoked only when "first-call" irrigation water is pumped directly from a river (IRRAPL = 3) and the mode of scheduling is a fixed amount per irrigation cycle (SCHED = 4). The "loopback" and other options are illustrated in Figure 13.3.1.

When, in the "loopback" procedure, the streamflow fails to satisfy total irrigation demand (i.e. crop requirement plus losses) on a given day, extractions from the reservoir operate on a "first-come - first-served" basis, where the water requirements of the most upstream subcatchment are satisfied first, followed in a cascade by those subcatchments with irrigation demands further downstream. The only exception to this operating rule occurs where irrigation is practised within that subcatchment which contains the reservoir - that subcatchment then enjoys a "right" to water from the reservoir first.

13.3.2 Water Supplies To Areas Outside The Catchment System

ACRU irrigation routines facilitate irrigation water to be demanded outside the catchment in which the water is generated or stored. Once demanded and applied, this water is "lost" to the catchment system and plays no further part in the water budgets of the catchment (Figure 13.3.1).

13.3.3 Irrigation Return Flows

Areas under irrigation on occasion generate "deep percolation" waters which drain out beneath the active root zone, either when over-irrigation has taken place or when soil water in the root zone is displaced downwards by rain falling on a wet (e.g. recently irrigated) soil. In *ACRU* an option exists for this water to return to the river system as irrigation return flow, which then supplements streamflows downstream. Owing to frequent over-irrigation, return flows, with their associated leachates, may contribute to a progressively worsening salinisation problem for downstream users in irrigation schemes strung along a river.

13.3.4 Timing Of And Areas Under Irrigation

Irrigation water supply may vary, depending, *inter alia*, on the area under irrigated crops, which in *ACRU* can be changed month by month. Similarly, there may be periods within the year when no irrigation water is required (it may even be detrimental if it were supplied), for example in months when harvesting or land preparation take place or when crops are ripening

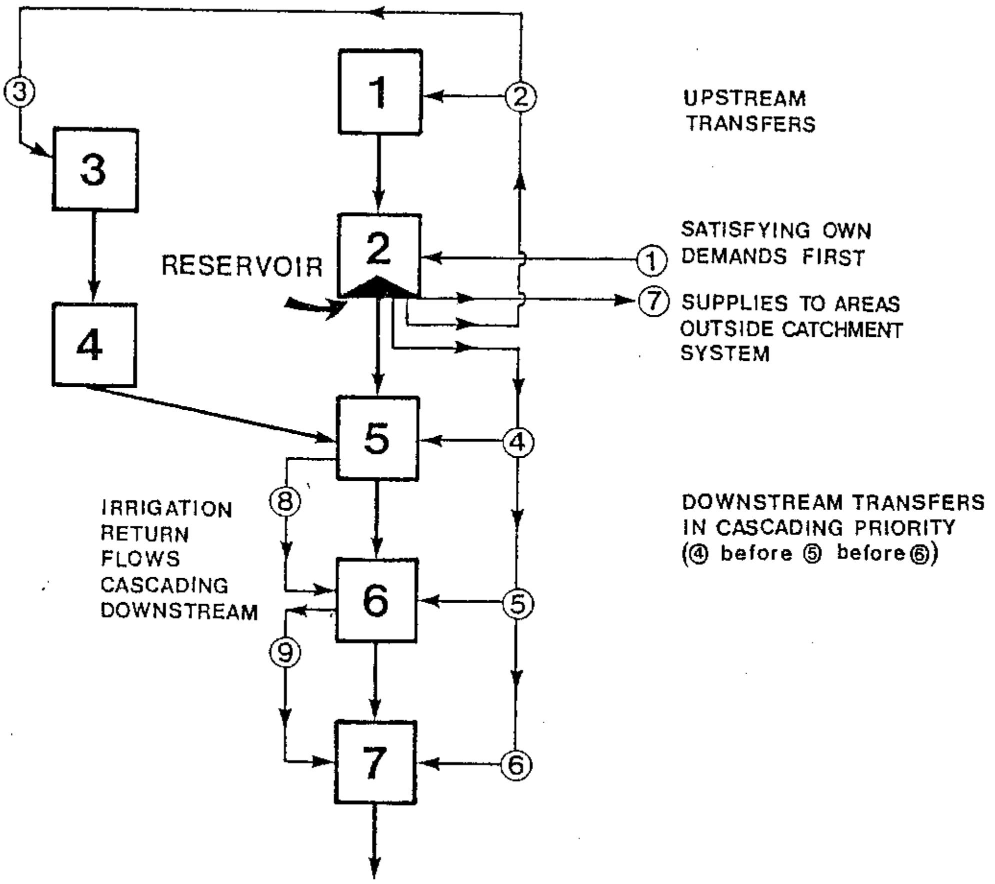

Figure 13.3.1 Illustration of inter-subcatchment transfers of irrigation waters available in *ACRU*

Timing of irrigation demands/supplies in *ACRU* are then specified month by month to account for different planting dates, crop rotations or demands.

13.4 IRRIGATION SUPPLY LOSSES

Water losses may occur between the source of irrigation water supply and the actual crop at the point of application.

13.4.1 Canal Conveyance Losses

Canal conveyance losses may be defined as the fraction of irrigation water lost between water released at a canal headworks and the water delivered to the farmer. These losses may be divided into so-called

* "unavoidable" losses, made up of
    - evaporation losses, usually only of the order of 0.3% (Butler, 1980), and dependent on the surface area of water in canals, and
    - seepage losses, estimated by Butler (1980) to be around 15% for design purposes, and dependent on the wetted perimeter area of the canal, the condition of the canal network as well as water table depth (Streutker, 1981); and
* "avoidable" losses, i.e. operational wastage

resulting from inadequate management, with one of the most critical faults being incorrect run times under varying climatic and demand conditions (9-17% losses according to Reid, Davidson and Kotze, 1986), but also dependent on variations of water delivery rates, scheme size and algal growth.

The following Table 13.4.1, containing values from Butler (1980), Streutker (1981) and Reid *et al.* (1986), provides a guideline of canal conveyance losses for use in southern Africa.

13.4.2 Balancing Dam Losses

Water supplies by canal systems are frequently stored temporarily by farmers in so-called "balancing" (on-farm) dams. In addition to the canal conveyance losses a fraction of this stored water may again be lost on the farm by evaporation and seepage. A typical balancing dam loss fraction is around 0.1, i.e. 10%.

13.4.3 Field Application Efficiency

Field application efficiency (*ACRU* variable EFFIRR) is the ratio of the quantity of water effectively irrigating the crop root zone to the quantity delivered to the field. Efficiencies of various irrigation systems vary considerably and the water losses (i.e. 1-EFFIRR) may be accounted for by a combination of inefficiencies in

* field equipment (e.g. non-uniform emission from nozzles), or
* management (e.g. surface runoff, tailend losses), or by
* local climatic factors (e.g. spray drift, evaporation).

Field application efficiency also depends to a large degree on the irrigation system as Table 13.4.2 indicates.

Table 13.4.1 Canal conveyance losses in southern Africa (after Reid *et al.*, 1986)

Canal System	Canal Conveyance Losses
Highly efficient (high water table)	.14
Highly efficient (low water table)	.22
Inefficient	.32
Typical southern African scheme	.24-26

Table 13.4.2 Typical field application efficiencies for different irrigation systems (various sources)

Irrigation System	Field Application Efficiency
Travelling big guns	0.70
Centre pivot	0.80
Drip trickle and micro	0.85 - 0.90
Sprinkler	0.75
Flood	0.60 - 0.70

13.4.4 Irrigation Water Requirement As A Fraction Of Supply, For Projects With Extensive Canal Networks

If canal conveyance losses of 25%, balancing dam losses of 10% and a field application efficiency of 80% are assumed to be typical, it may be calculated that the crop's actual irrigation water requirement would only be 54% of supply in large schemes with canal networks. It is thus vital for irrigation projects/systems to strive for optimum efficiency, particularly in regions of scarce water resources for which competition from various sectors will become a major issue in future.

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CHAPTER 14

RESERVOIR YIELD ANALYSIS

R.E. Schulze, E.J. Schmidt and S.J. Dunsmore

14.1 THE RESERVOIR WATER BUDGET

The reservoir yield analysis in *ACRU* operates on the principle of a daily mass balance in terms of the reservoir's water budget. This is illustrated diagrammatically in Figure 14.1.1, in which gains to the system are streamflows, inter-catchment transfers and precipitation on to the surface, while losses are made up of evaporation from the surface, normal flow releases, seepage losses, overflow and irrigation and other abstraction - all relative to the volume of water in the reservoir and the surface area related to that volume.

The components of the reservoir water budget are discussed next. Two components are highlighted and receive particular attention, viz. the surface area : capacity relationship when no prior surveys were undertaken and it has to be estimated, and the decrease of the reservoir's maximum capacity because of sedimentation.

14.2 COMPONENTS OF THE RESERVOIR WATER BUDGET

Throughout the reservoir water budget units are converted to volumes per day i.e. m^3.

14.2.1 Streamflow

The major gain into the system is by streamflow, i.e. both stormflow and baseflow. When operating in distributed mode the total of all streamflow from above the reservoir becomes inflow.

14.2.2 Precipitation

Precipitation falling onto the reservoir constitutes a second gain to the system. In *ACRU* all precipitation falling onto the entire surface area at full capacity is added, i.e. the premise is made that when the reservoir is not at capacity, that rain falling on the "dry" part of the reservoir is direct runoff with no abstractions into the soil taking place, on the assumption that the "dry" parts are compacted and surface sealing has taken place.

14.2.3 Inter-Catchment Transfers Into The Reservoir

When inter-catchment transfers (*ACRU* variable = PUMPIN) into a reservoir occur, the volumes of water are read in on a month by month basis and converted to daily values. Where, in an historical time series, transfers change from month to month/year to year, such values are input via the dynamic input file option in *ACRU*.

14.2.4 Normal Flow

Since most streams contain, in legal terms, "public" water, downstream users have a right to a certain amount of water that would likely have

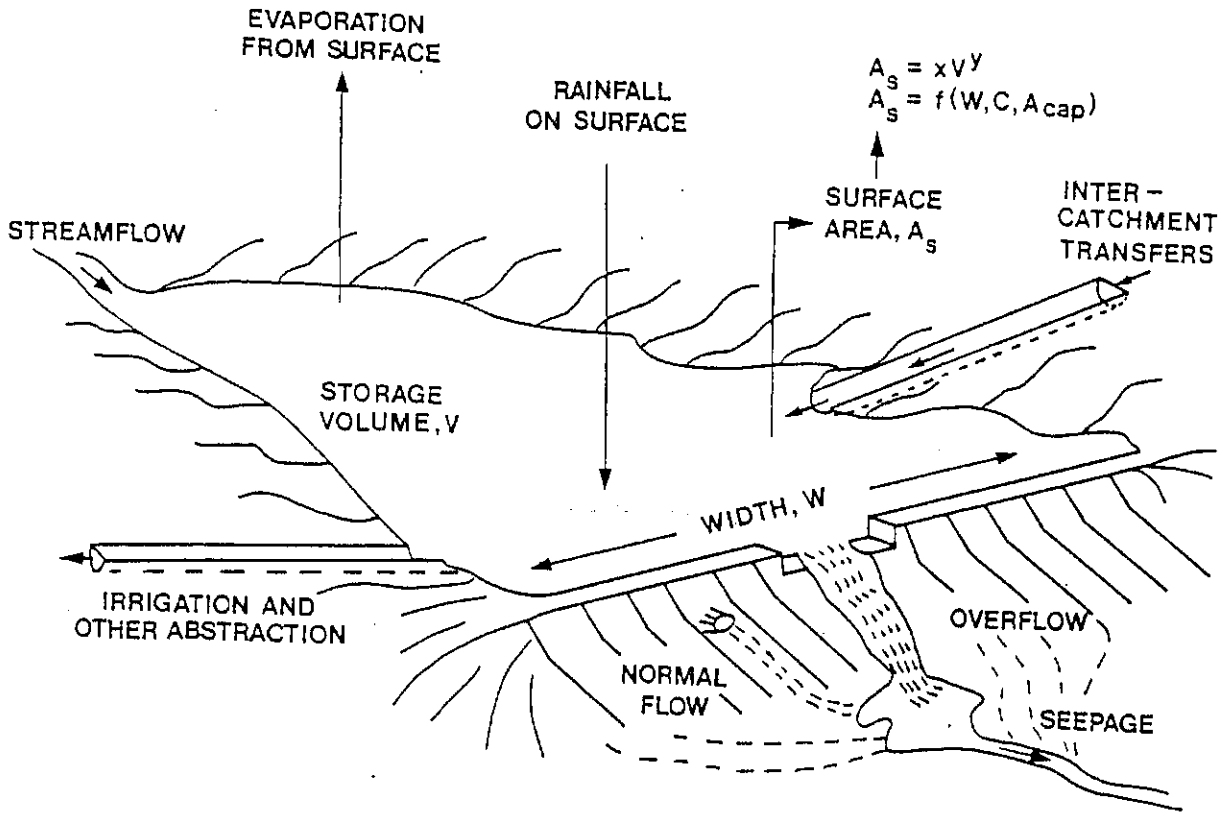

Figure 14.1.1 Diagrammatic depiction of the reservoir water budget in *ACRU*

been available as streamflow, had the reservoir not been constructed. A "compulsory" release of water from the reservoir, i.e. normal flow (*ACRU* variable = QNORM), thus has to be discharged downstream.

There is, in South African water law, no fixed definition as to what constitutes normal flow. However, a commonly used rule is that it is that amount of streamflow that would likely have been exceeded on 70% of occasions in the month of typically lowest flows. In order to obtain such a value, a simulation without the reservoir, but with a frequency analysis of the total catchment's runoff is first undertaken to determine a value of the 70th percentile of flow exceedence in the critical month and this value then constitutes normal flow in a second simulation with the reservoir.

14.2.5 Seepage

Where seepage losses can be estimated, these may be input to obtain a more realistic simulation. In *ACRU* seepage (*ACRU* variable = SEEP) is a constant value loss, i.e. no account can yet be taken of different amounts of seepage occurring at different storage volumes of the reservoir.

14.2.6 Evaporation Losses

With the high evaporation rates prevailing over most of southern Africa, this constitutes a major loss to the reservoir water budget (Midgley, Pitman and Middleton, 1983), in some cases up to 30% and even up to 60% (Van Ryneveld's Pass Dam) of mean annual runoff being lost by surface evaporation. Reservoir evaporation takes place from a "large" water body, thus the daily A-pan equivalent has to be corrected to a lake equivalent evaporation. In *ACRU* month by month correction factors are input, because the relationship between large water body and evaporation pan varies intra-annually and also regionally.

In southern Africa values of the lake to pan relationship commonly use the Symon's tank and not the A-pan as reference. Users therefore have to do a double conversion, from lake to S-tank for a region/month and then consider the S:A pan conversion for that region/month.

A major research thrust is currently (1989) underway to revise reservoir evaporation losses and the regional conversions of lake to S-tank evaporation ratios for southern Africa given below (Figure 14.2.1) should thus be viewed as a first approximation only. S-tank : A-pan ratios are given for southern Africa in the *ACRU* User Manual (Schulze and George, 1989).

14.2.7 Abstractions From The Reservoir

* *Irrigation Demands from a Reservoir.* When *ACRU* is operating in reservoir and irrigation modes simultaneously and the option is invoked that irrigation water is applied within the catchment in which the reservoir is located, and the irrigation water is obtained either from streamflow plus the reservoir combined or the reservoir only (Chapter 13), then daily irrigation demands are abstracted out of the reservoir automatically.

* *Complex Irrigation Demands from a Reservoir.* When irrigation demands can be made from a reservoir because of requirements outside the catchment system, or from subcatchments removed from the reservoir's own catchment, either downstream or upstream, then these abstractions are treated as a special case in the reservoir's daily water budget and the so-called "loopback" mode in *ACRU* is invoked and becomes operative. Special instructions regarding the details of what water demands are met from where, are then requested from the *ACRU* menu.

* *Other Abstractions.* More constant reservoir abstractions, be they domestic, irrigation or other, which leave the catchment system, are treated in *ACRU* by calling a month by month input of draft. Where such abstractions follow an irregular pattern in time, the changing values are input via the dynamic input file option in *ACRU*. The conversion from a monthly abstraction request to a daily value for water budget computations is programmed into *ACRU*.

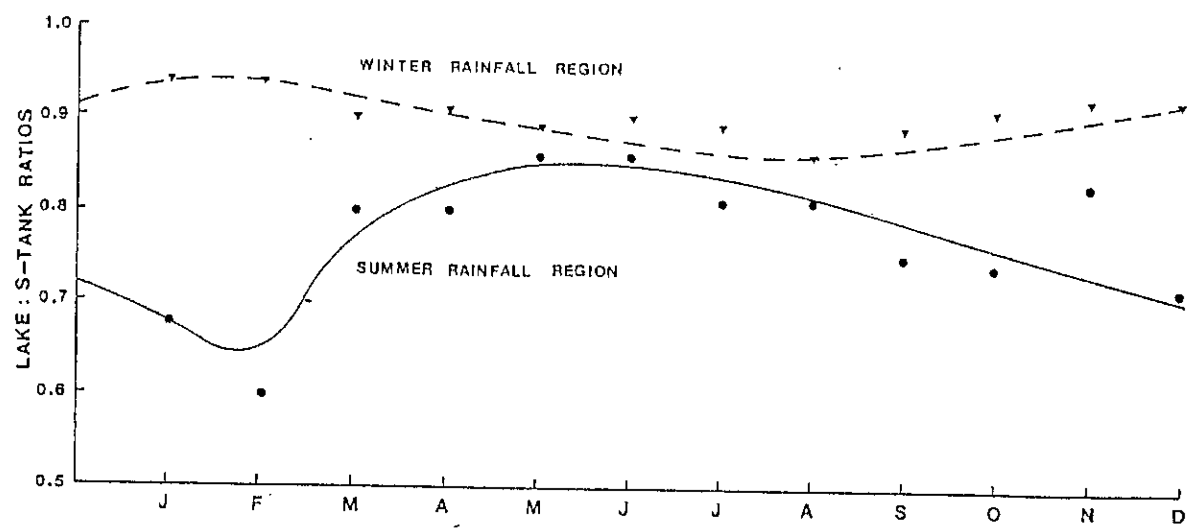

Figure 14.2.1 Lake : Symons-tank evaporation ratios for use in southern Africa

14.3 AREA : CAPACITY RELATIONSHIPS IN *ACRU*

14.3.1 Area : Capacity Relationship When Reservoir Has Been Surveyed

When a reservoir basin has been surveyed before its construction, a conventional area : capacity relationship is applied in *ACRU*, of the power function type, viz.

$$A_s = 100.a'. S_r^{b'}$$

in which

A_s = surface area of water (ha) on a given day

S_r = storage (volume) of water ($10^6 m^3$) calculated from the previous day's final reservoir water budget

a' = constant of the equation determined from the survey

b' = exponent of the equation, determined from the survey

100 = conversion, ha from km^2.

14.3.2 Default Area : Capacity Relationship In *ACRU* Without Reservoir Basin Survey

For small (and even not such small) dams often only the maximum capacity of the reservoir is known, but not a surface area : capacity relationship. In reservoir budget computations involving surface water evaporation the changing surface area thus has to be estimated. The following procedures were adopted in *ACRU* :

* The assumption was made that the maximum capacity was known and that both the surface area at maximum capacity as well as the width of the reservoir wall could be obtained from large scale maps or aerial/ orthophotos.

* It was further assumed that the reservoir basin had a "pyramid" shape with uniform side slopes and longitudinal profile, as illustrated in Figure 14.3.1.

From Figure 14.3.1 (a) surface area, A_s, at maximum capacity

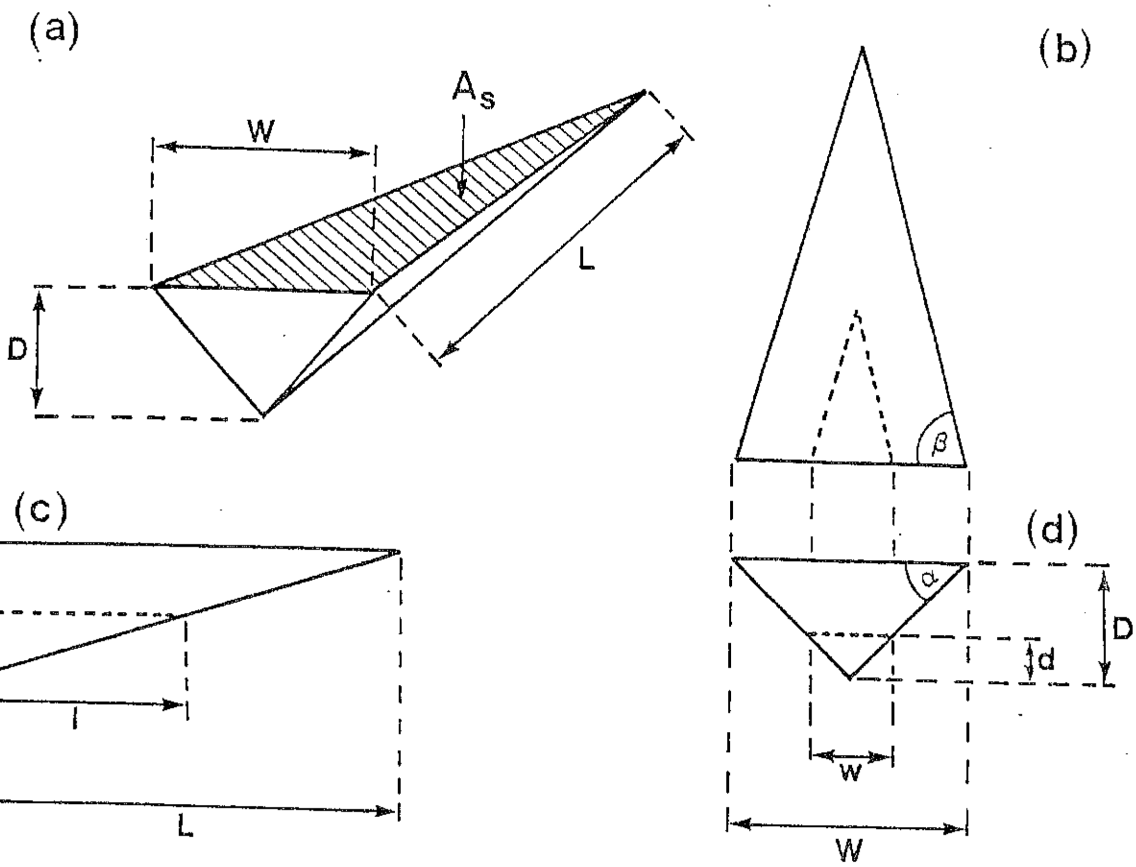

Figure 14.3.1 Diagrammatic views of assumptions made in *ACRU*'s default area : capacity relationship

$A_s = 1/2\ W.L$

The volume, S_c, of a pyramid can be estimated by one third the product of the base area and the perpendicular height. For the reservoir shown in Figure 14.3.1(a) the surface area is taken as the base area and the depth as the perpendicular height, viz

$$S_c = 1/3\ (1/2\ WL).D$$
$$= 1/6\ W.D.L.$$

To calculate the surface area for various percentages of maximum capacity (from a knowledge of maximum capacity, surface area at maximum capacity and wall width) the relationships between D, W and L must be determined.

Referring to Figure 14.3.1 (d)

$$\tan \alpha = 2\ D/W = 2\ d/w$$

and $\tan \alpha$ = constant for any particular dam.

Similarly, in Figure 14.3.1 (b)

$$\tan \beta = 2\ L/W = 2\ l/w$$

and

tab β = constant for any particular dam.

Hence the relationships

$$D = W/2 \ \tan\alpha$$

and $$L = W/2 \ \tan\beta$$

Therefore, if the reservoir is x% of capacity (i.e. at "vol")

$$vol = x/100 \ (1/6 \ W.D.L.)$$

i.e.

$$w.d.l. = x/100 \ W.D.L.$$

$$= x/100 \ W \ (W/2 \tan\alpha)(W/2 \tan\beta)$$

$$= x/100 \ W^3 \ (1/4 \tan\alpha.\tan\beta)$$

$$w^3 = x/100 \ W^3$$

i.e. $$w = (x/100)^{1/3} W$$

Similarly

$$d = W/2 \ (x/100)^{1/3} \tan\alpha$$

and $$l = W/2 \ (x/100)^{1/3} \tan\beta$$

Therefore, if the reservoir is at x% of capacity

$$vol = 1/6 \ w.d.l$$

and

$$a_s = 1/2 \ w.l$$

where w and l are as derived in the equation above and a_s is the surface area at x% of capacity.

Hence, under the simplifying assumption already named, the surface area at any percentage of capacity can be derived from maximum capacity, wall width at water level at maximum capacity and surface area at maximum capacity, all of which are either known or may be obtained easily from aerial photographs or orthophotos.

14.4 RESERVOIR SEDIMENTATION

Soil erosion has the combined deteriorating effect of reducing the production potential of agricultural lands in a catchment and increasing the sediment load in rivers, which results ultimately, through the deposition in reservoirs, in a reduced storage capacity and hence shortened design life of reservoirs.

Sediment yield from a catchment is computed in the *ACRU* modelling system using the Modified Universal Soil Loss Equation, MUSLE (Williams and Berndt, 1977). In this version of *ACRU* catchment sediment yield and reservoir sedimentation can only be computed for a lumped catchment for "external" cells of a distributed system. The MUSLE equation, which is repeated below, is discussed in greater detail in Chapter 11.

$$Y_{sd} = 11.8 \ (Qq_p)^{0.56} \ KLSCP$$

where

- Y_{sd} = sediment yield from an individual event (tonne)
- Q = storm runoff volume for the event (m^3)
- q_p = peak discharge ($m^3.s^{-1}$)
- K = soil erodibility factor (dimensionless)
- LS = slope length and gradient factor (dimensionless)
- C = cover and management factor (dimensionless) and
- P = support practice factor (dimensionless).

The simulation of runoff volume (Chapter 8) and peak discharge (Chapter 10) on a daily time step allows for the generation of a time series of daily sediment yields, given the assumptions embodied in the above equation. Typically, information on sediment yield is required for an assessment of the extent to which a reservoir of given capacity will meet future demand. Thus an evaluation is required of the proportion of the sediment leaving the catchment and which is retained by the reservoir.

Generally empirical methods such as the Brune and Churchill curves are used to provide an estimate of the proportion of the *annual* sediment load trapped in a reservoir. These methods are, however, based on sediment surveys from large dams and are not appropriate for use in smaller reservoirs. In addition, a method which accounts for the seasonal and daily variation in sediment yield and the prevailing storage status provides for a more realistic means of accounting for the processes resulting in sediment deposition.

The algorithms used in the *ACRU* Modelling System have been adapted from those included in the "Simulator for Water Resources in Rural Basins Model" (Williams, Nicks and Arnold, 1985). The daily outflow of sediment from the reservoir is computed as

$$Y_{os} = C_o Q_o$$

where

Y_{os} = outflow sediment yield (tons)

C_o = reservoir suspended sediment concentration ($t.m^{-3}$)

Q_o = outflow volume (m^3).

The suspended sediment concentration is equal to the average concentration at the start of the day (C_{o1}) and the end of the day (C_{o2}). The concentration of inflowing sediment (C_I) can be computed since Y_{sd} and Q are simulated. The final sediment concentration in the reservoir at the end of a day (C_{o2}) can be computed using continuity principles. Thus

$$VM_2\ C_{o2} = VM_1\ C_{o1} + Q_I C_I - Q_o C_o \quad \text{..... Eq. 14.3.1}$$

where

VM_1 and VM_2 = reservoir storage volumes at the beginning and end of the day (m^3)

Q_I = inflow volume (m^3) and

C_I = concentration of inflowing sediment ($t.m^{-3}$).

Since

$$C_o = \frac{C_{o1} + C_{o2}}{2}$$

the equation 14.3.1 can be written as

$$C_{02} = \frac{VM_1\ C_{o1} + Q_I C_I - (Q_o/2)\ C_{o1}}{VM_2 + (Q_o/2)}$$

Between storms the reservoir suspended sediment concentration decreases to an equilibrium concentration according to the sediment deposition equation

$$C_{s2} = (C_{o2} - C_{se}) \exp(-k_s.t.D_{so}) + C_{se}$$

where

C_{s2} = sediment concentration t days after the value of C_{o2} is obtained ($t.m^{-3}$)

k_s = decay constant = 0.184

D_{so} = median particle size of inflowing sediment (μm) and

C_{se} = equilibrium suspended sediment concentration.

The decay content of 0.184 is such that 99% of the $1\mu m$ particles are settled within 25 days. Median particle sizes are related to the texture of the eroded material in the catchment which is specified by the soil texture input to the menu (ITEXT). The equilibrium suspended sediment concentration, C_{se}, is typically very low but can be measured by sampling existing reservoirs in the area after a long period of no runoff. It is assumed to be equal to zero in the *ACRU* model.

The above equations thus combine to allow a continuous simulation of the accumulated sediment mass in a reservoir. Assuming a realistic density of deposited sediment, defaulted to a typical value of 1350 kg.m^{-3}, the *ACRU* model allows changes in the storage capacity of the reservoir to be determined on an event by event basis.

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CHAPTER 15

CROP YIELD ESTIMATION

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15.1 INTRODUCTION

15.1.1 Background To Crop Yield Modelling

The most important factors affecting crop production are:

* climatic potential i.e. the optimum interaction of rainfall and available solar energy, which interact to provide the "driving forces" for growth at a given location,
* soil properties, including depth, texture, surface and subsurface characteristics,
* climate of the respective season, through which is expressed the degree and amount of plant stress and which is induced by a lack or surplus of water in the soil during the growing season of a crop,
* hybrid selection, and
* farmer technology.

For a given level of technology seasonal crop yield fluctuations are attributable almost wholly to climate variability. In southern Africa it is well known that the supply of soil water to the plant is the most important factor in fluctuations of crop production. The high incidence of droughts or dry spells account for 50% of all maize production losses in South Africa (Gillooly and Dyer, 1977). The severe drought of the early 1980s, associated with recurring crop failures and the necessity to import staple food, testifies amply to this.

15.1.2 Why Crop Production Planning?

In crop production planning a major objective is the increase of production efficiency. In order to achieve this, according to Schulze (1985), decision-makers from State legislators to individual agriculturalists have to consider the following:

* What crop is grown optimally at a location?
* What yield of a given crop might be expected, on average, at a location?
* Are the average yields of this crop above the breakeven level of profitability?
* What is the probability of crop failure in the short and long terms?
* What factors are causing yield reduction?
* To what extent would irrigation assure yields close to the environmental optimum?
* Would alternative crops be less prone to drought-induced failure under dryland

conditions?

The last consideration is most important in low potential or marginal areas. Maize, for example, has been introduced successfully in many parts of southern Africa. However, the occasional good season has led farmers to plant maize in marginal production areas without thoroughly investigating the suitability of these environments to maize production. The climatic requirements of crops need to be characterised in order to establish whether such marginal areas are suitable for the production of certain crops.

Once the answers to the above questions are known, the individual farmer may proceed confidently with planning for effective cultivation of a crop - be it in terms either of maximum yield or maximum profit per unit of ground area. Only the climate remains "uncontrollable" and the answers to many of the questions posed above effectively lead to the determination of the question of climatic suitability for specific crops. There is a need to assess environmental conditions and to quantify the processes of crop growth - hence the development of crop yield models. The goal of applying crop yield models varies with users and generally the models are important tools in the determination of optimum planting dates, risk analyses of yield, irrigation water requirements, regional agroclimatology and overall crop production planning.

15.1.3 Crop Yield Models Of Differing Complexity

Crop yield models of differing complexity range from simple formulae to complex physiologically-based models. Each type of model has its limitations in terms of input data availability and model accuracy.

* *Simple crop yield models* have the advantage of simple, readily obtainable input requirements, but they may face problems with model accuracy in that there is a risk that they are not sufficiently representative of the physical system.

* *Complex crop growth models*, on the other hand, may be accurate predictors but difficulties are involved in securing adequate data/information for the various parameters. The development of such models also tends to be a relatively expensive and time-consuming process. The process of analysis, assembly of data, model construction and verification takes up costly resources in the form of skilled man hours and computer time.

* Crop production may be simulated by *soil water budgeting* and total evaporation-based models, which are sensitive to plant water stress and are of *intermediate model complexity*. The endeavour with this level of model is to capture the approximate response of a crop to environmental conditions while sacrificing certain details of physiological processes such as photo-synthesis and respiration. Crop yield subroutines in *ACRU* are intermediate level submodels. The modular structure of this modelling system facilitates the rapid addition of more refined subroutines of various complexities as they become available.

15.1.4 Features Of Crop Yield Submodels In *ACRU*

* One of the problems of many crop yield models is their empiricism and owing to this they are often only applicable in those regions for which they were developed. For this reason, the emphasis in *ACRU* encompasses the development of more *generic* yield submodels which are not site specific nor climate specific.

* A second problem encountered frequently with crop yield models is that a different, independent model often has to be operated for each individual crop. In *ACRU* all crop yield models available are "imbedded" within a *single* modelling system, using the identical basic soil water budgeting routines. Yield for different crops can be estimated by "switching" from one crop to another, with the *ACRU* Menubuilder then requesting general crop and/or specific crop input.

* By implication, *comparisons* of water utilization by crops, as well as of risk and the economic aspects of yields can be made rapidly with *ACRU*; all this without the need for local parameter fine tuning of different models.

* The model developers of *ACRU* appreciate fully the advantages as well as the disadvantages of the "imbedded" modelling philosophy regarding crop yield estimation. Results from *ACRU* must therefore be viewed in perspective, viz. that complex physiology/genetics-based models would be expected to give better simulations than *ACRU*, but that this is traded off against rapid, possibly somewhat more robust, results and direct comparisons possible by the *ACRU* modelling system.

* Crop related simulations contained in the present version of *ACRU* are
  - primary productivity (either for a "generalised crop" or for natural vegetation)

  and the crops of
  - maize
  - winter wheat
  - sugarcane.

15.2 ESTIMATION OF PRIMARY PRODUCTIVITY

15.2.1 General Introduction

When carrying out an agronomic study of a region, its agricultural productivity and/or potential in comparison with other regions often needs to be assessed by a general yield model. These productivity models are either based directly on climatic indices, such as temperature and rainfall, or they make use of a soil water budget. Of these two types of yield/productivity models, those based on climatic indices are relatively simple to apply. However, results are frequently usable only for delimiting optimum growth areas or for regions in which they were developed. Conversely, models based on the soil water budget are more versatile and more generally applicable. The basic components of such models are :

* additions of water by precipitation (or irrigation),

* losses of water by total evaporation, runoff or groundwater recharge, and

* the change in the storage of the plant available water, dependent on evaporative demand, which in turn depends on crop canopy, crop root and crop physiological factors.

The above concepts are "imbedded" in the *ACRU* system in a generic and widely applicable soil water budget based submodel using the Rosenzweig (1968) equation to estimate net primary productivity and in a submodel suggested by Albrecht (1971) for the estimation of percentage of potential productivity. Furthermore, a simpler productivity model, the Miami model, based directly on climatic indices is also included.

15.2.2 Net Primary Productivity By The Rosenzweig Model

Total evaporation is a measure of the simultaneous availability of the soil water and evaporative demand by the atmosphere. Being the amount of water actually entering the atmosphere through the soil/vegetation complex, it is a quantifiable measure of energy flow in a plant community. Because of the above characteristics, total evaporation has for several decades therefore been considered useful as a predictor of plant production.

Rosenzweig (1968), in a major scientific contribution, used total evaporation (i.e. "actual evapotranspiration") values from 26 environments ranging from desert to tundra to tropical forests to predict net primary productivity of terrestrial plant communities. The equation developed by Rosenzweig (1968) was

$$\log_{10}NAAP = 1.66\log_{10} E - 1.66$$

in which

NAAP = net annual above ground productivity in $g.m^{-2}$ and

E = annual total evaporation in mm.

15.2.3 Percentage Of Potential Productivity Model

The net primary productivity equation by Rosenzweig (1968) only implies, but does not reflect any, deficiencies of soil water supply to the plant which may control its yield of productivity. Albrecht (1971), in a detailed study of agricultural productivity and potential in the USA, tested numerous indices relating soil water supply to soil water demand of crops in order to predict yields. He obtained the best estimates of yield relative to potential productivity using the equation

$$PPP = \frac{\text{Total Evaporation}}{\text{Maximum Evaporation}} . 100$$

where

PPP = percentage of potential productivity.

Being in effect a ratio of supply to demand, low values will usually imply long periods of plant stress because of soil water deficiencies. Therefore, the above equation will be able to identify those areas which in their mean climates are prone to dry spells detrimental to crop production. Furthermore, the agricultural potential of an area can be evaluated in terms of soil water supply to the crop in relation to soil water demand of the crop.

15.2.4 The Miami Model

The Miami model uses non-linear regression equations to describe the correlation between net primary productivity and probably the two most common climatic indices/descriptors, viz. annual average temperature and annual total precipitation. It therefore differs from the previously defined equations which are dependent on a soil water budget. The basis of the Miami model, which is imbedded in *ACRU*, is described by Leith (1975). The equations were derived using data from 52 locations throughout the world and are as follows :

$$NPP = 30(1 + e^{1.315-0.119T_{an}})^{-1}$$

for the dependence of net primary productivity, NPP, (tonnes.ha.$^{-1}$.annum^{-1}) on annual mean air temperature, T_{an}(°C), and

$$NPP = 30(1 - e^{-0.000664P_{an}})$$

for the dependence of net primary productivity on annual precipitation, P_{an} (mm). An upper limit of 30 tonnes.ha^{-1}.annum^{-1} was set for both equations.

These two equations are applied independently at each location and that equation yielding the lowest productivity is taken as the limiting one. Productivity is taken as that portion of the gross productivity which is available for harvest by any form or means, commonly measured as dry organic matter synthesised per area per unit time (Pittock and Nix, 1986). It must be appreciated that the relationships were derived, in general, from undisturbed climax vegetation data.

The Miami model consists of equations which are empirical generalisations on a global scale. They therefore do not account explicitly for variations at the mesoscale level of radiation, soil water status and nutrient regimes. However, as stated by Pittock and Nix (1986) the model does have the advantage over site-specific regression relationships derived from year-to-year fluctuations in that it is valid over a range of climates far exceeding that normally experienced at a single location. It is thus more likely to be applicable in evaluating impacts of climatic change and variability outside the range of the historical record (Pittock and Nix, 1986).

15.2.5 Seasonality

In order to account for areas having totally different climatic regimes, for example, winter versus summer rainfall areas, the starting date for the annual cycle accumulations of total and maximum evaporation, or temperature and rainfall can be controlled in *ACRU* by specifying the starting day (ISTDAY) and month (ISTMO). Estimation of primary productivity can then be made for this specified annual period.

15.3 ESTIMATION OF MAIZE YIELD

15.3.1 The *ACRU* Maize Yield Submodel Using Growing Degree Days

* *The Equation.* With daily temperature information, either input *per se* or generated internally in *ACRU* from monthly temperature input, a generic phenologically based submodel based on concepts proposed by Jensen (1968) and Hanks (1974) and modified such that the phenological "clock"

is driven by growing degree days (Domleo, 1989), has been developed and tested extensively under southern African conditions. In this model, which has to operate with option EVTR = 2 (i.e. *ACRU* has to split crop transpiration from soil evaporation),

$$Y_m = Y_{pm} \ (E_{t1}/E_{tm1})^{\alpha 1} \ . \ (E_{t2}/E_{tm2})^{\alpha 2} \ . \ (E_{t3}/E_{tm3})^{\alpha 3}$$

where

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

Y_{pm} = potential maize grain yield ($t.ha^{-1}$) for the season

= obtained from local information or, if that is unknown, defaulted to

= 0.01078 E_{mgs} (after Du Pisani, 1978)

with

E_{mgs} = accumulated maximum evaporation (i.e. "potential evapotranspiration", mm) from the top- and subsoil horizons for the duration of the active growing season

E_t = accumulated crop ("actual") transpiration from both soil horizons for a given growth stage

E_{tm} = accumulated maximum transpiration from both horizons for a given growth stage

α = exponent to allow for weighting of different growth stages

1 = growth stage 1: emergence to flower initiation

2 = growth stage 2: flowering stage

3 = growth stage 3: end of flowering to maturity.

* *Delimitation of Growth Stages by Accumulated Growing Degree Days.* In order to model maize yield successfully using the above equation, the growth stages in the development of the maize plant need to be delimited such that account is taken of regional climatic differences and season by season as well as intra-seasonal climate/ soil water differences.

For this reason the over-generalised but commonly used commencement of a growth stage by calendar day after planting was replaced by the conceptually sounder, more accurate and environmentally determined growing degree day (GDD) concept. With this concept effective heat units for maize, between upper and lower threshold daily mean temperatures (10 °C and 30 °C respectively) are accumulated from date of planting and are used to delimit onset and end of growth stages. Default values of GDD at various states of phenological development are given in Table 15.3.1. These were derived by Domleo (1989) from a combination of data supplied by the Pioneer Seed Company and a relationship advanced by Sammis, Mapel, Lugg, Lansford and McGurkin (1985).

* *Determination of Crop Coefficients by Accumulated Growing Degree Days.* In order to be physically meaningful, crop coefficients (K_{cm}, Chapter 6) need to be transferable to account for different climatic conditions between years at a given location, and between locations with different

Table 15.3.1 Typical values of phenological states of maize related accumulated Growing Degree Days (GDD) after planting (Domleo, 1989)

Phenological State	GDD
Emergence	150
Onset of flowering	700
End of flowering	1150
Maturity	1700

climatic conditions. The concept of relating K_{cm} to GDDs is conceptually far superior to that of relating it to calendar data or using a fixed crop growth curve. Such a relationship was developed by Sammis *et al.* (1985) and has been incorporated into the *ACRU* maize yield submodel. The third order polynomial equation of Sammis *et al.* (1985) is shown in Figure 15.3.1. The solid line represents the "ideal" generated growth curve of K_{cm} when no water stress occurs, while the broken line deviates from the ideal curve under soil water stress conditions. Note that K_{cm} need not be input in the *ACRU* menu in this case.

* *Crop Coefficients under Conditions of Plant Water Stress.* Determination of the fraction of plant available water at which stress sets in, its relationship with crop and atmospheric demand and the linear reduction of E vs E_m for soil water content below the fraction 'f' have been discussed in detail in Chapter 7.

In the *ACRU* maize yield model the K_{cm} : GDD relationship proceeds as illustrated in Figure 15.3.1 when $E_t = E_{tm}$. When, however, the E_t:E_{tm} ratio is less than unity, and growth is in the vegetative phase, then the increase in "ideal" K_{cm} is reduced to the ratio E_t:E_{tm}. In other words, the crop coefficient advances at a reduced rate when the plant is under stress. When rainfall/irrigation occurs and soil water stress is relieved, K_{cm} will again resume at the "ideal" rate. When the threshold GDD for the onset of flowering is thus reached, *ACRU*'s maize crop will flower, as it would have under natural conditions, despite the K_{cm}'s possibly being at a reduced value. It should be noted that in the *ACRU* maize yield model there is no reduction of K_{cm} for stress during flowering.

* *Separation of Transpiration from Total Evaporation.* The separation of total evaporation into the soil evaporation and crop transpiration processes is undertaken by the Ritchie (1972) method described in Chapter 6. This method makes use of the leaf area index, which is derived from the K_{cm}, again by equations described in Chapter 6. By the procedures already described, daily E_t and E_{tm} are obtained which are used in the equation for maize yield.

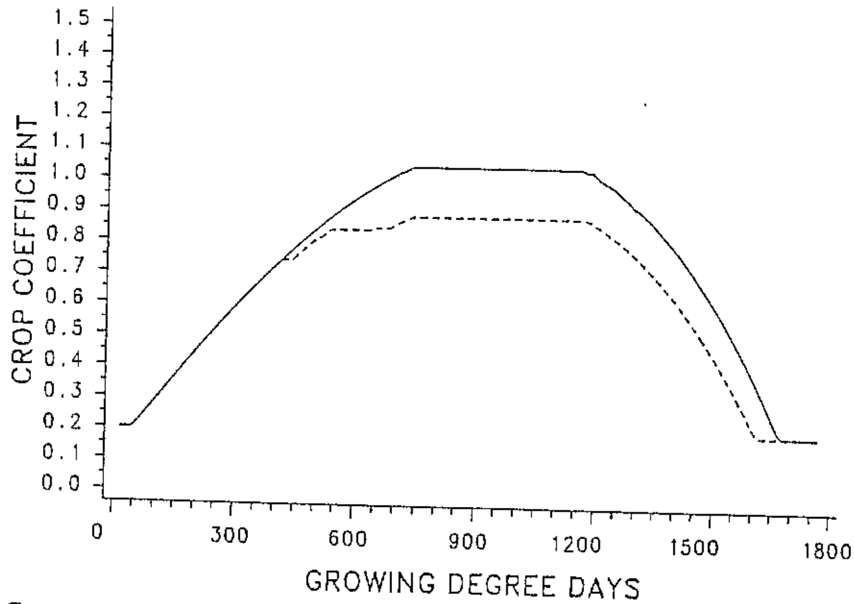

Figure 15.3.1 Crop coefficients for maize as related to accumulated Growing Degree Days

15.3.2 The *ACRU* Maize Yield Submodel Using Calendar Days

An option exists in ACRU whereby phenological stages are defined by calendar days after planting. When applying this option, which does not simulate maize yield as accurately as with the growing degree concept, soil evaporation and plant transpiration have to be considered as an entity (EVTR = 1) and the yield equation in *ACRU* becomes

$$Y_m = Y_{pm}(E_1/E_{m1})^{\alpha 1} \cdot (E_2/E_{m2})^{\alpha 2} \cdot (E_3/E_{m3})^{\alpha 3}$$

in which

- E = accumulated total evaporation (i.e. "actual evapotranspiration", mm) from both soil horizons for a given growth stage, and
- E_m = accumulated maximum evaporation (i.e. "potential evapotranspiration", mm) from both soil horizons for a given growth stage.

The number of calendar days per phenological state vary from region to region, according to climatic considerations. Default values used in *ACRU* are given in Table 15.3.2. In this option crop coefficients have to be input into the *ACRU* menu for each month of the year. The rate of advancement of K_{cm} from planting date until onset of flowering is adjusted by the model depending on whether or not stress conditions occurred.

15.3.3 Other Maize Yield Submodels In The *ACRU* System

Up until 1988 four empirical maize yield submodels were incorporated in the *ACRU* modelling system, three being based on total evaporation and a fourth focussing on reductions of yield due to stress in the critical flowering period in maize.

* *The De Jager (1982) Submodel.* This model suggested by De Jager (1982) is a robust

Table 15.3.2 Default values of phenological states of maize by calendar days after planting (Domleo, 1989)

Phenological State	Days After Planting
Emergence	10
Onset of flowering	70
End of flowering	100
Maturity	150

total evaporation-based model in which maize yield is expressed as

$$Y_m = \frac{30(E_{gs} - 100)0.45}{1000}$$

in which

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

E_{gs} = accumulated total evaporation (mm) from the soil and the plant from both the top- and subsoil horizons for the duration of the active growing season.

From the De Jager equation it may be seen that a threshold of 100 mm E_{gs} is required for the maize plant to yield grain.

* *The Du Pisani (1977) Submodel.* This very simple model relates

$$Y_m = 0.0092\ E_{gs}$$

There is no E_{gs} threshold in this equation; consequently it computes higher yields in dry years, but relatively lower yields in moist years when results are compared with those from the De Jager (1982) model.

* *The Stewart (1977) Submodel.* This model, developed in the USA by Stewart *et al.* (1977) estimates maize yield as

$$Y_m = 0.01845\ E_{gs} - 3.0825$$

This submodel has a threshold of maize yield at 167 mm E_{gs}. However, the Stewart equation has a steep slope, consequently it predicts higher yields than the De Jager and Du Pisani (1977) submodels described above in "good" years but lower yields in "poor" years and results in higher coefficients of variation of maize yield than the other two E-based models.

* *The Du Pisani (1978) Submodel.* The Du Pisani (1978) submodel was developed using data from several divergent locations in South Africa and estimates maize yield by

$$Y_m = P_{ym} 0.88^{MSD}$$

where

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

$$= \frac{4.575\ E_{mgs}}{424.4}$$

in which

E_{mgs} = accumulated maximum evaporation (mm) from the top- and subsoil horizons for the duration of the active growing season, and

MSD = number of soil water stress days for the critical flowering period, taken as 70-100 days after planting.

When used in the *ACRU* system a soil water stress day in terms of the Du Pisani (1978) approach has been defined as occurring when the E of both the top- and subsoil horizons was less than 0.5 E_m. Because the exponent MSD can be high in "dry" seasons, this has a severe effect, predicting very low yields when the flowering period of maize experiences stressed conditions.

* In the submodels presented in Section 15.3.3 above, maize yields are estimated by *ACRU* based on work by other researchers. No cognisance is taken of genetic factors or other technological development which may enhance yields. The yield estimate furthermore assumes good management and sound agronomic practices.

15.3.4 Planting Date And Length Of Growing Season

* The input variables to all maize submodels described in Sections 15.3.1 - 15.3.3 include two options for the selection of planting dates. The planting date (PLDATE) may be specified by day (ISTDAY) and month (ISTMO), which, when input through the *ACRU* Menubuilder, will remain identical for all years of a simulation unless the dynamic input file option is invoked, in which case they can be changed year by year. If, on the other hand, planting date is unknown, a defaulted computed planting date is requested. This is calculated within *ACRU* for southern Africa

  - as occurring after October 1 (before that, low soil temperature retards germination at most locations), and
  - on condition that a minimum of 25 mm rainfall has fallen within a period of five consecutive days after October 1.

This recommendation has been used in practice for many years now and implies that planting takes place after soil water has been recharged sufficiently to ensure that germination and some root development take place under favourable conditions. There is an extensive literature in southern Africa on "optimum" maize planting dates for different regions, related mostly to the apparent "mid-season drought" during the critical flowering period.

* In regard to the length of the active growing season (variable LENGTH in *ACRU*), this varies between 120 and 180 days depending on the hybrid and region, but 150 days is an average duration in southern Africa.

15.4 ESTIMATION OF SUGARCANE AND SUCROSE YIELDS

As early as the 1960s, accumulated results had led to the conclusion that a linear relationship between crop water use (total evaporation) and sugarcane yield might exist. Thompson (1976), collating overseas results from Hawaii, Australia and Mauritius with those from the South African Sugar

Association's experiments at Mount Edgecombe, Chakaskraal and Pongola, obtained an equation which, when metricated, may be expressed as

$$Y_c = 9.53\ (E/100) - 2.36$$

where

Y_c = annual sugarcane yield ($t.ha^{-1}$) and
E = annual total evaporation (mm).

It must be stressed that this equation estimated yield of cane for a 12-month period and not for the duration of a ratoon, which will vary between 12 and 24 months, depending mainly on regional and intra-seasonal climatic conditions. To obtain a yield for a "crop", the tonnage estimated therefore has to be adjusted to account for the duration of a particular growing cycle.

Similarly, an equation was derived by Thompson for tons sucrose yielded per hectare (Y_s) which gave

$$Y_s = -22.27 + 4.841(E/100) - 0.1395(E/100)^2$$

This empirical curvilinear sucrose yield equation, the r^2 of which was not very high, should be interpreted with some circumspection under dryland conditions in dry years, because it can result in negative values of Y_s (because of the high constant value in the equation).

The implications of the above yield equations are that approximately 9.5 t cane or 1.33 t sucrose can be produced for each 100 mm water utilised in total evaporation by the crop. For annual yield estimates *ACRU* assumes a July 1 to June 30 growing season for southern Africa. A default crop coefficient of 0.8 may be applied for each month of the year, following Thompson (1977), but more detailed regional and seasonal values of K_{cm} for sugarcane are given in the *ACRU* User Manual. Total evaporation is assumed to decline from the potential when total profile plant available water has depleted by 60%, i.e. f = 0.4.

Improved sugarcane yield models in *ACRU* are currently being researched and in time new relationships will replace those given above.

15.5 ESTIMATION OF WINTER WHEAT YIELD

Following a review of literature, a version combining aspects of the Rasmussen and Hanks (1978) spring wheat yield model and the Rasmussen (1979) winter wheat yield model (the latter developed originally from a large data set from the Great Plains of the USA coupled with remotely sensed satellite crop imagery) was "imbedded" into *ACRU*. Default parameter values were determined for southern African conditions (Domleo, 1989) and for soil water budgeting techniques incorporated within the *ACRU* system.

The phenologically-based winter wheat submodel with differential stress weighting incorporated into *ACRU* takes the general form

$$Y_w = Y_{pw}\ (E_{t1}/E_{tm1})^{\alpha 1} \cdot (E_{t2}/E_{tm2})^{\alpha 2} \cdot (E_{t3}/E_{tm3})^{\alpha 3}$$

in which

Y_w = wheat grain yield ($t.ha^{-1}$)
Y_{pw} = potential wheat yield ($t.ha^{-1}$)
E_t = accumulated ("actual") crop transpiration (mm) within a growth stage
E_{tm} = accumulated maximum transpiration (mm) within in a growth stage
α = exponent to allow for stress weighting of a growth stage
1 = growth stage 1 : emergence to jointing

2 = growth stage 2 : jointing to soft dough and

3 = growth stage 3 : soft dough to maturity.

The determination of default potential yield, exponent values and growth stage periods for southern African conditions was undertaken from a data set of observed wheat yields in the Orange Free State and Natal by Domleo (1989). Table 15.5.1 summarises findings of Domleo (1989) in regard to default values.

It is seen from Table 15.5.1 that different empirical best fit values of the exponent are obtained in tandem with *ACRU*'s water budgeting techniques, dependent on the derivation of A-pan equivalent information. It should be noted that in the absence of daily A-pan evaporation data the Linacre (1984) temperature-based equation for evaporation equivalents have been used in the derivation of exponents - this method should therefore be applied in wheat yield simulations with *ACRU*. Analysis of the exponent values shows clearly that the model gives a higher weighting to the soil water status of the jointing-to-soft dough growth stage, a critical stage in wheat grain development.

A default potential yield of 6.9 $t.ha^{-1}$ is suggested for use in southern Africa. This value appears to be a maximum yield of irrigation trials conducted by the Small Grain Centre of the Crops Research Institute at Bethlehem, SA.

All values above should be used only if experience does not suggest locally more appropriate input.

In this submodel the determination of maximum ("potential") crop transpiration is performed by starting with the winter wheat crop coefficients, K_{cm}, for different growth stages (as given, for example, in the *ACRU* User Manual). The value of E_{tm} for winter wheat is assumed zero from planting until emergence, increasing linearly to 0.5 K_{cm} at jointing, then increasing linearly to 0.9 K_{cm} at heading when maximum leaf area is attained, and then remaining at 0.9 K_{cm} until the soft dough stage is reached. This technique of obtaining E_{tm} from K_{cm} was adapted from Childs and Hanks (1975) and is illustrated in Figure 15.5.1. Values for "actual" crop transpiration depend on soil water status and are estimated by "standard" *ACRU* routines (Chapter 7).

Table 15.5.1 Default values for use with winter wheat yield modelling with *ACRU* in southern Africa (after Domleo, 1989)

Phenological State	Growth Stage	Days Since Planting	Exponent to be used in *ACRU* with	
			Daily A-pan observations	A-pan Equivalent by by Linacre (1984)
Emergence		15		
	1		0.10	0.20
Jointing		50		
	2		0.10	0.20
Soft Dough		80		
	3		0.60	0.75
Maturity		120		

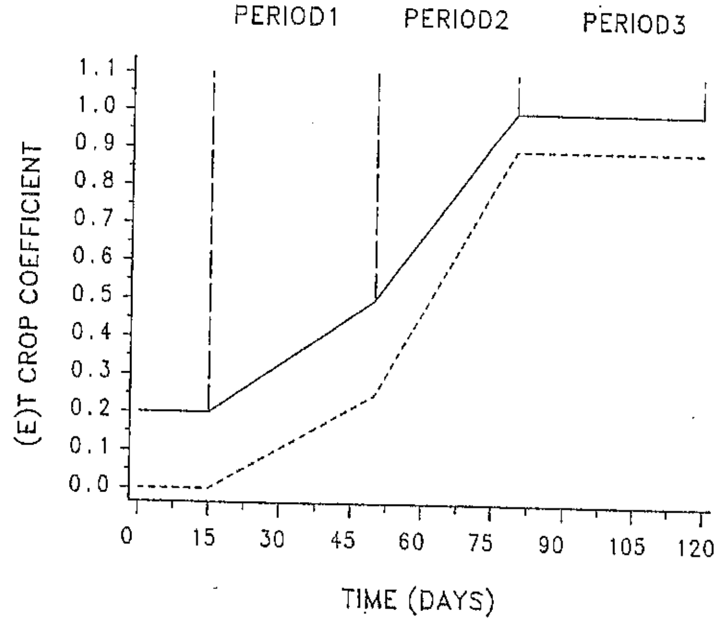

Figure 15.5.1 The estimation of maximum transpiration from crop coefficients for wheat at different growth stages (after Domleo, 1989)

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CHAPTER 16

STATISTICAL OUTPUT FROM *ACRU*

R.E. Schulze and E.J. Schmidt

16.1 INTRODUCTION

16.1.1 Model Performance

In agrohydrology a model can only be used with confidence if the user has the assurance that the model output has been tested, i.e. verified, against observed data and that the model's "performance" has met certain predetermined statistical criteria of goodness of fit. These aspects are discussed in Section 16.2.

16.1.2 Risk Analysis

Models are often used in planning and design to make objective decisions on future occurrences of, for example, flood peaks, volumes or crop yields from analysis of historical records or from simulations based on historical data input into the model. Such decisions usually revolve around

* predicting the *frequency* (i.e. expected probability of recurrence)

* of a given *magnitude* (i.e. how big, damaging or how severe the expected agrohydrological event would be), i.e.

* a *risk analysis* is undertaken, with

* risk being defined as the calculable probability of failure (Kite, 1977).

Ideally in agrohydrology risk has to be minimised, because the costs of failure (be they related to peak discharge, crop production or water supply to an irrigation scheme) are high, both in the short and the long term. Risk analyses in *ACRU* include both

* frequency analysis of non-exceedence and
* extreme value, i.e. return period, analysis.

In both these types of analyses the simulated values generally represent so-called

* *true risk*, i.e. "objective" risk, based on the assumption that the simulated values are correct (Kite, 1977).

* As a rule, values do not include an "uncertainty" factor, i.e. "subjective" risk (Kite, 1977), which would explain any random data errors, imprecise frequency distributions resulting from short data sets, or non-linearity of simulated output in a time series (as a result, for example, of land use or management or climate change).

* Subjective risk in *ACRU* is accounted for only where time series changes in agrohydrological response have been modelled specifically. This is undertaken by invoking the "dynamic" input file, which can account for gradual or abrupt changes in agrohydrological response by changing input

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Table 16.2.1 An example of the goodness of fit statistics between observed and simulated values, as used in *ACRU*

Statistics of performance of *ACRU* model, W1M16 Zululand

A comparison of simulated and observed flows for monthly values

Total observed flows	=	1412.967
Total simulated flows	=	1416.222
Mean of observed flows	=	39.249
Mean of simulated flows	=	39.340
Correlation coefficient	=	.986
Students T value	=	34.077
Regression coefficient	=	.999
Base constant for regrn. egn.	=	.137
Standard error of simulated flow	=	72.656
Variance of observed flow	=	5406.091
Variance of simulated values	=	5549.275
Standard deviation of X values	=	73.526
Standard deviation of Y values	=	74.493
Percentage difference in standard deviation	=	-1.316
Coefficient of determination	=	.972
Coefficient of efficiency	=	.975

No systematic errors detected

regression line of Q_s on Q_o

n = number of events (i.e. daily or monthly values) in the series.

* The *Arithmetic Mean*, for example of observed flows, is given as

$$\bar{Q}_o = (\sum_{i=1}^{n} Q_o)/n$$

* The *Correlation Coefficient*, r, which is the index describing the degree of association, i.e. correspondence, between the sets of simulated and observed values, is defined as

$$r = \frac{\Sigma(Q_o.Q_s) - (\Sigma Q_o)(\Sigma Q_s)/n}{\sqrt{(\Sigma Q_o^2 - (\Sigma Q_o)^2/n)(\Sigma Q_s^2 - (\Sigma Q_s)^2/n)}}$$

* *Students' 't' Test* is a statistic used in conjunction with a look-up table to test the hypothesis that observed and simulated values are not significantly different from one another and at what level of significance this hypothesis holds true. It is expressed as

$$t = \frac{r\sqrt{(n-2)}}{\sqrt{(1.0 - r^2)}}$$

* When comparing plots of observed vs simulated values by regression analysis to provide a line of best fit of the scatter of points, an important characteristic of the line of best fit is its *slope* (or regression coefficient). In a close direct association of observed and simulated point values the slope, b, which represents the line denoting the change of simulated relative to the change of observed trends, should tend to unity (i.e. 1.0). The equation for slope is given as

$$b = \frac{\Sigma(Q_o.Q_s) - (\Sigma Q_o)(\Sigma Q_s)/n}{\Sigma Q_o^2 - (\Sigma Q_o)^2/n}$$

values over time.

16.2 ANALYSIS OF MODEL PERFORMANCE

16.2.1 Introduction

In simulating a hydrological response the major aims are for simulated values to "mimic" corresponding observed values as closely as possible on a 1:1 basis, such that in a time series the

* means of simulated values are conserved when compared with means of observed values; furthermore that

* variances (i.e. deviations about the mean) are conserved; in order for

* simulated and observed values to show a close association with one another, as well as there being

* no systematic error, i.e. no bias, between simulated and observed trends and that there is,

* statistically, no significant difference between the sets of values at a given level of probability.

The present version of *ACRU* can undertake such statistical analyses of model performance either at

* *daily* level of output, or at
* *monthly* level, i.e. in a daily model, for summations in a particular month of the daily output,

for the following variables, viz.

* streamflow

* total evaporation and

* soil water status
  - for the topsoil horizon separately
  - for the subsoil horizon separately
  - for the entire soil profile

and this for values which can either be

* untransformed, or

* transformed logarithmically, the latter transformation being opted for where the range of values is very wide or where the relationship between simulated and observed is curvilinear.

The statistical programs in *ACRU* include some adaptations by Schultz (1983) and Schulze (1984) of programs first published by Roberts (1978). The equations of the statistics used in *ACRU* will be given and explained briefly and should be viewed in association with the example given in Table 16.2.1.

16.2.2 Goodness Of Fit Statistics Used In *ACRU*

The following symbols are used in explanations of the statistics used in *ACRU* :

Q_o = observed streamflow
$\bar{Q}_o$ = mean of the observed streamflows
Q_s = simulated streamflow
Q_e = estimated stormflow from the

streamflow. The error function F is the difference between D and E and the closer F is to zero the less systematic error occurs in the simulation. In *ACRU* therefore, when D > E a warning "Systemic Error Detected" is printed.

16.3 RISK ASSESSMENT BY FREQUENCY ANALYSIS

16.3.1 Cumulative Frequency Distributions In *ACRU*

Short data sets, often with skewed distributions, for which a risk analysis is required for planning and design purposes on a month by month as well as an annual basis, lend themselves to analysis and interpretation by frequency analysis.

The frequency analysis employed in *ACRU* is the CFD i.e. cumulative frequency distribution, or "ogive". The example in Table 16.3.1 shows a CFD in which month by month values of either observations or simulations are tabulated against percentiles of non-exceedence, i.e. against the proportion of non-occurrences expressed as percentages. The percentiles used, with their equivalent approximations, are

- 5% : the value exceeded on 95% of occasions, i.e. 19 times out of 20, thus approximating a 1:20 year recurrence value
- 10% : 1:10, i.e. worst year in 10 in the dry range
- 20% : 1:5, i.e. worst year in 5
- 33% : worst year in 3
- 50% : median (middle ranked) value of an information series, i.e. the value exceeded as often as it is not exceeded
- 67% : "wettest" value occurring once in 3 years
- 80% : 1:5, i.e. not exceeded in 4 years out of 5
- 90% : 1:10, wettest value expected every 10 years
- 95% : 1:20 "wet" year value of the statistic being analysed.

16.3.2 Other Statistics Included In The Frequency Analysis

The tables of CFDs in *ACRU* also include, for each month of the year and for annual totals (where applicable) the means, standard deviations and

* *Coefficients of Variation* (expressed as a percentage), C_v, where (for simulated runoff values, for example)

$$C_v = 100.(S_s/\bar{Q}_s)$$

Magnitudes of the standard deviations may be high or low, and when the ratio of S to the mean is analysed and expressed as a percentage, a more meaningful comparison of relative deviations can be made between months or between locations by interpretations of the C_v.

16.3.3 Interpretation Of Cumulative Frequency Distribution Tables

* In short data/information sets in which the sample distributions are not normal because they may contain outliers, *mean* values may be interpreted falsely as being representative averages, because they are highly influenced

* Ideally the regression line should intercept at zero. If the *intercept* (or base constant, a) is positive, there is a constant term in the predictive regression equation for simulated values, viz.

$$Q_s = a + bQ_o$$

which indicates oversimulation of low magnitudes and if it is negative, values are being underpredicted at low magnitude. The equation for the intercept is

$$a = \frac{(\Sigma Q_s) - b(\Sigma Q_o)}{n}$$

* The plots between simulated and observed values are unlikely to be along a perfectly straight line. Rather they will display a scatter of points about a trend. This scatter indicates that an error exists in the simulated values. This finds expression through the *Standard Error of the Estimate*, viz.

$$S_e = (\sqrt{\Sigma(Q_s^2) - (\Sigma Q_s)^2/n})(\sqrt{(1.0 - r^2)})$$

* The *Variances* (i.e. deviations) about the means of either the observations or simulations may be high or low and are computed (for example, for observed values) by the equation

$$V_o = \frac{(\Sigma (Q_o)^2 - (\Sigma Q_o)^2/n)}{n - 1}$$

* The *Standard Deviation* is another common index of variations of point values about the mean and is given (for example, for observed values) by

$$S_o = \sqrt{V_o}$$

* As a measure of goodness of fit between observations and simulations the *percentage difference between their respective standard deviations* is examined (S_s being the standard deviation of simulated values). In a good simulation this percentage difference, Δ%S, should be close to 0%. The equation is

$$\Delta\%S = 100\,(S_o - S_s)/S_o$$

* The variances accounted for by simulated values are a measure of the degree of association between observation and simulation, and this statistic, viz. the *Coefficient of Determination*, D (i.e. r^2), should tend to unity in a good fit.

$$D = \frac{\Sigma (Q_o - \bar{Q}_o)^2 - \Sigma (Q_o - Q_e)^2}{\Sigma (Q_o - \bar{Q}_o)^2}$$

* A simulation may show good agreement with observations, but the simulation may be over- or underestimating systematically, i.e. it may be biased. For this reason the *Coefficient of Efficiency*, E, is included in *ACRU* where

$$E = \frac{\Sigma (Q_o - \bar{Q}_o)^2 - \Sigma (Q_o - Q_s)^2}{\Sigma (Q_o - \bar{Q}_o)^2}$$

When considering D and E together, it is possible to ascertain whether systematic error is present (Aitken, 1973), the value of E being less than D when this is so. Both D and E will always be less than unity, and in both cases values approaching unity indicate accurate estimates of (say) streamflow. The error function F is the difference between D and E and the closer F is to zero the less systematic error occurs in the simulation. In *ACRU* therefore, when D > E a warning "Systemic Error Detected" is printed.

16.3 RISK ASSESSMENT BY FREQUENCY ANALYSIS

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* *Coefficients of Variation* (expressed as a percentage), C_v, where (for simulated runoff values, for example)

$$C_v = 100.(S_s/\bar{Q}_s)$$

Magnitudes of the standard deviations may be high or low, and when the ratio of S to the mean is analysed and expressed as a percentage, a more meaningful comparison of relative deviations can be made between months or between locations by interpretations of the C_v.

16.3.3 Interpretation Of Cumulative Frequency Distribution Tables

* In short data/information sets in which the sample distributions are not normal because they may contain outliers, *mean* values may be interpreted falsely as being representative averages, because they are highly influenced

example, daily runoff depth can be generated using an appropriate simulation model such as *ACRU*, the extreme value analysis procedures can be applied to fit an extreme value distribution to the generated flows. Various extreme value distributions (EVD's) have been included in the *ACRU* modelling system and the procedures for their application and options/alternatives of implementation are discussed in the following section.

16.4.1 Procedures

In order to apply extreme value analysis to a selected hydrological response variable, there are two methods in which the required information may be abstracted from the original recorded or simulated time series. These are

* the annual maximum series (AMS) and
* the partial duration series (PDS).

An *annual series* takes the largest event from each year of record and further analyses are based on this sample of n values which represent the events of "large" or "design" magnitude in the n year record. A disadvantage is that the second or third, etc. highest events in a particular year may be higher than the maximum event in another year and yet be excluded from the analysis.

This disadvantage is remedied in the *partial duration series* method in which, for example, the n largest events in a period of n years are extracted regardless of when they occurred as long as they are separate from and independent of one another. While annual maximum series and partial duration series are extracted using different procedures, results from the two methods approach one another for longer return periods (generally >10 years).

The principles discussed above can be extended to compute an EVD for any chosen month or group of months so that, for example, the expected frequency to a flood event of chosen magnitude occurring between July and October during construction of a storage dam can be computed.

The return period and probability of exceedence for each of the ranked events extracted using the AMS or PDS may be computed using the concept of probability. The assumed exceedence probability for each value is commonly determined using a formula of the form

$$P = \frac{m-b}{n+a}$$

where

P = probability of exceedence
m = ranked position of the observed value
n = total number of observations
a and b = constants.

Thus using, for example, the Weibull formula, which has been recommended for use in the *ACRU* model, and in which b = 0 and a = 1, the appropriate exceedence probability, P for each of the ranked values can be computed. Having computed P for each event, the points can be plotted on probability graph paper as event magnitude versus P, which is then called the plotting position, in order to interpolate or extrapolate to other probabilities of exceedence by fitting a straight or curved line through the plotted points. The return period, defined as the average elapsed time in years, between occurrences of an event with a certain magnitude or greater (Haan, 1977) can then be determined as the inverse of the probability of exceedence as

$$T = \frac{1}{P}$$

where

T = return period

P = probability of exceedence.

16.4.2 Extreme Value Distributions

When fitting a relationship to the data points to allow for extrapolation to return periods in excess of the record length, numerical procedures can be applied by taking account of the properties of the data set. The first property is the

* *mean* of the data set, the second the
* *standard deviation,* and the third the
* *skewness coefficient.*

These statistics are computed using the formulae given below, viz.

$$\bar{x} = \frac{\Sigma x}{n} \quad \text{(mean)}$$

$$s = \frac{\Sigma(x - \bar{x})^2}{n-1} \quad \text{(standard deviation)}$$

$$g = \frac{n.\Sigma (x-\bar{x})^3}{(n-1)(n-2)} \quad \text{(skewness coefficient)}$$

where

x = magnitude of an individual observation

n = total number of observations

$\bar{x}$ = mean of the sample of observations

s = standard deviation

g = skewness coefficient.

Various mathematical distributions can be computed in an attempt to fit the data series accurately, using the above three properties. The selection of the most appropriate one is generally based on the assumptions embodied in the chosen distribution and the extent to which the computed values represent the points plotted on probability paper. Three distributions are included in the *ACRU* system and are discussed below.

* *Extreme Value Type 1 (Gumbel) Distribution*

  This distribution assumes a fixed skewness coefficient equal to 1.1396. The sample mean and standard deviation are used to estimate the event magnitude of selected return period using the formula :

$$X_T = \bar{x} + s(0.780W_T - 0.450)$$

  where

  X_T = event magnitude of chosen risk to exceedence

  $\bar{x}$ and s = mean and standard deviation of data

  W_T = standardised variate related to risk of exceedence given in Table 16.4.1.

* *Log-Normal Distribution*

  This distribution assumes the skewness coefficient to be equal to zero when the data are transformed by applying the natural logarithm to each value. The general form of the equation is given as :

$$X_T = \bar{x} + s\,(W_T)$$

where

X_T = natural logarithm of the event magnitude of chosen risk of exceedence

$\bar{x}$ and s = mean and standard deviation of natural logarithm of data

W_T = standardised variate related to risk of exceedence given in Table 16.4.1.

* *Log-Pearson Type 3 Distribution*

This distribution allows for a range of skewness coefficients and is thus more versatile than the other two methods. As in the Log-Normal distribution x, s and g are computed using the natural logarithm transformation of each data point. The general form of the equation is

$$X_T = \bar{x} + s\,(K_T)$$

where

X_T = natural logarithm of the event magnitude of chosen risk of exceedence

$\bar{x}$ and s = mean and standard deviation of natural logarithm of data

K_T = function related to risk of exceedence and skewness coefficient of natural logarithm of data.

Values of K_T can be determined from the following equation when skewness coefficients are between 1.0 and -1.0 (United States Water Resources Council, 1976) :

$$K_T = \frac{2}{g}\left(W_T - \frac{g}{6}\right)\left(\frac{g}{6} + 1\right)^3 - 1$$

where

W_T = standardised variate assuming zero skewness given for the log-Normal distribution in Table 16.4.1

g = skewness coefficient.

Confidence limits can be developed to provide a measure of uncertainty in the magnitude computed for a selected exceedence probability. The confidence limits for the log-Normal distribution can be computed directly using methods discussed by United States Water Resources Council (1976). The 5% upper confidence limit would thus indicate there to be a 5% chance that the logarithm of the true value, be it a flood depth or rainfall depth, is greater than the value given. Conversely the 95% lower confidence limit indicates a 5% chance of the true value being less than that given.

16.4.3 Joint Association Of Rainfall And Runoff

It is generally assumed in applied hydrology that the T year rainfall event produces the T year runoff response. In other words it is assumed that the factors affecting runoff response are invariant between events. In practice, however, the effects of, for example, high soil water content prior to a relatively small incident rainfall event may result in a greater runoff response than that for a larger rainfall event falling on a drier catchment. The advantages of using a continuous soil water budget model such as *ACRU*, which accounts for changes in soil

Table 16.4.1 Values of the Standardised Variate (W_T) for the Gumbel and Log-Normal Distributions

Return Period T (years)	Exceedence Probability P	W_T	
		Gumbel Distribution	Log-Normal Distribution
2	.50	0.37	.00
5	.20	1.50	.84
10	.10	2.25	1.28
20	.05	2.97	1.64
50	.02	3.90	2.05
100	.01	4.60	2.33

water status, are thus evident. The various extreme value distributions discussed in Section 16.4.2 can therefore be applied to the generated time series of runoff response which includes the effects of soil water status, instead of using the rainfall depth of chosen return period and an assumed runoff response coefficient unrelated to antecedent conditions.

16.4.4 Model Options

Various options are available when applying extreme value distributions with the *ACRU* model. The variable used in the analysis may be one or more of :

* observed daily rainfall depth (mm)
* observed runoff depth (mm)
* simulated runoff depth (mm)
* observed peak discharge ($m^3.s^{-1}$)
* simulated peak discharge ($m^3.s^{-1}$)

Any combination of months may be used to extract extremes during selected seasons or periods during the year. The annual maximum series of the selected variable during the chosen period of interest is extracted in order to fit one of the following three extreme value distributions:

* Gumbel
* Log-Normal
* Log-Pearson Type 3

A plot of the annual maximum series using the Weibull plotting position and the computed extreme values maybe produced as an output option. The partial duration series may be selected in order to obtain a listing of the largest n independent events in the n year period of record, regardless of the year of occurrence. These values may be compared with the listing of the annual maximum series if consideration is to be given to return periods of less than 10 years. A listing of the 5 largest events of the selected variable in each year of record is produced together with the corresponding values of the other variables on the relevant date. This information can be used to assess the significance antecedent soil water status plays in catchment runoff response.

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CHAPTER 17

VERIFICATION STUDIES

R.E. Schulze (Editor)

17.1 AIMS OF VERIFICATION STUDIES IN *ACRU* - R.E. Schulze

A model such as *ACRU* can only be used with a degree of confidence if its output has been verified against observed data sets. The following aims were set for verification studies in *ACRU*.

* The objective functions in verification should include conservation of means and deviations, with efficiency in the goodness of fit around the 1:1 relationship between observed and simulated values. For these reasons, the statistics of goodness of fit, as outlined in Chapter 16, were incorporated into *ACRU*.

* In addition to verifying only the *end-product* of a simulation (e.g. streamflow or final crop yield), it is equally vital to verify the *internal state variables* of the model, i.e. those components and processes within the system which are simulated *en route* to "final" estimations (e.g. canopy interception, soil water status). If this is not done one may well be mimicking correct final answers for the wrong reasons. Furthermore, if the internal state variables are simulated realistically, the user has more confidence in applying a model outside the range of climates and land uses in which verifications have been performed.

* Models with a wide range of application must be verified over a wide range of agrohydrological regimes, including tests in humid areas, sub-humid and arid areas and with a variety of land uses.

* Models must, equally, be verifiable for a range of prevailing conditions within an agrohydrological regime, including "design" conditions, i.e. extremes such as particularly wet or dry periods.

* Where the model does not perform up to expectations with input data of good quality, the model developers should set out to check where, within the various subsystems being modelled, the problem may lie, that it can be addressed by way of further research, rather than by "massaging the data until it fits" or "tweaking parameters" until objective functions are met.

17.2 ON THE APPLICATION OF THE VON HOYNINGEN-HUENE INTERCEPTION EQUATION FOR NON-AGRICULTURAL LAND USES - R.E. Schulze

17.2.1 The Von Hoyningen-Huene Equation

Von Hoyningen-Huene (1983) developed a curvilinear equation of canopy interception loss per rainday for agricultural crops, which he verified extensively in Europe. The equation is given as

$$I_l = 0.30 + 0.27\,P_g + 0.13\,LAI - 0.013\,P_g^2 + 0.285\,P_g.LAI - 0.007\,LAI^2$$

in which

I_l = interception loss (mm.rainday^{-1})
P_g = gross rainfall (mm)
LAI = Leaf Area Index of the crop.

In *ACRU* P_g is the daily rainfall input and LAI is either input or derived internally from crop coefficients (Chapter 6). By virtue of its curvilinear nature this equation is "stable" up to a rainfall of 18 mm - daily rainfall above that amount is assumed not to induce any further canopy interception losses.

17.2.2 Verification

The need frequently arises to estimate canopy interception under afforested conditions, where its influence on the water budget may be more pronounced than for shorter agricultural crops. The Von Hoyningen-Huene (1983) equation was therefore tested on a stand of *Pinus patula*, in which canopy interception had been measured and an equation for its estimation derived from rainfall amount (Schulze, Scott-Shaw and Nänni, 1978). This stand of *Pinus patula*, at Cathedral Peak in Natal (latitude 29 ° S, longitude 29 ° E) was aged 10 years at the time of the experiment, with a density of 750 stems per hectare. The LAI of the stand was estimated independently by an experienced forest hydrologist to be 4.5.

Figure 17.2.1 illustrates the excellent fit of the Von Hoyningen-Huene (1983) interception estimate (large dots) against the line of best fit for the canopy interception experiment as derived by Schulze *et al.* (1978).

17.2.3 Conclusions

From Figure 17.2.1 it may be concluded that this equation may be used with confidence in simulations of canopy interception of *Pinus patula*. Care should, however, be exercised in using the equation on other commercial forest species, for example, *Eucalyptus grandis*, because of their often very different canopy properties.

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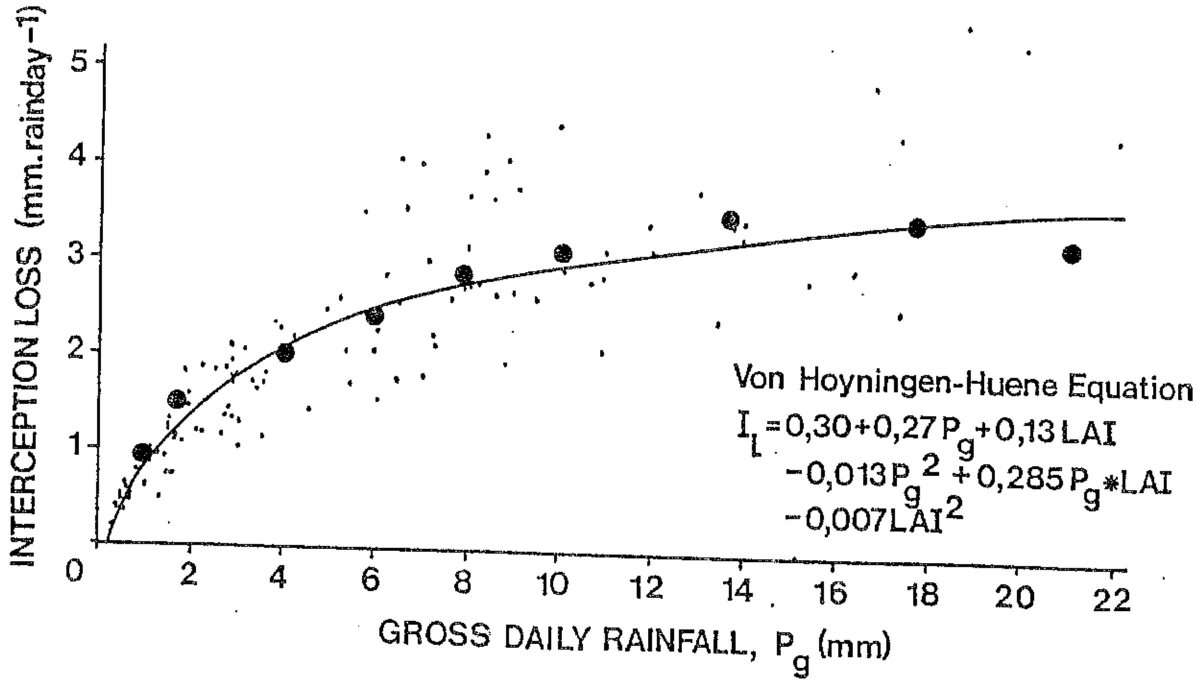

Figure 17.2.1 Simulations by the Von Hoyningen-Huene equation on the line of best fit of canopy interception measurements in *Pinus patula*

17.3 RAINFALL RELATED CORRECTION FACTORS TO DAILY POTENTIAL EVAPORATION ESTIMATES FROM MEAN MONTHLY VALUES - M.C. Dent

17.3.1 Introduction

For the estimation of daily A-pan equivalent potential evaporation (E_p), which is utilised as the reference E_p in *ACRU*, daily pan evaporation or, alternatively, daily surrogate temperature data are frequently not available. In such cases it is necessary to use monthly means of maximum and minimum temperature or monthly total evaporation data to generate daily E_p from a monthly E_p, as outlined in Chapter 4.

Potential evaporation, when converted from a monthly mean to a daily mean estimate by Fourier Analysis in *ACRU* gives an identical "recycled" value of E_p for any given day of the year in each year for which values are generated. To introduce a realistic perturbation into these identical daily E_p estimates it was hypothesised that suppressing the E_p below the mean on raindays and enhancing it above the mean on non-raindays would result in more realistic daily E_p simulations.

Since 1984, *ACRU* routines had enhanced non-rainday E_p by 5% and suppressed rainday E_p by 20%, where daily E_p was estimated from monthly totals. A study was therefore initiated to verify these correction factors for use in southern Africa.

17.3.2 Methodology

Daily rainfall and daily Class A-pan evaporation records from all stations on the Department of Agriculture and Water Supply data files in 1987 (approximately 740 000 daily values) from sites throughout southern Africa, were extracted. The mean daily evaporation value was calculated for each month of the record at each station. Thereafter the actual daily evaporation for each day was divided by the mean daily evaporation value for that month. The above-mentioned quotients were stored and a frequency analyses was performed separately on the rainday (defined as >5 mm rainfall) and non-rainday quotients.

17.3.3 Results

The results, which are presented as frequency distributions in Figure 17.3.1, show that the modal value of the quotient on raindays is approximately 0.83 and on non-raindays is 1.05. The median value in the case of non-raindays is also 1.05 and on raindays is 0.78. The correction factors 0.8 and 1.05 have therefore been adopted in *ACRU* routines for the procedures which use monthly mean E_p to generate daily E_p estimates for the *ACRU* model.

An interesting follow up of this study would be to investigate the distributions shown in Figure 17.3.1 for different seasons and geographical regions within southern Africa.

17.3.4 Reference

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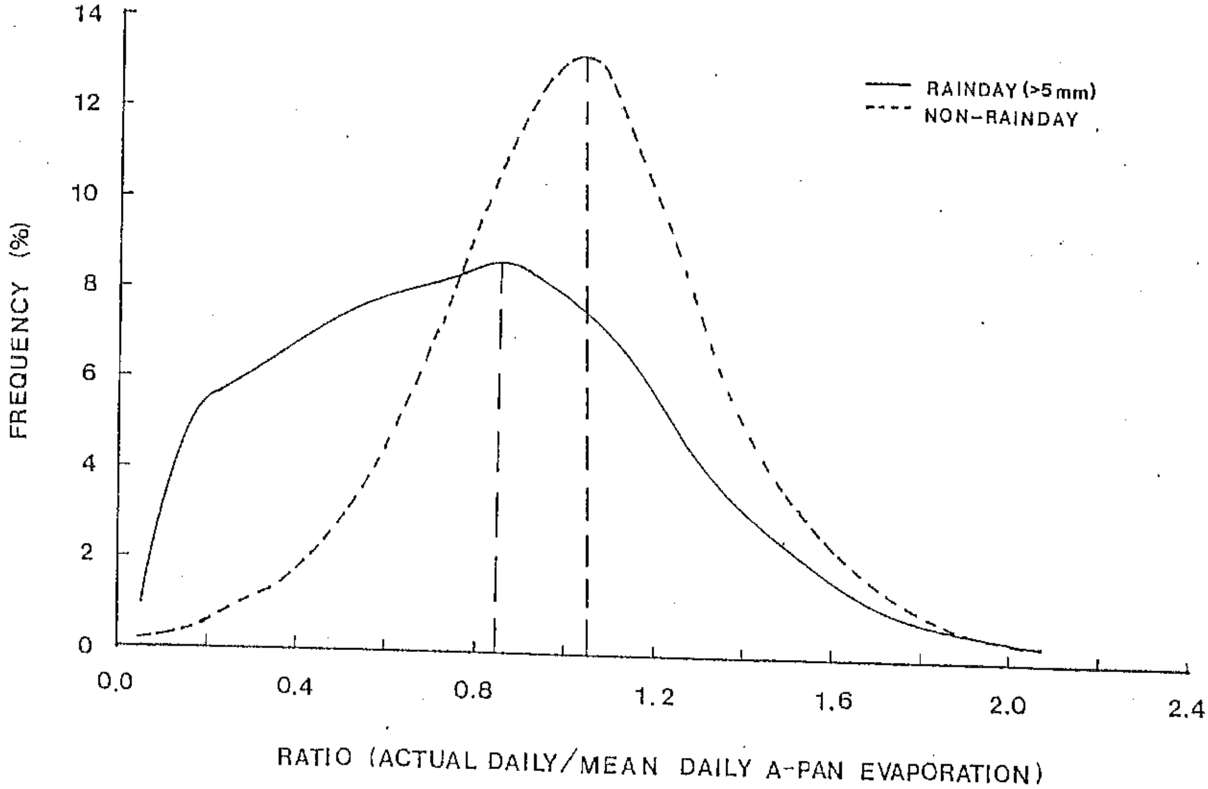

Figure 17.3.1 Frequency distributions of the ratio of actual daily evaporation to the means of generated daily evaporation for raindays and non-raindays (after Dent, Schulze and Angus, 1988)

17.4 SIMULATION OF SOIL WATER CONTENT BY *ACRU*

M.C. Dent and R.E. Schulze

17.4.1 Background

Accurate estimates of soil water content by the *ACRU* agrohydrological modelling system are important for many applications, since the soil water budget lies at the "heart" of the model. Runoff response to rainfall, crop yield estimates and irrigation requirement, for example, are all functions, to a greater or lesser extent, of soil water status. This section describes a verification of *ACRU*'s output of soil water content under irrigation.

17.4.2 Methods And Data

Observed soil moisture data were obtained from Nel (1987) at Roodeplaat and Mottram (1986) at Cedara. At each site the data for two replicate experiments, viz. Plots 6 and 16 planted to wheat at Roodeplaat and Plots 8 and 17 planted to soybeans at Cedara were used. Plot 6 at Roodeplaat and Plot 8 at Cedara were used to first model, by a combination of *a priori* and manual calibration, crop coefficients and root mass distributions of the respective crops. The values of these variables were then used without adjustment in the simulation of soil water content in Plots 16 and 17. The *ACRU* model performance on Plots 16 and 17 is therefore considered a true verification of its ability to estimate soil water status. The crop coefficients which were selected for a two-horizon soil profile simulation version by *ACRU* on Plot 6 at Roodeplaat were maintained for a single-horizon profile simulation with good results, as may be seen in Table 17.4.1.

Data from Nel (1987) consisted of daily rainfall and irrigation water applications, daily A-pan evaporation, the soil form and series (Hutton Shorrocks) according to the binomial system of soil classification for southern Africa (MacVicar *et al.*, 1977), estimates of the crop coefficient at various growth stages and the root mass distribution at maturity. Measurements of soil moisture by neutron probe were given in mm soil water for the topsoil horizon (0 - 0.9 m) and the subsoil horizon (0.9 - 1.8 m). In the verification study the soil water content in the profile was modelled in two horizons which corresponded with the horizons mentioned above, and also as a single uniform horizon (0 - 1.8 m). Values of the soil water retention constants field capacity (FC) and permanent wilting point (WP) were calculated for each horizon using the methods described in Schulze, Hutson and Cass (1985).

The data from Mottram (1986) were for soybeans grown on a complex of Hutton Doveton and Bainsvlei Metz soil series under research conditions in field Plots 8 and 17 at Cedara. The plots experienced a number of small to medium sized summer rainfall events and were irrigated when necessary. Soil moisture was measured by neutron probe at intervals of 0.05 m down the soil profile to a depth of 0.9 m. The integral of these moisture values was calculated and the profile was modelled as a single layer 1.0 m deep. This zone contained almost all the crop roots according to Mottram (1986). Values of the soil water retention constants FC and WP were provided by Mottram (1986).

Irrigation water was assumed to enter the soil in totality and was not reduced through runoff, whereas the rainfall was reduced to effective rainfall through subtraction of model estimated

Table 17.4.1 Comparison of observed and *ACRU* simulated soil water content, using field plot data at Roodeplaat and Cedara (after Dent, Schulze and Angus, 1988)

Statistic	Wheat at Roodeplaat								Soybean at Cedara	
	Plot 6				Plot 16				Plot 8	Plot 17
	Single Horizon (1.8m)	Double Horizon A (0.9m)	Double Horizon B (0.9m)	Double Horizon Total (A+B) (1.8m)	Single Horizon (1.8)	Double Horizon A (0.9)	Double Horizon B (0.9m)	Double Horizon Total (A+B) (1.8)	Single Horizon (1m)	Single Horizon (1m)
Mean observed (mm)	333	163	170	333	336	160	177	336	317	305
Mean simulated (mm)	338	164	179	343	308	160	160	317	315	307
Std. dev. observed (mm)	45	33	16	45	42	34	13	42	9	8
Std. dev. simulated (mm)	46	32	18	48	44	31	17	41	12	13
Regression coefficient	1.01	0.97	1.00	1.06	0.97	0.91	1.05	0.96	1.02	1.08
Base constant (mm)	3.1	6.2	9.4	-7.8	-19.1	11.8	-25.9	9.9	-8.4	-56.08
Correlation coefficient	0.98	0.98	0.88	0.97	0.93	0.98	0.81	0.91	0.76	0.72
Root Mean Square Error (mm)	8.8	5.4	8.8	10.3	17.0	6.4	10.1	14.6	8.1	9.3
Maximum observed (mm)	404	207	201	404	388	208	197	388	337	320
Maximum simulated (mm)	402	210	212	417	375	203	192	375	339	329
Minimum observed (mm)	247	106	135	247	248	97	148	248	303	290
Minimum simulated (mm)	249	106	146	254	227	100	135	244	296	284
Coeff. of Determination	0.96	0.96	0.77	0.94	0.86	0.96	0.66	0.88	0.58	0.52
Coeff. of Efficiency	0.93	0.98	0.30	0.92	0.38	0.95	-1.22	0.67	0.23	-0.38

runoff and interception by standard *ACRU* procedures, with the critical soil depth for stormflow response taken as 0.3 m.

17.4.3 Results

At Roodeplaat and Cedara the soil moisture was observed at intervals of between two and ten days. The simulated soil water status was noted for the days on which observations of soil moisture were available. Time series plots of observed and simulated soil water content for the sites at Roodeplaat and Cedara are presented in Figure 17.4.1. Further analyses of these results are presented in Table 17.4.1 which shows that the means, standard deviations and ranges of the observed and simulated soil water contents generally compare very well. In addition the Root Mean Square Error, RMSE, between the observed and simulated soil water contents is low in relation to the total water content in the soil profile. The regression intercepts, with the exception of that for Plot 17 at Cedara are close to zero, especially when one considers that the plotted points are at most in the range 250 to 400 mm and in some cases much lower. The correlation coefficients, with the exception of those at Plots 8 and 17, are high. The Coefficients of Efficiency are reasonably high, again with the exception of that for Plots 8 and 17 at Cedara and the subsoil horizon in both Plots 6 and 16. A comparison of the coefficients of determination and efficiency indicates that some systematic bias occurs in all the simulations except the topsoil horizon of Plot 6. The above-mentioned shortcomings may be attributed to the following factors :

* First, the range in the values of observed soil moisture is small, particularly at Cedara and in the subsoil horizon at Roodeplaat.

* The second reason is one which is valid in all simulation tests of this nature, i.e. that one poorly estimated rainfall event displaces the simulated soil water content for several days or even weeks thereafter. This phenomenon may be seen in the time series plots of observed and simulated soil water content presented in Figure 17.4.1. The rainfall intensity may play a major role in such unpredictable displacements since the amount of runoff and hence effective rainfall is often highly sensitive to intensity. This is an aspect which requires attention in future research.

* Thirdly, there is a question of the accuracy of determination of soil moisture. The inherent variability of soil water content, texture, bulk density and other properties lead to variability and error in the measurement of soil moisture. The neutron probe method was used by Mottram (1986) to determine soil moisture. Standard errors of between 3 and 10 per cent in the estimation of soil moisture by the neutron probe have been reported by many researchers, *inter alia* by Rawls and Asmussen (1973) and Mottram (1986). The total range of observed soil moisture in the Cedara field plot experiment was only 12 per cent of the mean. In the light of the above it may be appreciated that the Coefficient of Efficiency does not provide a useful objective function in this case and the RMSE is a preferable objective function to use in verification.

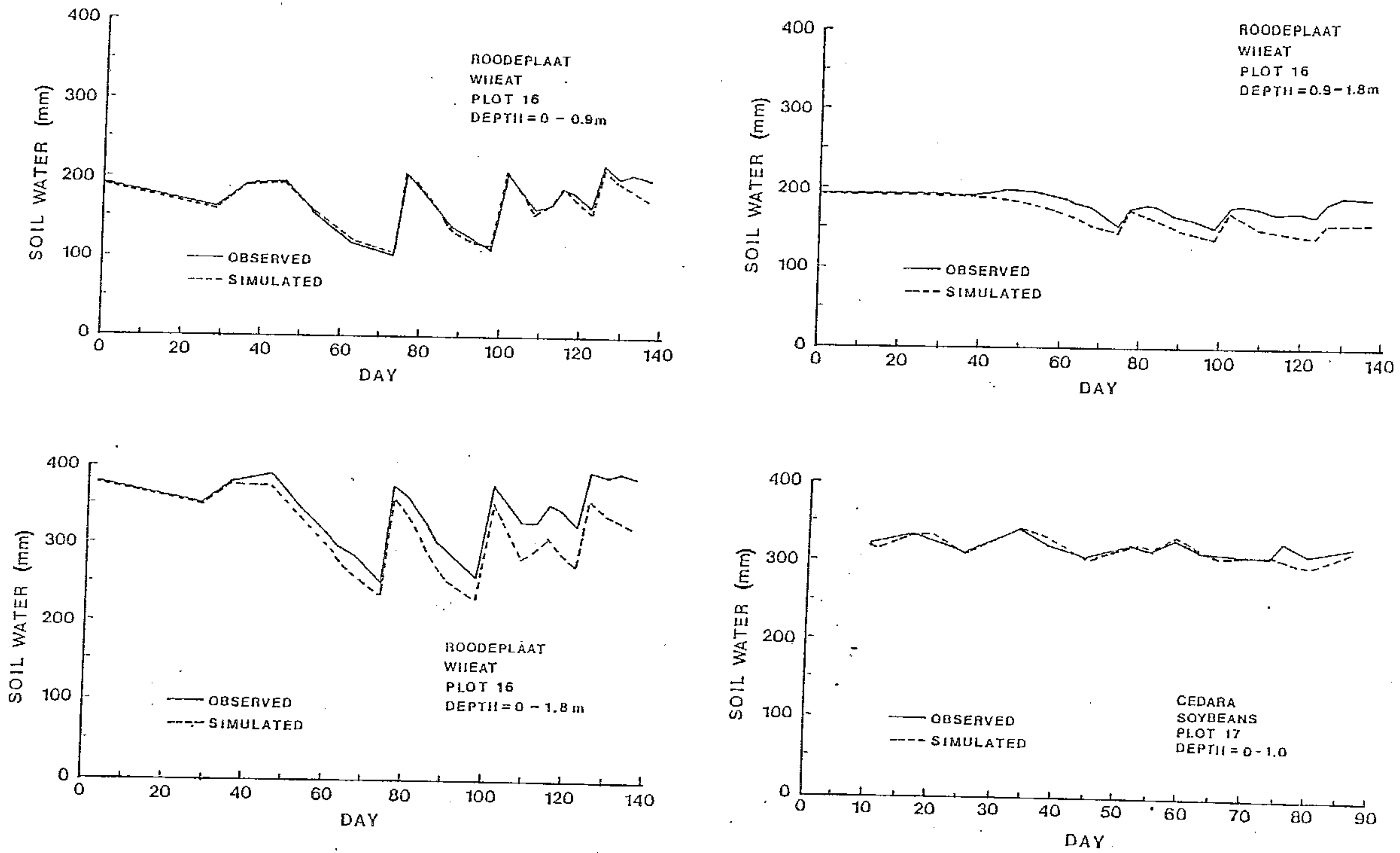

Figure 17.4.1 Simulated vs observed plots of soil water content at Roodeplaat and Cedara (after Dent, Schulze and Angus, 1988)

The *ACRU* model simulations of soil water content at Roodeplaat are particularly encouraging since they spanned the entire growing season (5 months), during which period the observed soil moisture in the top 0.9 m experienced a range of 100 mm, the nine irrigation applications ranged from 6 mm to 152 mm and the five rainfall events ranged from 9 mm to 80 mm.

17.4.4 Conclusions

The above comparison of observed and *ACRU* simulated soil water content at two locations with different climates, irrigation strategies and crops lends credence to the *ACRU* model's being able to simulate soil water content realistically. By implication it is believed that the model can be used with confidence in dryland and irrigation soil water budget calculations, for the sake of simulating soil water status *per se* as well as using soil water status as a critical determinant in runoff production.

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17.5 SIMULATION OF MONTHLY TOTALS OF DAILY STREAMFLOW FROM A LUMPED CATCHMENT AT CATHEDRAL PEAK, NATAL

- **W.J. George and R.E. Schulze**

17.5.1 Background

A simulation of streamflow (runoff volumes) was performed by *ACRU* in lumped catchment mode at Cathedral Peak Research Catchment II in the Natal Drakensberg (latitude 29 ° 00'S, longitude 29 ° 15'E). This case study of a runoff verification by *ACRU* has been extracted and summarised from a paper by Schulze and George (1987), to which further reference can be made for more details.

17.5.2 Catchment And Hydrometeorological Information

Catchment II faces north-northeast, is 1.949 km^2 in area and has an altitude range from 1844 to 2454 m (Figure 17.5.1). Soils are highly leached, basalt-derived silty clays. Based on research by Schulze (1975) on adjacent catchments, mean soil depth is 0.80 m (topsoil 0.20 m) and texture and field derived values for topsoil and subsoil horizon wilting points are, respectively, 0.250 and 0.245 $m.m^{-1}$, field capacities 0.370 and 0.376 $m.m^{-1}$ and porosities 0.476 and 0.491 $m.m^{-1}$ (Schulze, 1984). During the period of simulation, viz. 1949 - 1954, the catchment was predominantly under short *Themeda triandra* grassveld.

Monthly means of daily maximum and minimum temperatures from the Cathedral Peak meteorological site (1852 m altitude), 2 km NNE of the catchment's gauging weir, were used to estimate monthly potential evaporation, i.e. E_o, values by the Linacre (1977) technique which is a Penman-derived temperature/altitude/latitude based E_o estimator. The monthly E_o was then converted to daily values by Fourier analysis and adjusted up or down according to the occurrence or non-occurrence of rainfall.

Cathedral Peak Catchment II, which has a mean annual precipitation of 1400 mm of which 80% falls in the summer months October to March (Schulze, 1975), is served by three raingauges (Figure 17.5.1). Gauge IIAM is a monthly accumulator at 2283 m altitude while IIBR is an autographic raingauge at 1975 m and IICW is a weekly accumulator at 1871 m. Daily rainfall data for 1949 to 1967 were obtained from the digitised autographic record of IIBR, with any missing data "patched" using information from nearby recorders at IVCR and at the meteorological station and taking account of accumulated totals from IIAM and IICW. A weighted daily value for the entire catchment was obtained from long term relationships between the centrally located gauge IIBR and IIAM/IICW, with the monthly weighting coefficient applied to daily rainfall totals at IIBR ranging from 0.88 in July to 1.11 in December.

Daily observed streamflow records were derived from digitised data for Catchment II at weir V1M03. Both rainfall and streamflow data were provided by the Forestry Branch of the State Department of Environment Affairs. Since an afforestation programme of the catchment commenced in 1951 the simulation was therefore restricted to the period before the effects of the afforestation were felt, i.e. 1949 to 1954.

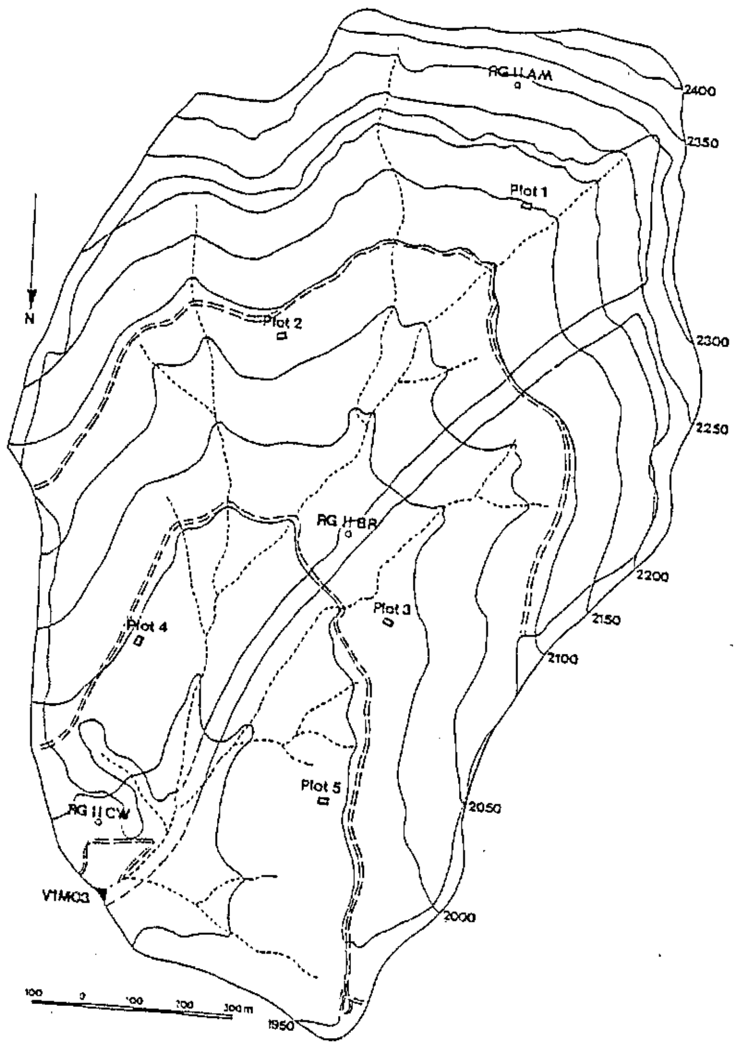

Figure 17.5.1 Cathedral Peak Research Catchment II (after Schulze and George, 1987)

17.5.3 Results

Figure 17.5.2 illustrates the simulated vs observed flows for monthly totals of daily streamflow from Cathedral Peak Catchment II. The statistics of model performance for this simulation (Table 17.5.1) which was a first run with no adjustments to variables or optimisation of parameters show good relationships between means (difference <5%), and highly acceptable relationships between variances of simulated and observed flows (difference 16%). The simulation explains over 91% of the variances of monthly streamflow accumulations. While generally overestimating by 5% (cf. means of 68.3 vs 65.6 mm), *ACRU* underestimates somewhat at high flows (regression coefficient 0.801) while over-simulating at low flows (base constant 15.8 mm).

17.5.4 References

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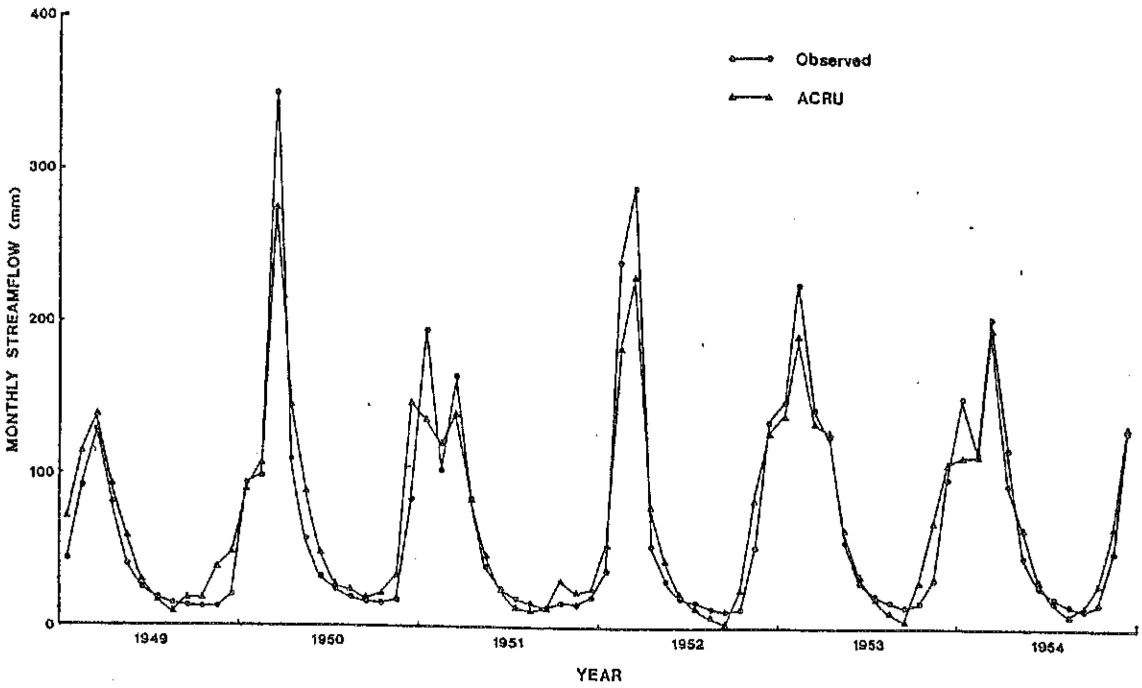

Figure 17.5.2 Simulation of monthly totals of daily streamflows at Cathedral Peak Catchment II for the period 1949-1954 (after Schulze and George, 1987)

Table 17.5.1 Statistics of *ACRU* model performance on Cathedral Peak Catchment II for monthly totals of daily streamflows, 1949-1954 (after Schulze and George, 1987)

Total observed values (mm)	4721.746
Total simulated values (mm)	4920.626
Mean of observed values (mm)	65.580
Mean of simulated values (mm)	68.342
Regression coefficient	.801
Base constant for regression equation (mm)	15.806
Standard deviation of observed values (mm)	71.477
Standard deviation of simulated values (mm)	59.932
Percentage difference in standard deviation	16.152
Coefficient of Determination	.913
Coefficient of Efficiency	.902

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17.6 PERFORMANCE OF THE *ACRU* DISTRIBUTED CATCHMENT MODEL

G.R. Angus and R.E. Schulze

17.6.1 Introduction

Although originally developed as a lumped model for small agricultural catchments, increasing demand that the model be applied to large catchments has resulted in the development of a distributed version of the *ACRU* model. By nature of its definition, a distributed model provides information at selected points within a catchment as well as at the catchment outlet. In order to verify a distributed model therefore, a catchment with nested gauged subcatchments should be selected for verification. The Zululand research catchments, which have been well documented by Hope and Mulder (1979), consist of a series of nested catchments with internal gauging weirs and it is for this reason that these catchments were selected for verification of the distributed *ACRU* model.

17.6.2 The Zululand Research Catchments

The Zululand research catchments are situated on the Natal coastal belt, inland of Mtunzini, at latitude 28°29'S and longitude 31°27'E. Although the catchments consist of five nested catchments, only W1M15, which has W1M16 and W1M17 as internal catchments, was selected for verification purposes. The catchments are 12 km inland from the coast with an altitudinal variation of about 260 m within the catchment. MAP varies by about 150 mm with the higher lying regions further from the sea receiving an MAP of about 1300 mm. Temperatures range from monthly means of daily maximum and minimum values of 30°C and 20.8°C in January to 23.6°C and 10.3°C in June.

The catchments are characterised by a large number of rocky outcrops in the higher lying regions and a gently undulating region near the gauging weir W1M15 (Hope and Mulder, 1979). Sandy clay loam covers about 70% of the catchments with most of the balance made up of 18% sandy clay and sandy loam. The upper regions of the catchments have predominantly deep soils ranging in depth from 0.7 - 1.2 m whilst the lower regions have shallower soils, usually less than 0.5 m.

As with rainfall and soil types, the land use is also influenced indirectly by elevation and hence associated climatic variations. The higher lying regions have a large amount of mixed indigenous forest and Ngongoni grassland whilst the lower regions are predominantly Ngongoni grassland (Hope and Mulder, 1979).

17.6.3 Catchment Discretisation

A 1:10 000 topographical map was used to subdivide W1M15 into 12 subcatchments or cells (Figure 17.6.1). The subcatchment outlets to Cells 1, 4 and 12 were selected to coincide with the nested catchments gauged by weirs W1M17, W1M16 and W1M15 respectively. Although homogeneity of land use and soils within a subcatchment is one of the objectives of catchment discretisation with a cell-type distributed model, this proved to be a problem in the Zululand catchments (Angus, 1987). It was decided to opt for homogeneity of altitude and topography at the expense of homogeneity of soil types because of the spatial diversity of soil and land use characteristics as recorded by Hope and Mulder (1979). However, as both soil

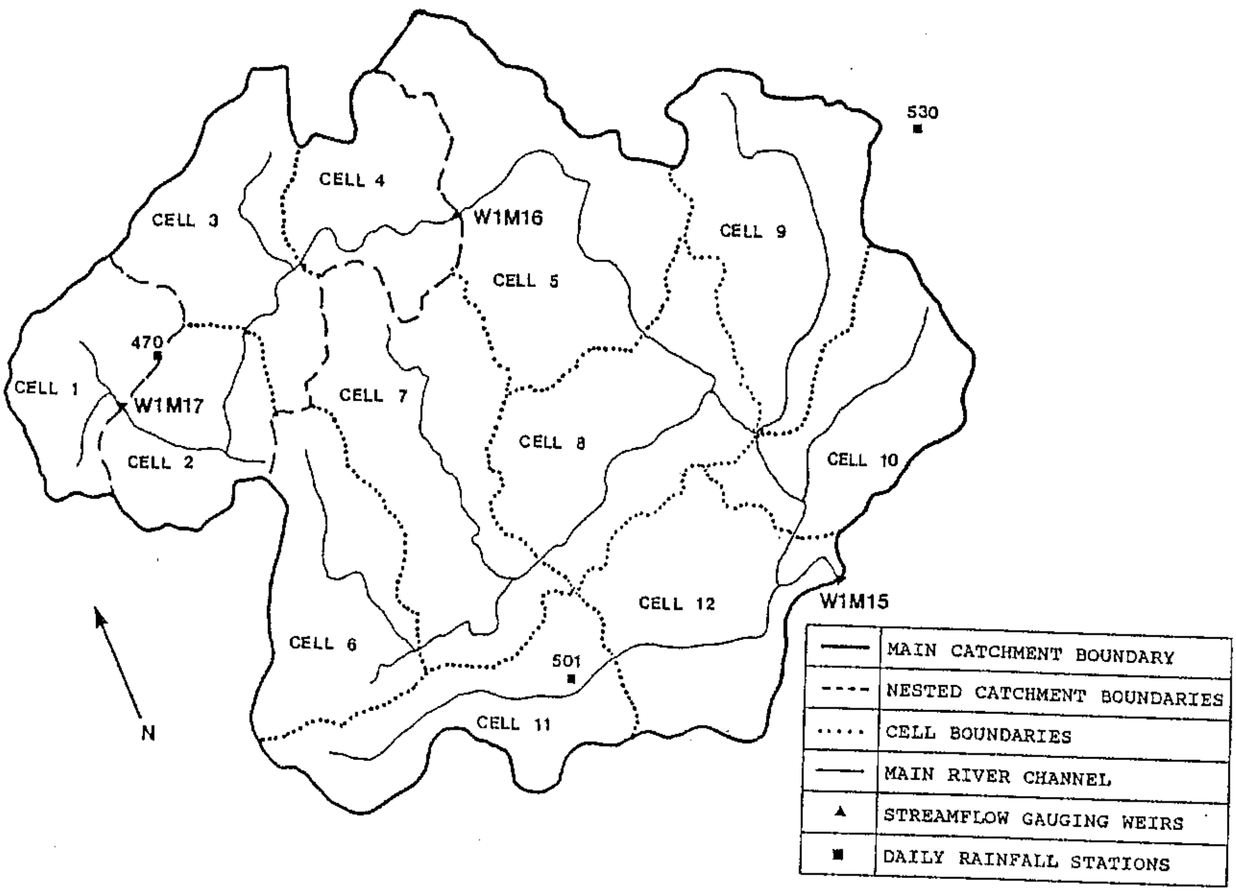

Figure 17.6.1 Subcatchment discretisation of Zululand research catchments (Angus, 1987)

and vegetation characteristics are indirectly related to topography and elevation it was believed that catchment discretisation based on these criteria would ensure the highest degree of homogeneity of hydrologically significant characteristics.

The areas of the 12 subcatchments are given in Table 17.6.1. Although it would be preferable to keep the subcatchments to a similar size, this is not always possible, as may be seen from Table 17.6.1.

Data from daily rainfall stations 470, 530 and 501 (Figure 17.6.1) were used as input to each subcatchment using an inverse distance weighting method. Daily temperature recorded at the University of Zululand adjusted according to an adiabatic lapse rate to account for elevation differences, was used in the temperature-based Linacre (1977) equation (cf. Chapter 4) as an estimate of potential evaporation for each subcatchment.

17.6.4 Simulation Results

Catchments W1M16 and W1M15 provide two situations where the relative performance of lumped and distributed versions of *ACRU* can be compared. However, only the performance of the lumped and distributed models at W1M15 will be discussed as W1M16 had major leakage problems.

Table 17.6.1 Zululand subcatchment areas (Angus, 1987)

Sub-catchment	Area (km)	Percentage of total area
1	0.670	4.91
2	0.785	5.75
3	1.010	7.41
4	0.750	5.53
5	1.770	12.97
6	1.030	7.55
7	1.570	11.50
8	1.355	9.90
9	1.385	10.15
10	1.030	7.55
11	1.010	7.40
12	1.280	9.38
TOTAL	3.645	100.00

An analysis of daily streamflow values for the period January 1977 until December 1981 yielded the results in Table 17.6.2. Only days for which observed streamflow and records were flagged as accurate have been included in the analysis. From the results it can be seen that the total simulated flows, which represent the sum of all simulated flows for 1136 observations, underestimate observed flows by about 4.0% and 9.7% for the distributed and lumped versions of *ACRU* respectively. Standard deviation of observed flows is more closely followed by the distributed model than by the lumped model. Although the correlation coefficient gives no indication of a markedly superior performance by the distributed model, this is not so in the case of the linear regression constant and slope coefficient. The linear regression slope coefficient for the distributed model, 0.979, approximates the 1:1 line more closely than the lumped model coefficient of 0.817. This also suggests that the lumped model will underestimate flows to a greater degree than the distributed model, a supposition which is borne out by the total of lumped and distributed flows mentioned previously.

The Coefficient of Efficiency suggests a greater degree of conformity between observed and simulated flows in the distributed model. However, in both cases the Coefficient of Efficiency is less than the Coefficient of Determination and this indicates systematic bias in both models (Aitken, 1973).

The analysis was extended to investigate the relative abilities of the distributed and lumped versions of the *ACRU* model to simulate high and low flow regimes. Low flow regimes would occur mostly on the recession limb of the hydrograph and this would usually represent a situation where baseflow contributes entirely to the streamflow. In these cases it was found that both the lumped and distributed models underestimated streamflow consistently. However, for events of a greater magnitude, particularly on the occasions where streamflow was in excess of a depth of about 10 mm, both models performed appreciably better. This investigation was extended to a seasonal analysis of performance

Table 17.6.2 Statistics of performance of the distributed and lumped models on catchment W1M15 using reliable data for the period January 1977 until December 1981 (after Angus, 1987)

Statistics of Performance	Distributed Model	Lumped Model
Total observed flows (mm)	1410.523	1410.523
Total simulated flows (mm)	1353.092	1273.858
Number of observations	1136	1136
Mean of observed flows (mm)	1.242	1.242
Mean of simulated flows (mm)	1.191	1.121
Standard deviation of observed flows (mm)	4.9927	4.927
Standard deviation of simulated flows (mm)	4.954	4.221
Percentage difference in standard deviation	-0.005	14.337
Correlation coefficient	0.974	0.953
Regression coefficient	0.979	0.817
Base constant for regression equation (mm)	-0.025	0.107
Standard error of simulated value (mm)	37.795	42.974
Coefficient of Determination	0.949	0.909
Coefficient of Efficiency	0.940	0.893

where once again the higher flows in summer were more accurately predicted than low flows in winter.

A graphical representation of monthly totals of observed and simulated flows for the period October 1977 until April 1979 is presented in Figure 17.6.2. Although the period of data is too short to identify any definite seasonal trends, it illustrates a better approximation of peak monthly flows by the distributed model than by the lumped model.

17.6.5 Conclusions

Although both versions of the models were found to simulate streamflow well, the distributed version of *ACRU* was found, overall, to be a better predictor of streamflow on the Zululand catchments than the lumped version. Besides better performance, the distributed model is also able to provide agrohydrological information at various selected points within a catchment, whereas a lumped model only provides information at the catchment outlet. A distributed model is better able to account for spatial variations in soil, land use and climatic information and is thus more likely to provide an accurate physical description of the hydrological processes within a catchment.

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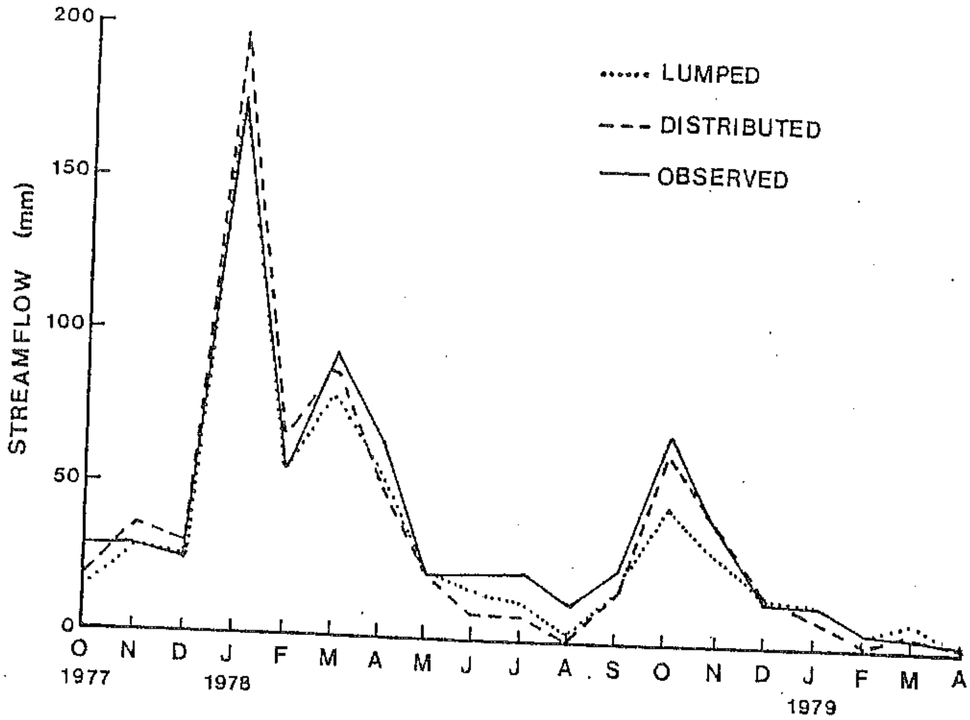

Figure 17.6.2 Monthly totals of daily streamflows as simulated by distributed and lumped versions of *ACRU* at W1M15 for the period October 1977 to April 1979 (after Angus, 1987)

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17.7 VERIFICATIONS OF DESIGN RUNOFF DEPTH AND PEAK DISCHARGE ESTIMATION BY *ACRU*

E.J.Schmidt, R.E.Schulze and S.J.Dunsmore

17.7.1 Introduction

One of the primary applications of hydrological models in water resources engineering has been for the determination of design flood magnitude. Given suitable long record gauged data, various statistical methods can be applied to determine the expected flood magnitude for a chosen frequency of non-exceedence. However, since accurate runoff measurements are rarely available at the location of interest, especially for the event of "design" magnitude, one usually has to apply conceptual/physical models which attempt to convert the "design" rainfall into a corresponding "design" flood of equivalent risk of non-exceedence, by accounting for the catchment's runoff response characteristics typically under assumed "average" antecedent soil water status.

A major limitation in design hydrology is the assumption that "average" antecedent soil water status can be used in design flood simulation to produce a runoff event of recurrence interval equal to that of the rainfall event. This assumption is frequently adopted due to a poor representation of the soil water component in hydrological models and inadequate information on associations between "extreme" event rainfall and corresponding catchment antecedent soil water conditions (Schmidt, Schulze and Dunsmore, 1985).

Extensive research as reviewed by Schmidt and Schulze (1987) has been conducted to investigate the relationships between the frequency of occurrence of a flood, its causative rainfall and the role antecedent soil water content plays in determining this relationship. Such research has generally indicated that procedures to account for the joint association of design rainfall and antecedent soil water status should be applied when determining design runoff response.

Numerous studies as reviewed by Dunsmore, Schulze and Schmidt (1986) have indicated the sensitivity of runoff models to antecedent soil water status. Indices to account for the effects of soil water on runoff response range from lumped antecedent rainfall depths such as used in the SCS model (United States Department of Agriculture USDA, 1972) through logarithmic depletion relationships which account for the day of rainfall occurrence and soil water depletion rates to soil water budget methods using observed rainfall data and estimated evaporation, drainage and transpiration rates, the latter approach being commonly adopted in continuous water yield models such as the *ACRU* model.

Verification of the *ACRU* model for the prediction of design runoff volume and peak discharge by accounting for the joint association of rainfall depth and soil water status has been undertaken by Schmidt *et al.* (1985) and by Dunsmore *et al.* (1986). The *ACRU* based estimates of runoff response were compared with estimates obtained using the SCS model in both studies. A summary of these verifications is presented in the following subsections.

17.7.2 <u>Design Runoff Depth Verifications</u>

Dunsmore *et al.* (1986), using long records of daily rainfall and runoff data from the USA, showed that there was little association between rankings of daily rainfall and resulting daily runoff depths, thereby indicating that the assumption of the T-year return period flood being the result of the T-year return period storm, inherent in many current flood estimation procedures, did not provide a sound basis for hydrological design. Figure 17.7.1 presents a plot of the storm rainfall rank, P, for a 29 year annual maximum series of events and the corresponding storm runoff rank, Q, for Catchment 2635 at Coshocton, USA. The Figure illustrates how rankings seldom correspond.

Dunsmore *et al.* (1986) used the SCS and the *ACRU* models to compare simulated daily runoff depths of "design" magnitude with corresponding observed daily runoff depths. The SCS model was chosen since it has been widely used internationally and had been adapted for southern African conditions. In the simulations the SCS model was applied firstly with the runoff curve number being representative of 'average" soil water status, SCS-II, and secondly with adjustments being made to the curve number according to the five-day accumulated rainfall total preceeding the event, SCS-adj (USDA, 1972). The *ACRU* model utilises principles of the SCS runoff depth estimation equation. However, it makes use of multi-layer soil water budgeting routines to provide conceptually based estimates of catchment soil water deficit.

Simulating the runoff response to all storms exceeding a certain threshold (20 mm per day on all but the arid Safford catchments, where a threshold of 10 mm per day was used), Dunsmore *et al.* (1986) found that the *ACRU* model performed better on five of the six catchments under study. The exception was an arid catchment (4503) on which all the methods simulated poorly and for which adequate land use information was not available. Table 17.7.1 presents statistics of simulations using the various model options. Statistical functions presented to evaluate model performance are :

* percentage error in mean runoff depth (M)
* percentage error in standard deviation of runoff depth (S)
* Coefficient of Efficiency (E)
* Coefficient of Determination (D).

Dunsmore *et al.* (1986) fitted Log-Normal frequency distributions to the annual maximum series of observed daily runoff (Q-OBS), and simulated daily runoff obtained using the *ACRU* model (Q-*ACRU*), SCS model assuming "average" conditions (Q-SCS-II) and SCS model using the 5-day rainfall adjustment index (Q-SCS-adj). The objective was to establish the adequacy of the various methods to estimate design runoff depths over a range of return periods. Figure 17.7.2 representing Catchment 4501 at Safford, typifies the results obtained.

It was concluded that extreme runoff series obtained with the *ACRU* model, utilising its soil water budgeting procedures to account for catchment wetness, provided close agreement with observed flow series and allowed for more accurate estimates of design runoff depth than the SCS based methods.

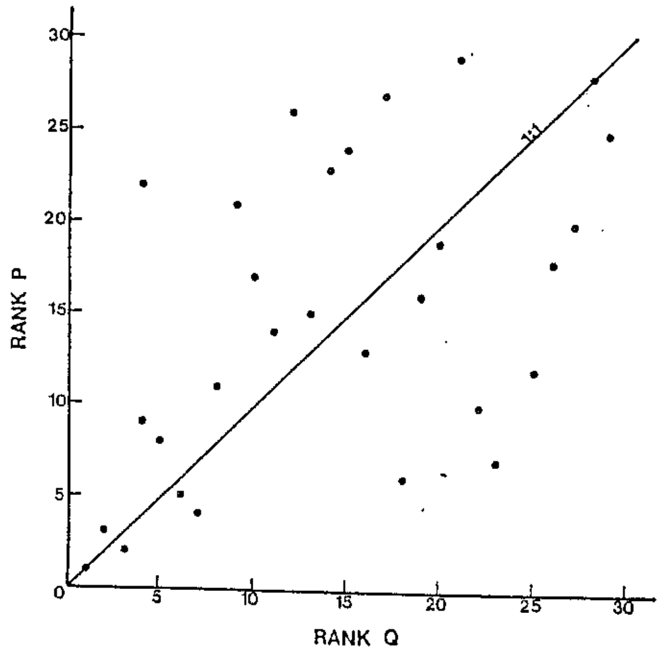

Figure 17.7.1 Plot of storm rainfall rank against storm runoff rank for Coshocton 2635 (after Dunsmore, Schulze and Schmidt, 1986)

Table 17.7.1 Statistics of performance of the *ACRU* and SCS model output for daily runoff response to storms above a threshold (after Dunsmore, Schulze and Schmidt, 1986)

Catchment	Model	M	S	D	E
Coshocton 2630	*ACRU*	26.9	-10.2	0.780	0.751
	SCS-adj	-78.1	-45.3	0.466	0.206
	SCS-II	-43.1	-27.8	0.563	0.489
Coshocton 2635	*ACRU*	31.3	-17.2	0.791	0.755
	SCS-adj	-72.3	-33.7	0.389	0.226
	SCS-II	-29.6	-9.6	0.572	0.522
Hastings 4401	*ACRU*	-4.3	-5.1	0.819	0.816
	SCS-adj	-64.5	-25.4	0.568	0.370
	SCS-II	-32.9	-23.4	0.760	0.697
Hastings 4403	*ACRU*	15.7	4.9	0.735	0.690
	SCS-adj	-56.7	-7.4	0.600	0.462
	SCS-II	-18.2	-0.8	0.605	0.548
Safford 4501	*ACRU*	-5.2	-16.0	0.602	0.598
	SCS-adj	-94.1	-81.4	0.172	-0.099
	SCS-II	-59.1	-47.1	0.618	0.466
Safford 4503	*ACRU*	70.5	119.3	0.228	-2.829
	SCS-adj	-73.8	-33.8	0.103	-0.141
	SCS-II	151.1	81.9	0.220	-5.837

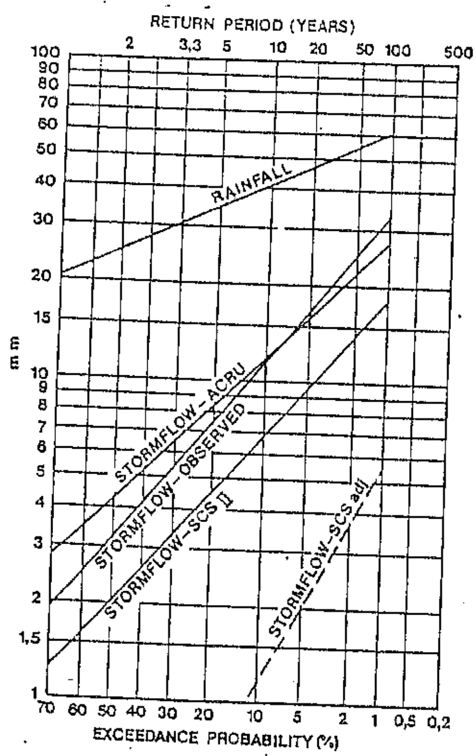

Figure 17.7.2 Log-Normal plots of maximum daily runoff series for observed data (OBS-Q), and from *ACRU* (Q-QCRU) and SCS (Q-SCS-adj and A-SCS-II) simulations for Safford 4501 (Dunsmore *et al.*, 1986)

17.7.3 Design Peak Discharge Verifications

In order to determine whether more realistic estimates of peak discharge could be made through joint consideration of design rainfall amount and catchment soil water status, Schmidt *et al.* (1985) used the USDA's SCS hydrograph generating technique (USDA, 1972) to simulate runoff hydrographs using different methods accounting for soil water status. The *ACRU* model was used to determine conceptually based estimates of soil water deficit and a comparison was made with the SCS method using both the five-day antecedent precipitation index to adjust the curve number (SCS-adj) and assumed "average" soil water conditions (SCS-II).

To establish the implication for design flood to compare recorded peak discharges of various exceedence probabilities with those simulated using the three methods. Three USA catchments with records longer than 25 years were used in this evaluation.

Goodness of fit statistics for simulations of the largest annual events on the USA catchments are presented in Table 17.7.2. The goodness of fit statistics are the same as discussed in Section 17.7.2 with the exception that peak discharge is used in addition to runoff depth. Details on the methods used and assumptions made when simulating peak discharge are presented by Schmidt *et al.* (1985). The *ACRU* model provided the best results for all catchments, while runoff depth was modelled more accurately than peak discharge.

Table 17.7.2 Statistics of performance of the *ACRU* and SCS model for annual maximum events on USA catchments (after Schmidt, Schulze and Dunsmore, 1985)

Catchment	Model	Peak Discharge			
		M	S	D	E
Coshocton 2630	*ACRU*	-12.4	20.8	0.499	0.423
	SCS-adj	71.3	64.2	0.167	-0.169
	SCS-II	59.1	55.1	0.389	0.130
Hastings 4401	*ACRU*	-0.9	-28.6	0.475	0.118
	SCS-adj	75.9	11.1	0.330	-0.543
	SCS-II	66.7	31.2	0.324	-0.287
Safford 4501	*ACRU*	24.1	-12.2	0.496	0.245
	SCS-adj	97.5	88.7	0.205	-1.129
	SCS-II	64.3	25.3	0.495	-0.037
		Runoff Depth			
Coshocton 2630	*ACRU*	-17.0	-9.4	0.620	0.483
	SCS-adj	66.4	48.2	0.335	-0.323
	SCS-II	54.9	34.5	0.429	-0.019
Hastings 4401	*ACRU*	0.8	-1.9	0.830	0.818
	SCS-adj	72.7	29.7	0.561	0.034
	SCS-II	63.5	42.9	0.828	0.312
Safford 4501	*ACRU*	20.4	18.9	0.553	0.518
	SCS-adj	70.4	80.7	0.036	-0.474
	SCS-II	61.5	44.4	0.559	0.244

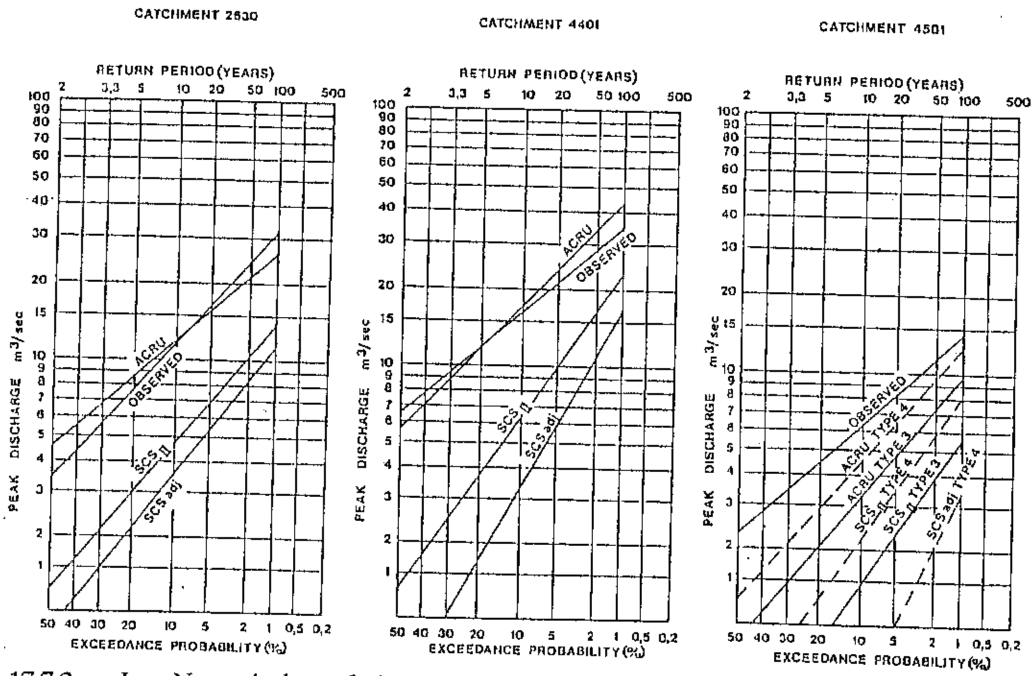

Figure 17.7.3 Log-Normal plots of observed and estimated peak discharge (Schmidt *et al.*, 1985)

Figure 17.7.3 presents the typical result obtained when fitting the Log-Normal distribution to the observed and simulated annual maximum series of peak discharge. Improved estimates of design peak discharge of various exceedence probabilities were obtained in all cases when using the *ACRU* model.

Schmidt *et al.* (1985) concluded that the soil water budgeting techniques included in the *ACRU* model provided more realistic estimates of peak discharge distribution when compared with the current SCS techniques. It was suggested that relationships between soil water status and design rainfall depth be determined on a regionalised basis for use in flood modelling.

17.7.4 References

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CHAPTER 18

SENSITIVITY OF OUTPUT TO *ACRU* MODEL INPUT

G.R. Angus

18.1 DIRECTORY

ABRESP = Fraction of "saturated" soil water to be redistributed each day from the topsoil horizon, when above field capacity, to the subsoil horizon.
e.g. 0.3 is slow, typical of clays
0.8 is fast, typical of sands
Default value = 0.5

BFRESP = Fraction of "saturated" soil water to be redistributed each day from the subsoil horizon, when above field capacity, into the intermediate/groundwater store.
e.g. 0.3 is slow, typical of clays
0.8 is fast, typical of sands
Default value = 0.5

CAY(I) = Average monthly crop coefficients, K_{cm}, for the vegetation of a catchment/subcatchment (i.e. the proportion of water "consumed" by a plant under conditions of maximum evaporation in relation to that evaporated by an A-pan in a given period).

COFRU = Coefficient of baseflow response (i.e. the fraction of the intermediate/groundwater store that becomes streamflow on a particular day).
e.g. COFRU = 0.02 = 2% per day - a typical value.

COIAM(I) = Coefficient of initial abstraction (i.e. a coefficient given month by month which is used to estimate the rainfall abstracted by interception, detention storage and infiltration before runoff commences).
e.g. COIAM = 0.2 is a typical value.

CONST = Fraction of the plant available water in the soil at which total evaporation is assumed to drop below the maximum evaporation.
e.g. 0.4 is a typical value.

CRLEPO = Critical leaf water potential of a plant, given in "-" bars. (If a value is entered, then CONST = 0).
e.g. CRLEPO
for maize : = -17(bars)
for grass : = -10(bars).

DEPAHO = Depth (m) of the topsoil horizon of the soil profile.

DEPBHO = Depth (m) of the subsoil horizon of the soil profile.

ITEXT = Soil texture classes, for which soil water retention constants etc. are preprogrammed in the MENUBUILDER (If PEDDINF = 0 or if EVTR=2)
ITEXT = 1 clay,
= 2 loam,
= 3 sand,
= 4 loamy sand,
= 5 sandy loam,
= 6 silty loam,
= 7 sandy clay loam,

= 8 clay loam
= 9 silty clay loam
= 10 sandy clay, and
= 11 silty clay.

QFRESP = Stormflow response factor for the catchment/subcatchment (i.e. the fraction of the total stormflow that will run off from the catchment/cell on the day of the event).

ROOTA(I) = Fraction of active root mass in the topsoil horizon, specified month by month.

SMDDEP = Effective depth of the soils (m) to be considered to contribute to stormflow production:
SMDDEP = 0 effective depth is not known and is assumed to be the depth of the topsoil horizon (DEPAHO), and
= 0 effective depth is as specified.

VEGINT(I) = Interception loss ($mm.rainday^{-1}$) by vegetation, given month by month.

18.2 INTRODUCTION AND BACKGROUND

McCuen (1973a) defines sensitivity as a measure of the effect of change of one factor on another factor. In terms of hydrological modelling this definition refers to a measure of the effect of changes in model input or model structure on model output. Thus sensitivity analysis can provide a useful tool to the hydrological modeller for a better understanding of the correspondence between the model and the physical processes being modelled (McCuen, 1973b). This technique can therefore provide potentially useful information in all phases of model development from model formulation and calibration through to verification and validation.

McCuen (1973a; 1973b) draws a distinction between parameter sensitivity and component sensitivity. He defines parameter sensitivity as a measure of the change in output resulting from a change in a parameter of the total system. However, the system in its entirety is made up of a number of components and in terms of the *ACRU* model these components would include

* the interception loss component,
* the potential evaporation component,
* the soil water budget component,
* the irrigation component,
* the crop yield component and
* the reservoir yield component.

A sensitivity analysis of any one of these components would comprise a component sensitivity analysis and an analysis of this nature would prove most useful in the formulation of a model or the addition of new components to a model. A parameter sensitivity analysis, however, is unable to distinguish between the effects of each individual component on a change in a single parameter, but rather provides an indication of the effect of the integrated model, comprising many components, on the model output.

A distinction occasionally drawn between a parameter and a variable is that a variable has physical meaning and is capable of being measured whereas a parameter is often a coefficient, the value of which is inferred empirically. According to this definition, with the exception of ITEXT, all the other input characteristics described in Section 18.1 are variables. However, for the *purposes of this study no distinction is drawn between variables and* *parameters and they are both referred to as parameters.*

In parameter sensitivity analysis, deriving the sensitivity of a single parameter has traditionally involved incrementing the value of the input parameter and determining the resulting change in output or the change in an objective function representing the output. However, determining the sensitivity of each parameter of a multiparameter system in a complex model involves an excessive amount of computer time (McCuen, 1973a). This, coupled with the inadequacy of a mathematical framework for sensitivity analysis of complex models has tended to limit the use of sensitivity analysis as a design criterion for hydrological simulation models (McCuen, 1973b).

The usefulness of the sensitivity analysis described in this chapter is not as an aid to model verification or model formulation, but rather as a tool to provide guidelines for the compilation of input parameter information bases for the Decision Support System (DSS) discussed in Chapter 2. Weddepohl (1985) conducted a sensitivity analysis on the *ACRU* model using the Zululand research catchments and this study is extending his analysis to include other model parameters and to present the results in graphical form. It is envisaged that the results of this study will provide guidelines as to the degree of accuracy of parameter estimation required in the compilation of information bases for the DSS. Thus, in collecting the information, those parameters to which the simulations are most sensitive will require greater accuracy in determination, either through measurement or through a literature search, than less sensitive parameters.

18.3 APPROACH TO PARAMETER SENSITIVITY ANALYSIS

18.3.1 A Review Of Sensitivity Studies On Complex Models

For simple, explicit models it is possible to take derivatives of the output with respect to input and express the sensitivity as explicit functions. However, as models become more complex, sensitivity is more easily expressed in the form of relative changes, graphs and tables rather than functions. This was the approach adopted by Lane and Ferreira (1980) in investigating the sensitivity of the CREAMS model. They recognised the main shortcomings of this method as

* the fact that because parameters are varied individually, complex interactions are difficult to detect and

* a large number of simulation runs and hence computer time is required.

Lane and Ferreira (1980) conducted their sensitivity analysis on three components of CREAMS, namely

* the hydrological component,
* the erosion/sediment yield component and
* the chemistry component of the model.

They selected base values for input parameters for each component of the model and performed an initial base run, the output of which was used by subsequent incremental runs to compare output sensitivity. The relevant input values were varied by +50%, +25%, -25% and -50% subject to the actual realistic values of these parameters and the sensitivity of the output was classed as significant, moderate, slight or none. The classification was based on the change in output caused by a +50% or -50% change in input parameter where

* 0% change in output equals a class none,
* less than 10% change in output equals class slight,
* between 10% and 50% is moderate and
* greater than 50% is significant.

They took pains to emphasise, however, that results are site specific and they suggest that users should perform similar exercises for particular applications.

Rogers, Beven, Morris and Anderson (1985) performed a sensitivity analysis on the Institute of Hydrology Distributed Model (IHDM). The IHDM is a physically based distributed model, with parameters that can, in principle, be derived from experimental work or estimated *a priori*. As such the model can be used to predict streamflow in ungauged catchments or the hydrological effects of land use changes in gauged catchments.

Rogers *et al.* (1985) limited their study to surface flow roughness and soil properties. They found the model to be particularly sensitive to Chezy C value and saturated hydraulic conductivity. They used the hydrological peak as a measure of sensitivity for five storm periods and presented their results in graphical form.

Bathurst (1986) conducted a sensitivity analysis of the Systeme Hydrologique Europeen (SHE) model in order to determine the accuracy with which parameter sets for physically-based distributed catchment models must be prepared and calibrated. He conducted the analysis on two streamflow hydrographs for a catchment in Wales. He found the model to be most sensitive to soil and flow resistance coefficients and least sensitive to vegetation coefficients. He thus concluded that the former should be evaluated by point measurement and a few representative sites and the latter from literature.

Bathurst (1986) defined an arbitrary ranking system based on the objective functions defined in the analysis in order to attempt to compare input sensitivities. This he believed to be moderately successful. However, he stressed that further research was needed to delineate likely ranges of various catchment parameters for different soils, land use and catchments topography.

The approach adopted in this study has drawn from these previous studies those aspects which would be most suited to the *ACRU* model, its developers and its users. These will be discussed in detail in the following section.

18.3.2 Approach To Sensitivity Analysis Of The *ACRU* Model

The investigation conducted by Lane and Ferreira (1980) was a very extensive study including most of the major components of CREAMS. The sensitivity analysis of the *ACRU* model has, however, opted for a more intensive approach focussing rather on the core of the *ACRU* model, viz. the daily soil water budgeting routine. All the other components are dependent on the soil water budgeting component and thus a clearer insight into the sensitivity of this routine will provide information on the driving mechanism of the other components.

* *Site Selection*

Owing to the time and computer intensive nature of this study it was decided to confine the initial sensitivity analysis to one site only, namely Cedara in Natal. Once the most sensitive input parameters have been identified from this study, further investigations into the sensitivity of the model to those input parameters at other locations under different climatic conditions should be undertaken.

Cedara was selected because of the comprehensive meteorological data available. This station was, furthermore, used by Furniss (1988) to investigate the sensitivity of estimated irrigation water requirements from the *ACRU* model to climatic inputs. This station was also used by Dent, Schulze and Angus (1987) to investigate the sensitivity of the *ACRU* model to daily and monthly mean temperature based evaporation estimates.

The Cedara meteorological station is situated at 29°32'S and 30°17'E at an altitude of 1067 m. This analysis was conducted with 22 years of daily rainfall and A-pan data. Cedara has a MAP of about 840 mm and the standard deviation of annual precipitation is about 130 mm.

* *Climatic Input Data*

Daily rainfall and A-pan data from January 1960 until November 1982 was used as the basic climatic input data for this analysis. Crop water demand was estimated using A-pan data and monthly crop coefficients. These were the only measured data used as input to the model, the output of which is used as base values for comparative purposes. All the other soils, land use and runoff input parameters were realistic generalised values.

Having defined the base input to the model, the model was run using these base values as input and the output was stored to be used as a base set against which output from incremental change to input in subsequent runs was to be compared. Daily rainfall values were varied within the range +50% to -50% and output from each incremental changed compared to the base output. The same procedure was followed varying daily A-pan values by the same incremental range as rainfall and keeping all other input constant.

* *Soil Input*

The base soils input and their range of variation appear in Table 18.3.1. The soil texture selected as a base texture is a sandy clay loam and soil water retention constants for the various textures are given in Chapter 5. The ratio DEPAHO : DEPBHO at 1:2.25, has been kept constant for varying soil depths to eliminate the possible influence that changes to other input parameters, which may be physically plausible, could have on output. For example, for a total soil depth of 0.1 m it is highly unlikely that the majority of roots will be found in the topsoil horizon, however, in order to determine the influence of changes in soil depth only on output, this physiological inconsistency must be accepted.

Table 18.3.1 Base soil input parameters and their range of variation

Parameter	Base Value	Range of Variation								
ITEXT	7	1, 2, 3, 4, 5, 6, 8, 9, 10, 11								
DEPAHO (m)	0.20	0.031	0.046	0.063	0.092	0.154	0.231	0.308	0.462	0.615
DEPBHO (m)	0.45	0.069	0.104	0.137	0.208	0.346	0.519	0.692	1.038	1385
ABRESP	0.50	0.10	0.20	0.30	0.40	0.60	0.70	0.80	0.90	
BFRESP	0.50	0.10	0.20	0.30	0.40	0.60	0.70	0.80	0.90	
CONST	0.40	0.10	0.20	0.30	0.50	0.60	0.70	0.80	0.90	
CRLEPO	-	-4	-5	-10	-15	-18	-20			

SMDDEP, i.e. the critical depth (m) of soil for stormflow generation, has been set to the depth of the topsoil horizon throughout the sensitivity analysis on soil depth. The two response factors governing the vertical redistribution of soil water, viz. ABRESP and BFRESP, have been set equal to a base value of 0.5, which would be typical of a sandy clay loam. The 0.4 base value for CONST is typical of dryland conditions. The sensitivity of the more sophisticated Slabbers (1980) approach to the onset of stress (Chapter 7) has been investigated for a range of critical leaf water potentials, CRLEPO. These results are, however, compared to the results obtained from holding CONST equal to 0.4 and CRLEPO *per se* has not been used as a base value. A discussion of the results of this analysis as well as the results for climate, land use and runoff parameter variations are presented in Section 18.3.

* *Land Cover Parameters*

Month by month base values for CAY, VEGINT and ROOTA are presented in Table 18.2.2. These values are considered representative of a catchment with a combination of land covers, typically veld, pastures and a summer crop. The representative monthly CAY and VEGINT input parameters have been subjected to a total of 12 incremental changes, ranging from -50% to +50%. The monthly values for the extremes of the incremental changes are presented in Table 18.3.2. ROOTA represents the total mass of roots in the topsoil horizon. The monthly base values for ROOTA indicate that from July to September, 95% of the root mass occurs in the topsoil horizon. The upper limit bounding the maximum amount of roots in the topsoil horizon is obviously 100% of roots in topsoil horizon. This upper limit represents a change in the base

Table 18.3.2 Base values and their range of variation for land cover parameters

Parameter		Base Values and The Extremes Bounding incremental Variation											
		J	F	M	A	M	J	J	A	S	O	N	D
CAY	BASE	0.80	0.80	0.70	0.60	0.50	0.40	0.40	0.40	0.45	0.55	0.65	0.75
	-50%	0.40	0.40	0.35	0.30	0.25	0.20	0.20	0.20	0.20	0.27	0.33	0.38
	+50%	1.10	1.10	1.05	0.90	0.75	0.60	0.60	0.60	0.60	0.83	0.98	1.10
VEGINT	BASE	1.00	1.00	0.80	0.70	0.60	0.50	0.50	0.50	0.50	0.70	0.80	0.90
	-50%	0.50	0.50	0.40	0.35	0.30	0.25	0.25	0.25	0.25	0.35	0.40	0.45
	+50%	1.50	1.50	1.20	1.05	0.90	0.75	0.75	0.75	0.75	1.05	1.20	1.35
ROOTA	BASE	0.80	0.80	0.80	0.85	0.90	0.95	0.95	0.95	0.95	0.90	0.85	0.80
	-50%	0.40	0.40	0.40	0.43	0.45	0.47	0.47	0.47	0.47	0.45	0.43	0.40
	+5.8%	0.84	0.84	0.84	0.91	0.96	1.00	1.00	1.00	1.00	0.96	0.91	0.84

value of +5.8%. Thus the upper extreme is bounded by physical constraints to an increase in the base value of 5.8%, however, in order to remain constant with changes to base values of other land cover parameters, the lower limit represents a -50% change in the base values. At this lower limit the bulk of the root mass occurs in the subsoil horizon. From Table 18.3.2 it can be noted that the model imposes certain restrictions on some input parameters in order to screen for realistic values. By *ACRU* "convention" the maximum value for CAY is 1.10 and the minimum value is 0.20.

* *Runoff Parameters*

The sensitivity of four input parameters namely, SMDDEP,COFRU, COIAM and QFRESP was investigated and their base values and range of variations are presented in Table 18.3.3. It should be borne in mind that the two soil horizon depths are maintained at their base values for all changes in runoff parameters. COIAM is an array of 12 monthly values of coefficients of initial abstraction utilised by the SCS equation for stormflow generation. In this investigation the values are kept constant throughout the year for each incremental change in COIAM. COFRU and QFRESP control the rate of subsurface drainage release and quickflow response respectively.

18.3.3 Model Output

Having discussed the input parameters and how they were varied about base values, the next step is to discuss the model response to changes in input. Streamflow can be regarded as an integral result of all the processes occurring within the water budgeting component of the *ACRU* model. Thus streamflow and the components of which it is comprised, viz. baseflow and quickflow, have been selected to test the sensitivity of model response. Streamflow is possibly the most important output from the model, particularly with regard to water resources management. Changes in quickflow indicate the sensitivity of the upper region of the soil profile to land use, soil and runoff parameter changes. Whilst baseflow is an integrator of the movement of water through the soil profile. By considering baseflow, quickflow and streamflow in conjunction, a realistic appraisal of the interactive processes occurring within the system can be made.

Table 18.3.3 Base values and their range of variation for runoff response parameters

Parameter	Base Value	Range of Variation							
SMDDEP	0.20	0.05	0.10	0.15	0.20	0.25	0.30	0.40	0.50
COFRU	0.02	0.005	0.010	0.015	0.020	0.025	0.030	0.060	0.100
COIAM	0.20	0.05	0.10	0.15	0.20	0.25	0.30	0.50	
QFRESP	0.50	0.05	0.10	0.15	0.20	0.50	1.00		

In view of the *ACRU* modelling system's being used increasingly often in the field of crop yield simulation, an additional output from the model, namely, total evaporation has been investigated since many crop yield models are driven by the total evaporation process. Although for most agricultural crops the major contributor to total evaporation would be the topsoil horizon, for the purposes of this study both the top- and subsoil horizons have been considered.

18.4 RESULTS

18.4.1 Selection Of Objective Function

The estimation of parameter sensitivity requires a measure of the change in an output function represented by an objective function. The choice of the specific objective function is subjective. However, the selection of an objective function is a very important decision and thus the function selected should reflect the intended hydrological characteristic adequately (McCuen, 1973a).

For the purposes of this study, where the intention has been to present the results of this sensitivity analysis in graphical form, it has been decided to adopt the percentage change in accumulated output over the entire period of record as the objective function. This can be represented by

$$PC = \frac{\sum_{i=1}^{N} O_i - \sum_{i=1}^{N} O_{BASE,i}}{\sum_{i=1}^{N} O_{BASE,i}} \times 100$$

where

PC = per cent change in output

O_i = output from a particular change in input parameter

$O_{BASE,i}$ = output from the base input and

N = number of years of data.

A single input parameter is varied at a time and a value for PC determined from the change in output using the objective function defined above. The input parameter is varied over a range of values, revealing an associated range of values for PC. A number of output parameters are investigated with each change in input parameter, namely

* streamflow, which consists of
* stormflow and
* baseflow,
* evaporation (E) from the A-horizon and
* E from the B-horizon.

Thus for each change in input parameter, five resultant changes in output parameters have been recorded. These results can be presented in graphical form on the same set of axes to allow for comparison. It must be emphasised that these values represent per cent changes in absolute base output values. A large per cent change in a base value may not necessarily represent a large change in the absolute value of that base value, particularly if the base value is small. For example, using the base input data set to the *ACRU* model at Cedara, it was noted that stormflow and baseflow contributed 70.3% and 29.7% respectively to streamflow. In this instance the absolute base values differ greatly. If a change of input to the model resulted in a 10% change in the base value of accumulated baseflow, an equivalent absolute volume change in stormflow only represents a 4.1% change in the base value of accumulated stormflow. Thus when comparing per cent changes to base values of stormflow and baseflow it must be borne in mind that a greater per cent change in baseflow than stormflow need not necessarily mean a greater change in absolute accumulated volume.

Having obtained output values for the range of variations in input as described in Section 18.3.2, these results are subjected to a spline interpolation technique in order to fit a curve to the output data. These results are presented in the sections following.

18.4.2 Sensitivity Of Output To Climatic Input Changes

Both daily rainfall and daily potential evaporation input data were varied through a range of from +50% to -50% of the original data set and the results are presented in Figure 18.4.1 and Figure 18.4.2 respectively. In these two figures and all those following (with the exception of those depicting CRLEPO) the intersection of the curves at the point 0% change in parameters for both axes, corresponds to base condition.

From both figures it can be seen that baseflow is the most sensitive of the output parameters investigated with respect to climatic input data. Stormflow appears to be largely unaffected by variation in potential evaporation input data but is substantially more sensitive to variations in rainfall.

Figure 18.4.1 indicates that the higher the rainfall the closer the relationship between accumulated streamflow and accumulated rainfall approaches linearity. In this region of approaching linearity, the gradient of the curve, being steepest, implies that a greater portion of rainfall becomes streamflow under higher rainfall conditions than in lower rainfall conditions.

Baseflow, stormflow and streamflow for the base data set were then considered separately for those years having less than the median annual rainfall and years having more than the median annual rainfall of 793 mm. For the lower rainfall years it was observed that baseflow and stormflow contributed 17.3% and 82.7% of streamflow respectively. However, for years with rainfall in excess of the median annual rainfall, this proportion of contributions to streamflow changed to 34.8% baseflow and 65.2% stormflow. Thus the ratio baseflow:stormflow changed from 1:4.8 to 1:1.9 from dry years to wet years. For the entire period of record (i.e. considering wet and dry years together) of rainfall data used in this study the same ratio is 1:2.4. It can thus be seen that although baseflow

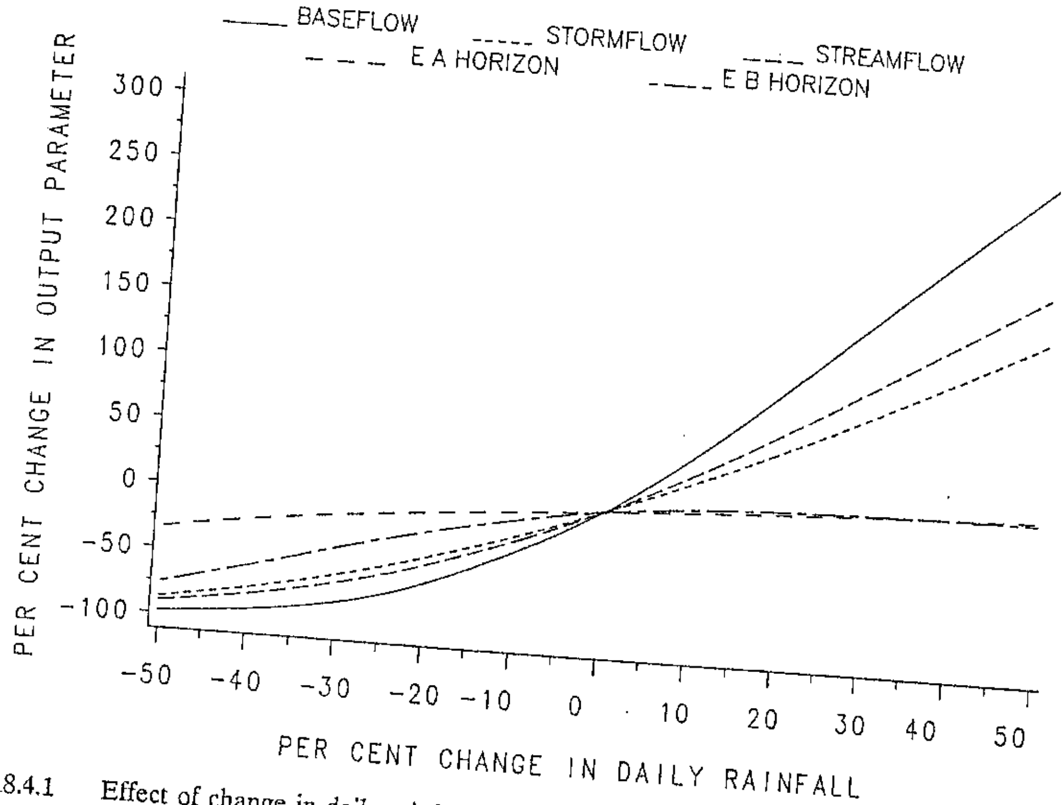

Figure 18.4.1 Effect of change in daily rainfall input on selected output parameters

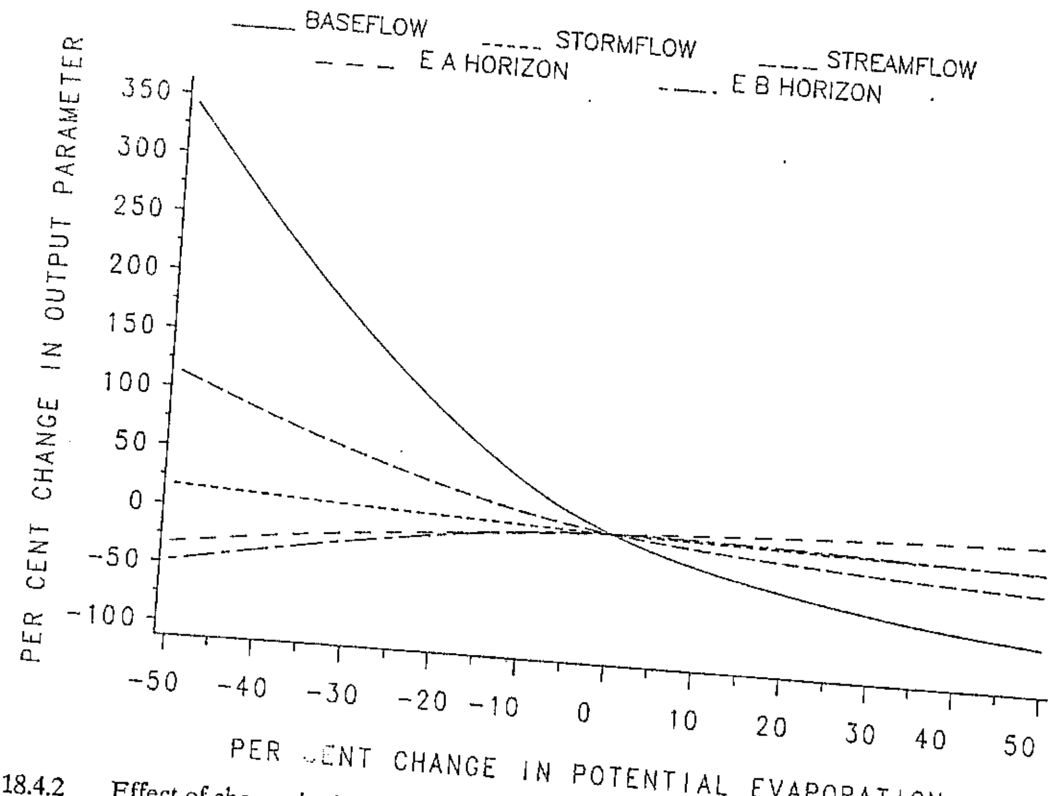

Figure 18.4.2 Effect of change in daily potential evaporation (A-pan) input on selected output parameters

represents a smaller portion of streamflow at Cedara (using base input data), the rate of increase in baseflow with increased rainfall has a significant effect on streamflow.

Figure 18.4.3 provides for a direct comparison between the effect of changes in rainfall and potential evaporation input on streamflow. Clearly streamflow estimates by the *ACRU* model are much more sensitive to rainfall input variations than potential evaporation input variations. Also, streamflow simulations appear to be more sensitive to underestimates of potential evaporation than to overestimations thereof. This trend is reversed in the case of rainfall.

18.4.3 Sensitivity Of Output To Soils Parameter Changes

For the purpose of this sensitivity analysis the ratio DEPAHO : DEPBHO has been kept constant at 1:2.25 throughout the range of variation of soil depth. The effective depth of the soil profile contributing to stormflow, SMDDEP, has been assumed to be equal at DEPAHO. From Figure 18.4.4 stormflow and hence streamflow was observed to be highly sensitive to total soil depths, particularly shallow soils. For total soil depths in excess of 1.0 m the gradients are less steep indicating that output parameters are less sensitive in this range.

Soil depth variation has a more consistent effect on stormflow than it has on baseflow. The shallower the soil, the shallower the effective soil depth (DEPAHO) available for stormflow generation and hence the greater the amount of stormflow. However, the influence of soil depth on baseflow is less simple. In very shallow soils a large portion of rainfall becomes stormflow and only a small amount of water percolates through the soil profile. As a result, there is very little soil water potentially available for baseflow generation. As soil depth increases stormflow decreases, subsurface soil water content thus increases and hence the storage potential available for deep percolation also increases. Thus from an initial shallow depth baseflow increases with increasing soil depth until a soil depth of about 1.1 m. For soils deeper than this, an increase in soil depth actually leads to a decrease in baseflow. The probable reason for this is because the subsoil horizon is becoming so large that it in fact rarely reaches field capacity and the downward movement of soil water from the subsoil horizon to the groundwater store is dependent on the subsoil horizon's being above field capacity. The subsoil horizon in turn, is replenished when the topsoil horizon reaches saturation. However, the topsoil horizon is also increasing its water holding capacity and hence less water is moving vertically from the topsoil to subsoil horizon, thereby reducing the degree of saturation of the subsoil horizon and hence also the amount of water entering the groundwater store which releases baseflow.

The movement of water through soils is highly dependent on soil texture. A sandy clay loam has been selected as an "average" soil and has been used in the menu as the base soil texture. The *ACRU* model was run for the other ten soil textures described in Chapter 5 and the change in streamflow resulting from these soil textures is represented by the asterisks in Figure 18.4.5. The soils ranging from sand to silty loam are arranged on the X axis in order of ascending plant available water. It can be seen that sandy

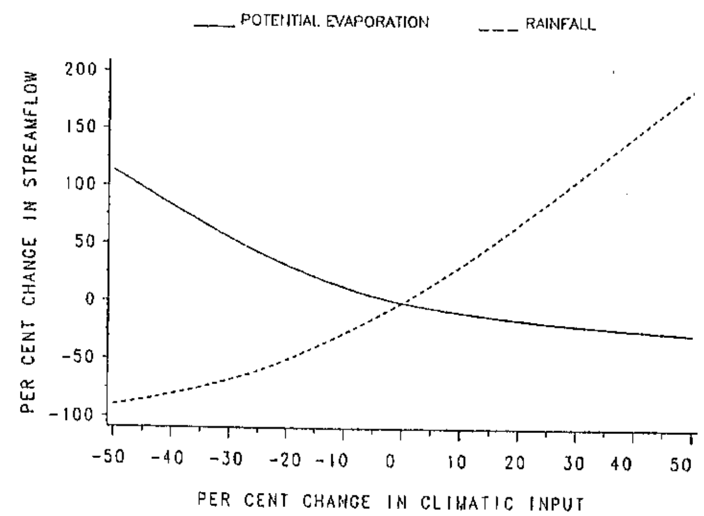

Figure 18.4.3 The effect of changes in climatic input data on streamflow

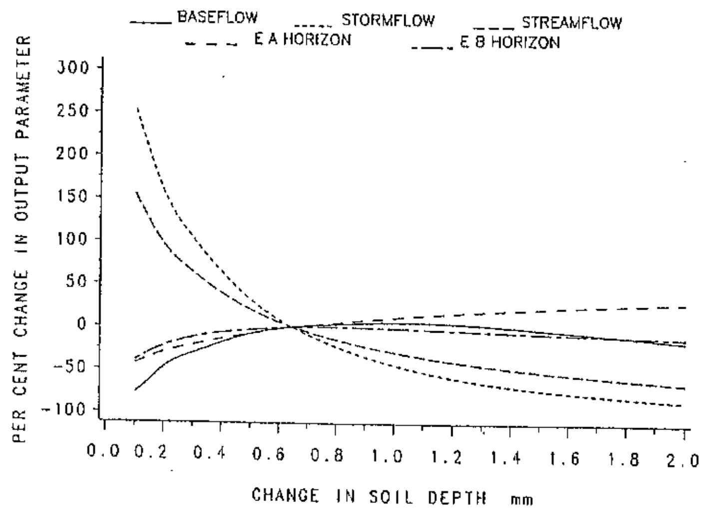

Figure 18.4.4 Effect of changes in total soil depth on selected output parameters

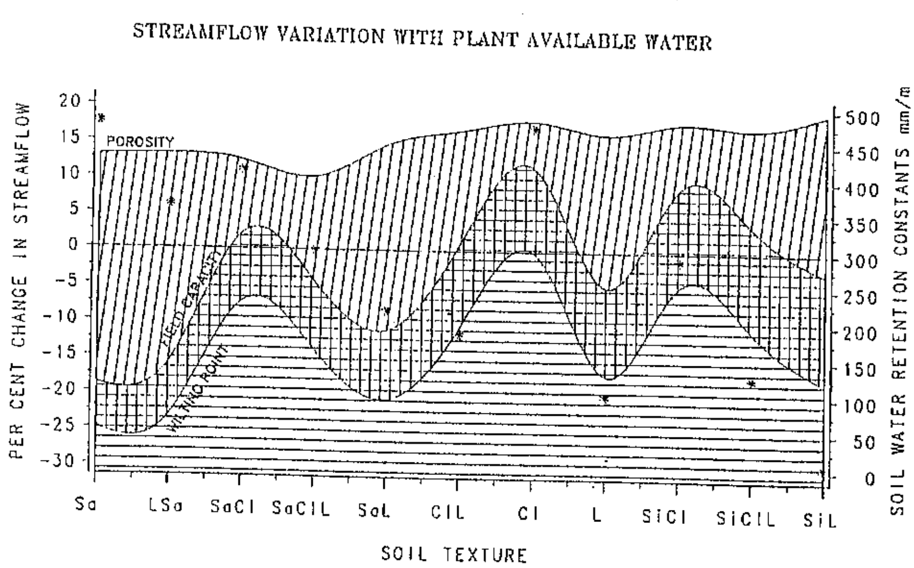

Figure 18.4.5 Relationship between soil texture and streamflow

clay loam representing the base texture has an asterisk on Y = zero line, representing the base streamflow. With the exception of clay, all the other soils follow the basic trend whereby soils with a smaller water holding capacity (FC minus WP) have increased streamflow and soils with a greater water holding capacity have a reduced streamflow over a period of time.

An analysis was done to determine the most important soil water retention properties affecting streamflow. In the regression analysis the following parameters were fitted as independent variables and are listed in order of ascending sensitivity

X1 = field capacity,
X2 = porosity minus field capacity,
X3 = wilting point,
X4 = porosity and
X5 = plant available water (field capacity minus wilting point).

These results are presented in Table 18.4.1.

Although the R^2 values for the univariate models appear to indicate that streamflow is most sensitive to plant available water, where two variables are fitted to regression equations, the interaction between variables appears to detract from the unique sensitivity of streamflow to plant available water.

A R^2 value of 0.907 was obtained for the five combinations of four independent variable models as well as for a regression model using all five independent variables.

The sensitivity of various output parameters to changes in ABRESP and BFRESP are represented in Figure 18.4.6 and Figure 18.4.7 respectively. The scale of Y-axis has been kept the same in both Figures to allow for a direct comparison of the sensitivity of *ACRU* model output to ABRESP and BFRESP. It is clear that the model output considered is substantially more sensitive to ABRESP than to BFRESP.

Table 18.4.1 R^2 values for regression models with per cent change in streamflow as the dependent variable and soil water retention properties of 11 soil textures as independent variables

Number of independent variables	Independent variables	R^2
1	X1	0.006
1	X2	0.008
1	X3	0.027
1	X4	0.252
1	X5	0.505
2	X3,X2	0.152
2	X1,X2	0.305
2	X1,X4	0.305
2	X4,X2	0.305
2	X4,X3	0.391
2	X4,X5	0.521
2	X5,X2	0.803
2	X1,X3	0.874
2	X3,X5	0.874
2	X1,X5	0.874

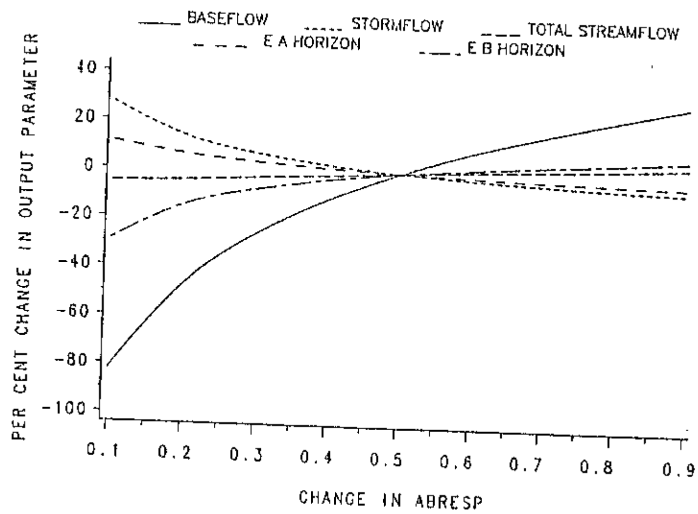

Figure 18.4.6 The effect of changes in ABRESP on selected model output

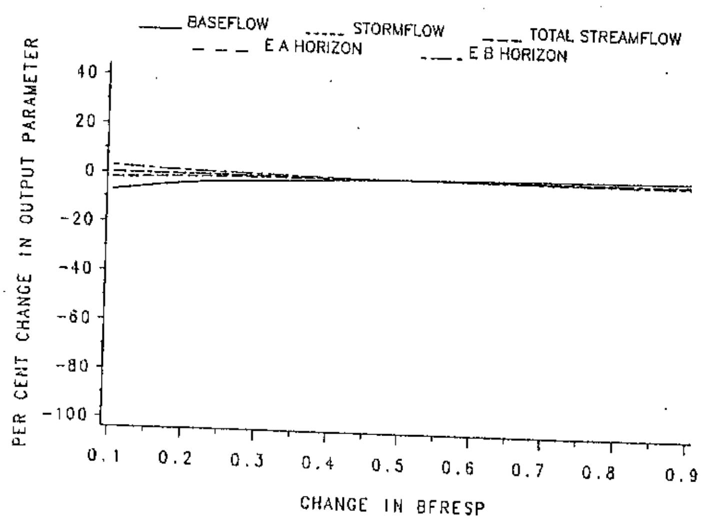

Figure 18.4.7 The effect of changes in BFRESP on selected model output

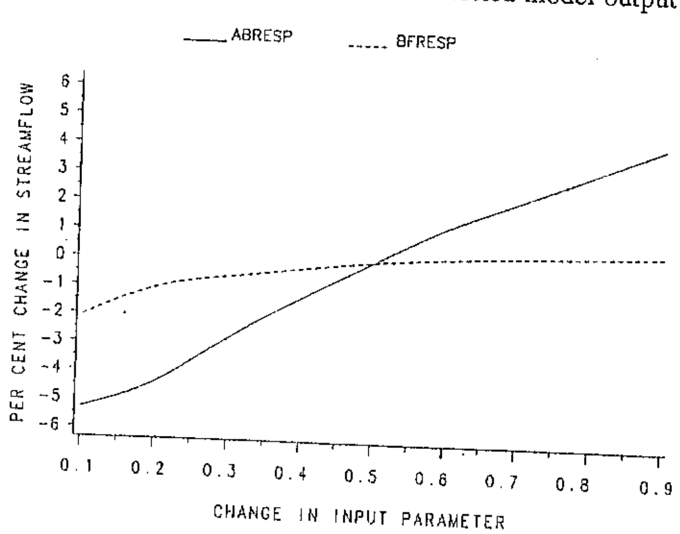

Figure 18.4.8 Th relative sensitivities of streamflow to ABRESP and to BFRESP

Figure 18.4.8 considers the sensitivity of streamflow only to changes in ABRESP and BFRESP. Although streamflow is more sensitive to ABRESP than BFRESP, the degree of sensitivity is negligible when compared with its sensitivity to soil properties such as total soil depth and soil texture.

The final two parameters considered in the soils sensitivity analysis are CONST and CRLEPO. They both control the rate of actual evaporation as a function of plant available water. The influence on output of changes in CONST and CRLEPO are represented in Figures 18.4.9 and 18.4.10 respectively. The base run used the parameter CONST and not CRLEPO in order to control the rate of evaporation of water from the soil profile.

Figures 18.4.9 and 18.4.10 indicate that CONST and CRLEPO are directly related with the only difference perhaps being the limit of their ranges.

18.4.4 Land Cover Parameters

The land cover parameters investigated are CAY, VEGINT and ROOTA. Figure 18.4.11 represents the sensitivity of the *ACRU* model output to changes in month-by-month values of CAY. Once again baseflow appears to be very sensitive to CAY. Evaporation appears to be virtually insensitive to CAY values in excess of the base values. However, for values of CAY less than the base values, all output parameters appear to have steeper gradients indicating greater sensitivity.

In Figure 18.4.12, the same Y-axis as in Figure 18.4.11 has been maintained and from this it is apparent that the model output is relatively insensitive to VEGINT. The reason for this is that, although VEGINT reduces the amount of effective rainfall entering the soil profile, it also satisfies a certain amount of the atmospheric evaporative demand, hence reducing the amount of water being evaporated from the soil profile.

The relative influences of CAY and VEGINT on streamflow can be inferred from Figure 18.4.13. The degree of sensitivity of streamflow to CAY decreases with increasing CAY. For values of CAY in excess of about 30% greater than base CAY, there is little change in streamflow.

The range of variation in rooting distributions is tabulated in Table 18.3.2 and the sensitivity of selected output parameters to ROOTA is represented in Figure 18.4.14. Stormflow is largely unaffected by changes in rooting distributions, though baseflow is more sensitive to ROOTA. The lower limit of the X-axis, -50%, represents an annual average value for ROOTA of 0.43. The upper value of the incremental variation, +5.8% represents an annual average value of 0.93 for ROOTA. Thus the rooting distributions range from about 43% to 93% roots in the topsoil horizon. These two values represent a wide range of rooting distributions and within that range the gradient of the various curves remain fairly constant.

Evaporation from the subsoil horizon is noticeably insensitive to rooting distribution, particularly in the range where the majority of roots are in the topsoil horizon. This is as expected because of the fact that evaporation from the subsoil horizon is directly proportional to the amount of roots in that horizon and if a scarcity of roots in the subsoil horizon means that evaporation from that horizon will be low.

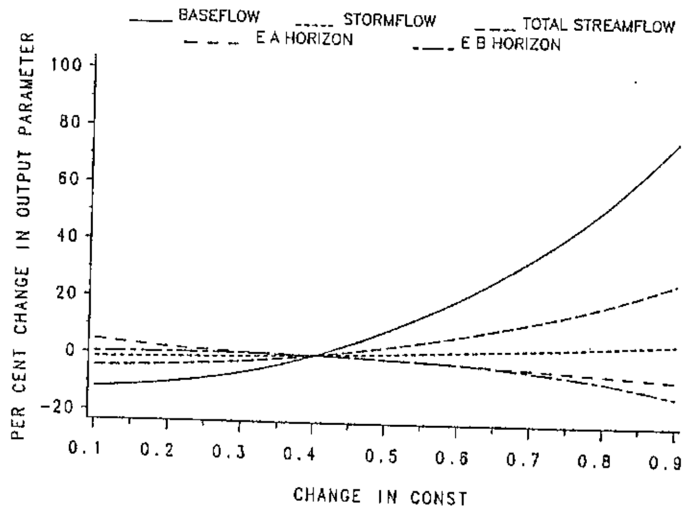

Figure 18.4.9 The effect of changes to CONST on selected model output

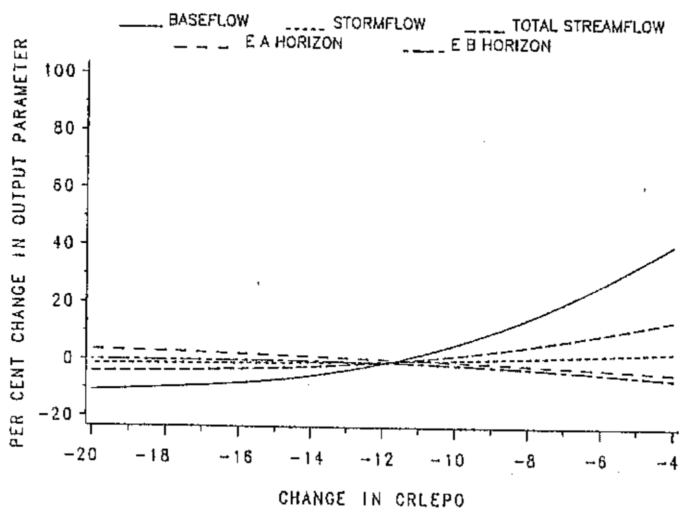

Figure 18.4.10 The effect of changes to CRLEPO on selected model output

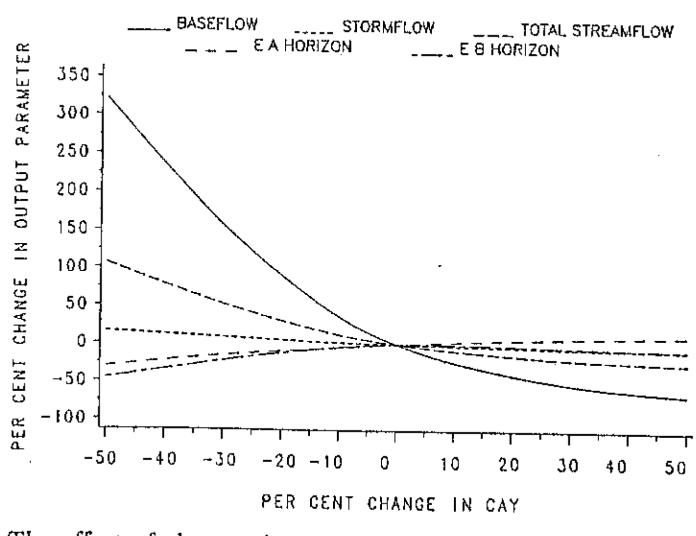

Figure 18.4.11 The effect of changes in CAY on selected model output

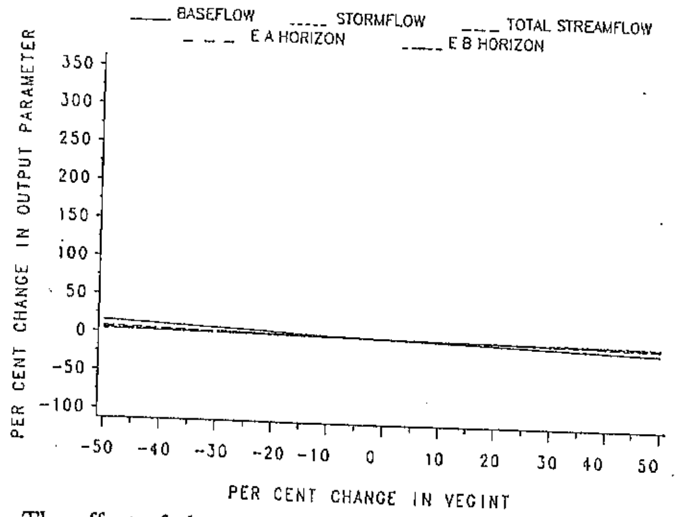

Figure 18.4.12 The effect of changes in VEGINT on selected model output

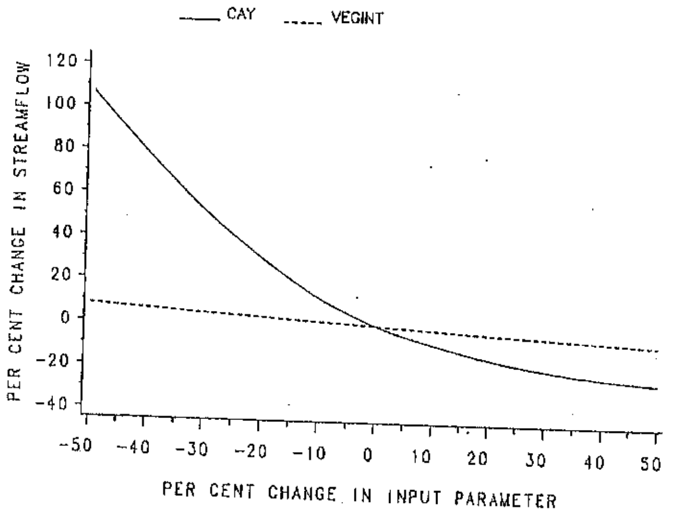

Figure 18.4.13 The relative sensitivity of streamflow to CAY and VEGINT

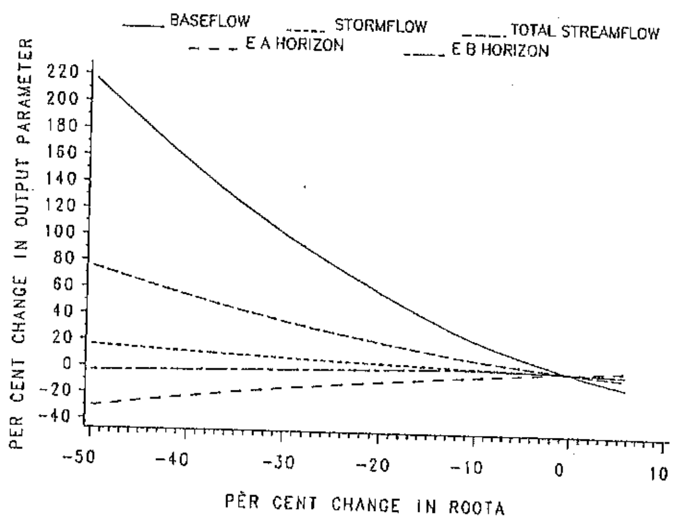

Figure 18.4.14 The effect of changes in ROOTA on selected model output

18.4.5 Runoff Parameters

The input parameters controlling runoff which have been considered in this section are SMDDEP, COIAM, COFRU and QFRESP. Of these the model has been found to be the most sensitive to SMDDEP and COIAM. Figure 18.4.15 represents the influence of changes in SMDDEP on selected *ACRU* output parameters. The opposing effect which low values of SMDDEP have on stormflow and baseflow are similar to the trend encountered in the analysis on soil depth. This occurs for the same reasons as those stated in the soil depth analysis. However, the contribution of baseflow to streamflow continues to increase with increasing SMDDEP, whereas previously as seen in Figure 18.4.4, its contribution diminishes with increasing total depth.

In both instances, the contribution of stormflow to streamflow decreases steadily throughout the range of input parameter changes. The probable reason for the difference in baseflow contributions is that in this case the depth of the subsoil horizon, DEPBHO, remains constant with increasing soil depth, whereas in the soil depth analysis DEPBHO increased. Thus, with a decrease in stormflow there is an associated increase in effective rainfall infiltrating the soil profile. The topsoil horizon will thus be wetter and more likely to reach saturation and hence the vertical downward movement of soil will be more pronounced. This results in a wetter subsoil horizon and thus a larger amount of water will move through to the groundwater store and hence become baseflow.

It is interesting to observe that, for values of SMDDEP in excess of 0.25, there is little change in evaporation from either horizon and also little change in streamflow. In fact, evaporation from the topsoil horizon is largely unaffected by changes in SMMDEP perhaps only with the exception of SMDDEP values less than 0.10.

Like SMDDEP, COIAM is a parameter used in the SCS-based equation governing the generation of stormflow. From Figure 18.4.16 it can be seen that stormflow increases with decreasing COIAM. Conversely, baseflow is reduced at low COIAM values due to the larger proportion of rainfall being converted to stormflow and hence less water infiltrating the soil profile. This trend is reversed as COIAM increases and hence stormflow decreases.

These converse relationships between baseflow and stormflow tend to reduce the sensitivity of streamflow to COIAM. It is likely that in regions of lower rainfall where baseflow is a less significant portion of streamflow, that streamflow will be more sensitive to COIAM than has been observed at Cedara. The relative influences of COIAM and SMDDEP on streamflow are illustrated in Figure 18.4.17. Quite clearly simulated streamflow at Cedara is more sensitive to SMDDEP than to COIAM. This is particularly the case for values of these two parameters less than 0.25. For values greater than 0.25, streamflow is relatively insensitive to both SMDDEP and COIAM.

An investigation of the sensitivity of the same selected outputs to QFRESP and COFRU input revealed that the output is highly insensitive to these two parameters. In both cases varying the input parameters over the ranges described in Section 18.3.2(e), the largest change in output parameter was less than 0.5%.

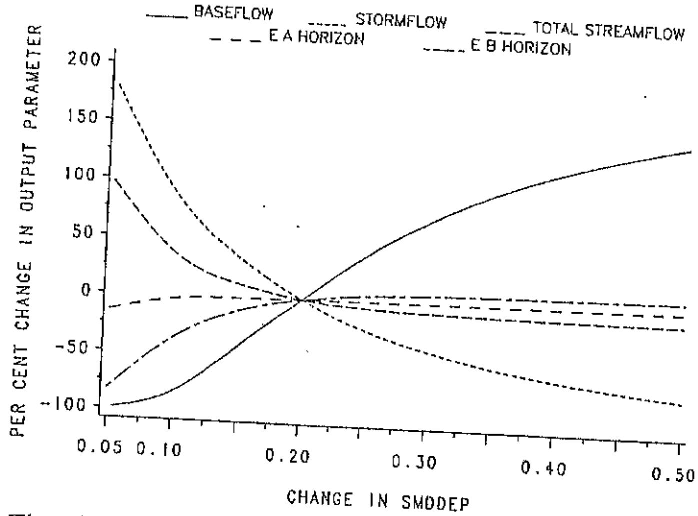

Figure 18.4.15 The effect of changes in SMDDEP on selected model output

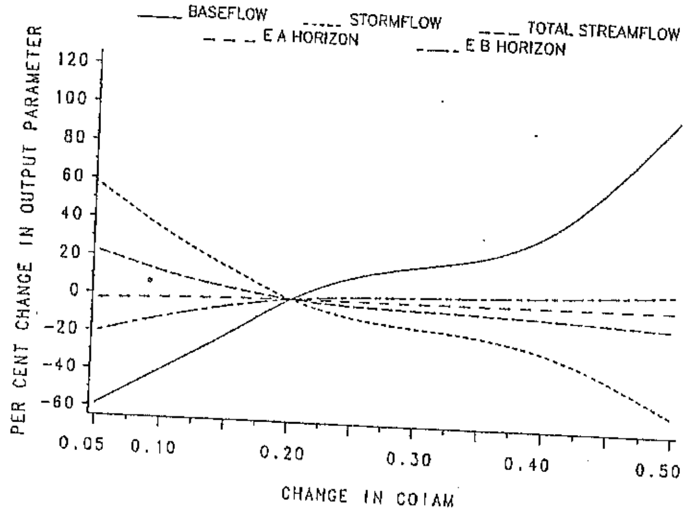

Figure 18.4.16 The effect of changes in COIAM on selected model output

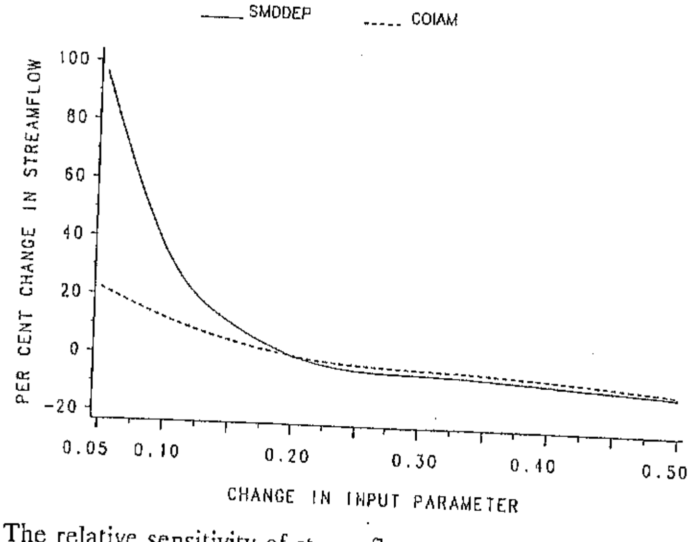

Figure 18.4.17 The relative sensitivity of streamflow to SMDDEP and COIAM

18.5 DISCUSSION AND CONCLUSIONS

It is opportune to stress once again that the results of this analysis are specific to locations with similar climatic conditions to those encountered at Cedara. This should be borne in mind particularly when considering the sensitivity of baseflow to various input parameters. Baseflow represents a fairly large proportion of total streamflow simulated at Cedara. However, in many lower rainfall regions of southern Africa this is unlikely to be the case. Hence in regions where baseflow is less significant, it may not be necessary to consider the sensitivity of the *ACRU* model to inputs affecting baseflow.

Daily rainfall and daily A-pan input values were varied and output from the model was found to be sensitive to both these inputs. Baseflow was the most sensitive output amongst those investigated. The model appears to be more sensitive to rainfall than to potential evaporation and a 10% change in rainfall was found to produce a change of about 30% in streamflow. This illustrates the importance of reliable rainfall data in the use of the *ACRU* model for water resources assessments.

Of the soil parameters, the *ACRU* model appears to be most sensitive to total soil depth. This is particularly so for soil profile depths of less than 1 m. For soil depths deeper than 1 m, the gradients of the curves in Figure 18.4.4 are far less steep than for shallower soils. For example, a change in soil depth of 0.9 m from 0.1 m to 1 m results in a 184% change in streamflow. However, a change in soil depth from 1.0 m to 1.9 m results in only a 31% change in streamflow.

In comparison to soil depth, soil texture has less effect on streamflow. The range of variation between the highest runoff producing soil texture, sand, and the lowest runoff producing texture, silty loam, is 47%. It is somewhat unexpected to observe that sand is the soil texture yielding the greatest amount of runoff. It was observed that the single most important factor influencing the amount of streamflow simulated by the model, is plant available water.

Baseflow is relatively sensitive to ABRESP, but streamflow substantially less so. The model is generally less sensitive to ABRESP values greater than 0.5 than it is to values less than 0.5. The model is rather insensitive to BFRESP.

The *ACRU* model produces similar results for CONST and CRLEPO. The CRLEPO value of -12 is similar to the base CONST value of 0.5. Streamflow is also less sensitive to CONST and CRLEPO than soil depth.

In considering land use inputs to the model, model output was found to be sensitive to both CAY and ROOTA, but rather insensitive to VEGINT. Streamflow appears to be less sensitive to CAY values greater than about 0.67. However, no such region of particular sensitivity could be identified for variations in ROOTA.

Of the four parameters controlling land use, SMDDEP is the most sensitive, followed by COIAM. Output streamflow volumes generated by the *ACRU* model are, however, very insensitive to COFRU and CRLEPO. If the objective function had been selected to be sensitive to the timing of streamflow, then COFRU and QFRESP may have proved to be more sensitive than this study has found them to be. Streamflow is most sensitive to SMDDEP and COIAM in the range 0.05 to 0.20. This study has demonstrated the usefulness of sensitivity analysis as a tool for obtaining an understanding of the complex interactions between components of the *ACRU* model. It has assisted in the identification of input parameters to which model output is sensitive and this is of importance when collecting input information for the formulation of a DSS. This study has identified which input data need to be collected with due care and deliberation and which data are less important in terms of the effect they have on model output.

18.6 ACKNOWLEDGEMENTS

This study has been greatly assisted by the availability of computing facilities at the Computer Centre for Water Research, University of Natal, Pietermaritzburg.

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