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Flood Volume and Peak Discharge from Small Catchments in Southern Africa, based on the SCS Technique

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PREFACE AND ACKNOWLEDGEMENTS

For a number of years now there has been a need in southern Africa* for a versatile and objective, yet simple, conceptually based technique of estimating storm runoff volumes and peak discharge on small catchments, to be used for both design and natural storms. In 1979 the then Division of Agricultural Engineering requested the Department of Agricultural Engineering at the University of Natal in Pietermaritzburg to prepare a report, in the form of a user manual, on the United States Department of Agriculture's Soil Conservation Service (SCS) hydrograph generating technique, for use under southern African conditions.

The report "Estimation of Volume and Rate of Runoff in Small Catchments in South Africa, Based on the SCS Technique" by Schulze and Arnold (1979) was subsequently published and since then has been used widely by State Departments, consulting engineers and other organisations responsible for the design of hydraulic structures. Since 1979 considerable further research has been conducted in the Department of Agricultural Engineering to improve the application of the SCS model. The research, funded by the Water Research Commission, has been directed primarily at the following four components of the model :

a) synthetic rainfall distributions in southern Africa;
b) adjustments to the runoff response coefficient (Curve Number) for antecedent moisture status;
c) catchment response time; and the
d) coefficient of initial abstraction.

In addition to the research conducted locally, much research has been directed internationally in recent years towards improving estimates by the SCS model. Furthermore, the expansion of daily

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* In the context of this report southern Africa refers to South Africa, Lesotho, Swaziland and the national states.

rainfall data bases in southern Africa has also allowed for improved estimates of design daily rainfall totals for use with the model. It was decided therefore, that the 1979 SCS manual was to be rewritten, incorporating both relevant results from overseas and the research findings emanating from the Department of Agricultural Engineering at the University of Natal. The revised report is structured in a similar way to its predecessor, with the first section providing the background and theory to the SCS model, the second outlining procedures for the use of the model in Southern Africa in the form of a user manual and the third comprising maps, nomographs and tables for use with the manual. A separate volume containing appendices to be used in conjunction with the report has been published. In addition a simplified user manual (excluding the background and theory), more suitable for use in the field, has been published.

The authors should like to acknowledge the assistance of Mr J van der Merwe of the South African Weather Bureau who supplied the autographic rainfall data used to regionalise the design rainfall distributions and Mr B du Plessis of the Directorate of Hydrology, Department of Water Affairs who supplied the extreme daily rainfall data used for mapping design daily rainfall depths. Various organisations, including Steffen, Robertson and Kirsten (Civil) Inc, Rhodes University (Hydrological Research Unit), Witwatersrand University (Water Systems Research Programme), Department of Environment Affairs and the University of Zululand contributed to the project by supplying hydrological data in various forms. Many of these data, incorporated at great cost (in terms of time spent reformatting, checking, revision and processing) into the existing hydrological data files of the Department of Agricultural Engineering, were used in the verification of model components during the course of this project.

The staff of the Computing Centre for Water Research (CCWR) at the University of Natal are thanked for their assistance and most of the data analysis and graphics were undertaken on the CCWR computer. Special thanks go to Mrs S Neuwirth who wrote a large number of computer programs and was involved in all phases of the project from data capture and processing, model verification and design analysis through to the final computer graphics. Thanks are also expressed to Mr S J Dunsmore and Mr J P Weddepohl who assisted in the project whilst completing their masters degrees. The assistance of Mr D R Weston in data preparation and model testing is also acknowledged. The staff of the Department of Agricultural Engineering, especially Messrs G R Angus, M C Dent, S D Lynch, and H D Tarboton are thanked for their contributions towards the project especially with regards to the establishment of the 712 climatic data sets. The department's secretaries, Miss J M Whyte and Mrs K M Temple are thanked for the typing of the document.

The research reported in this document was undertaken in terms of the following research project which was funded by the Water Research Commission (WRC) :

Design stormflow and peak discharge rates for small catchments in southern Africa.

The Steering Committee responsible for the project comprises the following people :

Mr D W H Cousens	Water Research Commission	(Chairman)
Mr P W Weideman	Water Research Commission	(Secretary)
Dr P J T Roberts	Water Research Commission	
Dr D A Hughes	Rhodes University	
Mr B J Middleton	Steffen, Robertson and Kirsten (Civil) Inc.	
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Mr Z Kovacs	Department of Water Affairs	
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Mr P W L Lyne	University of Natal	

Please note that throughout this report the decimal point rather than the comma has been used, in order for nomenclature to be compatible with that from computer printouts, which form an integral part of this document.

EXECUTIVE SUMMARY

Background

There is a need in southern Africa for hydrological information which will assist engineers/hydrologists responsible for the planning of hydraulic structures, in making economic and safe design decisions. Estimates of design flood characteristics (e.g. peak discharge, runoff volume and hydrograph shape) from small catchments ($< 8\ km^2$) in southern Africa are generally derived by the use of mathematical runoff models, since only limited gauged hydrological data are available. A major problem associated in the use of such flood estimation models is the scarcity of adequate input information to the models and the lack of familiarity with the various techniques.

In 1979 a report, "Estimation of Volume and Rate of Runoff from Small Catchments in South Africa, Based on the SCS Technique" was published by Schulze and Arnold of the Department of Agricultural Engineering of the University of Natal, Pietermaritzburg, to address the above needs. The report presented the theory of the SCS model, and the procedures to applying this design flood estimation model, developed originally in the USA, to southern African conditions. Since 1979 the report has been used widely by State Departments, consulting engineers and other organisations responsible for the design of hydraulic structures. In the 1979-1984 Water Research Commission (WRC) funded project "Hydrological Investigation of Small Rural Catchments in Natal with Particular Reference to Flood Events" considerable effort was expended into researching/modifying individual components of the SCS runoff equations. In June 1984 the present contract was entered into between the WRC and the University of Natal with two major objectives :

a) A complete update and revision of the SCS manual for the estimation of design floods in southern Africa was to be undertaken, following further testing using expanded data sets from diverse climates, land uses and soils and incorporating/ integrating research findings from previous projects. The revised manual was to be presented at two levels : a simple user manual for field use and a comprehensive manual, including theoretical and research aspects for use by the professional designer.

b) Research on the effects of the joint association of rainfall and catchment moisture status on runoff generation was to be conducted with an aim to providing realistic estimates of design runoff for different regions of southern Africa. General methods currently used in southern Africa (and in most parts of the world) for estimating design runoff, apply design rainfall of a given recurrence interval to a catchment, assuming "average" antecedent moisture conditions for the catchment, to estimate design runoff for the same recurrence interval. Such an approach does not account for the regional variation in what may be termed "average" conditions in an area of vast heterogeneity with respect to soil moisture conditions and hydrological response. Furthermore, such an approach does not account for the likelihood that rainfall of a given return period does not necessarily generate runoff of equivalent return period, there being a possibility of a large flood being produced by a relatively small rainfall event's falling on a wet catchment. A user-oriented manual for design flood estimation from small catchments, incorporating the effects of the joint association of rainfall and catchment moisture status, was to be produced should test results prove successful.

Methods

A literature review was conducted to evaluate recent research directed towards improving the SCS model and to review the role of antecedent soil moisture in the runoff/rainfall process. Hydrological data were obtained from various monitoring organisations in South Africa and the USA to supplement existing data sets available at the Department of Agricultural Engineering, in order to test the component equations of the SCS model and the relationship between rainfall and runoff frequency. The hydrological data, which were incorporated at great cost (in terms of time spent reformatting, checking and processing) into the existing hydrological data files of the Department of Agricultural Engineering, form a valuable data base for other researchers involved in small catchments hydrology.

The major research effort directed at the component equations of the SCS model focussed on:

a) the inclusion of moisture budgeting techniques to adjust the runoff response used in the SCS approach according to catchment antecedent moisture status;

b) the estimation of catchment response time between incident rainfall and runoff response (lag time) using empirical lag equations; and

c) the regionalisation of synthetic storm distributions, which depict the variation of design rainfall intensity with time.

Some details to these three areas of research are provided below:

a) A moisture budget model, developed at the Department of Agricultural Engineering, University of Natal, viz. the ACRU model, was used to account for soil moisture status prior to events of design magnitude. This allowed a comparison to be made between observed daily runoff depth and simulated daily runoff depth, obtained using
   i) the standard SCS model, with only an index of antecedent precipitation amount being used to account for moisture status; and
   ii) the ACRU model with its conceptually based continuous moisture budgeting routines.

The results, presented in a report to the WRC (155/1/86) entitled "Antecedent Soil Moisture in Design Runoff Volume Estimation" indicated the significantly improved design runoff estimates obtained using the ACRU model when compared with the standard SCS model. It was also concluded that there was little association between rankings of observed daily rainfall and resulting daily runoff depths, indicating that the assumption of the T-year return period flood being the result of the T-year return period storm, inherent in current flood estimation procedures, does not provide a sound basis for hydrological design.

The results illustrated that the ACRU model accounted realistically for the major processes affecting the moisture variation in the soil profile and that the moisture budgeting routines could be used with confidence to adjust the SCS model's runoff coefficient (Curve Number) according to moisture status, for use in a revised SCS design manual. To account for the role of antecedent moisture condition on design runoff generation in southern Africa using the ACRU and SCS models, the region was divided into 712 zones of relatively "homogeneous" potential soil moisture replenishment (rainfall) and atmospheric demand (evaporation). For each zone long term observed daily rainfall data and temperature based estimates of potential evaporation were determined from key stations within the zone. The establishment of this data base was accomplished in conjunction with another WRC project conducted at the Department of Agricultural Engineering entitled "A Detailed Regional Soil Moisture Deficit Analysis for Irrigation Planning in Southern Africa".

The rainfall and temperature data for each zone were used in the ACRU model to determine a soil moisture index prior to the five highest daily rainfall events in each year of record for 27 land use/soil combinations. An analysis was performed on the soil moisture indices for each land use/soil class to determine the most frequently expected moisture status for each zone and land use/soil combination, which was used to adjust the SCS Curve Number for prevailing expected moisture status. In addition, runoff depth was estimated for each event according to the specific moisture conditions prior to the event and a frequency analysis was undertaken of the annual maximum runoff series generated for each zone and land use/soil combination. This provided estimates of design runoff depth which accounted for the joint association of daily rainfall total and antecedent moisture condition, which could be included in the design manual.

b) Catchment response time (lag time) has a marked effect on peak discharge and estimates of this parameter are usually based upon hydraulic calculations applied to the major flow paths in a catchment. When such hydraulic calculations cannot be made, empirical equations derived from gauged catchment data are generally used. An empirical lag equation (Schmidt-Schulze lag equation), derived in a previous WRC project conducted by the Department of Agricultural Engineering, was re-evaluated against the original SCS lag equation to determine accuracy of peak discharge estimation. The two lag equations were tested using a large data base of small catchment hydrographs and their causative rainfall hyetographs. The results indicated that the Schmidt-Schulze lag equation generally provided more accurate estimates of catchment response time on natural catchments than the original SCS lag equation, thereby confirming the need for its inclusion in a revised SCS manual.

c) The distribution of rainfall over time is an important consideration in determining peak discharge. The two design storm distributions originally accepted for use with the SCS model in southern Africa, which express the accumulated rainfall depth with time as a fraction of the 24-hour rainfall depth, were derived in the USA. Improved design storm distributions were proposed in a previous project, based on research conducted using digitised autographic data for nine Natal rainfall stations. Regionalisation of the areas outside of Natal for which each distribution was applicable was accomplished in the previous project using manually extracted "clock time" data from other autographic rain gauges in South Africa. During the course of the present project digitised autographic rainfall data were obtained from the South African Weather Bureau for a number of rainfall stations throughout the subcontinent. This data base was used to improve the regionalisation of the design storm distributions for use in the revised SCS manual.

Documentation

The results of the research project have been presented in four separate reports:

a) The first report, "Antecedent Soil Moisture in Design Runoff Volume Estimation" (WRC 155/1/86), documents the research results when design rainfall is considered in association with catchment antecedent moisture conditions (as determined using the ACRU moisture budgeting model). Using gauged data the method is shown to produce better estimates of design runoff volume than those obtained using the SCS model. The significance of the role of antecedent soil moisture in runoff response is indicated and the ACRU model is shown to be suitable for estimating soil moisture status prior to design storms.

b) The second report, "Flood Volume and Peak Discharge from Small Catchments in Southern Africa, Based on the SCS Technique" (TT 31/87), incorporates the research results of this project and previous projects conducted by the Department of Agricultural Engineering, into a design manual. In Part 1 of this report detailed background information and theory is given for the professional designer requiring a comprehensive guide to modelling assumptions and research findings. Part 2 outlines procedures for use of the SCS model in southern Africa, and provides a detailed breakdown of the steps required to determine runoff volume, peak discharge and hydrograph shape. Various alternatives to solutions are given and procedures to estimate design runoff depth accounting for the joint association of rainfall and antecedent moisture condition for southern Africa are included. Worked examples are also given in Part 2 of the document. These provide step by step solutions to a range of problems for which SCS-based methods are likely to be applied. Part 3 consists of tables, maps and nomographs for application of the SCS method in southern Africa.

c) A third much shorter and simpler report, "User Manual for SCS-Based Design Runoff Estimation in Southern Africa" (TT 33/87), is presented as a design aid for use for less expensive structures. This report contains a minimum of theory (given in Parts 1 and 2) to provide the necessary background information to perform manual calculations, but focusses, by way of worked examples (Part 3), on the use of nomographs, tables and maps to provide quick (but thoroughly researched) estimates of runoff volume and peak discharge.

d) A fourth report, "Flood Volume and Peak Discharge from Small Catchments in Southern Africa, Based on the SCS Technique : Appendices" (TT 32/87), contains appendices relevant to both the second and third reports, and consists of tables of hydrological information for each of the climatic zones and a computer program.

Conclusions and Recommendations

The reports presented by this project offer an up-to-date guide to the engineer and hydrologist on the application of SCS-based techniques in design hydrology for small catchments in southern Africa. The role of antecedent soil moisture is shown to be very important in runoff generation and design runoff information based on the joint association of design rainfall and antecedent moisture condition is thus given.

A most important component of this project remains the transfer of technology to the end user through the presentation of workshops on the use of the manuals at various centres in southern Africa. It is envisaged that these workshops should take place as soon as the documents have been published.

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INTRODUCTION

There is a frequent need for hydrological information for planning, design and management of water resources systems. Since actual measurements, for example of storm runoff volumes and peak discharge rates, are rarely available for small agricultural or peri-urban catchments, this information has to be generated or be estimated.

Estimations of design floods from small catchment areas in southern Africa are usually effected by the use of one of the following methods, viz.

- Method 1 : Empirical formulae
- Method 2 : Rational method
- Method 3 : Unit Hydrograph techniques
- Method 4 : Time Area method
- Method 5 : Kinematic method.

A survey conducted by Campbell, Ward and Middleton (1986) revealed the Rational method to be the most commonly applied technique in southern Africa, while the other methods were all used by a significant number of respondents using flood estimation techniques. The survey also revealed that :

a) while flood estimation techniques are used primarily to determine peak discharge and runoff volume there is a definite need for the generation of the storm hydrograph;
b) flood estimation techniques listed above are being applied primarily to catchment areas smaller than 10 km^2; and
c) a major problem associated with the use of flood estimation techniques appeared to be the paucity of adequate data and a lack of familiarity with the different techniques.

The major attraction of the Rational method is undoubtedly its ease of use. However, the method is only designed to estimate peak discharge. The Unit Hydrograph, Time Area and Kinematic techniques have in the past suffered from the need for excessive computational steps to determine runoff volume, peak discharge and especially hydrograph shape. While computer programs are available for use with the Time Area model (Watson, 1981; 1983) and the Kinematic model (Green and Stephenson, 1984), manual computation techniques are sometimes preferred, due either to :

a) lack of suitable computer systems;
b) problems in mounting programs on available computer hardware; and/or
c) difficulties in operating the programs due to inadequate model documentation or unfamiliarity with the method being used.

Simplified manual techniques, based on the model theory have thus been developed by Stephenson (1982) using kinematic theory and by Schulze and Arnold (1979) using the unit hydrograph technique of the United States Soil Conservation Service (SCS model).

Campbell et al. (1986) conducted an evaluation of small catchment design flood estimation techniques using Methods 2, 3, 4 and 5 given above and a data file of small catchment hydrological data established by van Schalkwyk, Ward and Middleton (1985). The evaluation indicated that in general none of the methods tested performed adequately with uncalibrated parameters. The evaluation, however, included a number of small rainfall:runoff events which were not representative of design events and a further statistical analysis was undertaken by Schulze, Schmidt, Neuwirth and Weston (1986) omitting rainfall events less than 20 mm. From their statistical analysis the following conclusions were drawn by Schulze et al. (1986).

a) The Rational Method generally grossly overestimated peak discharge and did not provide satisfactory simulations for any catchment size class or land use class (urban, agricultural, forest and veld).
b) The more complex models such as ILLUDAS (Time Area) and WITWAT (Kinematic) did not perform consistently well on the catchments/events used in the analysis. While these models could only be tested on a reduced data base (owing

to limitations in the size and number of subcatchments which could be used) it became evident that the increased complexity of the models did not produce improved simulations.

c) The SCS-based models (particularly the southern African adaptation) performed well enough to be recommended for design on a considerable number of land use and catchment size categories.

The southern African adaptation of the SCS model (Schulze and Arnold, 1979) has seen widespread use since it is simple to use, due to the provision of graphical solutions to the computational steps, and extensive guidance is given to parameter estimation. The method, which can be used for the estimation of storm runoff depth (and hence volume through the introduction of catchment area), peak discharge and hydrograph shape in catchments of 8 km^2 or less and slopes not exceeding 30%, was developed by Mockus and others over the past three decades, originally for the eastern USA, Puerto Rico and the Virgin Isles (NEH-4, 1972; Kent, 1973). The method has since become internationally used (Hawkins, 1978) and was proposed for application in South Africa as an alternative to the Rational formula as early as 1962 by Reich. More recently it has been tested at research catchment level in southern Africa by, inter alia, Cousens (1976), Arnold (1980), Schulze (1982), Hope (1984), Schmidt and Schulze (1984) and Dunsmore, Schulze and Schmidt (1986), while Hiemstra and Frances (1978) have used the SCS method in conjunction with run-hydrograph theory.

Factors affecting storm runoff depth include rainfall amount, land use/treatment/soils characteristics and antecedent catchment moisture status, while peak discharge rate is affected by time distribution of rainfall, runoff depth and catchment response time. Research into the SCS model has been conducted both locally and internationally since the publication of the original design manual for southern Africa (Schulze and Arnold, 1979). At the Department of Agricultural Engineering, University of Natal, research has been directed mainly at the:

a) effects of antecedent moisture status on runoff depth;
b) coefficient of initial abstraction;
c) time distribution of rainfall; and
d) catchment response time.

The recent research findings (local and international) have been included in this updated version of the SCS manual for use in southern Africa. This report is divided into three parts, the first giving the background and theory to the SCS model, the second outlining procedures for the use of SCS-based methods in southern Africa in the form of a user manual and the third consisting of maps, nomographs and tables for use with the manual. A separate volume containing appendices to be used in conjunction with the report has been published (Schmidt, Schulze and Dent, 1987) and a simplified user manual has also been produced for use in the field (Schmidt and Schulze, 1987).

PART 1 : BACKGROUND AND THEORY

THE ESTIMATION OF RUNOFF VOLUME

1.1 THE SCS RUNOFF EQUATION

The relationship between accumulated rainfall and accumulated runoff used in the SCS model is an empirical one which nevertheless has a conceptual basis. The relationship allows for the determination of stormflow depth from rainfall depth, given an index describing catchment runoff response characteristics. Stormflow represents the direct runoff response (quickflow), consisting of both surface and subsurface runoff, to a given rainfall event but excludes baseflow, which consists of delayed subsurface response. The stormflow depth represents a uniform depth over a catchment or subcatchment and may be converted to volume by introducing catchment area. Rallison and Miller (1982) provided a summary of the development of the runoff equation. This forms a basis for the discussion which follows.

Analysis of storm event rainfall and runoff records indicates that there is a threshold which must be exceeded before runoff commences, i.e. in SCS terms the rainfall magnitude must be sufficient to satisfy interception and depression storages plus the quantity of infiltration before the start of runoff. The rainfall required to satisfy the above volumes is termed the initial abstraction, I_a. After runoff begins, additional loss occurs mainly in the form of infiltration. The total actual retention for the event after start of runoff is designated the symbol F.

After runoff begins, F increases with increasing rainfall up to some maximum retention, S. Runoff response, Q, also increases as the rainfall amount, P, increases. Figure 1.1.1 illustrates the relationship among these variables.

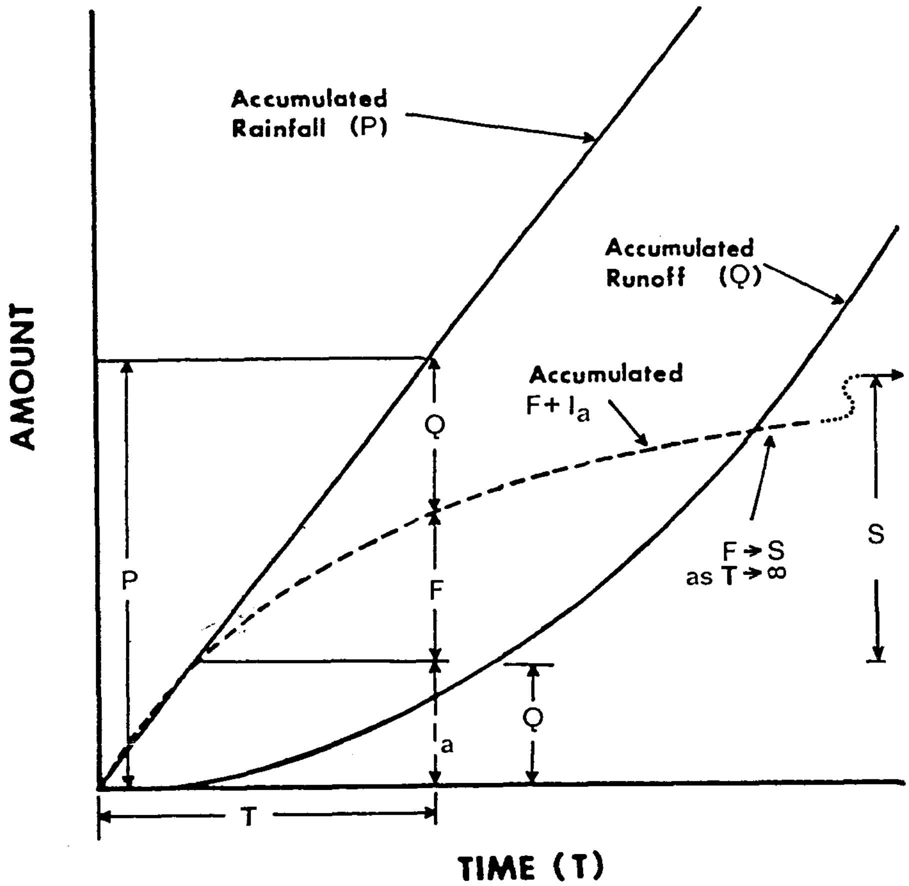

Figure 1.1.1 Schematic curves showing relationships used in the derivation of the SCS runoff equation (after Schulze and Arnold, 1979)

The ratio of actual retention (F) to maximum retention (S) is assumed to be equal to the ratio of runoff (Q) to rainfall minus initial abstraction (P-Ia). The assumed relationship in mathematical form is

$$Q/(P-I_a) = F/S \qquad \text{... Eq. 1}$$

where

Q = accumulated runoff (mm) at time T

P = accumulated rainfall (mm) at time T

F = accumulated infiltration (mm) from the time at which runoff commences until time T

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

I_a = initial abstraction (mm).

In the limit, as $P \to \infty$, $F \to S$ and the ratio $F/S \to$ unity. The ratio of $Q/(P-I_a)$ also approaches unity although it can never actually reach unity. When $P = I_a$, $F = 0$ and the ratio of $F/S = 0$. As P becomes greater than I_a the ratio of F/S is still near zero and the ratio $Q/(P - I_a)$ is also near zero. Since the relationship holds at the two end points, it is assumed to hold for all intermediate points (Rallison and Miller, 1982). After runoff begins at $(P-I_a)$, all rainfall becomes either runoff or actual retention (Figure 1.1.1), i.e.

$$(P - I_a) = F + Q \qquad \text{... Eq. 2}$$

Solving equations 1 and 2 for Q when $P > I_a$ yields

$$Q = (P - I_a)^2/((P - I_a) + S) \qquad \text{... Eq. 3}$$

and when $P < I_a$, $Q = 0$

To eliminate the necessity of estimating both variables (I_a and S) in equation 3, I_a is estimated as a function of moisture deficit by the empirical relationship

$$I_a = cS$$

which, when substituted for I_a in equation 3, results in the equation

$$Q = \frac{(P - cS)^2}{P + (1 - c)S} \qquad \text{... Eq. 4}$$

This is the equation used to estimate the depth of runoff, Q, resulting from a storm rainfall, P, on a catchment with catchment characteristics, c and S. Runoff depth may be converted to volume by introduction of catchment area. It must be reiterated, however, that this equation only applies when $P > I_a$ (i.e. $P > cS$), since runoff can only occur if the rainfall amount P is greater than the initial abstraction (cS).

The potential maximum retention of the soil (i.e. its moisture deficit), S, is related to the soil type and cover conditions and the moisture status of the catchment. Theoretically, the magnitude of S can vary from 0 to ∞. The practical upper and lower limits of S, however, are approached at the permanent wilting point and porosity of the soil in the catchment.

In order to keep this catchment characteristic inside workable limits, S has been transformed to a catchment response index to rainfall, called the runoff Curve Number, CN. This transformation, which further serves to make interpolation, averaging and weighting operations more nearly linear is expressed (for S in mm) as

$$CN = \frac{25\ 400}{S + 254} \qquad \text{... Eq. 5}$$

From the above equation it may be deduced that CN can range from zero (for $S = \infty$) to 100 (for $S = 0$). It is dimensionless and varies according to catchment soil and cover conditions and its antecedent soil moisture condition (AMC)(Sections 1.3, 1.4 and 1.7).

Solving for S, equation 4 can be rewritten as

$$S = \frac{(1-c)Q + 2cP - \sqrt{(c^2-2c+1)Q^2 + 4cPQ}}{2c^2} \qquad \text{... Eq. 6}$$

This equation is useful for determining appropriate S and hence CN values for gauged catchments where observed values of rainfall, P, and runoff, Q, are known.

1.2 STORM RAINFALL AMOUNT

Actual streamflow measurements are rarely available for small catchments in which soil and water conservation measures and hydraulic structures are being designed. Extensive rainfall data sets are, however, available for southern Africa from the South African Weather Bureau and other organisations such as the Department of Agriculture and Water Supply, the South African Sugar Association, Department of Environment Affairs and also from municipalities, mining houses and private individuals. It is therefore desirable that rainfall be used as a basic input in this model.

The most generally available rainfall data in southern Africa are daily amounts from standard, non-recording rainguages and it was for the use of such daily rainfall data that the SCS runoff: rainfall relationship was developed. This relationship therefore excludes time as an explicit variable, i.e. rainfall intensity is not included in the estimation of runoff depth.

For a specific storm the measured one-day rainfall is used directly as the rainfall input in this model. For "design" storms of a given recurrence interval a probability analysis has to be performed on historical records of daily rainfall to provide a rainfall amount of specified risk of exceedence. Previously the 24-hour rainfall amount was recommended for use with the SCS model in southern Africa (Schulze and Arnold, 1979). Since only daily data are widely available this required a correction factor to convert the one-day rainfall to the 24-hour rainfall. Multiplication of the one-day total by the factor 1.13 to convert to the 24-hour rainfall of the same return period has generally been accepted for southern Africa (Alexander, 1978). Analysis of digitised autographic rainfall data from Natal, however, shows the correction factor to vary regionally and with recurrence interval (Schulze, 1984). Problems also occur when analysing autographic data for large events over a 24-hour period due to frequent missing data during a portion of the 24-hour period. It was thus decided that for this report the one-day rainfall amount would be used in the model. Adamson (1981) has published one-day design rainfall depths for 2 400 stations in southern Africa and South West Africa/Namibia. A further 270 stations covering the highly diverse eastern regions of southern Africa were analysed subsequent to the publication of the report in 1981 (Adamson, 1986). Based on the above data, which were supplied by the Department of Water Affairs (Directorate of Hydrology) maps have been prepared especially for this report depicting, for southern Africa, the maximum expected one-day rainfall for selected standard frequencies, namely for 2, 5, 10, 20, 50 and 100-year return periods (Figure 3.1). The one-day design rainfall values were obtained using the censored log-Normal distribution applied to the partial duration series of extreme one-day rainfalls (Adamson, 1981). Mapping was accomplished using computer-based interpolation and smoothing techniques.

The maps given in Figure 3.1 are generalised maps which should be used with caution in areas where there is a marked change in design rainfall depth over a short distance (e.g. areas of rapid change in topography). In such cases users should refer to Appendix 5 where one-day rainfall depths for various return periods have been given for the 2 200 stations (South West African/Namibian stations excluded) from which Figure 3.1 was derived. The nearest daily rainfall station to the design location should be selected from Appendix 5 by determining the South African Weather Bureau sector number in which the design location occurs (Appendix 5) and referring to the rainfall stations situated in that sector. The first three digits of the Weather Bureau rainfall station numbers, listed in ascending order in Appendix 5, represent the Weather Bureau sector number.

When more than one rainfall station is found near the design location preference should be given to the station with the greater number of years of record. A station with a mean annual rainfall similar to that of the catchment in question should also be given preference. One should be cautious not to use design recurrence intervals greatly in excess of the station's record recurrence intervals greatly in excess of the station's record length. Adjustment of rainfall with respect to area (i.e. the areal reduction factor) is not usually applied in the SCS method because of its general application to catchment areas of less than 8 km^2.

It should be noted that the theory of extremes embraces the concept that large magnitude is associated with low frequency (i.e. high return period) and similarly that small magnitude is associated with high frequency of occurrence (i.e. low return period). It should be stressed, however, that the computed maximum expected rainfall for a given return period, say 20 years, is a <u>statistical</u> long-term <u>mean</u> value, and that this maximum expected value can, in nature, be exceeded in consecutive years, or alternatively not recur for centuries.

1.3 HYDROLOGICAL SOIL GROUPS

1.3.1 Background

In estimations of flood volumes and peaks a vital role is played by soil, for it is the capacity of the soil to absorb, retain and release water that is a prime regulator of the hydrological response of a catchment. Pronounced differences in magnitude and sequence of hydrological processes have been observed in soil units within a catchment. The delineation of soil units or groups which are relatively homogeneous with respect to hydrological response is thus necessary.

The parameter which provides the basis for a hydrological classification of soils in southern Africa is a "typical amount of infiltration for the soil at likely moisture content to the point of maximum runoff rate" (Schulze and Arnold, 1979). This premise is somewhat different in concept to the one described by the SCS in the relevant National Engineering Handbook (NEH-4, 1972) in which the "minimum rate of infiltration for a thoroughly wetted base soil assuming maximum swelling..." forms the basis of soils grouping. The reason for altering the concept of classification is that a comparison of the actual physical properties of soil series in the U.S.A. and their hydrological grouping showed that many series had intuitively been classed according to "typical or "likely" moisture characteristics in the field.

As in the SCS literature (NEH-4, 1972), four basic hydrological soil groups have been recognised in southern Africa. Hydrologically, the limiting properties in a soil profile may be

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

b) its permeability (i.e. the rate at which water moves in the soil and which is controlled by properties of the soil horizons); and

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

The four basic hydrological soil groups are given below, together with a brief description of each group. Typical permeability and final infiltration rates are given for each soil group (United States Department of Agriculture, 1986).

Soil Group A Low stormflow potential. Infiltration rate is high and permeability is rapid in this group. Overall drainage is excessive to well-drained. (Final infiltration rate $\simeq 25$ mm.h^{-1}. Permeability rate $>$ 7.6 mm.h^{-1}).

Soil Group B Moderately low stormflow potential. The soils of this group are characterised by moderate infiltration rates, effective depth and drainage. Permeability is slightly restricted. (Final infiltration rate $\simeq 13$ mm.h^{-1}. Permeability rate 3.8 to 7.6 mm.h^{-1}).

Soil Group C Moderately high stormflow potential. The rate of infiltration is slow or deteriorates rapidly in this group. Permeability is restricted. Soil depth tends to be shallow. (Final infiltration rate $\simeq 6$ mm.h^{-1}. Permeability rate 1.3 to 3.8 mm.h^{-1})

Soil Group D High stormflow potential. Soils in this group are characterised by very slow infiltration rates and severely restricted permeability. Very shallow soils and those of high shrink-swell potential are included in this group. (Final infiltration rate $\simeq 3$ mm.h^{-1}. Permeability rate <1.3 mm.h^{-1}).

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

1.3.2 Classification procedures

Each soil form, according to its overall diagnostic properties, was initially placed in one of the seven groups. The series within each soil form were then graded up or down from the general soil group assigned to the form, according to their specific physical/chemical properties.
The following properties were considered relevant :

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

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

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

d) Crusting (c) Soil forms which typically displayed a crusted surface but where crusting was absent at series level were upgraded one group, and vice versa. Soils exhibiting a hardening of the B-horizon (e.g. a ferrihumic B-horizon) were downgraded one group.

At the present stage a degree of uncertainty still exists as to the overall effects of soil coloration and calcareousness on infiltration and permeability rates.

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

a) Soil depth Where typically deep soils are in the shallow phase, (generally less than 0.5m) they should be downgraded one group.

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

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

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

The hydrological soil groupings for the 501 soil series given in MacVicar *et al*. (1977) are listed in Table 3.1. Table 3.1 also contains, for each soil form and series, a typical textural class and a category of potential for interflow as given by Schulze (1984). Interflow may provide a large portion of the stormflow response when restrictions to water movement in the soil profile occur due to textural changes or the presence of unconsolidated rock directly below the A-horizon. A threefold grouping into potential interflow has been given, namely :

a) interflow unlikely (0);
b) low interflow potential (X); and
c) high interflow potential (XX).

Further details regarding the procedure of classification are given in Schulze (1984).

In assessing the hydrological reponse of a catchment the information on soil groups is used in conjunction with different agricultural and non-agricultural land use and treatment classes, which are discussed in the following section. The classification of hydrological responses (CN) for various soils and land use and treatment classes is given in Table 3.2.The sensitivity of CN to soil group is evident from Table 3.2. Criticism has been directed in the USA towards the categories into which soils have been placed in the SCS approach and the classification procedures used by the SCS (e.g. Wood and Blackburn, 1984). Various authors have attempted to quantify infiltration characteristics based upon the SCS soil groups (Terstriep and Stall, 1974; Hawkins, 1980) and include more soil characteristics to define them. The hydrological soil groupings for southern Africa were, however, determined as a collaborative effort by a number of South Africa's foremost soil scientists and hydrologists and should thus be recognised as a sound basis for categorising soil hydrological response potential. Local experience should, however, be used when necessary to make adjustments.

1.4 LAND USE AND TREATMENT CLASSES

1.4.1 Classification of land use and treatment

In the SCS method of runoff estimation the effects of the surface conditions of a catchment are evaluated by means of land use and treatment classes. Land use is the catchment cover and it includes every kind of vegetation, litter, mulch and fallow as well as non-agricultural uses such as water surfaces (lakes, swamps, etc.), urban/suburban land uses and impervious surfaces (roads, roofs, etc.). Land treatment applies mainly to agricultural land uses and it includes mechanical practices such as contouring or terracing and management practices such as grazing control or rotation of crops. The classes consist of use and treatment combinations actually to be found in catchment areas.

Hydrological condition affects the runoff potential from the land and is given in Table 3.2 to assist in CN determination. High runoff potential will prevail when poor hydrological conditions exist while low runoff potential occurs when the land is in good hydrological condition.

Land use and treatment classes are obtained either by observation or by measurement of plant and litter density and extent on sample areas. The land use and treatment classes discussed below have been adapted from SCS literature. In Part 3 they are listed in Table 3.2, which also shows the runoff Curve Numbers (CN) for the hydrological condition and for hydrological soil-cover complexes in which the classes are used. The Curve Number classifications given in Table 3.2 are based on work conducted in the USA and do not cover some of the land use characteristics typically found in southern Africa. Interpolation between similar land use classes given in Table 3.2 must be resorted to in such instances.

1.4.2 Cultivated land

Fallow is the agricultural land use and treatment with the highest potential for runoff because the land is kept as bare as possible to conserve moisture for use by a succeeding crop. The loss due to runoff is offset agriculturally by the soil moisture retention due to reduced transpiration. Other kinds of fallow, due to various conservation tillage practices, are discussed later.

Row crop is any field crop (e.g. maize, soybeans, tomatoes) planted in rows far enough apart that most of the soil surface is exposed to rainfall impact throughout the growing season. At planting time it is equivalent to fallow and may be so again after harvest. In most evaluations average seasonal condition is assumed, but special conditions can be evaluated. Row crops are planted either in straight rows or on the contour and they are in either a poor or good rotation.

Small grain (e.g. wheat, oats, barley) is planted in rows close enough that the soil surface is not exposed except during planting and shortly thereafter. Land treatments are those used with row crops.

Close-seeded legumes or rotation meadow (e.g. lucerne, clover), are either planted in close rows or broadcast. This cover may be allowed to remain for more than a year so that year round protection is given to the soil. The land treatments used with row crops are also used with this cover, except for row treatments if the seed is broadcast.

Rotations are planned sequences of crops, and their purpose is to maintain soil fertility or reduce erosion or provide an annual supply of a particular crop. Hydrologically, rotations range from "poor" to "good" in proportion to the amount of dense vegetation in the rotation, and they are evaluated in terms of hydrological effects. Poor rotations are generally one-crop land uses such as continuous maize or continuous wheat (monoculture) or combinations of row crops, small grains and fallow. Good rotations generally contain lucerne or other close-seeded legume or grass to improve tilth and increase infiltration. Their hydrological effects may carry over into succeeding years after the crop is removed, though normally the effects are minor after the second year. The carry-over effect is not considered.

Straight row fields are those farmed in straight rows usually across the slope. Where land slopes are less than about 2 per cent, farming across the slope in straight rows is equivalent to planting on the contour and should be considered as such when using Table 3.2. The hydrological effect of planting on the contour is the added surface storage provided by the furrows because the storage prolongs the time during which infiltration can take place. The amount of storage depends not only on the dimensions of the furrows but also on the land slope, crop and manner of planting and cultivation. "Average" conditions for the growing season are used in Table 3.2. The relative effects of planting on the contour for all croplands shown in the Table are based on data from slopes of 3 to 8 %. The conservation structure entries in Table 3.2 refer to systems containing open-end level or graded terraces, grassed-waterway outlets and contour furrows between the terraces. The hydrological effects are due to the replacement of a low-infiltration land use by grassed waterways and to the increased opportunity for infiltration in the furrows and terraces.

In the case of sugarcane, limited cover refers to cane newly planted, or ratooned cane with a limited root system, with canopy covering less than 1/2 the field area; partial cover refers to cane in the transition period between limited and complete cover, with canopy cover over 1/2 to nearly the entire field and complete cover implies cane from the stage of growth when full canopy is provided to the stage at harvest.

1.4.3 Grassland

Grassland areas can be evaluated by means of the three hydrological conditions of veld shown in Table 1.4.1, which are based on cover effectiveness and not forage production. The percentage of area covered (or density) and the intensity of grazing are estimated visually. In making the estimates it should be borne in mind that grazing on any but dry soils will result in lowering of infiltration rates due to compaction of the soil by hooves, an effect that may carry over for a year or more even without further grazing.

Meadow is a field on which grass is continuously grown, protected from grazing and generally mowed for hay. Drained meadows (those having artificially lowered water tables) have little or no surface runoff except during storms that have high rainfall intensities. Undrained meadows (those having high water tables) may be so wet as to be the equivalent of water surfaces in runoff computations. If a wet meadow is drained, its soil group classification as well as its land use and treatment class may change.

Table 1.4.1 Hydrological classification of veld conditions

Vegetative condition	Hydrological condition
Grazed heavily or burnt. Has no mulch or has plant cover on less than 1/2 of the area.	Poor
Not grazed heavily. Has plant cover on 1/2 to 3/4 of the area.	Fair
Grazed lightly. Has plant cover on more than 3/4 of the area.	Good

1.4.4 Woods

Woods are usually small isolated groves of trees being raised for farm use. The woods can be evaluated in terms of hydrological response as shown in Table 1.4.2, which is based on cover effectiveness, not on timber production. The hydrological condition is estimated visually.

Table 1.4.2 Hydrological classification of woods

Vegetative condition	Hydrological condition
Grazed heavily or burnt regularly. Litter, small trees and brush are destroyed.	Poor
Grazed but not burnt. There may be some litter but these woods are protected.	Fair
Protected from grazing. Litter and shrubs cover the soil.	Good

1.4.5 Forest

Estimations of runoff depth by the SCS technique have generally not been sucessful under forest conditions. However, in State or commercial plantations of the eastern and southern regions of southern Africa, soil group, humus type and humus depth are suggested as the principal factors used in a method of determining CN. The undecomposed leaves or needles, twigs, bark and other vegetative debris on the forest floor form the litter from which humus is derived.

Humus is the organic layer immediately below the litter layer from which it is derived. It may consist of mull, which is an intimate mixture of organic matter and mineral soil, or of mor, which is practically pure organic matter unrecognisable as to origin from material lying on the forest floor. A depth of some 150mm humus is considered the maximum attainable under average conditions. Under good management practices (proper use, protection and improvement), humus is porous and has high infiltration and storage capacities. Under poor management practices (burning, overcutting, or overgrazing) humus is compact enough to impede absorption of water.

Humus is evaluated by means of its degrees of compaction. These are given below.

a) Compact : Mulls and mors are firm.
b) Moderately compact : A transition stage.
c) Loose or friable : Mulls and morse are spongy.

1.4.6 Conservation tillage

Conservation tillage practices are used as a means of conserving soil and water and decreasing production costs. Such practices leave most or all crop residue on the soil surface, thereby promoting infiltration and reducing stormflow response. The degree to which runoff is reduced depends on the percentage of surface covered by mulch. Local information in this regard, obtained from rainfall simulator studies in southern Africa has been published by McPhee and Smithen (1985) and McPhee, Smithen, Venter, Hartman and Crosby (1983). A table quantifying the effects of conservation tillage on CN was presented by Rawls and Richardson (1983) and is given in Table 3.2b.

1.4.7 Curve Numbers obtained using remote sensing techniques

The conventional approach to estimating CN through the identification of areas of homogeneous soil and land use in the field can prove time consuming. Some studies have indicated that a satisfactory level of accuracy in runoff estimation can be obtained using remotely sensed estimates of land use and hence CN (Ragan and Jackson, 1980; Bondelid, Jackson and McCuen, 1980; Slack and Welch, 1980; Cermah, Feldman and Webb, 1981). Remotely sensed data obtained using LANDSAT or high altitude photography can only be used to classify cover into coarse categories. Jackson and Rawls (1981) presented a table of CNs for a range of land cover categories that could be identified using LANDSAT data (Table 3.2c). The CNs for each category were derived by modifying the CNs presented in Bondelid et al. (1980) and Rawls, Shalaby and McCuen (1980) into the various cover categories.

Bondelid, McCuen and Jackson (1982) indicated that the use of LANDSAT derived CNs did not result in large errors in estimated peak discharge and runoff volume when compared with estimates based on conventional field derived CNs. This is more likely to be the case for fairly large catchments when the CNs for small subcatchments of homogeneous runoff response tend to cancel one another in terms of overall runoff response. The rapid data capture using LANDSAT thus makes it a cost-effective approach to determine CNs for large areas.

The procedure for use of the land use and treatment classes in assigning runoff Curve Numbers is illustrated in PART 2.

1.5 DERIVATION OF RUNOFF CURVE NUMBERS

1.5.1 Original derivation of Curve Numbers

The catchment Curve Numbers for various soil and cover conditions given in Table 3.2 were developed from gauged catchment data where soils, cover and hydrologic conditions were known. The Curve Number for a particular combination of soil and cover characteristics was developed by plotting daily rainfall and runoff volumes for the annual maximum floods on graph paper (NEH-4, 1972; Rallison, 1980). Laid over this plot was a graph of Equation 4 for various Curve Numbers (and hence values of S) for an assumed value of c = 0.2. The median Curve Number, i.e. the one which had an equal number of data points either side of the plotted curve, was assigned the "average" catchment CN. Curve Numbers were developed in this way for many soil-cover complexes.

The research catchments from which the data were used were located throughout the United States (NEH-4, 1972; Rallison, 1980) and the derived median curve numbers for all catchments of the same soil-cover complex were averaged to provide CNs representative for the whole of the USA. Interpolation was undertaken to derive CNs for soil-cover complexes for which gauged data were not available. The CN derived for a catchment represents the "average" response coefficient for a range of independent events. The CNs presented for each soil and cover condition represent average conditions for the specific soil-cover complex over a range of climatic regimes. The variability of the plotted annual maximum pairs for each catchment may be attributed, inter alia, to differences in initial soil moisture, infiltration rates and rainfall intensity. Mockus (1964), however, attributed the variability solely to soil moisture status since rainfall intensity and hence infiltration rates had to be ignored due to the nature of the model, i.e. its being a daily model (Mockus, 1964). Two further CN curves enveloping the spread of data were used to represent CN for "wet" (AMC-III) and "dry" (AMC-I) conditions which were related to 5-day antecedent rainfall totals (Section 1.7.1).

1.5.2 Curve Number estimation from gauged catchment data

Most runoff generation models suffer from inadequacies in parameter estimation for the model. One of the strengths in the use of the SCS model is the detailed information of CNs for a wide range of soil-cover complexes (Table 3.2). The use of the coefficient of initial abstraction as a fraction of the soil moisture deficit (S) therefore requires the estimation of a single catchment parameter (CN) to estimate runoff volume. Many runoff models make use of infiltration equations to determine direct runoff from a rainfall hyetograph. Such models suffer from the disadvantage that while the CN is an index of hydrological condition on a catchment scale, an infiltration curve is a hydrological index for a small area within the catchment and suitable routing techniques are required to determine total catchment runoff response. In addition, little scientific literature is available on the influence of soil type, cover, land use and site moisture on infiltration capacity (Hawkins, 1980).

Since the CN is the sole index representing a catchment's runoff response, an accurate estimate of the Curve Number is required. Chen (1982a) has indicated that errors in CN and hence antecedent moisture adjustments to CN have much more serious consequences on the runoff estimate than errors of similar magnitude in initial abstraction or rainfall. Hawkins (1975) has shown that for design it is important to estimate CN to within 2 CNs of its "true" value. While Sections 1.3, 1.4 and 1.7 detail the procedure for CN determination for an ungauged catchment it is worth considering procedures for CN determination where gauged data are available. This aspect is considered in the following three sections.

1.5.3 Transformation of frequency distributions

Hjelmfelt (1983) recognised that, since the SCS runoff equation was originally developed to determine a design runoff depth based on a design rainfall depth of given recurrence interval, the runoff equation should be tested for its ability to convert a rainfall frequency distribution into a runoff frequency distribution. Schaake, Geyer and Knapp (1967) originally adopted a similar approach with the Rational method for peak discharge and more recently Hjelmfelt (1980; 1983) and Haan and Wilson (1986) have applied it to the SCS runoff equation.

For a catchment with gauged runoff data the annual maximum series of daily stormflow can be determined from the runoff records. For small catchments stormflow depth or volume may be taken to be near equal to total runoff depth or volume for the annual maximum day's flow. An estimate of expected maximum one-day runoff depth for a given risk of exceedence may be made, based either on a line fitted by eye to the plotted points of the annual maximum series (using, for example, the Weibull distribution) or a numerical computation of "extreme" value depth following standard statistical procedures. Similarly, the annual maximum daily rainfall series for the same years of record may be used to define the one-day rainfall depth for the same risk of exceedence. The parameter S may then be determined using Equation 6. For a coefficient of initial abstraction, c = 0.1, for example, Equation 6 simplifies to

$$S = 10 \left(4.5Q + P - \sqrt{20.25\, Q^2 + 10\, P\, Q}\,\right) \qquad \text{... Eq. 7}$$

The computed S and hence CN (Equation 5), which may vary slightly with return period, may be taken to represent the catchment curve number. This procedure should only be applied when sufficient years' data are available to fit an extreme value distribution with confidence.

1.5.4 Event runoff

Equation 7 may be applied directly to a daily runoff:rainfall pair from small catchments to determine the CN for a specific event. Following the original SCS procedures to derive runoff Curve Numbers, the median Curve Number calculated for the annual flood events using Equation 7 will represent the Curve Number for average antecedent moisture conditions for the location under consideration under prevailing soil/land use characteristics. Hjelmfelt, Kramer and Burwell (1982) have indicated a procedure for determining CNs for wet and dry antecedent moisture conditions following this approach. Springer, McGurk and Hawkins (1980) also applied the technique for local calibration of CN and indicated that the use of a large sample of runoff:rainfall events of small magnitude resulted in a higher calculated CN than obtained when using the annual maximum events i.e. an inherent bias was thereby achieved. Hawkins, Hjelmfelt and Zevenbergen (1985) caution against the use of "small" events in such an analysis which give rise to higher CNs and recommend that only events for which the ratio of rainfall depth to potential maximum retention for "average" conditions exceeds 0.46 should be used. A trial and error procedure for accomplishing this is outlined by Hawkins *et al*. (1985).

Techniques similar to the above have been used by Hanson, Neff, Doyle and Gilbert (1981) and Cooley and Lane (1982) to determine CNs for agricultural catchments from gauged data. The approach has also been applied to rainfall simulator data from runoff plots (Rawls, Onstad and Richardson, 1980; Steichen, 1983) to evaluate the effects of tillage and conservation practices on CN.

1.5.5 Infiltration characteristics

Numerous researchers have presented infiltration capacity equations based on the SCS curve number equation (Aron, Miller and Lakatos, 1977; Hawkins, 1980; Hjelmfelt, 1980; Chen, 1982a, 1982b; Kumar and Jain, 1982). The reasons for the use of such equations are the lack of data available to determine "default values" for coefficients used in existing infiltration equations such as the Horton or Green and Ampt equations and the extensive field information available to assist in the estimation of CN. Hawkins (1980) and Hjelmfelt (1980) presented the following infiltration equation which was derived from the SCS runoff equation and which is valid for $P \quad cS$:

$$\frac{dF}{dt} = \frac{S^2}{(P + (1-c)S)^2} \frac{dP}{dt} \qquad \text{... Eq. 8}$$

where

$\frac{dF}{dt}$ = infiltration rate (mm.h^{-1})

$\frac{dP}{dt}$ = rainfall intensity (mm.h^{-1})

S = soil moisture deficit prior to storm event (mm)

P = accumulated storm rainfall (mm)

c = coefficient of initial abstraction.

Hjelmfelt (1980) has shown this equation to be equivalent to Holtan and Overton's infiltration equation for rainfall of uniform intensity and a final infiltration capacity of zero mm.h^{-1}. Criticism has been directed at the above equation (Chen, 1982b; Hjelmfelt, 1983) since it does not agree with the traditional infiltration relationships, in that it depicts a final infiltration capacity of zero and requires infiltration capacity to be dependent upon rainfall intensity and total storm rainfall. Hawkins (1979, 1980), however, showed how the equation could be used to solve for S using rainfall simulator data when a uniform rainfall intensity was applied to a plot of land. Solving the above equation for S in terms of f, i.e. the infiltration rate, and i, the rainfall intensity. Hawkins (1979, 1980) gave the following equation to determine S and hence CN

$$S = P\sqrt{\frac{f}{i}} \bigg/ (1 - c\sqrt{\frac{f}{i}}) \qquad \text{... Eq. 9}$$

Thus, knowing the infiltration rate (f) at the end of a simulator run of duration D hours and applied intensity i mm.h^{-1} (P = ixD) and for a given initial abstraction coefficient, the parameter S and hence CN can be determined for the experimental plot data.

The fact that the SCS-based infiltration equation does not conform entirely with infiltration theory, and problems exist in extrapolating the CN determined from plot to catchment scale, limit the use of the procedures outlined above. In addition the use of a controlled rainfall intensity in the plot experiment could introduce problems in deriving CNs to be representative of natural events. The procedure does, however, provide an opportunity to expand the interpretation of the CN for a wide range of soil/land use conditions using, for example, the extensive data base accumulated in South Africa during the rainfall simulator programme of the Directorate of Agricultural Engineering and Water Supply (McPhee *et al.*, 1983). The procedures discussed in Section 1.5.4 would, however, be more satisfactory in this regard.

The use of SCS procedures for design flood estimation will usually be directed at the ungauged catchment and the methods outlined in Sections 1.3 and 1.4 would thus be applied to determine a realistic value of CN. The expanding data bases of rainfall and runoff data for southern Africa should, however, where possible, be used to derive a CN representative of the prevailing soil and land use conditions using the methods discussed in this section.

1.6 THE COEFFICIENT OF INITIAL ABSTRACTION

The initial abstraction, I_a , is defined to include all the storm rainfall occurring before surface runoff commences. It therefore consists mainly of interception, surface storage and that infiltration which occurs before runoff begins. For purposes of estimating runoff depth the initial abstraction is estimated by the empirical relation

$$I_a = cS \qquad \text{... Eq. 10}$$

where

c = coefficient of initial abstraction
S = potential maximum retention of the soil (mm).

The United States Department of Agriculture, by a regression of I_a on S, found the coefficient of initial abstraction to be 0.2 (NEH-4, 1972). A large degree of scatter was present and was attributed to the difficulty inherent in measuring the initial abstraction. A regression analysis of the data of I_a and S presented in the NEH-4 (1972) was undertaken by Arnold (1980) with the aim of determining an alternative empirical relationship between I_a and S which would account for a greater proportion of the variability than would $I_a = 0.2S$. A number of linear and non-linear regression equations were fitted to the data, both with a constant term and forcing the regression through the origin. A simple linear model was chosen for the purpose of estimating I_a because more complex quadratic models and log transformation did not appear to be more efficient. The slope of the regression line of the linear model was 0.12, which was shown to be statistically different to the 0.2 as suggested by the original authors of the SCS model. While it has been suggested that the data points obtained from NEH-4 (1972) may not be fully representative of the complete data base which was originally available to the authors of the SCS model, it is noteworthy that the coefficient 0.12 given by Arnold (1980) is far more in line with values suggested by numerous other researchers. Aron *et* *al.* (1977) found that a value of 0.2 for I_a was too high for small to medium storms and they suggested a value of 0.1 or an even lower value be used. Based on similar experience, 0.15 was used by Fogel, Hekman and Duckstein (1980). Springer, McGurk, Hawkins and Clotharp (1980), working with data from both humid and semi-arid catchments in the USA, also found that in most cases the coefficient was less than 0.2 and on several catchments was zero.

It is to be expected that the coefficient of I_a is a variable and Smith (1978) maintains that it varies within a storm and with rainfall intensity and duration. Golding (1979), on the other hand, suggests a variation of the coefficient with Curve Number when simulating stormflow in urban areas. Using storm data from catchments in Natal, South Africa, Arnold (1980) investigated the extent to which the coefficient of I_a was dependent on season and antecedent moisture condition. It was concluded that antecedent moisture status did not significantly affect the coefficient of I_a, and that the general increase of the coefficient of I_a with antecedent moisture condition, exhibited within a season, reflected inadequacies in the procedure for adjusting Curve Numbers according to antecedent moisture conditions. Similarly, there was no significant difference between coefficients of I_a between seasons (Arnold, 1980) although the coefficient tended to be lower in the dormant than in the growing season. It was suggested that a coefficient of I_a of 0.05 be generally more applicable to the Natal catchments tested.

Schulze, George, Arnold and Mitchell (1984) investigated the extent to which the coefficient of I_a was dependent upon physiographic features of a catchment as well as the characteristics related to rainfall characteristics of the event and prior to the event. A series of multivariate equations was developed which resulted in improved estimates of stormflow by SCS procedures, although such equations were found to be location-specific and could only be used within the limited range of values of individual variables for which they were developed and within certain constraints.

It is thus evident that there are no simple universal associations by which improved estimates of the coefficient of I_a may be obtained. Furthermore, the results from research to improve estimates of I_a must be considered in the light of assumptions adopted and the data base used in the various analyses. The use of inaccurate field estimates of CN, subjective categories of antecedent moisture class (Section 1.7.1) and a data base dominated by either small storms, a predominance of storms falling in a particular season, or a limited range in climatic/physiographic characteristics of research catchments will all affect the recommended coefficient of I_a.

Based on the research which has been reviewed it is evident that a value of 0.2 for the coefficient of I_a appears too high and it is suggested that the more conservative value of 0.1 be used in design analysis. A coefficient of I_a of 0.1 has therefore been used throughout in this report.

1.7 EFFECT OF ANTECEDENT SOIL MOISTURE ON RUNOFF

The SCS maintains that second to storm rainfall, the stormflow response depth is essentially a function of the soil's antecedent moisture condition (AMC), i.e. the soil moisture status prior to a stormflow event's occurring on a catchment (NEH-4, 1972). The runoff Curve Numbers given for different land use classes, their treatment/practice, their hydrological condition and hydrological soil groups in Table 3.2 assume so-called "average" antecedent soil moisture conditions. The CNs, however, have to be adjusted for different catchments of dissimilar soil moisture regime and between storms on a catchment if moisture conditions deviate from the average. Hawkins (1975), Chen (1982a) and Bondelid et al. (1982), in testing the sensitivity of the SCS procedure to CN variation, conclude that accurate estimates and adjustments of CN are more important than accurate estimates of rainfall.

Procedures to adjust runoff response for soil moisture status range from simple empirical methods using, for example, an antecedent precipitation index, to complex moisture budgeting routines. These procedures for adjustment may be used with a range of models. Watson (1981) presents antecedent soil moisture adjustments to the Horton infiltration equation based on a 5-day antecedent precipitation index used in the Time Area method. Lambourne and Stephenson (1986a) review a range of procedures to adjust AMC for application with models such as WITWAT (Green, 1984). Lambourne and Stephenson (1986a) present a simple moisture budget model which can be used to derive soil antecedent moisture, and based on rainfall simulator results they give adjustments to initial abstraction and final infiltration rate due to moisture status.

This section describes

a) the original SCS procedure of CN adjustment for varying AMC;
b) a more conceptually based and versatile procedure of CN modification based upon the work by Hawkins (1978);

c) regional indices to adjust CN for design storms in southern Africa; and
d) a moisture budget model which accounts for soil moisture variation.

1.7.1 The original* SCS procedure of CN adjustment for AMC

The SCS originally suggested three antecedent moisture classes, described in terms of runoff potential (NEH-4, 1972). These are

AMC-I	"dry" conditions, i.e. lowest limit of soil moisture, or upper limit of potential maximum retention (S),
AMC-II	the "average" antecedent soil moisture condition for which the CN in Table 3.2 apply,
AMC-III	"wet" conditions, i.e. upper limit of soil moisture or lower limit of S.

These antecedent soil moisture conditions are estimated from the five-day antecedent rainfall, i.e. the accumulated total of the rain in the five days preceding the runoff event under consideration (Table 1.7.1). The use of five days' accumulated antecedent rainfall has been based on subjective judgement of rainfall: runoff data scatter in the USA at various antecedent rainfall time periods (Miller, 1979). Different rainfall class limits for AMC groups have been defined for the "growing" and the "dormant" seasons, these having been developed from empirical relationships based on experience (Miller, 1979).

Having established from observed land use and soil characteristics a catchment's CN for "average" AMC, i.e. for AMC-II, this CN is then adjusted for AMC prior to the storm event. A complete list of CN adjustments for AMC-I and AMC-III is given in

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* In previous reports, for example, Schulze and Arnold (1979) or Schulze (1982), this procedure was termed the "standard" SCS procedure. It is no longer recommended for general use by the SCS (Hawkins, 1986).

Table 1.7.1 Antecedent rainfall limits for classifying antecedent moisture conditions

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

Table 1.7.2. Sobhani (1976) derived the following algebraic expressions to adjust CN from the average to wet (CN-III) and dry (CN-I) conditions which may be used for computer analysis :

CN-I = CN-II/(2.334 - 0.01334 CN-II) ... Eq. 11

CN-III = CN-II/(0.4036 + 0.0059 CN-II) ... Eq. 12

The adjusted CN is the final value which is entered into Equation 5 to solve for S, which is then used in the runoff depth estimation (Equation 4).

1.7.2 Hawkins' procedure of CN adjustment for AMC

In determining catchment moisture status by the originally proposed SCS procedure some scale and conceptual difficulties arise (Hawkins, 1978). Firstly, in assigning the AMC, evapotranspiration is considered only in very gross terms, (i.e. the "dormant" and "growing" season), while depletion of catchment storages due to drainage is omitted. Secondly, the relationship between catchment moisture status and Curve Numbers is shown to be discrete and not continuous, implying sudden shifts in Curve Numbers, with corresponding "quantum jumps" possible in calculated stormflow (Hawkins, 1978). Thirdly, the consideration of antecedent rainfall over five days may be too short a period, ideal or too long a period (Hawkins, 1961) depending, inter alia, on topography, soil characteristics, vegetation or climate. In addition the net amount of rainfall (rainfall minus runoff and

Table 1.7.2 Adjusted runoff Curve Numbers for AMC-I and AMC-III

CN for condition II	CN for AMC I	CN for AMC III
100	100	100
98	94	99
96	89	99
94	85	98
92	81	97
90	78	96
88	75	95
86	72	94
84	68	93
82	66	92
80	63	91
78	60	90
76	58	89
74	55	88
72	53	86
70	51	85
68	48	84
66	46	82
64	44	81
62	42	79
60	40	78
58	38	76
56	36	75
54	34	73
52	32	71
50	31	70
48	29	68
46	27	66
44	25	64
42	24	62
40	22	60
38	21	58
36	19	56
34	18	54
32	16	52
30	15	50
25	12	43
20	9	37
15	6	30
10	4	22
5	2	13
0	0	0

interception) entering the soil is not considered. An early edition of the National Engineering Handbook (NEH-4, 1959) states that "experience and some soil studies have indicated that a 5-day period is a minimum for estimating antecedent conditions. Longer periods such as two weeks are sometimes desirable but the additional work does not always produce additional accuracy in the runoff estimates". The computerised extraction of antecedent rainfall data nowadays of course nullifies the argument of "additional work" which was relevant 20 years ago. In a personal communication Miller (1979) concedes that the SCS did not base their choice of five days on "physical reality" but rather on "subjective judgement".

Numerous researchers (Hawkins, 1961 ; Dickey, Mitchell and Scarborough, 1979) have found other antecedent periods to give improved estimates of stormflow. Hope and Schulze (1982), for example, used a 15-day antecedent period in an application of the SCS procedure in the humid east of South Africa while Schulze (1982) found a 30-day antecedent period to yield better simulations of stormflow in humid areas of the USA but a 5-day period to be applicable to catchments in arid zones.

Having recognised the weaknesses of the antecedent moisture component of the SCS model, Hawkins (1978) developed an alternative method which included stormflow, drainage, evapotranspiration and antecedent rainfall and expressed the relationship between Curve Numbers and antecedent moisture condition as a continuum rather than discrete steps. This method was based on the following principle:

$$V_2 = V_1 + AE + D - P + Q$$

where

V_1 = storage available at time 1

V_2 = storage available at time 2

AE = evapotranspiration losses

D = interim drainage

P = interim rainfall

Q = interim stormflow.

This principle was incorporated into the equation to calculate Curve Number for "average" antecedent moisture condition from the potential storage of the soil (Equation 5), from which Hawkins then derived an equation, given below in generalised and metricated form :

$$CN_f = \frac{(1 + c) \times 1\ 000}{\frac{(1 + c) \times 1\ 000}{CN} - \frac{(P - Q - D - AE)}{25.4}} \quad \text{... Eq. 13}$$

where

CN_f = final Curve Number calculated for the catchment moisture status

CN = Curve Number for the hydrological soil-cover complex of the catchment (assuming AMC-II)

c = coefficient of initial abstraction

P = antecedent rainfall (mm)

Q = antecedent runoff (mm)

D = antecedent drainage (mm)

AE = antecedent actual evapotranspiration (mm).

The terms AE, P ,D and Q are the interim or antecedent values that act on an initial condition of a given CN, to effect change to CN_f. Application of the Hawkins approach to catchment data has shown this method to yield significantly improved estimates of stormflow volumes when compared with estimates using the original SCS procedures (Schulze, 1982; Hope, 1984) and it is suggested that the Hawkins method be used in estimations of CN in preference to the original procedure.

The application of the Hawkins procedure requires the estimation of antecedent rainfall, actual evapotranspiration, runoff and drainage for the selected period. For a specific event, daily rainfall records can be used to establish antecedent rainfall characteristics. Interim runoff and drainage (often assumed equal to 0) can also be estimated on consideration of land use and soil characteristics, while estimates of actual evapotranspiration can be made by accounting for vegetation characteristics and potential evaporation rates (from evaporation pans or temperature-based estimates of potential evaporation).

For design analysis a regional index of antecedent soil moisture storage change (P-Q-D-AE), which is dependent upon climatic regime as well as soil and land use characteristics, is required for events of "design" magnitude. The following section outlines the determination of such indices for homogeneous climatic response zones in southern Africa.

1.7.3 Regional indices of antecedent soil moisture storage change for design storms in southern Africa

The analysis required the delimitation of southern Africa into regions of homogeneous potential moisture recharge (rainfall) and atmospheric demand (potential evaporation). This was accomplished in conjunction with another project on regional soil moisture deficits funded by the Water Research Commission (Dent, Schulze and Angus, 1988).

A classified digital image of altitudes covering southern Africa at a resolution of 1 minute x 1 minute of a degree was used as a basis for the delimitation. The locations of all rainfall stations with record length of 10 years or longer were superimposed on the above-mentioned image map, together with the record length and mean annual precipitation (MAP) of each station. On consideration of altitude and MAP the boundaries of 712 (Figure 3.9) regions were delimited around "key" long-term rainfall stations of, where possible, record lengths exceeding 30 years' daily rainfall data. Since altitude has a major influence on the distribution of both rainfall and temperature (and hence potential evaporation), it was assumed that within a reasonably small geographic (equi-altitudinal) area, weather systems would likely be relatively homogeneous with respect to long-term patterns of daily rainfall amount and temperature distributions. For each region, a key temperature station was chosen on the basis of record length and altitudinal representativeness. Table 3.3 lists the rainfall stations used for each region. Mean monthly maximum and minimum temperature data for the chosen station was used together with the Linacre equation for the estimation of mean monthly potential evaporation, PE (Linacre, 1977). The Linacre equation has been shown by Schulze (1983) to yield markedly more reliable estimates of A-pan values in all months of the year when compared with other temperature-based equations commonly in use. A Cubic Spline curve fitting technique was used to derive daily totals of potential evaporation, which together with the continuous daily rainfall record, formed the daily climatic data base for each region. The rainfall data were "patched" on days of missing data using the synthetic rainfall generation procedures of Zucchini and Adamson (1984) to provide unbroken series of daily rainfall record.

To provide information on typical antecedent storage change prior to "design" events for each region, two approaches were adopted.

Approach 1. At each of the 712 stations the daily rainfall records were analysed and the 5-day and 30-day antecedent rainfall totals prior to each of the five highest daily rainfall totals in each Julian year were stored. A frequency analysis of the antecedent totals was then undertaken, providing information on the percentage of the time the antecedent totals exceeded a certain depth. The use of this information, together with the Hawkins CN adjustment equation (Equation 13), requires the designer to determine the expected depths of runoff, drainage and evapotranspiration according to prevailing soil and land use conditions in order to derive the net gain or loss of moisture to the soil during the antecedent period. Hope (1984) stressed the importance of both accurate estimates of the initial Curve Number (for average moisture conditions) and the need for accurate estimates of antecedent actual evapotranspiration and runoff when using the Hawkins Curve Number adjustment procedure. Such estimates can best be made by using a moisture budget model, accounting for daily rainfall conditions and evaporative demand and soil and land use characteristics to simulate the moisture changes in the soil profile. This formed the basis of the second approach.

Approach 2. The daily rainfall records were analysed and the daily rainfall totals and temperature-based estimates of PE for 30 days prior to each of the five highest daily rainfall totals in each year were stored. A water budget model (ACRU model) was then used to account for actual evapotranspiration, runoff and drainage prior to each event under a range of land use and soil characteristics. The ACRU model was run iteratively for each land use/soil combination for each year of record for each of the 712 regions and a frequency analysis of antecedent storage change was undertaken. This provided a direct estimate of antecedent storage change for use in the Hawkins equation for each region and land use/soil class.

1.7.4 Moisture budget simulation of AMC with the ACRU model

The ACRU model is a conceptual/physical water budget model which has been verified under highly varying hydrological regimes on gauged catchments in southern African and USA (Schulze, 1984, 1986; Dunsmore, Schulze and Schmidt, 1986; Schulze and George, 1986). The concept and structure of the model have been detailed elsewhere (Schulze, 1984; Schulze, 1986). The model was designed as a daily, two-soil layer moisture budgeting model which has been structured to be sensitive to land use changes on soil moisture, runoff regimes and actual evapotranspiration rates. The model simulates the soil moisture status given observed daily rainfall records, observed or estimated daily potential evaporation rates and variables describing the effect of the soil and vegetation characteristics on the movement of moisture in the soil profile. Assuming an initial soil moisture content of 50% plant available moisture (PAM) the model was used to estimate the change in soil moisture storage between initial conditions commencing 30 days before a selected event and the simulated actual moisture status just prior to the storm for a range of soil/vegetation categories. An initial moisture content equal to 50% PAM was used to comply with the assumptions adopted in the SCS model, namely that the initial unadjusted Curve Number was representative of "average" moisture conditions. A further assumption that "wet" soil conditions approximate field capacity, "dry" soil conditions approximate permanent wilting point and "average" moisture conditions 50% PAM had been used successfully previously in the USA by Schulze (1982). The moisture budget was run for a 30-day period since computer simulations using the ACRU model on gauged catchments indicated the model to provide better estimates of soil moisture status and runoff response for an assumed initial moisture status of 50% PAM when using a 30-day period as against a shorter time period. A frequency analysis was performed on the estimates of moisture storage change for each of 27 land use/soil combinations to provide a direct estimate of soil moisture variation for each region which could be used directly in the Hawkins (1978) equations for Curve Number adjustment.

Three soil depth categories, three texture classes and three vegetation classes were used in the analysis giving the total of 27 land use/soil combinations. The main characteristics defining each category are given in Table 1.7.3.

While the categories were chosen to cover a wide range of hydrological response regimes, they had to be limited in number in order to restrict the number of computer runs. An appropriate soil depth category for a specific design situation may be chosen on the basis of the horizon depths given in Table 1.7.3. Soil texture classes were selected to represent a range of moisture retention constants which affect the quickflow response and drainage characteristics of a soil. Moisture retention constants for each texture class were determined from the literature (Rawls, Brakensiek and Saxton, 1982). Coarse textured soils (sand) exhibit a low PAM (field capacity minus permanent wilting point) and high total moisture retention (porosity minus permanent wilting point). As a result, quickflow response is generally low, as is actual evapotranspiration when compared with fine textured soils which have a high PAM and low total moisture retention, with corresponding quickflow responses and accumulated actual evapotranspiration therefore high. Quickflow response will vary depending, inter alia, upon the critical depth of the soil which produces the quickflow. For the analysis this depth was

Table 1.7.3 Soil and vegetation characteristics used in moisture budget analysis

Category	Soil Depth Depth A-horizon (m)	Depth B-horizon (m)
Deep	0.30	0.80
Intermediate	0.25	0.50
Shallow	0.15	0.15

Category	Soil Texture Moisture retention ($mm.m^{-1}$) Porosity	Field capacity	Permanent wilting point
Coarse (Sand)	430	112	50
Medium (Loam)	464	251	128
Fine (Clay)	482	416	298

Category	Vegetation % Roots in A-horizon	Interception loss (mm)	Cropping coefficient
Dense	0.60	3.00	1.00
Intermediate	0.80	1.75	0.75
Sparse	1.00	0.50	0.50

assumed to be equal to the depth of the A-horizon. Under natural conditions experience with the ACRU model points to this depth likely to increase in humid regions and decrease in arid regions (Dunsmore et al., 1986). Drainage between the soil horizons and to groundwater are also important in terms of the moisture balance. Drainage of soils wetter than field capacity is related to soil texture (Rawls et al., 1982) and sands have high drainage rates with clays low drainage rates. Dense land use cover (forest, full canopy crop) has high interception losses. In addition, actual evapotranspiration rates approach potential evaporation rate (cropping coefficient = 1.00) when the plant is not under stress (i.e. when soil moisture is not depleted below a critical value, taken in this study to be 0.5 PAM).

1.7.5 Summary of procedure of analysis

The procedure of analysis conducted for each of the 712 regions to determine a design antecedent moisture status can thus be summarised as follows:

a) The file of daily rainfall data (previously infilled where missing data occurred) is read in for each region.
b) The file of average maximum and minimum daily temperature for each month is read in.
c) The file of daily estimates of potential evaporation generated using the Linacre (1977) equation and Cubic Spline curve fitting techniques is created.
d) The 5 highest daily rainfall events are selected for each year.
e) Accumulated 5-day and 30-day rainfall totals are stored for each event selected.
f) Frequency analysis for the accumulated 5-day and 30-day rainfall totals is undertaken.
g) For each of the 27 land use/soil categories, moisture budgets are computed for each event selected for a 30-day antecedent period and the accumulated 30-day antecedent storage change is stored.
h) Frequency analyses are undertaken for the 30-day storage change totals of each land use/soil category.

The results of the frequency analyses for points (f) and (h) above, are presented for each region in Appendices 1 and 2 respectively. Adjustments to the Curve Number for "average" moisture condition, CN-II (Table 3.2), may thus be made in one of the following two ways :

Use of antecedent rainfall data

a) Select CN-II from Table 3.2.
b) Determine antecedent rainfall depth (P), for the relevant region, antecedent period and risk (Appendix 1).
c) Estimate likely antecedent runoff (Q), drainage (D) and actual evapotranspiration (AE) for the chosen period from field experience and local conditions.

d) Calculate adjusted Curve Number for prevailing moisture conditions using Hawkins' equation for Curve Number adjustment (Equation 13).

Use of antecedent storage change data (30-day period)

a) Select CN-II from Table 3.2.
b) For the relevant region (Figure 3.9) and land use/soil combinations (Table 1.7.3) determine antecedent storage change (P-Q-D-AE) for chosen risk using the information contained in Appendix 2.
c) Calculate adjusted Curve Numbers according to antecedent storage change using Equation 13.

A nomograph for the solution of the Hawkins (1978) equation and the calculation of runoff depth for a given daily rainfall depth is given in Figure 3.3. The nomograph assumes the coefficient of initial abstraction (c) to be 0.10. For an initial Curve Number determined from Table 3.2, and an estimate of antecedent storage change (Appendix 2), the adjusted CN for antecedent moisture conditions (Equation 13) may be determined from the first quadrant of the nomograph. Alternatively the runoff response depth (mm) may be determined directly given the one-day rainfall depth (mm) obtained from Figure 3.1. The nomograph has been drawn to allow CN adjustment within the range limited by Equations 11 and 12. Examples of the use of Hawkins' procedure are given in PART 2 of this document.

The antecedent rainfall data given in Appendix 1 can be used in applications other than the SCS model. The data provides valuable information for adjusting infiltration characteristics used in the Time Area procedure (Watson, 1981). Lambourne and Stephenson (1986a) have used a similar approach to determine AMC classes but for only 31 selected rainfall stations in southern Africa. The antecedent storage change data presented in Appendix 2 can be presented in a similar form to the output from the WAMM model (Lambourne and Stephenson, 1986a) for use in the WITWAT model (Green, 1984). Lambourne and Stephenson (1986a) present probabilities for various antecedent moisture classes where antecedent moisture is a percentage of the soil porosity. Appendix 2 presents storage change from 50% plant available moisture. Using the moisture retention constants presented in Table 1.7.3, typical actual storage amount and hence percentage of porosity can thus be derived for 712 regions in Southern Africa. Soil moisture as a percentage of PAM may be determined directly from the antecedent storage change indices for the various soil texture and depth classes using Figure 1.7.1.

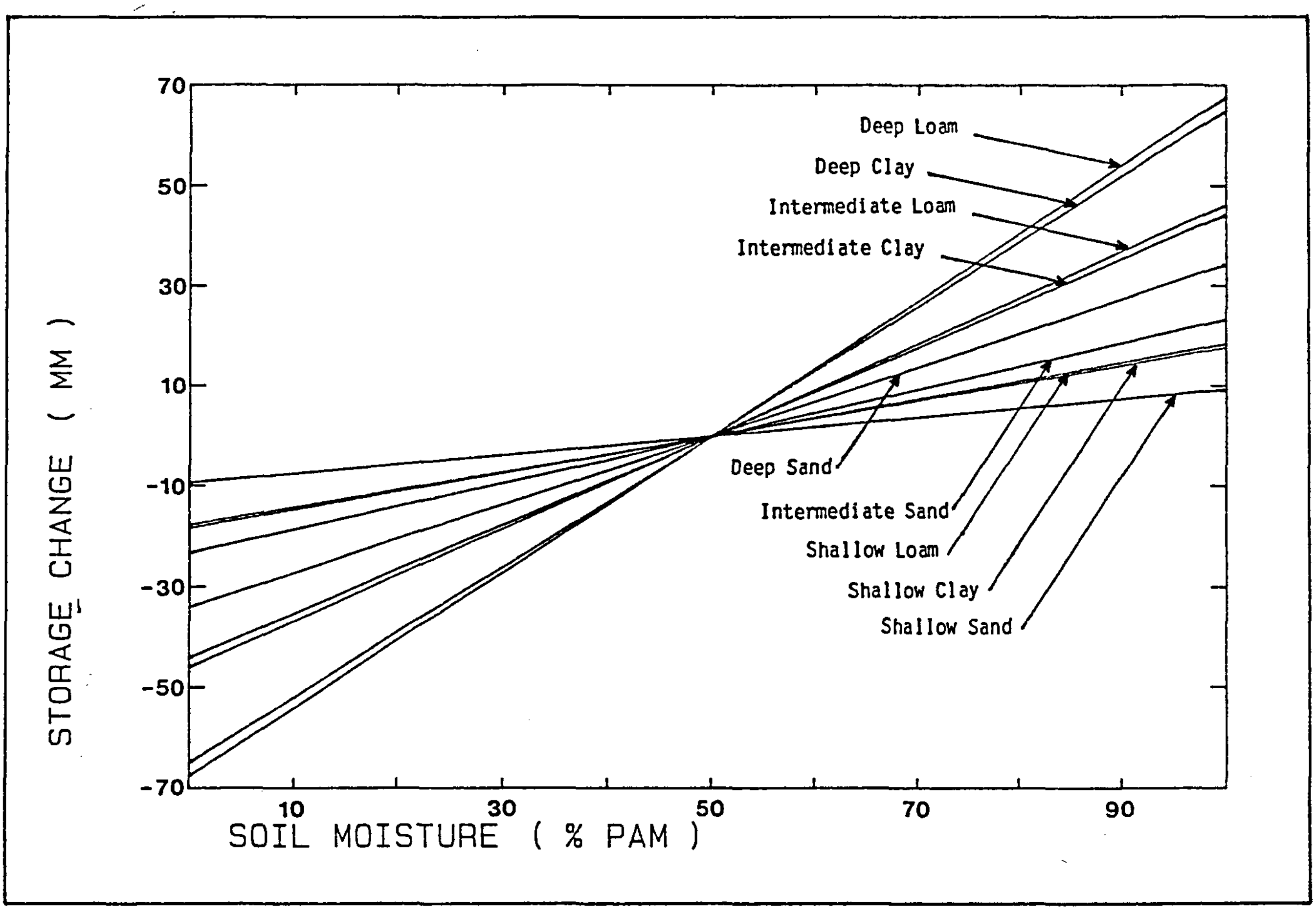


Figure 1.7.1 Relationship between storage change from 50% PAM and soil moisture as a percentage of PAM

1.8 RUNOFF ESTIMATION BY JOINT ASSOCIATION OF RAINFALL AND ANTECEDENT SOIL MOISTURE

Section 1.7 addressed methods of computing regional variation in antecedent soil moisture for combinations of soil and land use classes. Adjustments to a Curve Number representing "average" antecedent moisture conditions were given for the chosen soil and land use conditions, thereby accounting for inter-regional moisture regimes. Over and above such regional differences, the variation of the antecedent moisture status between storms falling on a catchment is also of importance. Generally methods currently used in southern Africa for estimating design runoff apply a design rainfall amount for a given recurrence interval to a catchment, assuming average antecedent moisture conditions for the catchment, to estimate design runoff for the same recurrence interval. While regional differences in what may be termed "average" conditions have been given in Section 1.7 and in Appendix 2, joint association between rainfall amount and antecedent soil moisture conditions for a particular location needs to be addressed in order to account for the possibility of say the third or fourth highest event of a year producing the biggest flood owing to moist antecedent conditions of the soil.

1.8.1 Motivation for analysis

Extensive research has been conducted to investigate the relationships between the frequency of occurrence of a flood and its causative rainfall and the role antecedent wetness plays in determining this relationship. Hiemstra and Reich (1967) found that no apparent relationship existed between the return periods of the rainfall and runoff of corresponding events. Reich (1970) suggested, however, that the effects of antecedent soil moisture could reveal some relationship between extreme value statistics of rainfall and runoff. In accounting for the variability between storms on a catchment of the dimensionless runoff coefficient used in the Rational formula (c), Schaake, Geyer and Knapp (1967) suggested that antecedent wetness be used to account for changes in c. Larson and Reich (1973), using runoff and rainfall records from 20 small catchments, indicated by means of a rank correlation diagram that there was a wide variation between the ranks of corresponding rainfall and runoff events but suggested that it was appropriate to assume that on average the design storm would produce a design flood of equal return period. Cordery (1970) claimed that factors such as initial loss and continuing loss, both a function of soil wetness, would introduce joint probabilities which might cause the return period of the design flood to be different from that of the design storm. Hughes (1977) suggested that the probabilities of occurrence of a given runoff volume due to a specific rainfall volume would be proportional to the joint probabilities of the rainfall amount and loss rate, which is dependent upon antecedent moisture condition. Hughes (1985) used a bivariate normal distribution to describe joint probabilities of rainfall depth and antecedent soil moisture, but noted the difficulties in incorporating such associations realistically under practical design situations. Packman and Kidd (1980) and Beaudoin, Rouselle and Marchi (1983) noted that antecedent soil moisture was a major factor affecting the relationship between the return periods of rainfall and corresponding runoff. Packman and Kidd (1980) indicated that the higher the mean annual precipitation the higher the design value of antecedent wetness. The work of Cordery (1970) and Diaz-Granados, Valdes and Bras (1984) also indicated that the role of antecedent soil moisture will vary with climate. Lambourne and Stephenson (1986b), recognising the role catchment wetness played in runoff generation, presented a computer technique to generate flood frequency curves accounting for both the deterministic runoff processes and the stochastic relationship between rainfall magnitude and catchment wetness.

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. Dunsmore et al. (1986) illustrated that the significance of the role of antecedent soil moisture in daily runoff response varied between humid and arid catchments and with the size of the rainfall event. It was found in the study that extreme runoff series fitted to simulated annual maximum daily runoff depth, obtained using the ACRU model which utilises moisture budgeting procedures to account for catchment wetness, provided close agreement with observed annual maximum daily runoff series. The simulated series yielded more accurate estimates of design runoff depth than the conventional SCS-based method with an assumed average antecedent moisture status. Schmidt, Schulze and Dunsmore (1985) had previously shown that conceptual moisture budgeting techniques provided more realistic estimates of design peak discharge than those obtained using conventional SCS techniques. It was therefore surmised that simulations using a suitable moisture budget model for a large number of daily rainfall stations to identify regional relationships between moisture status and design rainfall depth would lead to improved estimates of design flood depth and peak discharge.

Procedures to account for the joint association of design rainfall and antecedent wetness may be applied in combination with the SCS model by making use of the Hawkins Curve Number adjustment technique and the ACRU moisture budget model as discussed in Section 1.7. The use of the daily rainfall and temperature data base for the 712 regions of similar potential moisture recharge would allow for account to be taken of both inter and intra-regional variation in moisture status in design runoff simulation.

1.8.2 Design runoff by joint association of rainfall and antecedent conditions for Southern Africa

The daily data base for the 712 regions used in this study has been discussed in Section 1.7.3. The long-duration daily rainfall records were analysed and daily rainfall totals and temperature-based estimates of PE for 30 days prior to each of the five highest independent daily rainfall totals (i.e. rainfall not on successive days) in each year were stored. The water budget model (ACRU) was used to simulate antecedent actual evapotranspiration, runoff and drainage for the 27 land use/soil combinations discussed in Section 1.7.3. The computed storage change prior to each event for the 27 land use/soil classes was used together with Equation 13 to adjust the curve number for average antecedent moisture conditions according to the moisture status prior to the event. The adjustment to CN was made for a range of CNs (50, 60, 70, 80, 90) within the limits set by Equations 11 and 12. Daily runoff depth was computed for each of the adjusted curve numbers as determined from the initial CN for average antecedent moisture conditions and the land use/soil class. The annual maximum series of simulated one-day runoff depth was determined for each category of initial CN and land use/soil class. The log-Normal and log-Pearson Type 3 extreme value distributions were fitted to this annual maximum series and a frequency analysis of the series was also undertaken. The procedure of analysis conducted for each of the the 712 regions can thus be summarised as follows :

a) The file of daily rainfall data (previously infilled where missing data occurred) is read in for each region.
b) The file of average maximum and minimum daily temperature for each month is read in.
c) The file of daily estimates of potential evaporation is generated using Linacre (1977) equation and Cubic Spline curve fitting technique.
d) The five highest independent daily rainfall totals are selected for each year.
e) For the 27 land use/soil categories, moisture budget computations are performed for each event selected, using a 30-day antecedent period.
f) Revised Curve Numbers are computed according to the 30-day change in moisture storage for a range of initial "average" Curve Numbers.
g) One-day runoff depths for each event and each revised respective Curve Number are computed.
h) Frequency analysis is undertaken and extreme value distributions are fitted to the annual maximum series of simulated one-day runoff depths for each category of initial Curve Number and land use/soil class.

The above procedure has the advantage over that discussed in Section 1.7.3 in that not only the "typical" soil moisture status of a region is accounted for, but also the joint association of daily rainfall total and antecedent conditions prior to the day in question is considered in determining design runoff. The results of the analysis for each region are given in Appendix 3.

It was decided that the 50, 80, 90 and 95 percentile non-exceedence values of daily runoff depth determined from the frequency analysis be presented instead of daily runoff depths for various return periods as determined from the extreme value analysis. The reason for this was the inability for any one distribution to represent adequately all data sets. Furthermore, the simulated annual maximum values of daily runoff depth frequently had years with zero runoff, especially when a low runoff response category was used in the arid regions. This introduced large discrepancies between the plotted points of the annual maximum series and the analytical extreme value distributions. Furthermore, atypical outliers distort magnitudes of expected maximum values for return periods approaching and exceeding record length.

The results presented thus give, for example, the 90 percentile non-exceedence daily runoff depth, which is the runoff depth which was exceeded in 10% of the years. This approximates the 10-year return period. Similarly, the 95 percentile approximates the 20 year return period, the 80 percentile the 5-year return period and the 50 percentile the 2-year return period. Since the data generally had a long record length, the procedure adopted is a reasonable one for lower return period floods and thus the frequency analysis has only been extended to the 95 percentile. The percentile values do exhibit interpolative limitations and extrapolation is not recommended. However, an estimate for other frequencies of occurrence can be obtained, if necessary, by drawing a smooth curve through the data on probability paper and using the curve to define magnitudes of floods with various risks.

It should be noted that the runoff depths given in Appendix 3 are determined using the daily rainfall data file representing each zone. While the rainfall files generally had long record lengths (Table 3.3), and should thus be representative of prevailing conditions, the results in Appendix 3 do not always compare well with those obtained using the methods of Section 1.7.5. This is due, in part, to the different approach adopted (i.e. joint consideration of rainfall and soil moisture versus the use of a regional "average" soil moisture index) and to the fact that in Section 1.7.5 use is made of the "extreme" one-day rainfalls of Figure 3.1 which may not be fully represented by the daily data base used in this study. A frequency analysis of the annual maximum daily rainfall totals for each region is given in Appendix 4, which can be used to compare low risk rainfall depths with those obtained from Figure 3.1.

Examples illustrating the use of Appendix 3 are given in PART 2 of this document.

1.9 DESIGN CONSIDERATIONS

Two design procedures accounting for antecedent moisture status have been outlined in the preceding sections. In Section 1.7 the design daily rainfall depth (Figure 3.1) of chosen recurrence interval was used together with an index of antecedent storage change for a range of frequencies of non-occurrence (viz. 20%, 50% and 80%), given in Appendix 2 for a particular climate zone and land use/soil condition, to determine design runoff depth of equal recurrence interval. A nomograph (Figure 3.3) was provided to determine the runoff depth from the unadjusted Curve Number (Table 3.2), the antecedent storage change (Appendix 2) and design rainfall depth (Figure 3.1). The choice of which percentile antecedent storage change to use (Appendix 2) is left largely to the engineer or hydrologist. The use of a "wetter" index (i.e. 80 percentile) would result in a more conservative design than that for the median condition (50 percentile).

Section 1.8 embodies a more realistic approach whereby the choice of antecedent moisture probability associated with the chosen rainfall recurrence interval need not be made. The results of Section 1.8 (Appendix 3) account for the joint association of rainfall depth and catchment wetness for individual events to provide estimates of runoff depth for a range of frequencies of non-exceedence. The following points should, however, be considered when using the results given in Appendix 3 :

a) The results of Appendix 3 are based upon the daily rainfall records for each rainfall station used in the study. A frequency analysis of the annual maximum daily series is given for each rainfall station in Appendix 4. These values can be compared with the expected maximum daily rainfall totals for various return periods given in Figure 3.1, which were obtained from the truncated log-normal probability distribution as used by Adamson (1981). The results are generally similar for low return periods (2 or 5 years) but may differ markedly for return periods of 10 years or longer.

b) The runoff depths presented in Appendix 3 are derived from a frequency analysis of the annual maximum daily runoff depths generated for a particular CN and soil/land use condition. Results from mathematically fitted extreme value distributions are not presented due to the lack of a consistently good representation of all the data by any one distribution. The results of the frequency analysis are only presented to the 95 percentile since only a few points would be used to define runoff magnitude for higher percentile values. This limits the return period for which runoff depth may be estimated using Appendix 3 to the 20-year return period.

c) Since a mathematical distribution has not been fitted to the annual maximum runoff series, return period magnitudes *per se* should be deduced from Appendix 3, as interpolation between the percentile values is sometimes difficult and extrapolation is not recommended.

Owing to the above considerations it is recommended that the results in Appendix 3 be used only for the lower return periods and that the methods of Section 1.7 generally be used for the design of hydraulic structures where recurrence intervals in excess of 20 years are required. The choice as to whether the 20, 50 or 80 percentile antecedent storage change be used (Appendix 2) is dependent, in part, upon the joint association of rainfall magnitude and moisture status. In a region where large rainfall events frequently follow conditions wetter than those typically prevailing, the 80 percentile antecedent storage change would be more appropriate to use than the median condition. The results of Appendix 3 can give guidance in this regard and for important designs it is recommended that the procedure which follows be given consideration.

The rainfall depth for various frequencies of occurrence (Appendix 4) should be used together with the antecedent storage change data given for the 20, 50 and 80 percentile levels in Appendix 2 to determine design runoff depth for each combination of rainfall frequency and antecedent storage change. These results should be compared with those obtained using the methods of Section 1.8 given in Appendix 4, to determine the antecedent storage percentile giving runoff estimates in closest agreement with the results for low return periods in Appendix 4. An example illustrating this approach is given below :

EXAMPLE

Latitude 29°29' S — Longitude 30°34' E
Zone 403 (Figure 3.9)
Rainfall station 270119 (Table 3.3)
CN-II = 70
Deep soil, loam texture, sparse cover

Frequency of non-occurrence of annual maximum, daily rainfall (mm) (Appendix 4)

Percentile			
50 %	80 %	90 %	95 %
60 mm	83 mm	92 mm	107 mm

Antecedent storage change (mm) (Appendix 2)

Percentile		
20 %	50 %	80 %
0.1 mm	27.9 mm	60.1 mm

Runoff depth (mm) (Figure 3.3)
(or Equations 4, 11, 12 and 13)

Percentile of antecedent storage change	Percentile of annual maximum rainfall 50 %	80 %	90 %	95 %
20%	15.3	28.7	34.6	45.1

50%	19.7	35.2	41.8	53.4
80%	27.4	45.6	53.2	66.2

Runoff depth by method of joint association (mm) (Appendix 3)

Percentile			
50 %	80 %	90 %	95 %
26.0 mm	39.3 mm	50.7 mm	70.0 mm

From the above it is evident that the use of the 50 percentile antecedent storage change underestimates design runoff at this location and for the assumed land use/soil combination (e.g. 19.7 vs 26.0 mm). The 80 percentile antecedent storage change (representing wetter conditions) should preferably be used to reflect the incidence of large rainfall totals in conjunction with conditions wetter than the median condition (e.g. 27.4 vs 26.0 mm). On the other hand, a similar excercise for zone 371 under the same soil/land use conditions would indicate that the 50 percentile antecedent storage change provides close estimates of the runoff depths in Appendix 3 for the lower return periods and should thus be used in design.

The storage change value given in Appendix 2 and runoff depth value given in Appendix 3 reflect the moisture movement in a soil profile which does not have drainage or surface runoff restrictions other than those imposed by the textural and depth characteristics of the soil. Three typical examples where this is not the case are given below :

a) Sands which inherently have high drainage rate properties but overlie an impermeable clay pan or unconsolidated rock will typically have a higher moisture status and hence runoff potential than given in Appendices 2 and 3.
b) Similarly, clay soils typically have poor drainage and high quickflow response characteristics. Clay soils located in bottomland regions, where topographical position results in frequently saturated conditions are

likely to exhibit a higher moisture status and storm runoff response than would otherwise be expected.

c) The effects of surface crusting should also be considered in this regard. Soils which are characterised by surface crusting produce a high overland flow response. Runoff response for such soils is influenced less by moisture status than would otherwise normally be the case. Soil subject to surface crusting will generally be assigned a high runoff Curve Number which, as indicated in Figure 3.3, limits the range in Curve Number change that can be attributed to soil moisture variation.

The designer should thus give consideration to local conditions and make adjustments to the expected antecedent storage change accordingly. For saturated conditions or small impervious areas an adjusted CN approaching 100 should be used. The heterogeneous nature of many catchments and the relatively large runoff contribution from small areas within such catchments (for example, from saturated areas around the river channel, as found commonly in the moist regions of the country) make it important to compute runoff contributions separately for subareas of heterogeneous catchments and to summate them to determine a catchment total.

1.10 THE SCS PEAK DISCHARGE EQUATION

In the SCS technique calculation of peak discharge is based on a standard unit hydrograph, which is considered to be an average characteristic of a small catchment and is assumed invariable, given a certain pattern of rainfall. The peak discharge of the unit hydrograph is proportional to the runoff depth.

The SCS model uses a dimensionless unit hydrograph developed from a large number of natural unit hydrographs. This standard unit hydrograph, which has 37.5% of the total runoff volume under the rising limb, can be approximated by a triangle to give a triangular unit hydrograph, provided the same proportion of the total volume is under the rising limb (Figure 1.10.1)

The triangular unit hydrograph is a practical presentation of a single peaked stormflow with only one rise, one peak and one recession. It is a very useful concept in the design of soil and water conservation measures and discharge rate estimations for spillway and channel capacities. Its geometric shape, which can be easily described mathematically, is shown in Figure 1.10.2.

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

$$T_p/T_b = 0.375 \qquad \text{... Eq. 14}$$

Also,

$$T_b = T_p + T_r \qquad \text{... Eq. 15}$$

where

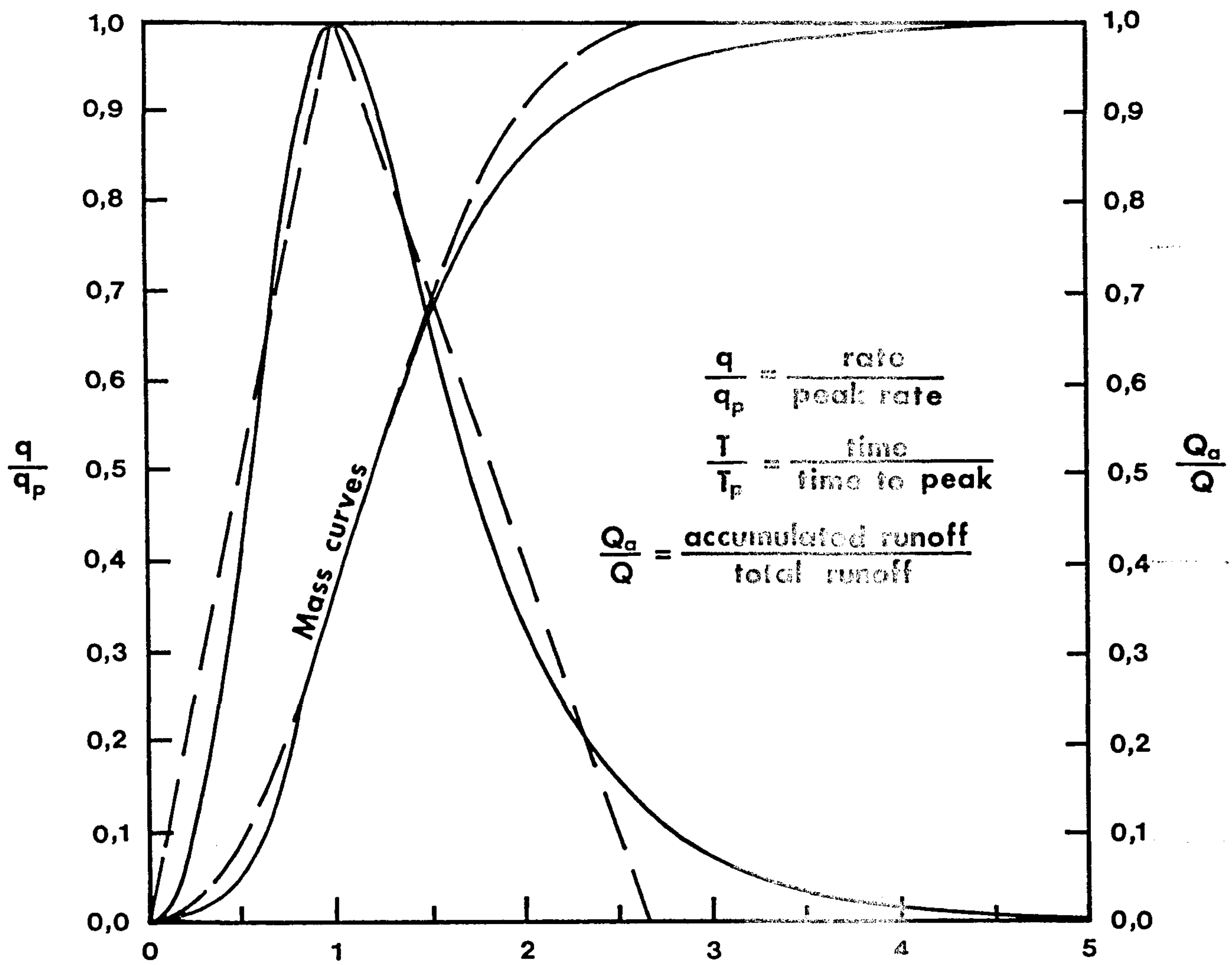


Figure 1.10.1 Dimensionless unit hydrograph and mass curve (Schulze and Arnold, 1979)

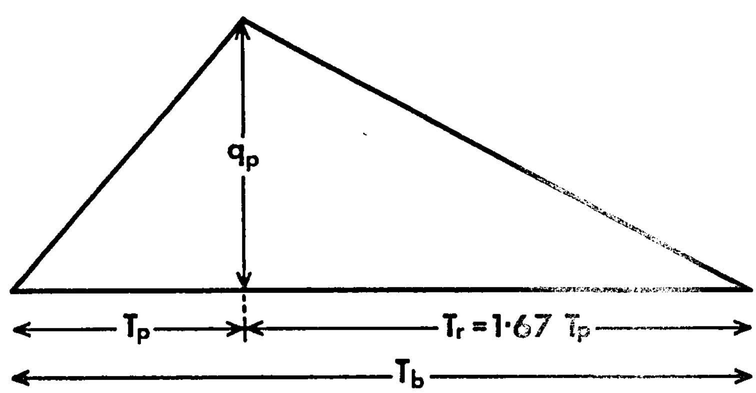


Figure 1.10.2 Geometric shape of the triangular unit hydrograph (Schulze and Arnold, 1979)

T_b = time of base of triangular hydrograph
T_p = time to peak
T_r = time of recession.

Combining Equations 14 and 15 gives

$$T_r = 1.67 \; T_p \qquad \text{... Eq. 16}$$

or

$$T_p/T_r = 3/5 \qquad \text{... Eq. 17}$$

From Figure 1.10.2, the total volume under the triangular unit hydrograph is given by

$$Q = 1/2 \; q_p \; (T_p + T_r) \qquad \text{... Eq. 18}$$

where

Q = runoff volume (mm)
q_p = peak discharge ($mm.h^{-1}$)
T_p = time to peak (h)
T_r = time of recession (h).

Solving Equation 18 for q_p yields

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

Since from Equation 16 $T_r = 1.67 \; T_p$

$$q_p = \frac{2Q}{(1 + 1.67) \; T_p}$$

i.e. $$q_p = \frac{0.75 \; Q}{T_p} \quad (mm.h^{-1})$$

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

$$q_p = \frac{0.75\ AQ}{T_p} \qquad (mm.km^2.h^{-1})$$

$$q_p = \frac{0.75x10^{-3}x10^6\ A\ Q}{3\ 600\ T_p} \qquad (m.m^2.s^{-1})$$

$$q_p = \frac{0.2083\ A\ Q}{T_p} \qquad (m^3.s^{-1}) \qquad \text{... Eq. 19}$$

According to SCS conventions the time to peak, T_p, as illustrated in Figure 1.12.2, is given by Equation 20 below.

$$T_p = D/2 + L \qquad \text{... Eq. 20}$$

where

D = effective storm duration in hours

L = catchment lag in hours (Section 1.12).

Therefore the equation for the estimation of peak flow becomes

$$q_p = \frac{0.2083\ A\ Q}{D/2 + L} \qquad (m^3.s^{-1}) \qquad \text{... Eq. 21}$$

Equation 21 assumes storms with a uniform rainfall distribution. Total storm rainfall, however, rarely (if ever) occurs uniformly with respect to time. In order to estimate the peak rate of runoff it is therefore necessary to divide the storm into increments of shorter duration and compute the corresponding increments of runoff. The peak discharge equation for an increment of runoff is

$$\Delta q_p = 0.2083\ \frac{A\ \Delta Q}{T_p} = 0.2083\ \frac{A\ \Delta Q}{\Delta D/2 + L} \qquad \text{... Eq. 22}$$

where

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

Δ Q = increment of runoff (mm)

Δ D = incremental duration of effective rainfall (h).

Figure 1.10.3 illustrates how the ordinates of the individual incremental triangular hydrographs are added to produce the composite hydrograph, using the principle of superpositioning. Thus the discharge rate may be computed at any time during the storm. Note how each incremental hydrograph is displaced one incremental duration, ΔD, to the right for each successive time increment.

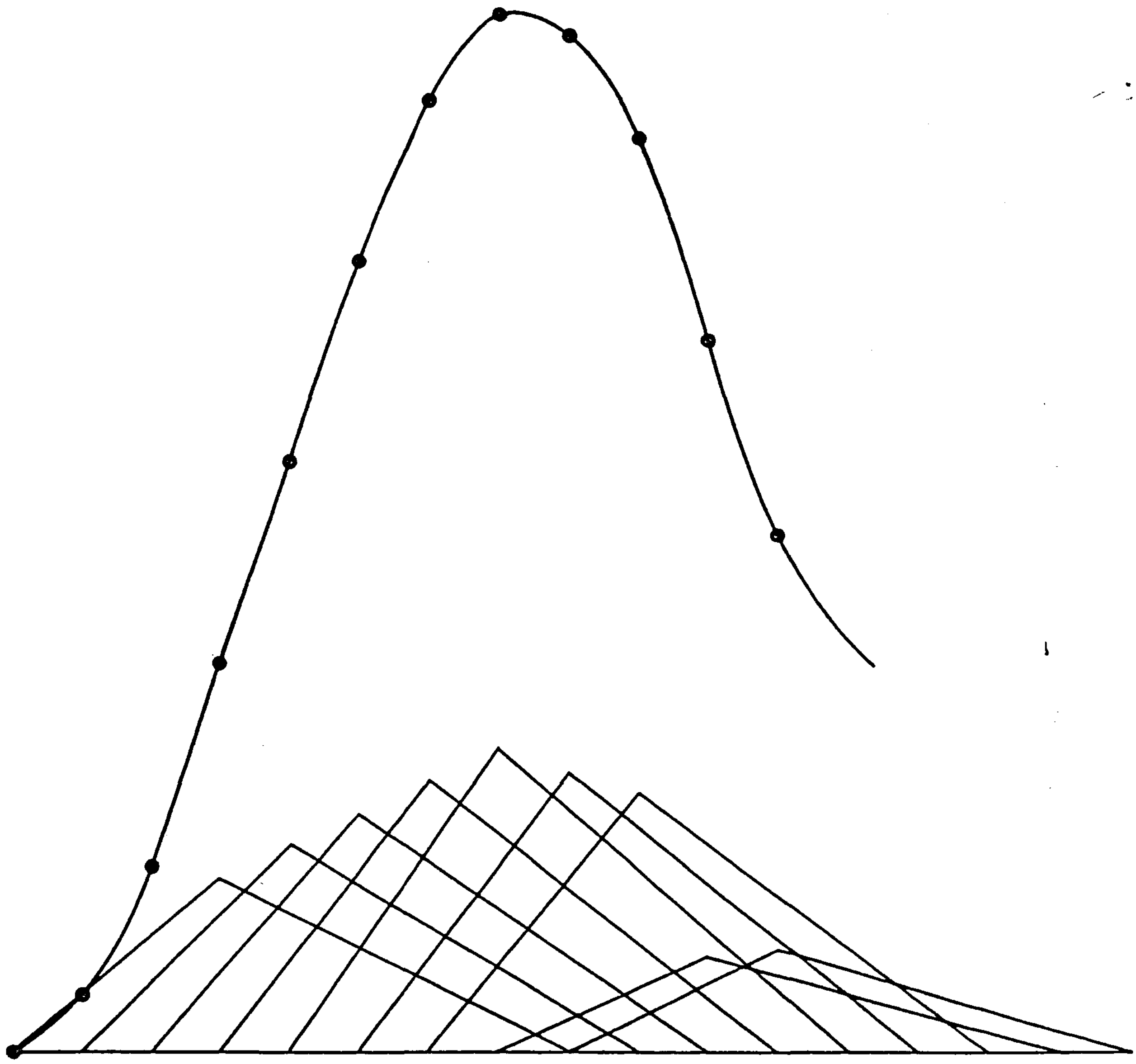


Figure 1.10.3 Superpositioning of incremental triangular unit hydrographs (Schulze and Arnold, 1979)

1.11 STORM RAINFALL DISTRIBUTION

In estimating the peak rate of runoff from a catchment the distribution of storm rainfall with respect to time is an important consideration because rainfall intensity varies considerably during this time. Originally two typical 24-hour storm distributions, Type I and Type II, were developed from data in the USA for use in the SCS model. These two rainfall distributions, in which the D-hour duration rainfall is expressed as a ratio of the 24-hour rainfall were re-evaluated by Cronshey (1982) for the eastern USA where more intense distributions were found. The two original SCS distributions were provisionally adopted for use in southern Africa (Schulze and Arnold, 1979). An analysis of design rainfall distribution by Schulze (1984), based on digitised data for Natal, illustrated the need for a revision of synthesised storm distributions in southern Africa. Some of the D-hour to 24-hour ratios determined from his study were well in excess of those derived from Midgley and Pitman (1978) and Adamson (1981), which in turn were markedly higher than the two original SCS distributions.

Previously southern African studies on short-duration design rainfall (e.g. Midgley and Pitman, 1978; Adamson, 1981) used a data base consisting of manually extracted "clock time" 15, 30, 45 and 60 minute and 24-hour annual maximum rainfall values, requiring correction factors developed overseas to convert them to "real time" values. Some marked differences between manual and digitised rainfall were noted by Schulze (1984) and depth-duration-frequency studies in southern Africa have to date been characterised by the use of many relatively short data sets or the complete omission of data from key stations.

1.11.1. Procedure to develop revised synthetic rainfall distributions for southern Africa

Schulze (1984) developed four revised synthetic rainfall distributions using a digitised rainfall data base for Natal (9 stations). The procedure adopted in developing the four distributions can be summarised as follows :

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

b) These ratios were plotted against the 24-hour duration symmetrically about a central point, for durations of 5, 10, 15, 30, 45 and 60 minutes and 2, 4, 6, 8, 10, 12, 16 and 20 hours. On the same graph the two original SCS and the Adamson (1981) distributions were also plotted. The assumption of a symmetrical distribution, which has also been used by Cronshey (1982), simplifies computational procedures and introduces an element of safety, since a symmetrical distribution (i.e maximum intensity at the centre of the 24-hour period) produces a higher peak discharge than a distribution with an initial high intensity, which is more common for short-duration events.

c) From the range of plots the four storm distributions were identified. These four distributions approximate the following:

SA Type 1 : SCS Type I distribution
SA Type 2 : Durban's 10-year return period and SCS Type II distribution.
SA Type 3 : Adamson's summer rainfall region distribution
SA Type 4 : Estcourt's 50-year return period distribution

The analysis indicated that not only were the synthetic distributions markedly different from existing estimates, but regional differences were more complex than simple "inland" vs. "coastal" or "summer" vs. "winter" rainfall region classifications adopted previously. The ratios of D-hour to 24-hour rainfalls were also shown to vary with recurrence interval, as did the correction factors for the conversion of "clock time" to "real time" intensities, which furthermore varied regionally. The choice of extreme value distribution was shown to be unimportant and the log-normal, log-Pearson Type 3 and log-Gumbel distributions all yielded similar results (Schulze, 1984).

1.11.2 Regionalisation of revised synthetic rainfall distributions for southern Africa

A tentative regionalisation of the distributions for southern Africa was undertaken by Schulze (1984) by comparing the D-hour to 24-hour ratios from the autographic data base supplemented by information published by the South African Weather Bureau (1974) and Midgley and Pitman (1978), with the ratios and range of ratios applicable to the four distributions. A map representing the regions for which the different distributions would apply was prepared based on the D-hour to 24-hour ratios for the 50-year recurrence interval.

Subsequent to this work of Schulze's (1984) a data base of digitised rainfall data for 40 stations throughout Southern Africa was obtained from the South African Weather Bureau. These data were used to revise, where necessary, the 1984 map indicating the regional patterns of the four synthetic rainfall distributions (Weddepohl, 1988).

The previous study (Schulze, 1984) had indicated a range in correction factors varying regionally and with return period to convert from a one-day rainfall depth of given recurrence interval to a 24-hour rainfall depth of equal recurrence interval. Owing to the variation in the correction factors and the availability of one-day expected maximum rainfall depth estimates for over 2 600 locations in southern Africa (Adamson, 1981), it was decided to rather express the synthetic storm distributions in terms of D-hour to one-day rainfall depth ratios. The procedure of analysis, conducted by Weddepohl (1988), was thus as follows :

a) Compute, using the log-normal extreme value distribution, the rainfall depths for one-day duration and various probabilities of exceedence. For this analysis the rainfall series for the 24-hour duration was used instead of the series for one-day rainfall, since tests using the data from the 40 autographic stations (Table 1.11.4), and daily data for the same period of record derived from the daily rainfall station at or nearest to the autographic station, displayed a range of correction factors which were in some cases less than one.

b) Compute ratios of D-hour to one-day rainfall for selected durations and exceedence probabilities.

c) Select the appropriate synthetic rainfall distribution for the station in question by comparing computed ratios with the ratios and range of ratios representing the four distributions given in Table 1.11.1. Again the dependence of appropriate storm distribution was found to vary with duration and recurrence interval. In selecting the distribution, emphasis was given to the 10- and 20-year return periods and to durations between 15 and 120 minutes. The 10- and 20-year return periods were chosen since the digitised data records available were generally of the order of 20 years in length. Storm durations of less than 15 minutes are often not well represented by the digitised autographic rainfall trace due to digitising inaccuracies and processing corrections while, storms of duration exceeding 120 minutes are usually of less importance in producing the critical flood on a small catchment in response to the synthetic rainfall distributions.

d) A map representing the regionalisation of synthetic rainfall distributions was drawn from the above results, with adjustments to regional boundaries being made based on physiographical and climatological considerations (Figure 3.2).

In order to simplify the use of the synthetic rainfall distributions, equations were derived to represent them. The equations derived relate the ratio of the D-hour storm depth to that for one-day for the same risk and take the form

$$R = \frac{a \cdot D}{(b + D)^c} \qquad \text{... Eq. 23}$$

where

R = ratio of D-hour to one-day storm depth

D = duration for which ratio is to be computed (h) and

a,b,c = regression constants.

Table 1.11.1 D-hour to one-day ratios and range of ratios (bracketed) for the four synthetic rainfall distributions

Duration (hours)	Ratios and ranges of ratios () for storm rainfall distributions			
	SA TYPE 1	SA TYPE 2	SA TYPE 3	SA TYPE 4
.083	.083 (0-.108)	.134 (.108-.153)	.173 (.153-.191)	.209 (.191-1.000)
.167	.126 (0-.165)	.024 (.165-.242)	.281 (.242-.314)	.347 (.314-1.000)
.250	.155 (0-.202)	.249 (.202-.302)	.355 (.302-.399)	.444 (.399-1.000)
.333	.178 (0-.230)	.283 (.230-.346)	.410 (.346-.463)	.517 (.463-1.000)
.500	.215 (0-.273)	.332 (.273-.409)	.487 (.409-.552)	.618 (.552-1.000)
.750	.256 (0-.320)	.384 (.320-.472)	.561 (.472-.635)	.710 (.635-1.000)
1.000	.289 (0-.355)	.422 (.355-.515)	.609 (.515-.688)	.768 (.688-1.000)
1.500	.341 (0-.409)	.478 (.409-.575)	.672 (.575-.753)	.835 (.753-1.000)
2.000	.383 (0-.451)	.520 (.451-.616)	.713 (.616-.793)	.873 (.793-1.000)
3.000	.449 (0-.515)	.582 (.515-.674)	.767 (.674-.841)	.916 (.841-1.000)

Table 1.11.2 Regression constants for the four southern African synthetic rainfall distributions

Distribution type	a	b	c
1	.29935	.059	.62
2	.45321	.100	.75
3	.73402	.230	.90
4	1.01330	.320	1.00

The regression constants for the four distributions are given in Table 1.11.2. Table 1.11.1 indicates the D-hour to one-day ratios derived using Equation 23 for durations up to 3 hours. The range of ratios (brackets) used to regionalise the four rainfall distributions is also given. Equation 23 is also used to determine the time distributions of accumulated rainfall depth divided by total rainfall depth, given in Figure 1.11.1 and Table 1.11.3. The rainfall distributions represent an exponentially increasing rainfall intensity to a peak at the mid-time of the one-day duration followed by an exponential decrease in intensity until the end of the storm. Thus the ratio R given in Table 1.11.1 for a 1-hour storm for a Type 1 distribution (0.289) can be derived from Table 1.11.3 as the difference between the ratios given for the 0.5 hours before and after peak intensity (for example, 0.644-0.355 = 0.289). Table 1.11.4 identifies the digitised autographic rainfall data sets used in the study.

It should be noted that in the context of this report the maximum 24-hour rainfall series was used instead of the one-day rainfall series to regionalize the application of Equation 23 and the synthetic rainfall distribution curves. A correction factor to convert from a one-day rainfall depth of given recurrence interval to a 24-hour rainfall depth of equal recurrence interval may be used for other applications of Equation 23 given a suitable estimate of such a correction factor.

Table 1.11.3 Ratios of accumulated rainfall to total rainfall for storm distribution Types 1, 2, 3, 4

Time before or after peak intensity	Type 1	Type 2	Type 3	Type 4
12.000	.000	.000	.000	.000
11.000	.016	.011	.005	.001
10.000	.034	.023	.010	.001
9.000	.052	.036	.016	.002
8.000	.072	.049	.022	.003
7.000	.093	.064	.029	.005
6.000	.116	.081	.037	.006
5.000	.142	.101	.047	.009
4.000	.172	.123	.059	.013
3.000	.206	.151	.076	.019
2.000	.249	.187	.099	.031
1.500	.275	.210	.117	.042
1.000	.309	.242	.143	.063
.750	.329	.263	.164	.082
.500	.355	.292	.195	.116
.375	.372	.311	.220	.145
.250	.393	.338	.256	.191
.167	.411	.363	.295	.241
.125	.422	.380	.322	.278
.083	.437	.404	.359	.326
.042	.458	.438	.413	.395
.000	.500	.500	.500	.500
.042	.542	.563	.587	.605
.083	.563	.596	.640	.673
.125	.577	.619	.678	.722
.167	.589	.637	.705	.758
.250	.607	.662	.747	.809
.375	.628	.689	.780	.855
.500	.644	.708	.805	.884
.750	.670	.737	.836	.918
1.000	.691	.758	.857	.937
1.500	.724	.790	.883	.958
2.000	.751	.813	.901	.969
3.000	.794	.849	.924	.981
4.000	.828	.877	.940	.987
5.000	.858	.899	.953	.991
6.000	.884	.919	.963	.993
7.000	.907	.935	.970	.995
8.000	.928	.951	.978	.997
9.000	.948	.964	.984	.998
10.000	.966	.977	.990	.999
11.000	.984	.989	.995	.999
12.000	1.000	1.000	1.000	1.000

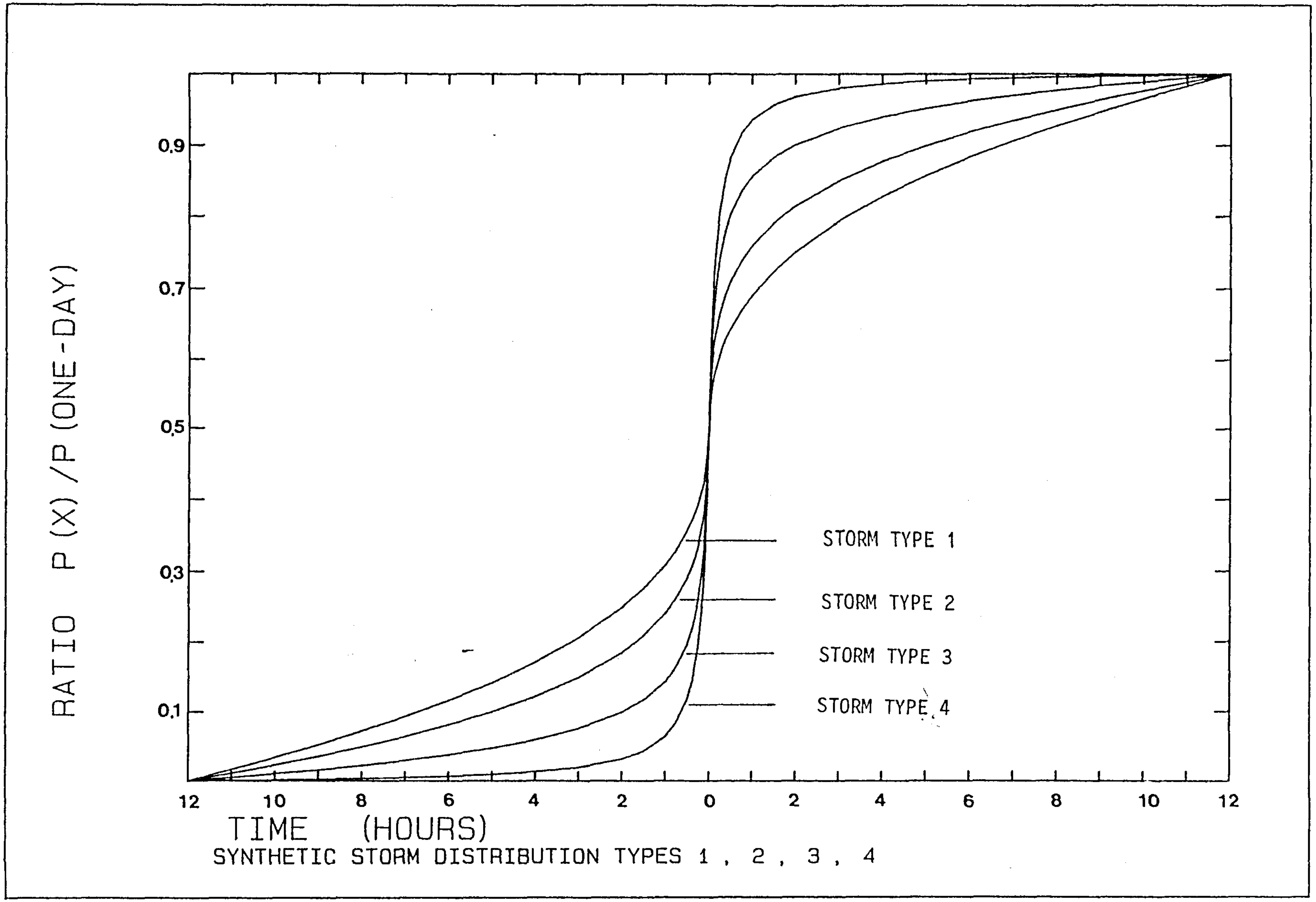


Figure 1.11.1 Time distributions of accumulated rainfall depth divided by total rainfall depths

Table 1.11.4 Autographic rainfall stations used in delimiting regions of synthetic rainfall distributions

STATION	LATITUDE (°S)	LONGITUDE (°E)	YEARS OF RECORD
Alexander Bay	28° 34'	16° 32'	1969 - 1985
Aliwal North	30° 41'	26° 43'	1960 - 1985
Armoedsvlakte	26° 57'	24° 38'	1969 - 1985
Bethlehem	28° 10'	28° 18'	1957 - 1983
Calvinia	31° 28'	19° 46'	1970 - 1985
Carolina	26° 04'	30° 07'	1969 - 1982
Cedara	29° 32'	30° 17'	1969 - 1985
De Aar	30° 39'	24° 01'	1962 - 1985
D F Malan Airport	33° 58'	15° 36'	1960 - 1982
Dohne	32° 31'	27° 28'	1964 - 1976
East London	33° 02'	27° 50'	1970 - 1985
Estcourt	29° 01'	29° 52'	1961 - 1972
Fauresmith	29° 46'	25° 19'	1961 - 1985
Fraserburg	31° 55'	21° 31'	1957 - 1977
Grootfontein	31° 29'	25° 02'	1960 - 1986
Jan Smuts Airport	26° 08'	28° 14'	1960 - 1981
Kimberley	28° 48'	24° 46'	1952 - 1985
Kokstad	30° 32'	29° 25'	1959 - 1985
Ladysmith	28° 34'	29° 46'	1949 - 1985
Louis Botha Airport	29° 58'	30° 57'	1956 - 1985
Levubu	23° 05'	30° 17'	1969 - 1985
Lydenburg	25° 06'	30° 28'	1969 - 1985
Makatini	27° 24'	32° 11'	1966 - 1985
Marnitz	23° 10'	28° 13'	1969 - 1985
Newcastle	27° 44'	29° 57'	1956 - 1985
Pietermaritzburg	29° 36'	30° 23'	1947 - 1985
Pofadder	29° 08'	19° 23'	1962 - 1977
Port Elizabeth	33° 59'	25° 36'	1970 - 1985
Potchefstroom	26° 44'	27° 05'	1962 - 1984
Potgietersrus	24° 11'	29° 01'	1970 - 1985
Pretoria	25° 44'	28° 11'	1970 - 1985
Prieska	29° 40'	22° 45'	1971 - 1984
Richards Bay	28° 47'	32° 01'	1970 - 1978
Riversdale	34° 06'	21° 16'	1970 - 1981
Skukuza	24° 59'	31° 36'	1970 - 1985
Standerton	26° 55'	29° 13'	1973 - 1985
Umtata	31° 35'	28° 47'	1960 - 1976
Upington	28° 26'	21° 16'	1951 - 1985
Waterford	29° 51'	29° 20'	1962 - 1980
Wepener	29° 44'	27° 02'	1961 - 1985

1.12 CATCHMENT RESPONSE TIME

Time of concentration of a catchment is the time it takes for runoff to travel from the hydraulically most distant point (i.e. point of longest water travel time) of the catchment to the point of reference. In hydrograph analysis it is frequently assumed equal to the time from the end of excess rainfall to the point of inflexion on the falling limb of the hydrograph (Figure 1.12.1). It may be estimated for ungauged catchments using hydraulic principles, by summing the flow time for the various flow phases as the water travels towards the catchment outlet, or by means of empirical equations. These flow phases are generally overland flow, including flow over spill and through forest litter, shallow channel flow towards larger channels and flow in open channels, both natural and improved. The travel time in these various flow phases depends on the length of travel, determined from the map of largest scale and the flow velocity.

Flow velocity for overland flow and shallow channel flow can be estimated using the Upland method (Figure 1.12.2). Flow velocity for open channels can be estimated from Manning's equation assuming the channel is flowing full. Once the velocity in each flow segment is determined the time of concentration is computed from

$$T_c = \sum_{i=1}^{n} \frac{l_i}{v_i} \times \frac{1}{3\ 600} \qquad \text{... Eq. 24}$$

where

T_c = time of concentration (h)
n = number of flow segments
l_i = hydraulic length of segment i (m)
v_i = flow velocity for segment i $(m.s^{-1})$.

Hydraulic principles should be used in preference to empirical equations where it is deemed that realistic estimates of flow time can be calculated for the various flow phases making up the

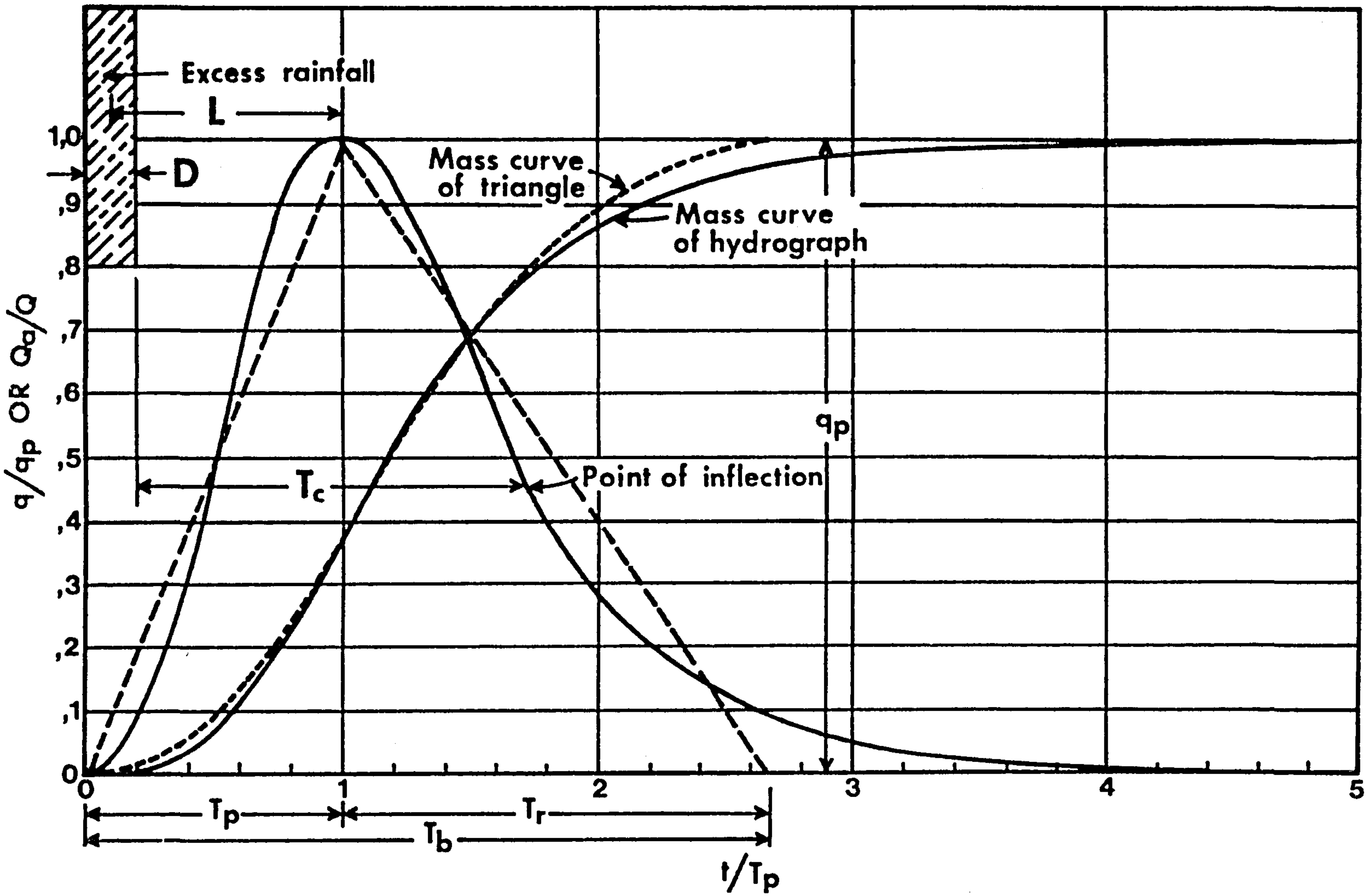


Figure 1.12.1 Illustration of time parameters L and T_c in relation to the SCS unit hydrograph (Schulze and Arnold, 1979)

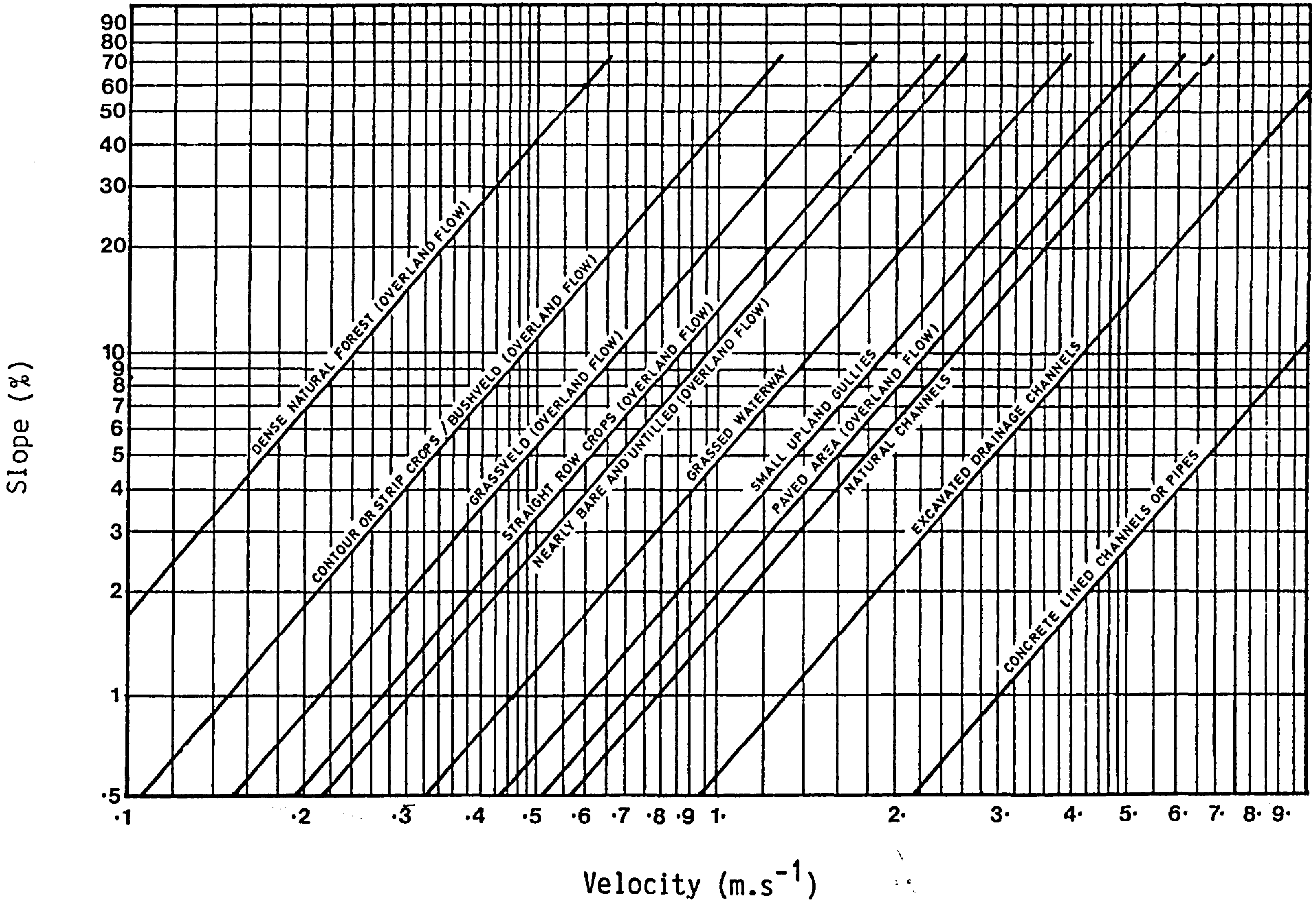


Figure 1.12.2 Flow velocities for the Upland method of estimating T_C (after Schulze and Arnold, 1979)

flow path from the hydraulically most distant part of the catchment. The adoption of the time of concentration concept requires that the entire catchment be contributing to runoff. Care should thus be taken to ensure that account is taken in the calculation of the time of concentration of upland areas (which may make up a major portion of the catchment) which have a delayed contribution to runoff. Care should also be taken when using hydraulic estimates of overland flow travel times when stormflow from a catchment contains a large proportion of subsurface quickflow. The contributions of portions of the catchment (i.e. near the channel system) may be accounted for by identifying the time of concentration for the portion in question and determining the area enclosed by an isochrone equal to the time of concentration of the sub-catchment. When using empirical equations care should be taken that the catchment under consideration falls within the range of catchments from which the empirical equation was developed.

Catchment lag, which is used to determine peak discharge in the SCS model, is envisaged as a weighted average of the time for runoff, from each point of the catchment, to reach the catchment outlet. Lag is defined as the time from the centre of mass of excess rainfall (Figure 1.12.1) and is related to the physical properties of a catchment. It can be estimated from historical hydrographs or from specific catchment characteristics such as catchment slope, hydraulic length and flow retardance using hydraulic principles, or by means of empirical equations.

To avoid the excessive computation required to compute travel times from a large number of positions within a catchment, lag may be related to the catchment's time of concentration with the equation given by Kent (1973) as

$$L = 0.6\ T_c \qquad \text{... Eq. 25}$$

where

L = lag (h)

T_c = time of concentration (h).

The empirical equation originally developed by the SCS for the estimation of lag (NEH-4, 1972) is

$$L = \frac{l^{0.8} (S' + 25.4)^{0.7}}{7\ 069\ y^{0.5}} \qquad \text{... Eq. 26}$$

where

L = lag (h)
l = hydraulic length of the catchment (m)
y = average catchment slope (%)

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

where

CN' = retardance factor approximated by the runoff Curve Number unadjusted for antecedent soil moisture.

The use of Equation 26 is limited to areas of less than $10km^2$. This method for estimating lag was developed to span a broad set of conditions ranging from heavily forested catchments with steep channels, or meadows, providing a high retardance to surface runoff (i.e. low CN'), to smooth land surfaces and long paved parking areas (i.e. high CN'). However, a CN' value of less than 50 or greater than 95 should not be used in the solution of lag by Equation 26 (NEH-4, 1972).

Equation 26 expresses lag time solely as a function of invariant physiographic factors, suggesting that storm intensity plays little role in determining travel times. Consideration of the laws of hydraulics indicates that flow velocity is related to flow depth and hence rainfall intensity. Much research, as summarised by Schmidt and Schulze (1984), has thus been directed at the incorporation of indices representing rainfall intensity in unit hydrograph procedures. Schmidt and Schulze (1984) utilised these techniques to derive storm lag times from gauged catchment data for seven catchments in the USA and five catchments in South Africa. These techniques, which included superimposed incremental hydrographs, single triangular approximations of recorded hydrographs and the measured time response between effective rainfall and runoff, were used to establish empirical relationships of lag times. Schmidt and Schulze (1984) developed an empirical lag equation for estimating catchment lag times which was given as

$$L = \frac{A^{0.35}\ MAP^{1.1}}{41.67\ y^{0.3}\ \bar{I}_{30}^{\ 0.87}} \qquad \text{... Eq. 27}$$

where

L	=	catchment lag time (h)
A	=	catchment area (km^2)
y	=	average catchment slope (%)
MAP	=	mean annual precipitation (mm)
$\bar{I}_{30}$	=	regional mean of the most intense thirty minute period of rainfall, which can be estimated as the two-year return period 30-minute rainfall intensity ($mm.h^{-1}$).

Schmidt and Schulze (1984) suggested that the poor estimates of peak discharge obtained when using the original SCS empirical lag equation (Equation 26) were due to the inability of the equation to distinguish between the predominant overland flow found in drier catchments and the marked subsurface flow response evident in many natural catchments found in moist climates. Climate, through its influence on the soil, vegetation and rainfall patterns, all of which affect the extent to which rainfall enters the soil profile, plays a major role in determining dominant runoff process and was introduced into Equation 27 through MAP. Of a number of variables tested the two-year return period 30-minute rainfall intensity was found to be that rainfall variable affecting the catchment lag time most significantly. The most intense 30-minute period of rainfall in each storm also appeared to be the best variable when simulating storm to storm variations in lag time within a single catchment. Catchment area and mean catchment slope were the dominant physiographic parameters affecting catchment lag time. During the course of this project Equations 26 and 27 were evaluated for peak discharge estimation on a bigger data base consisting of 262 large runoff events from 21 South African catchments and 14 catchments in the USA. On 30 of the 35 catchments Equation 27 provided the better estimates of catchment lag time and on two of the catchments both equations gave similar estimates. It was evident from the simulations that lag times were underestimated severely by both equations on some of the catchments with forest cover which were dominated by subsurface flow.

When estimating catchment lag time care should be taken to determine the dominant flow process occurring. On catchments where distinct flow phases can be identified, it is recommended that hydraulic calculations or the Upland method be used for the estimation of the time of concentration and hence lag time. On natural catchments where the flow phases contributing to the hydraulically most distant point are not clearly defined, the empirical equations should be used. Equation 27 should be preferred, especially where subsurface quickflow is a major factor. Equation 26 generally gives shorter lag times and appears more suited to drier catchments of limited vegetation cover and shallow soils. Nomographs for the solution of Equations 26 and 27 are given as Figures 3.4 and 3.5.

1.13 COMPUTATION OF PEAK DISCHARGE AND HYDROGRAPH SHAPE

The computation procedures for the estimation of peak discharge have been outlined in Section 1.10. The computations are laborious when done manually and a graphical solution has thus been provided. Four nomographs for the determination of peak discharge are given in Figure 3.8, one for each of the four design storm distributions identified for southern Africa.

In preparing the nomographs for the determination of peak flow rates, 15 incremental hydrographs were used in calculations. The time to peak was chosen to be

$$T_p = 6\,\Delta D$$

It follows from

$$T_p = 6\,\Delta D = \frac{\Delta D}{2} + L$$

that

$$\Delta D = \frac{L}{5.5}$$

where

L = lag (h)

ΔD = unit storm duration (h).

The inputs to the peak flow rate nomographs (Figure 3.8) are lag (L), the ratio I_a/P, rainfall depth (P) and catchment area (A). The ratio I_a/P may be determined from Figures 3.6 or 3.7 depending on whether runoff depth in mm (Appendix 3 and Figure 3.3) or adjusted Curve Number (Figure 3.3) are known. The curves were all derived from Equation 22 which was given as :

$$\Delta q_{pi} = 0.2083 \frac{A \quad \Delta Q_i}{T_p}$$

where

Δq_{pi} = peak flow rate of incremental hydrograph 'i' ($m^3.s^{-1}$)

A = catchment area (km^2)

T_p = time to peak (h)

ΔQ_i = increment of runoff (mm)

$$= \frac{(P_i - I_a)^2}{P_i - I_a + S} - \frac{(P_{i-1} - I_a)^2}{P_{i-1} - I_a + S}$$

where

P_i = rainfall amount at time i as obtained from the rainfall distribution curve

$S = \frac{25\ 400}{CN} - 254$

CN = runoff Curve Number

I_a = initial abstraction (mm)

= cS

where

c = coefficient of initial abstraction

= 0.1

In the previous design manual (Schulze and Arnold, 1979) information and examples on the manual solution to estimations of peak flow rates were given. These have not been repeated since it is unlikely that the design engineer would be required to undertake the manual computations when a graphical solution is available.

It is sometimes necessary to compute the complete hydrograph shape, for example, for flood routing computations and the determination of a composite hydrograph from subareas of a catchment. The hydrograph is constructed using incremental hydrographs superimposed for the full one-day rainfall distribution. Again it would not be feasable to do the computations manually. A short computer program (Appendix 6) has therefore been given for the determination of the complete hydrograph shape.

PART 2 : PROCEDURES FOR USE OF THE SCS-BASED METHODS IN SOUTHERN AFRICA

THE ESTIMATION OF RUNOFF VOLUME

2.1 DETERMINATION OF RAINFALL DEPTH FOR USE IN RUNOFF DEPTH ESTIMATION

Natural storms

a) Determine the rainfall amount, as measured at a rain station representative of (i.e. within, or closest to) the catchment under consideration, for the storm being considered (e.g. Cedara, 30 December 1977: 93 mm).

b) Where rainfall amounts from several rain gauges within and/or adjacent to the catchment under consideration are available, a weighted storm rainfall may be derived using any of the standard methods (Thiessen polygons, arithmetic mean, etc).

Design storms

a) Determine the location of the catchment, either by latitude and longitude, or by the standard South African Weather Bureau (SAWB) map of "sectors", Figure 3.10 or Appendix 5 (e.g. Aliwal North is at 30°41'S, 26°43'E; or in SAWB sector 175).

b) Select the desired return period for the design storm. For present application in South Africa, magnitudes of the one-day expected maximum rainfall for return periods (RP) of 2, 5, 10, 20, 50 and 100 years have been mapped (Figure 3.1).

c) Referring to Figure 3.1, look up the one-day design storm rainfall amount, interpolating between the isohyets shown on the map (e.g. at Queenstown, latitude 31°54'S, longitude

26°52'E the rainfall amount for the 20-year return period would be 85 mm by interpolation). Alternatively the SAWB sector number can be determined for the given latitude and longitude from Appendix 5 (SAWB sector for Queenstown = 123) and the information contained in Appendix 5 consulted to find the nearest rainfall station for which data are available (e.g. Queenstown, sector = 123, has a 20-year return period one-day rainfall depth = 85 mm).

2.2 DETERMINATION OF RUNOFF CURVE NUMBER UNADJUSTED FOR ANTECEDENT MOISTURE CONDITIONS

Hydrological soil groups

a) Obtain, either from existing maps (e.g. Department of Agriculture and Water Supply) or by a field survey, a soils map of the catchment (e.g. Figure 2.1), using the binomial system of classification into soil forms and series for southern Africa (MacVicar et al., 1977).

b) Referring to Table 3.1, assign a hydrological soil group to each of the soils units found in the catchment. (e.g. Figure 2.2)

c) Following fieldwork, make adjustments to the soil groups within the catchment where these are necessary. These adjustments depend on local conditions related to soil depth, surface sealing, topographic position of unit or parent material. Details are given in Section 1.3.

Land use and treatment classes

a) From fieldwork, recent aerial photographs, orthophotos or other information, prepare a land use map of the catchment, noting also the treatment and hydrological condition of the land use classes as described in Section 1.4. (e.g. Figure 2.3)

b) Superimposing the land use and the soil groups maps, delimit the main hydrological response units. Units covering less than 5% of the catchment area should be combined with an adjacent unit of similar land use or soils. (e.g. Figure 2.4)

c) Referring to Table 3.2, assign runoff Curve Numbers, CN, for "average" conditions to each of the units delimited. (e.g. Figure 2.4)

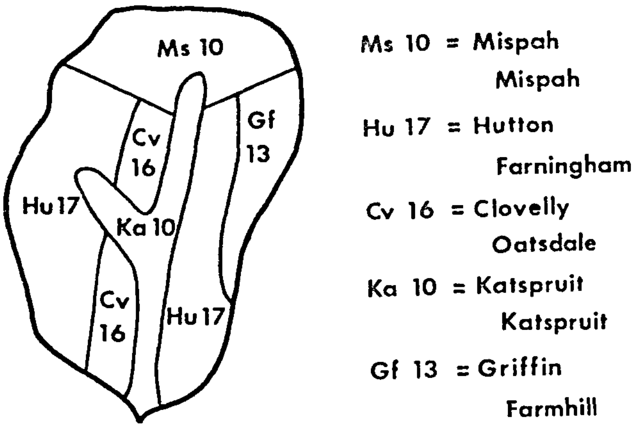


Figure 2.1 Example of soil units within a catchment at soil form and series level

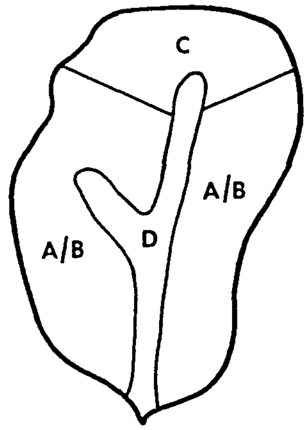
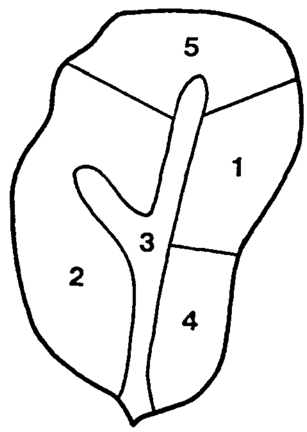


Figure 2.2 Assignment of hydrological soil groups to soil units

Figure 2.3 Example of land uses and treatments/hydrological conditions within a catchment



UNIT	CN
1	74
2	51
3	81
4	46
5	74

Figure 2.4 Assignment of Curve Numbers to hydrological response units

2.3 ADJUSTMENTS TO CURVE NUMBERS FOR ANTECEDENT MOISTURE CONDITIONS

2.3.1 Natural storms

a) Summate, for a selected number of days preceding the storm event, the total interim (i.e. antecedent) rainfall, P. (Example : 5 days' antecedent rainfall before storm = 45 mm or 30 days' antecedent rainfall = 80 mm).

b) Estimate, for the selected number of days preceding the storm event, the total actual evapotranspiration, drainage and runoff and calculate antecedent storage change.

<u>Method 1</u> : Potential evapotranspiration, PET, may be estimated from evaporation pan data, available maps or empirical temperature-based formulae, e.g. Linacre (1977) together with an estimate of cropping coefficient which accounts for the effect of canopy cover upon transpiration. The actual evapotranspiration AE for a given day will be less than potential evapotranspiration if the vegetation is under stress (e.g. if soil moisture is less than, for example, 50% plant available moisture, PAM). Interim runoff, Q, may be determined as a percentage of rainfall depending on runoff response characteristics of the catchment and the distribution of the rainfall during the antecedent period.

Example : 5 days' interim actual evapotranspiration, drainage and runoff = 20 mm. Thus the 5-day storage change = P - (AE + D + Q)

= 45 - 20 = 25 mm

<u>Method 2</u> : An estimate of typical amounts of AE, Q and D for a 30-day period for the prevailing land use/soil conditions may be gleaned for the location from Appendix 1 and Appendix 2. Assume, for example, your catchment to be in homogeneous zone 371, as shown in Figure

3.9 (SAWB rainfall station No. 299357, Table 3.3), with a loam soil of intermediate depth (0.6 m) and a sparse cover (poor veld conditions). Appendix 2 indicates for the relevant land use/soil conditions that 50% of the 30-day antecedent periods for the highest 5 events of each year result in a net gain of 43.7 mm of moisture to the soil at that station in zone 371. Since the median 30-day antecedent rainfall was 161 mm (Appendix 1), the losses from storage (AE+Q+D) were on average 161 - 43.7 = 117.3 mm (3.9 $mm.day^{-1}$ for 30 days). While this gives an estimate of <u>average</u> runoff, drainage and actual evapotranspiration rates for the region, they are unlikely to apply directly to a specific event unless such an event's antecedent rainfall and temperature characteristics could be classed as representative of average conditions for the region. A 30-day antecedent rainfall total of 80 mm could not be classed as average (it is exceeded approximately 80% of the time, Appendix 1) and for the drier conditions it is likely that the 20 percentile antecedent storage change of 17.7 mm would be more representative of prevailing condition. Appendix 2 is essentially a statistical summary of the antecedent storage change characteristics of a zone that should be used in design analysis for which information on a specific event is not required.

c) Referring to Figure 3.3 the adjusted Curve Number and the resulting runoff depth is obtained as follows :

(i) Enter the initial Curve Number on bottom right axis.

(ii) Move vertically to the interim storage change.

(iii) Move horizontally to the right and read off adjusted CN.

(iv) Move horizontally to the left to the storm rainfall total (mm) for which runoff response is desired.

(v) Move vertically down to read off resulting runoff response depth (mm).

Example : Storm rainfall depth = 100 mm
CN-II = 70
Antecedent storage change = 20 mm
From Figure 3.3 CN adjusted = 73.7
Runoff depth = 45.5 mm

(vi) As an alternative to the above steps Equations 13 and 4 may be solved.

2.3.2 Design storms

Method 1 : Use of antecedent rainfall data (Note : Method 2 utilising the storage change data in Appendix 2 is more likely to be applied for Design Storms).

a) Determine, for the relevant region in Appendix 1, the expected 5-day or 30-day antecedent rainfall depth for chosen risk.

b) Estimate likely antecedent runoff, drainage and actual evapotranspiration and hence storage change for the antecedent period from field experience or local conditions.

c) Compute the revised Curve Number and resulting runoff depth for the design one-day rainfall depth (Figure 3.3) following the procedure given in Section 2.3.1 (c).

Example : Postmasburg lat. = $28^{o}20'$S long. = $23^{o}04'$E
Zone 304; SAWB rainfall station No. 321110 (Figure 3.9 and Table 3.3)
From field inspection CN-II = 80
20-year RP one-day rainfall = 86 mm (Appendix 5)
50 percentile 30-day antecedent rainfall depth = 35 mm (Appendix 1)
Estimated 30-day AE+D+Q = 50 mm
(Potential evapotranspiration rates are likely to be higher than 5 mm.day^{-1}; however, actual evapotranspiration rates will be markedly reduced due to depleted soil moisture typically found in an arid region. Runoff and drainage are likely to be near zero for the low 30-day rainfall total).

Estimated 30-day storage change =

35-50 mm = -15 mm

From nomograph Figure 3.3 adjusted CN = 76.7 and

One-day runoff depth = 39.4 mm.

Note : For conservative design the 80 percentile antecedent rainfall may have been chosen giving a higher design runoff depth.

Method 2 : Use of antecedent storage change data (30-day antecedent period)

a) For relevant zone and land use/soil combinations determine 30-day antecedent storage change (P-Q-D-AE) for chosen risk, i.e. percentile of non-occurrence (Appendix 2).

b) Compute the revised CN and resulting runoff depth for the design one-day rainfall depth following the procedures given in Section 2.3.1 (c)

Example : Postmasburg lat. = $28^{o}20'$S long. = $23^{o}04'$E

Zone 304 (Figure 3.9)

From field inspection CN-II = 80

20-year RP one-day rainfall = 86 mm (Appendix 5)

Assume a sparse cover, with soil of intermediate depth and clay texture.

From Appendix 2 it can be seen that for the above land use/soil combination, 50 % of the time the 30-day antecedent storage change exceeded -13.6 mm (i.e. net drying out of profile).

From the nomograph (Figure 3.3) the adjusted CN (77.0) and runoff depth (39.8 mm) would be determined to be similar to that computed in Method 1. Again, a conservative design could be adopted by applying the 80 percentile antecedent storage change value of -1.9 mm which gives an adjusted CN of 79.6 and associated runoff depth of 43.7 mm for the 86 mm rainfall.

2.4 NOMOGRAPHIC ESTIMATION OF RUNOFF DEPTH

General comment

In the estimation of storm runoff depths, be it by nomograph or by the runoff equation (Section 1.1), two approaches are possible where the catchment consists of more than one soil-cover complex:

a) An average CN representative of the entire catchment is computed by weighting individual unit CN's by area.

b) The runoff may be estimated separately for each soil-cover unit and the total runoff then computed by area weighting.

For the given data the second method, although involving a little more work, will always give the more correct estimate, and it is recommended that it be used in preference to the first method. The two approaches may give marked differences in the final estimate of runoff, particularly with small rainfall amounts, i.e. less than 50 mm. The worked Example 2 at the conclusion of Part 2 illustrates these differences.

Nomographic solution

Referring to Figure 3.3 the following procedure is used.

a) Enter the CN (unadjusted for antecedent conditions) on the bottom horizontal axis of the right hand quadrant.

b) Move vertically up to the selected antecedent storage change ("positive" indicates wet conditions, "negative" dry conditions).

c) Move left horizontally to the selected rainfall amount.

d) Move down vertically to read off the estimated runoff depth in mm.

Solution by equations

Runoff depth may, alternatively, be estimated by applying Equations 13 and 4.

2.5 ESTIMATION OF DESIGN RUNOFF DEPTH USING THE JOINT ASSOCIATION OF RAINFALL AND ANTECEDENT MOISTURE CONDITION

a) Determine the CN for average moisture conditions from Table 3.2.

b) Identify the zone in which catchment is located (Figure 3.9).

c) Identify the land use/soil category best describing catchment conditions for antecedent moisture adjustment.

d) From the design runoff table appropriate to the zone under consideration (Appendix 3) read off the one-day runoff depth for the chosen percentile (i.e. frequency of non-occurrence) and land use/soil class.

Example : Windy Hill lat. $29^{0}29'$S long. $30^{0}34'$E
Zone 403 SAWB rainfall station no. 270119
(Figure 3.9 and Table 3.3)
From field inspection CN-II = 70
Assume a sparse cover with deep soils of a loam texture.
Design frequency of occurrence = 5 years (this is equivalent to a 20% probability of exceedence, i.e. 80 percentile value (probability of non-exceedance) to be used).
From Appendix 3 : one-day runoff depth 80 percentile = 39.3 mm.

Note : This can be compared with the approach of Section 2.3.2, Method 2
From Appendix 2, median antecedent storage change = 27.9 mm
From Appendix 5 or Figure 3.1, the 5-year design rainfall depth = 86 mm
From Figure 3.3, the one-day runoff depth = 37.4 mm

The results between the two approaches will differ for various locations depending on

a) the joint association trends of rainfall and catchment moisture status in the region, and
b) the relationship between the expected maximum daily rainfall totals of the data base used in this study and the "extreme" one-day rainfall depths of Appendix 5 or Figure 3.1. For example, the 80 percentile one-day rainfall depth from Appendix 4 is 83 mm compared with the 5-year return period of 86 mm from Appendix 5.

2.6 ASSESSMENT OF TEMPORAL DISTRIBUTION OF RAINFALL

Natural storms

a) The use of one of the four synthetic rainfall distributions for peak discharge estimation of a natural event is not strictly correct. Generally, information on the storm duration and rainfall intensity variations would be available. The correct procedure for peak discharge determination would be to make use of a computer program, similar to that given in Appendix 6, to superimpose unit hydrographs according to the available rainfall hyetograph.

b) If a synthetic storm distribution is to be used, an appropriate choice may be made by considering the ratio of rainfall depth for a range of durations straddling the most intense period of the storm to total rainfall depth and comparing such ratios with those given in Table 1.11.1 for the four synthetic storm distributions applicable to southern Africa.

Design storms

a) Referring to Figure 3.2, determine the storm type zone in which the catchment is located.

b) Where peak flow rates are critical for design purposes or near zone boundaries, it may be advisable to opt for a more intense distribution (i.e. one type higher) than indicated.

2.7 DETERMINATION OF CATCHMENT LAG TIME

Decide which method is to be used to estimate lag time. Section 1.12 gives recommendations in this regard.

2.7.1 Determination of lag time using estimates of flow velocity

This method is recommended when velocity can be computed for distinct flow phases from the hydraulically most distant point in the catchment.

a) Identify the hydraulically most distant point of the catchment from the point of reference (i.e. point of longest water travel time).
b) Delineate reaches of likely similar flow velocity.
c) Determine flow velocities for each reach, using either
   (i) Figure 1.12.2, or
   (ii) Manning's or a similar equation.
d) Compute travel time for each reach (length of reach divided by velocity).
e) Sum all contributing travel times to determine time of concentration in hours.
f) Compute lag time as $L=0.6\ T_C$ (Equation 25).

2.7.2 Determination of lag time using empirical equations

This equation is recommended for use on arid catchments of limited vegetation cover and shallow soils providing a quick response time.

EQUATION 1 : The original SCS lag equation

$$L = \frac{l^{0.8}(S' + 25.4)^{0.7}}{7\ 069\ y^{0.5}}$$

where

L = lag (h)

l = hydraulic length of the catchment (m)

y = mean catchment slope (%)

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

where

CN' = retardance factor, approximated by the runoff Curve Number, unadjusted for AMC. (Where CN' is less than 50, a value of 50 is assumed and where greater than 95 a value of 95 is assumed).

a) Compute catchment lag time using the above equation.

b) A nomographic solution to the equation is given as Figure 3.4. This figure is used as follows :

(i) Enter with the hydraulic length on the horizontal axis in the right quadrant.

(ii) Move vertically to the desired catchment slope.

(iii) Move horizontally to the left to the value of CN'.

(iv) Move down vertically and read off lag time (h).

Notes:

Mean Catchment Slope (%), y

(i) Mean catchment slope (%), y, may be calculated by any of the standard methods.

(ii) A suggested method gives

$$y = \frac{M\ N \times 10^{-4}}{A} \quad (\%)$$

where

M = total length of all contour lines within the catchment (m)

N = the contour interval used (m)

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.

Hydraulic Length, l

(i) The hydraulic length of a catchment, l, is the length in metres, along the main stream to the furthest catchment divide.

(ii) Hydraulic length is usually measured off the largest scale contour map of the catchment that is available.

(iii) In the absence of a contour map, l may be approximated as $l = 1\ 738\ A^{0.6}$, where A is in km^2.

EQUATION 2 : The Schmidt-Schulze lag equation

This equation is recommended for use on natural catchments where fairly deep, well drained soils with a good vegetation-cover are likely to limit the surface runoff component, thereby providing a slow response time.

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

where

L = lag (h)

A = catchment area (km^2)

y = mean catchment slope (%)

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

MAP = mean annual precipitation (mm)

a) Compute catchment lag time using the above equation.

b) A nomographic solution to the equation is given as Figure 3.5 which is used as follows :

(i) Enter with catchment area (km^2) on the horizontal axis in the top right quadrant.

(ii) Move vertically to the desired slope (%).

(iii) Move horizontally to the left to the mean annual precipitation (mm).

(iv) Move down vertically to the 2-year 30-minute intensity.

(v) Move horizontally to the right and read off the lag time (h).

Notes :

Mean annual precipitation (mm), MAP

(i) Mean annual precipitation may be derived from published maps. Most recent ones for Southern Africa are by Dent, Lynch and Schulze (1988).

(ii) The mean annual precipitation for the rainfall stations representative of each of the 712 zones in Figure 3.9 are given in Table 3.3.

Two-Year 30-Minute Intensity ($mm.h^{-1}$), $\bar{I}_{30}$

(i) Determine the 2-year one-day rainfall (Figure 3.1 or Appendix 5).

(ii) Select the appropriate storm distribution type for given zone (Figure 3.2).

(iii) Multiply the 2-year one-day rainfall by the appropriate factor given below for each storm distribution type to determine the two-year 30-minute rainfall intensity ($mm.h^{-1}$).

	STORM DISTRIBUTION TYPE			
	1	2	3	4
Multiplication Factor	0.430	0.664	0.974	1.236

2.8 NOMOGRAPHIC ESTIMATION OF PEAK DISCHARGE

a) The ratio I_a/P must first be determined since it is an input to Figure 3.8. The ratio I_a/P is determined using Figure 3.6 when the runoff Curve Number (adjusted for antecedent conditions) is to be used and using Figure 3.7 when the runoff depth is known.

Method 1

When adjusted CN is known, refer to Figure 3.6.

(i) Enter CN (adjusted Curve Number) on the horizontal axis.

(ii) Move vertically to the predetermined one-day rainfall depth (mm).

(iii) Move horizontally to read off the ratio I_a/P.

Method 2

Alternative method, when runoff depth is known, refer to Figure 3.7.

(i) Enter the predetermined one-day rainfall depth on the horizontal axis.

(ii) Move vertically to the one-day runoff depth (from Figure 3.3 or Appendix 3).

(iii) Move horizontally to read off the ratio I_a/P.

Note : The one-day rainfall depth will be as predetermined from Figure 3.1 or Appendix 5 and is used to compute runoff depth (Figure 3.3). When runoff depth is determined directly from Appendix 3 (using the methods of Section 1.8) the one-day rainfall depth used must be derived from the daily rainfall data base from which the runoff estimates in Appendix 3 were determined. The one-day rainfall is in this case determined from Appendix 4 for the same percentile value for which runoff was determined.

b) The nomograph applicable to the predetermined storm rainfall distribution is now selected to determine peak discharge (Figure 3.8) :

(i) Enter the I_a/P ratio determined above on the horizontal axis of the top right quadrant.

(ii) Move vertically to the value of catchment lag (h).

(iii) Move across horizontally to the one-day rainfall depth (mm) (refer to Note in 2.8(a)).

(iv) Move down vertically to the catchment area (km^2).

(v) Move across horizontally to read off the peak discharge ($m^3.s^{-1}$).

WORKED EXAMPLES

EXAMPLE 1 : Computation of storm runoff depth for natural events

A small catchment with group C soil and pasture cover in fair condition had a rainfall of 80 mm. Assuming average antecedent soil moisture conditions to have prevailed, estimate the storm runoff.

Solution

Step 1 : Using Table 3.2, under hydrological soil group C for pasture, fair condition, read CN = 79. Since average moisture conditions prevail no AMC adjustment is necessary.

Step 2 : Enter Figure 3.3 with CN = 79, move up to antecedent storage change = 0 move across to P = 80 mm, then move down to read off Q = 38 mm.

Alternatively, $$S = \frac{25\,400}{CN} - 254$$

$$= \frac{25\,400}{79} - 254$$

$$= 67.52 \text{ mm}$$

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

For $c = 0.1$

$$Q = \frac{(80 - 0.1 \times 67.52)^2}{80 + (1 - 0.1) \times 67.52}$$

$$= 38.1 \text{ mm}$$

EXAMPLE 2 : Computation of runoff volume for design events, accounting for typical antecedent moisture conditions using the methods outlined in Section 1.7

A catchment of area 3 km^2 is located at latitude 29^{o}29'S and longitude 30^{o}34'E. Determine the 10-year return period daily runoff volume (m^3) if the soil and land use characteristics have been identified to be as follows:

Subcatchment number	Soil characteristics	Land use and condition	Area (km^2)
1	Clovelly Clydebank Depth = 1.0 m	Veld, poor condition, overgrazed	1.5
2	Griffin Farmhill Depth = 0.6 m	Forest, 50 mm humus, moderate compaction	0.8
3	Glenrosa Paardeberg Depth = 0.4 m	Veld, good condition,	0.7

Solution

Step 1 : From Figure 3.9 determine the climatic zone in which the catchment lies (i.e. Zone 403). Details of the rainfall station (SAWB No. 270119) representative of the zone are given in Table 3.3.

Step 2 : From Figure 3.1 or Appendix 5 determine the 10-year return period daily rainfall depth as determined by Adamson (1981). One-day rainfall depth = 102 mm.

Step 3 : Determine the hydrological soil groups and soil texture classes (Table 3.1) and the Curve Numbers applicable to each soil-cover complex for average antecedent conditions, CN-II (Table 3.2).

Subcatchment number	Hydrological soil group	Texture	CN-II
1	B	Clay	79
2	A/B	Clay	54
3	B	Sand	61

Step 4 : Table 1.7.3 can be used to identify/interpolate the relevant soil texture/depth/cover class to determine typical antecedent moisture conditions for each sub-catchment for the chosen risk (e.g. 50%) using Appendix 2.

Subcatchment number	Cover	Depth	Texture	Antecedent storage change, 50 percentile
1	Sparse	Deep	Clay	+14.4
2	Dense	Intermediate	Clay	-22.9
3	Intermediate	Shallow	Sand	-0.5

Step 5 : Determine adjusted CN and runoff depth (Q) for each subcatchment for the design rainfall (102 mm), using Figure 3.3 or Equations 13 and 4.

Subcatchment number	Area (km^2)	CN-II	Adjusted CN	Q (mm)	Q x Area ($mm.km^2$)
1	1.5	79	82.3	61.7	92.6
2	.8	54	51.7	19.4	15.5
3	.7	61	61.0	29.6	20.7
Total	3.0				128.8

Therefore weighted runoff depth $= \dfrac{128.8 \text{ mm.km}^2}{3.0 \text{ km}^2} = 42.9$ mm

and runoff volume $= \dfrac{42.9 \text{ mm} \times 3 \text{ km}^2 \times 1000 \times 1000}{1\ 000} = 128\ 800 \text{ m}^3$

(NB: Numerator 1 000 x 1 000 converts km^2 to m^2
Denominator 1 000 converts mm runoff to m depth)

Alternatively (Using weighted CN)

Step 6 : Mean catchment adjusted Curve Number =

$$\frac{(82.3 \times 1.5) + (51.7 \times 0.8) + (61.0 \times 0.7)}{3.0} = 69.2$$

From Figure 3.3 assuming antecedent storage change to be zero (adjustment has been completed) and rainfall depth = 102 mm

$$Q = 40.4 \text{ mm}$$
$$= 121\ 200 \text{ m}^3$$

The mean catchment Curve Number unadjusted for moisture status (CN-II) for the catchment is 68.1 mm. It does not differ much from the adjusted CN in this example since adjustments for the various subcatchments tend to cancel each other.

The two different methods of estimating runoff volume can be seen to yield different answers. Each method has its advantages and disadvantages. The method of weighted - Q gives the hydrologically more correct result in terms of the data given, but it requires more computation than the weighted CN method, especially when a catchment has many different soil cover complexes. The weighted CN method is easier to use, but when there are large differences in Curve Number within the catchment, this method will under or over-estimate the runoff volume, depending on the magnitude of the storm rainfall.

It is therefore suggested that the weighted CN method be used only for catchments with single or similar hydrological response units and that the weighted Q method be used when there are large differences in Curve Number within the catchment, or when there are significant areas of impervious surfaces within the catchment.

Note : For more conservative design the 80 percentile antecedent storage change information from Appendix 2 could have been used, which would have given wetter antecedent conditions and consequently a higher runoff response. The information given in Section 1.9 should be used for important designs when more information is required on the appropriate antecedent storage change percentile to use.

Appendix 1 gives the 5-day and 30-day antecedent rainfall totals of various percentiles for the zone. This information may be useful to evaluate catchment moisture status prior to a natural storm of known antecedent rainfall depth as indicated in Section 2.3.1.

EXAMPLE 3 : Computation of runoff volume for design events, accounting for the joint association of rainfall and antecedent moisture status

For the catchment given in Example 2 determine the 90 percentile daily runoff depth.

Note : The 90 percentile runoff depth is the daily runoff depth that is exceeded 10% of the time. It approximates the 10-year return period amount.

Step 1 : From Figure 3.9 determine the climatic zone in which the catchment lies (i.e. Zone 403). Details of the rainfall station (SAWB No. 270119) used for the zone are given in Table 3.3.

Step 2 : Determine the hydrological soil groups and soil texture classes (Table 3.1) and the Curve Numbers applicable to each soil-cover complex for average antecedent conditions, CN-II (Table 3.2).

Subcatchment number	Hydrological soil group	Texture	CN-II
1	B	Clay	79
2	A/B	Clay	54
3	B	Sand	61

Step 3 : Table 1.7.3 can be used to identify/interpolate the relevant soil texture/depth/cover class to determine from Appendix 4 daily runoff depth (Q) for chosen risk (90 percentile) and Curve Number for average antecedent conditions (CN-II). Interpolation between the classes given in Appendix 4 (e.g. CN) should be used to determine Q.

Subcatchment number	Area (km^2)	Cover	Depth	Texture	CN-II	Q (mm)	QxArea ($mm.km^2$)
1	1.5	Sparse	Deep	Clay	79	59.7	89.5
2	.8	Dense	Intermediate	Clay	54	15.6	12.5
3	.7	Intermediate	Shallow	Sand	61	25.2	17.6
Totals	3.0						119.6

e.g. Deep, clay, sparse cover : for

CN = 70, Q = 41.8 mm

CN = 80, Q = 61.7 mm

Therefore, for CN = 79, Q = 41.8 + 0.9 x (61.7 - 41.8) mm

= 59.7 mm

$$\text{Therefore weighted runoff depth} = \frac{119.6 \text{ mm.km}^2}{3.0 \text{ km}^2} = 39.9 \text{ mm}$$

$$\text{Runoff volume} = \frac{39.9 \text{ mm} \times 3.0 \text{ km}^2 \times 1\ 000 \times 1\ 000}{1\ 000} = 119\ 600 \text{ m}^3$$

<u>Note</u> : The results from Example 3 differ from those of Example 2 when using the weighted Q due to two reasons :

1. The design rainfall depth for the 10-year return period used in Example 2 and determined from Appendix 5 was 102 mm. The frequency analyses for daily rainfall totals for the daily rainfall data base used to compute Appendix 3 is given in Appendix 4. It is evident that the value of 102 mm obtained by statistical extreme value parameter estimation is slightly higher than the 90 percentile value in the frequency analysis of the real data (92 mm).
2. By accounting for the joint association of rainfall and antecedent wetness (Appendix 3), no assumption was made as to "average" moisture status, as was made when using the 50 percentile storage change values in Appendix 2. Section 1.9 should be consulted in this regard.

EXAMPLE 4 : Peak discharge determination

Compute the peak discharge for Example 2 using both the empirical lag equations 26 and 27. The catchment characteristics are as given below.

Average slope (y) = 10%

Hydraulic length (l) = 3360 m

Catchment Curve Number (unadjusted for AMC)

$$= \frac{(79 \times 1.5) + (54 \times 0.8) + (61 \times 0.7)}{3.0} = 68.1$$

$$S' = \frac{25\,400}{CN'} - 254 = 119.0 \text{ mm}$$

Step 1 : Determine catchment lag time

Step 1.1 : Lag by the original SCS lag equation (Equation 26)

$$L = \frac{l^{0.8}\,(S' + 25.4)^{0.7}}{7\,069\,y^{0.5}}$$

Substituting into the equation

$$L = \frac{3360^{0.8}\,(119 + 25.4)^{0.7}}{7\,069 \times 10^{0.5}}$$

$$= 0.96 \text{ h}$$

Alternatively, the nomograph in Figure 3.4 can be used to solve for lag by this equation.

Step 1.2 : Lag by the Schmidt-Schulze (1984) lag equation (Equation 27)

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

Step 1.2.1 : Determine mean annual precipitation (MAP) for the location. Table 3.3 gives MAP for those rainfall stations used in each region which may be used. Thus for Zone 403 MAP = 998 mm. This may or may not be representative of your exact location's MAP. More exact values may be read off maps by Dent et al. (1988).

Step 1.2.2 : Determine 2-year return period half hour intensity ($\bar{I}_{30}$). Figure 3.1 gives the one-day two-year return period rainfall depth for the location as 64 mm. Figure 3.2 indicates the Type 3 storm distribution to be applicable. The conversion factor to determine I_{30} is given at the end of Section 2.7.2 as 0.974. Thus Thus $I_{30} = 0.974 \times 64 = 62 \text{ mm.h}^{-1}$.

Step 1.2.3 : Substituting into the equation

$$L = \frac{3^{0.35} \times 998^{1.1}}{41.67 \times 10^{0.3} \times 62^{0.87}}$$

$$= 0.97 \text{ h}$$

Alternatively the nomograph in Figure 3.5 can be used to solve for lag by this equation.

Step 2 : From Figure 3.2 determine the synthetic rainfall distribution applicable to the catchment (i.e. Type 3).

Step 3 : Determine the ratio I_a/P required for input to Figure 3.8. I_a/P is determined using either Figure 3.6, when adjusted CN is known (e.g. using weighted CN from Step 6 of Example 2), or Figure 3.7, when runoff depth (mm) is known. Since weighted runoff depth is the recommended procedure, Figure 3.7 will be used in this example. From Figure 3.7 with P = 102 mm and Q = 42.9 mm (Step 5, Example 2), $I_a/P = 0.10$

Step 4 : Given catchment area = 3 km^2

One-day rainfall depth = 102 mm

I_a/P = 0.1

Select appropriate nomograph from Figure 3.8 for synthetic storm distribution Type 3.

In this example the two estimates of lag time are almost equal.

Assume lag time = 0.97 h

Peak discharge = 16.2 $m^3.s^{-1}$

Note :

The design 10-year peak discharge would be 16.2 $m^3.s^{-1}$. As indicated in Section 1.10 of Part 1 of the document, Equation 27 has, on the basis of numerous tests on gauged catchments, been shown to give the best estimates of lag time for natural catchments. The graphical procedure can be applied with sufficient ease to undertake a sensitivity analysis on the possible errors in peak discharge due to errors in lag time estimation. The steps in this example may be used to determine peak discharge for Example 3. However, design rainfall depth will in this case be determined from Appendix 4.

EXAMPLE 5 : Determination of hydrograph shape

Determine the runoff hydrograph based on the information in Examples 2 and 5.

The computer program in Appendix 6 is used to generate the hydrograph. Data is input to the program when prompted. Prompts and inputs for the example would be as follows

INPUT CATCHMENT AREA (km^2)
3.
INPUT DESIGN DAILY RAINFALL DEPTH (mm)
102.
INPUT SYNTHETIC RAINFALL DISTRIBUTION TYPE (1 to 4)
3
INPUT RUNOFF CURVE NUMBER (ADJUSTED). IF RUNOFF DEPTH IS KNOWN, INPUT 0 FOR CN
0
INPUT DESIGN RUNOFF DEPTH (mm)
42.9
INPUT CATCHMENT LAG TIME (hours)
0.97

The resulting output is given on page 110.

****

* RAINFALL DEPTH	=	102.00000
* STORM DISTRIBUTION TYPE	=	3.0000000
* CURVE NUMBER	=	70.952084
* LAG TIME	=	.97000000
* RUNOFF DEPTH	=	42.899996
* PEAK DISCHARGE	=	16.241850

****

TIME(MINUTES)	DISCHARGE(LITRES/SEC)
609.	0.
619.	1.
630.	3.
641.	8.
651.	18.
662.	36.
672.	67.
683.	119.
694.	212.
704.	396.
715.	883.
725.	2755.
736.	5222.
746.	7948.
757.	10784.
768.	13588.
778.	15993.
789.	16242.
799.	15558.
810.	14467.
821.	13143.
831.	11664.
842.	10078.
852.	8418.
863.	6713.
873.	5006.
884.	3438.
895.	2664.
905.	2227.
916.	1931.
926.	1713.
937.	1543.
948.	1406.
958.	1294.
969.	1199.
979.	1118.
990.	1048.
1000.	986.
1011.	932.
1022.	884.
1032.	841.
1043.	802.
1053.	766.
1064.	734.
1074.	705.
1085.	678.
1096.	653.
1106.	630.
1117.	608.
1127.	588.
1138.	570.
1149.	552.
1159.	536.
1170.	521.
1180.	506.
1191.	493.
1201.	480.
1212.	468.
1223.	456.
1233.	445.
1244.	435.
1254.	425.
1265.	416.
1276.	407.
"	"

EXAMPLE 6 : Determination of Curve Number from gauged data

Assume a catchment to be near the catchment for which a design is required, with similar soil and land use characteristics and where gauged rainfall and runoff data are available. From the rainfall and runoff records the following seven runoff depths and causative rainfall depths have been identified. Section 1.5.3 issues a word of caution on the use of "small" events. The largest independent storms on record should be used.

Event No.	Rainfall depth (mm)	Runoff depth (mm)
1	80	18.8
2	120	38.9
3	50	3.2
4	75	10.7
5	55	8.3
6	72	19.5
7	60	15.0

Step 1 : Compute the Curve Number for each event using Figure 3.3. The nomograph is worked in reverse with an antecedent moisture change equal to zero assumed.

Thus for Storm 1 CN = 61.9
2 CN = 59.9
3 CN = 53.7
4 CN = 54.2
5 CN = 62.6
6 CN = 67.3
7 CN = 69.6

Alternatively Equations 7 and 5 could have been used for the above computations.

Step 2 : The median (i.e. middle ranked) CN is determined as 61.9 which may be taken as an estimate of the average Curve Number for prevailing land use/soil and climate conditions in the region.

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PART 3 : TABLES, MAPS AND NOMOGRAPHS FOR APPLICATION OF THE SCS METHOD IN SOUTHERN AFRICA

Table 3.1 Hydrological classification of soil forms and series found in southern Africa (Source : Schulze, 1984)

Legend

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

Cl - clay
S - sand
Lm - loam
0 - no/low interflow potential
X - some interflow potential
XX - high interflow potential

Soil Form	Code	Soil Series	SCS Group -ing	SCS Adjust- ment Factor	Typical Text- ural Class	Inter- flow Poten- tial
ARCADIA C/D	Ar 40	Arcadia	C/D		Cl	0
	Ar 11	Bloukrans	C/D		Cl	0
	Ar 21	Clerkness	C/D		Cl	0
	Ar 41	Eenzaam	C/D		Cl	0
	Ar 20	Gelykvlakte	C/D		Cl	0
	Ar 10	Mngazi	C/D		Cl	0
	Ar 32	Nagana	C/D		Cl	0
	Ar 12	Noukloof	C/D		Cl	0
	Ar 31	Rooidraai	C/D		Cl	0
	Ar 30	Rydalvale	C/D		Cl	0
	Ar 42	Wanstead	C/D		Cl	0
	Ar 22	Zwaarkrygen	C/D		Cl	0
AVALON B	Av 13	Ashton	A/B	+l	SLm	X
	Av 26	Avalon	B		SClLm	X
	Av 12	Banchory	A	+l/+t	S	X
	Av 27	Bergville	B/C	-t	SCl	X
	Av 37	Bezuidenhout	C	-t/-l	SCl	X
	Av 33	Bleeksand	B/C	-l	SLm	X
	Av 34	Heidelberg	B/C	-l	SLm	X
	Av 20	Hobeni	A/B	+t	LmS	X
	Av 14	Kanhym	A/B	+l	SLm	X
	Av 24	Leksand	B		SLm	X
	Av 10	Mastaba	A	+l/+t	LmS	X
	Av 32	Middelpos	B	+t/-l	S	X
	Av 31	Mooiveld	B	+t/-l	LmS	X
	Av 25	Newcastle	A/B	+t	SLm	X
	Av 17	Normandien	B	+l/-t	SCl	X
	Av 22	Rossdale	A/B	+t	S	X
	Av 16	Ruston	B	+l	SClLm	X
	Av 36	Soetmelk	B/C	-l	SClLm	X
	Av 21	Uithoek	A/B	+t	LmS	X
	Av 30	Viljoenskroon	B	+t/-l	LmS	X
AVALON (contd)	Av 23	Villiers	B		SLm	X
	Av 11	Welverdiend	A	+l/+t	LmS	X
	Av 35	Windmeul	B	+t/-l	SLm	X
	Av 15	Wolweberg	A	+l/+t	SLm	X
BAINSVLEI A/B	Bv 23	Ashkelon	A/B		SLm	X
	Bv 36	Bainsvlei	B	-l	SClLm	X
	Bv 12	Camelot	A	+t	S	X
	Bv 20	Chelsea	A	+t	LmS	X
	Bv 30	Delwery	A/B	+t/-l	LmS	X
	Bv 13	Dunkeld	A/B		SLm	X
	Bv 16	Elysium	A/B		SClLm	X
	Bv 10	Hlatini	A	+t	LmS	X
	Bv 34	Kareekuil	B	-l	SLm	X
	Bv 31	Kingston	A/B	+t/-l	LmS	X
	Bv 26	Lonetree	A/B		SClLm	X
	Bv 25	Maanhaar	A	+t	SLm	X
	Bv 11	Makong	A	+t	LmS	X
	Bv 27	Metz	B	-t	SCl	X
	Bv 22	Oosterbeek	A	+t	S	X
	Bv 37	Ottosdal	B/C	-t/-l	SCl	X
	Bv 24	Redhill	A/B		SLm	X
	Bv 32	Trekboer	A/B	+t/-l	S	X
	Bv 15	Tygerkloof	A	+t	SLm	X
	Bv 33	Vermaas	B	-l	SLm	X
	Bv 21	Vungama	A	+t	LmS	X
	Bv 35	Wedgewood	A/B	+t/-l	SLm	X
	Bv 17	Wilgenhof	B	-t	SCl	X
	Bv 14	Wykeham	A/B		SLm	X
BONHEIM C	Bo 41	Bonheim	C/D	-t	LmS	0
	Bo 20	Bushman	C		SClLm	0
	Bo 30	Dumasi	C		SClLm	0
	Bo 31	Glengazi	C/D	-t	SCl	0
	Bo 10	Kiora	C		SClLm	0
	Bo 21	Rasheni	C/D	-t	SCl	0
	Bo 11	Stanger	C/D	-t	SCl	0
	Bo 40	Weenen	C		SClLm	0

Table 3.1 (continued)

Soil Form	Code	Soil Series	SCS Group -ing	SCS Adjust- ment Factor	Typical Text- ural Class	Inter- flow Poten- tial
CARTREF C	Cf 10	Amabele	B/C	+t	LmS	0
	Cf 12	Arrochar	C		SClLm	0
	Cf 13	Byrne	C/D	-t	SCl	0
	Cf 21	Cartref	C		SLm	0
	Cf 22	Cranbrook	C		SClLm	0
	Cf 30	Grovedale	B/C	+t	S	0
	Cf 31	Kusasa	B/C	+t	SLm	0
	Cf 32	Noodhulp	C		SClLm	0
	Cf 11	Rutherglen	C		SLm	0
	Cf 20	Waterridge	B/C	+t	LmS	0
CHAMPAGNE D	Ch 11	Champagne	D		SLm	0
	Ch 21	Ivanhoe	D		SClLm	0
	Ch 10	Mposa	D		SLm	0
	Ch 20	Stratford	D		SClLm	0
CLOVELLY A/B	Cv 33	Annandale	B	-l	SLm	0
	Cv 18	Balgowan	B	-t	Cl	0
	Cv 40	Bleskop	A	+t	LmS	0
	Cv 36	Blinkklip	B	-l	SClLm	0
	Cv 17	Clovelly	B	-t	SCl	0
	Cv 28	Clydebank	B	-t	Cl	0
	Cv 35	Denhere	A/B	+t/-l	SLm	0
	Cv 46	Dudfield	A/B		SClLm	0
	Cv 11	Geelhout	A	+t	LmS	0
	Cv 25	Gutu	A	+t	SLm	0
	Cv 47	Klippan	B	-t	SCl	0
	Cv 38	Klipputs	B/C	-t/-l	Cl	0
	Cv 10	Lismore	A	+t	LmS	0
	Cv 12	Lundini	A	+t	S	0
	Cv 34	Makuya	B	-l	SLm	0
	Cv 14	Mossdale	A/B		SLm	0
	Cv 48	Nelspan	B	-t	Cl	0
	Cv 27	Newport	B	-t	SCl	0
	Cv 16	Oatsdale	A/B		SClLm	0
	Cv 23	Ofazi	A/B		SLm	0
	Cv 41	Oranje	A	-t	LmS	0
	Cv 32	Paleisheuwel	A/B	+t/-l	S	0
	Cv 31	Sandspruit	A/B	+t/-l	LmS	0
	Cv 22	Sebakwe	A	+t/-l	S	0
	Cv 45	Skipskop	A	+t	SLm	0
	Cv 21	Sonnenblom	A	+t	LmS	0
	Cv 26	Southwold	A/B		SClLm	0
CLOVELLY (contd)	Cv 15	Soweto	A	+t	SLm	0
	Cv 24	Springfield	A/B		SLm	0
	Cv 30	Sunbury	A/B	+t/-l	LmS	0
	Cv 37	Summerhill	B/C	-t/-l	SCl	0
	Cv 42	Thornhill	A	+t	S	0
	Cv 44	Torquay	A/B		SLm	0
	Cv 20	Tweefontein	A	+t	LmS	0
	Cv 43	Vaalbank	A/B		SLm	0
	Cv 13	Vidal	A/B		ClLm	0
CONSTAN -TIA B	Ct 25	Cintsa	B		Lm/SClLm	XX
	Ct 12	Constantia	B		LmS	X
	Ct 23	Dwesa	B		SLm/SClLm	XX
	Ct 22	Fencote	B		S/SClLm	XX
	Ct 13	Harkerville	B		SLm	0
	Ct 24	Kromhoek	B		SCl/SClLm	XX
	Ct 14	Noetzie	B		SLm	0
	Ct 20	Palmyra	B		LmS/SClLm	XX
	Ct 10	Strombolis	B		LmS	X
	Ct 11	Tokai	B		S	X
	Ct 21	Vlakfontein	B		LmS/SClLm	XX
	Ct 15	Wynberg	B		SLm	0
DUNDEE B/C	Du 10	Dundee	B/C		SLm	0
ESTCOURT D	Es 20	Assegaai	D		LmS/SClLm	XX
	Es 11	Auckland	D		LmS/SLm	XX
	Es 22	Avontuur	D		S/SClLm	XX
	Es 35	Balfour	D		LmS/SClLm	XX
	Es 40	Beerlaagte	D		LmS/SClLm	XX
	Es 37	Buffelsdrif	D		SCl/Cl	XX
	Es 42	Darling	D		S/SClLm	XX
	Es 13	Dohne	D		SLm/SClLm	XX
	Es 31	Elim	D		LmS/SLm	XX
	Es 33	Enkeldoorn	D		SLm/SClLm	XX
	Es 36	Estcourt	D		SClLm/SCl	XX
	Es 14	Grasslands	D		SLm/SClLm	XX
	Es 41	Heights	D		LmS/SClLm	XX
	Es 10	Houdenbeck	D		LmS/SLm	XX
	Es 21	Langkloof	D		LmS/SClLm	XX
	Es 30	Mozi	D		LmS/SLm	XX

Table 3.1 (continued)

Soil Form	Code	Soil Series	SCS Group -ing	SCS Adjust- ment Factor	Typical Text- ural Class	Inter- flow Poten- tial
ESTCOURT (contd)	Es 12	Potela	D		S/SLm	XX
	Es 16	Rosemead	D		SClLm/SCl	XX
	Es 32	Soldaatskraal	D		S/SLm	XX
	Es 34	Uitvlugt	D		SLm/SClLm	XX
	Es 15	Vredenhoek	D		LmS/SClLm	XX
	Es 17	Zintwala	D		SCl/Cl	XX
FERNWOOD A	Fw 40	Brinley	C	-w	SLm	XX
	Fw 11	Fernwood	A		SLm	0
	Fw 21	Langebaan	A		SLm	0
	Fw 42	Mambone	C	-w	SLm	XX
	Fw 10	Maputa	A		SLm	0
	Fw 20	Motopi	A		SLm	0
	Fw 22	Saldanha	A		SLm	0
	Fw 12	Sandveld	A		SLm	0
	Fw 30	Shasha	B	-w	SLm	XX
	Fw 41	Soetvlei	C	-w	SLm	XX
	Fw 32	Trafalgar	B	-w	SLm	XX
	Fw 31	Warrington	B	-w	SLm	XX
GLENCOE B	Gc 16	Appam	B		SClLm	X
	Gc 33	Beatrix	B/C	-l	SLm	X
	Gc 20	Boskuil	A/B	+t	LmS	X
	Gc 15	Delmas	A/B	+t	SLm	X
	Gc 10	Driepan	A/B	+t	LmS	X
	Gc 24	Dunbar	B		SLm	X
	Gc 26	Glencoe	B		SClLm	X
	Gc 37	Graspan	C	-t/-l	SCl	XX
	Gc 11	Hartog	A/B	+t	LmS	XX
	Gc 13	Klipstapel	B		SLm	XX
	Gc 32	Kwezana	B	+t/-l	S	XX
	Gc 34	Leeudoorn	B/C	-l	SLm	XX
	Gc 36	Leslie	B/C	-l	SClLm	XX
	Gc 27	Ontevrede	B/C	-t	SCl	XX
	Gc 21	Penhoek	A/B	+t	LmS	XX
	Gc 31	Ribblesdale	B	+t/-l	LmS	XX
	Gc 17	Shotton	B/C	-t	SCl	XX
	Gc 23	Strathrae	B		SLm	XX
	Gc 22	Talana	A/B	+t	S	XX
	Gc 12	Tranendal	A/B	+t	S	XX
	Gc 35	Uitskot	B	+t/-l	SLm	XX
	Gc 30	Vlakpan	B	+t/-l	LmS	XX
	Gc 14	Weltevrede	B		SLm	XX
	Gc 25	Wesselsnek	A/B	+t	SLm	XX
GLENROSA B/C	Gr 28	Achterdam	B/C		SClLm	X
	Gr 27	Dothole	B/C		SClLm	X
	Gr 24	Dunvegan	B/C		SLm	X
	Gr 15	Glenrosa	B	+t	SLm	X
	Gr 13	Kanonkop	B/C		SLm	X
	Gr 22	Knapdaar	B	+t	S	X
	Gr 26	Lekfontein	B/C		SClLm	X
	Gr 25	Lomondo	B	+t	SLm	X
	Gr 21	Majeng	B	+t	LmS	X
	Gr 20	Malgas	B	+t	LmS	X
	Gr 10	Martindale	B	+t	LmS	X
	Gr 11	Oribi	B	+t	LmS	X
	Gr 12	Paardeberg	B	+t	S	X
	Gr 14	Platt	B/C		SLm	X
	Gr 29	Ponda	C	-t	SCl	X
	Gr 18	Robmore	B/C		SClLm	X
	Gr 19	Saintfaiths	C	-t	SCl	X
	Gr 23	Southfield	B/C		SLm	X
	Gr 17	Trevanian	B/C		SClLm	X
	Gr 16	Williamson	B/C		SClLm	X
GRIFFIN A	Gf 10	Burnside	A		SLm	0
	Gf 11	Cleveland	A		SClLm	0
	Gf 32	Cradock	B	-t/-l	SCl	0
	Gf 20	Erfdeel	A		SLm	0
	Gf 13	Farmhill	A/B	-t	Cl	0
	Gf 12	Griffin	A/B	-t	SCl	0
	Gf 22	Ixopo	A/B	-t	SCl	0
	Gf 30	Runnymeade	A/B	-l	SLm	0
	Gf 33	Slagkraal	B	-t/-l	Cl	0
	Gf 21	Umzimkulu	A		SClLm	0
	Gf 31	Welgemoed	A/B	-l	SClLm	0
	Gf 23	Zwagershoek	A/B	-t	Cl	0
HOUWHOEK C	Hh 20	Albertinia	C		LmS	X
	Hh 10	Elgin	C		LmS	X
	Hh 21	Garcia	C		SLm	XX
	Hh 31	Gouna	B/C	+t	SLm	XX
	Hh 30	Houwhoek	B/C	+t	S	X
	Hh 11	Stormsrivier	C		SLm	XX

Table 3.1 (continued)

Soil Form	Code	Soil Series	SCS Group -ing	SCS Adjust- ment Factor	Typical Text- ural Class	Inter- flow Poten- tial
HUTTON A	Hu 10	Alloway	A		LmS	0
	Hu 11	Arnot	A		LmS	0
	Hu 18	Balmoral	A/B	-t	Cl	0
	Hu 25	Bontberg	A		SLm	0
	Hu 22	Chester	A		S	0
	Hu 24	Clansthal	B		SLm	0
	Hu 27	Doveton	A/B	-t	SCl	0
	Hu 17	Farningham	A/B	-t	SCl	0
	Hu 31	Gaudam	A	-l/+t	LmS	0
	Hu 47	Hardap	A/B	-t	SCl	0
	Hu 16	Hutton	A		SClLm	0
	Hu 21	Joubertina	A		LmS	0
	Hu 15	Kyalami	A		SLm	0
	Hu 23	Lichtenburg	A		SLm	0
	Hu 40	Lowlands	A		LmS	0
	Hu 43	Maitengwe	A		SLm	0
	Hu 37	Makatini	B	-t/-l	SCl	0
	Hu 44	Malonga	A		SLm	0
	Hu 33	Mangano	A/B	-l	SLm	0
	Hu 38	Marikana	B	-t/-l	Cl	0
	Hu 14	Middelburg	A		SLm	0
	Hu 48	Minhoop	A/B	-t	Cl	0
	Hu 32	Moriah	A	-l/+t	S	0
	Hu 26	Msinga	A		SClLm	0
	Hu 41	Nyala	A		LmS	0
	Hu 35	Portsmouth	A	-l/+t	SLm	0
	Hu 42	Quaggafontein	A		S	0
	Hu 30	Roodepoort	A	-l/+t	LmS	0
	Hu 46	Shigalo	A		SClLm	0
	Hu 36	Shorrocks	A/B	-l	SClLm	0
	Hu 12	Stonelaw	A		S	0
	Hu 45	Vergenoeg	A		SLm	0
	Hu 28	Vimy	A/B	-t	Cl	0
	Hu 13	Wakefield	A		SLm	0
	Hu 20	Whithorn	A		LmS	0
	Hu 34	Zwartfontein	A/B	-l	ClLm	0
INANDA A	Ia 10	Fountainhill	A		SClLm	0
	Ia 11	Inanda	A		SCl	0
	Ia 12	Sprinz	A		Cl	0
INHOEK C	Ik 11	Coniston	C/D	-t	SCl	0
	Ik 10	Cromley	C		SClLm	0
	Ik 21	Drydale	C/D	-t	SCl	0
	Ik 20	Inhoek	C		SClLm	0
KATSPRUIT C/D	Ka 10	Katspruit	C/D		SCl	0
	Ka 20	Killarney	C/D		SCl	0
KRANSKOP A	Kp 10	Kipipiri	A		SClLm	0
	Kp 11	Kranskop	A		SCl	0
	Kp 12	Umbumbulu	A		Cl	0
KROONSTAD C/D	Kd 17	Avoca	C/D		SClLm/SCl	XX
	Kd 16	Bluebank	C/D		SClLm/SCl	XX
	Kd 22	Katarra	C/D		S/SClLm	XX
	Kd 20	Koppies	C/D		LmS/SClLm	XX
	Kd 13	Kroonstad	C/D		SLm/SClLm	XX
	Kd 14	Mkambati	C/D		SLm/SClLm	XX
	Kd 10	Rocklands	C/D		LmS/SLm	XX
	Kd 15	Slangkop	C/D		LmS/SClLm	XX
	Kd 12	Swellengift	C	+t	S/SLm	XX
	Kd 18	Uitspan	C/D		SClLm/SCl	XX
	Kd 21	Umtentweni	C/D		LmS/SClLm	XX
	Kd 11	Velddrif	C/D		LmS/SLm	XX
	Kd 19	Volksrust	D	-t	SCl/Cl	XX
LAMOTTE A/B	Lt 10	Alsace	A/B		LmS	X
	Lt 21	Burgundy	B	+c	LmS	XX
	Lt 14	Chamond	A/B		SLm	X
	Lt 22	Franschhoek	B	+c	LmS	XX
	Lt 25	Hooghalen	B	+c	SLm	XX
	Lt 12	Lamotte	A/B		LmS	X
	Lt 11	Laparis	A/B		LmS	X
	Lt 15	Lillesand	A/B		SLm	X
	Lt 20	Lorraine	B	+c	LmS	XX
	Lt 24	Ringwood	B	+c	SLm	XX
	Lt 23	Tillberga	B	+c	SLm	XX
	Lt 13	Vevey	A/B		SLm	X
LONGLANDS C	Lo 22	Albany	C/D	-t	SClLm	XX
	Lo 32	Chitsa	C/D	-t	SClLm	XX

Table 3.1 (continued)

Soil Form	Code	Soil Series	SCS Group -ing	SCS Adjust- ment Factor	Typical Text- ural Class	Inter- flow Poten- tial
LONGLANDS (contd)	Lo 21	Longlands	C		SLm	XX
	Lo 10	Orkney	C		LmS	XX
	Lo 30	Tayside	C		S	XX
	Lo 31	Vaalsand	C		SLm	XX
	Lo 20	Vasi	C		LmS	XX
	Lo 11	Waaisand	C		SLm	XX
	Lo 12	Waldene	C/D	-t	SClLm	XX
	Lo 13	Winterton	C	-t	SCl	XX
MAGWA A/B	Ma 12	Frazer	A/B		Cl	0
	Ma 11	Magwa	A/B		SCl	0
	Ma 10	Milford	A	+t	SClLm	0
MAYO C	My 10	Mayo	C		SClLm	0/X
	My 11	Msinsini	C/D	-t	SCl	0/X
	My 21	Pafuri	C/D	-t	SCl	0/X
	My 20	Tshipise	C		SCl	0/X
MILKWOOD C	Mw 10	Dansland	C		SClLm	0/X
	Mw 21	Graythorne	C/D	-t	SCl	0/X
	Mw 11	Milkwood	C/D	-t	SCl	0/X
	Mw 20	Sunday	C		SClLm	0/X
MISPAH C	Ms 21	Hillside	C		SClLm	XX
	Ms 22	Kalkbank	C		SClLm	XX
	Ms 11	Klipfontein	C		SClLm	XX
	Ms 12	Loskop	C		SClLm	XX
	Ms 23	Misgund	C		SClLm	XX
	Ms 10	Mispah	C		SClLm	XX
	Ms 20	Muden	C		SClLm	XX
	Ms 13	Plettenberg	C		SClLm	XX
	Ms 14	Winchester	C		SClLm	XX
	Ms 24	Vredendal	C		SClLm	XX
NOMANCI B	No 11	Lusiki	B		SCl	0
	No 10	Nomanci	B		SClLm	0
OAKLEAF B	Oa 43	Allanridge	B		SLm	0
	Oa 45	Calueque	A/B	+t	SLm	0
	Oa 21	Doornlaagte	A/B	+t	LmS	0
OAKLEAF (contd)	Oa 25	Hazelwood	A/B	+t	SLm	0
	Oa 17	Highflats	B/C	-t	SCl	0
	Oa 22	Holpan	A/B	+t	S	0
	Oa 36	Jozini	B		SClLm	0
	Oa 23	Kirkton	B		SLm	0
	Oa 13	Klipplaat	B		SLm	0
	Oa 37	Koedoesvlei	B/C	-t	SCl	0
	Oa 16	Leeufontein	B		SClLm	0
	Oa 26	Letaba	B		SClLm	0
	Oa 34	Levubu	B		SLm	0
	Oa 46	Limpopo	B		LClLm	0
	Oa 41	Lovedale	A/B	+t	LmS	0
	Oa 11	Madwaleni	A/B	+t	LmS	0
	Oa 24	Magersfontein	B		SLm	0
	Oa 27	Makulek	B/C	-t	SCl	0
	Oa 12	Mbanyana	A/B	+t	S	0
	Oa 47	Mutale	B/C	-t	SCl	0
	Oa 42	Naulila	A/B	+t	S	0
	Oa 30	Oakleaf	A/B	+t	LmS	0
	Oa 44	Okavango	B		SLm	0
	Oa 31	Oshikango	A/B	+t	LmS	0
	Oa 15	Pollock	A/B	+t	SLm	0
	Oa 14	Rockford	B.		SLm	0
	Oa 32	Sezela	A/B	+t	S	0
	Oa 10	Smaldeel	A/B	+t	LmS	0
	Oa 33	Vaalriver	B		SLm	0
	Oa 35	Venda	A/B	+t	SLm	0
	Oa 40	Voorspoed	A/B	+t	LmS	0
	Oa 20	Warrenton	A/B	+t	LmS	0
PINEDENE B	Pn 27	Airlie	B/C	-t	SCl	X
	Pn 12	Bethlehem	A	+t/+l	S	X
	Pn 25	Chatsworth	A/B	+t	SLm	X
	Pn 15	Eykendal	A	+t/+l	SLm	X
	Pn 10	Fortuin	A	+t/+l	LmS	X
	Pn 13	Graymead	A/B	+l	SLm	X
	Pn 22	Hermanus	A/B	+t	S	X
	Pn 17	Kilburn	B	-t/+l	SCl	X
	Pn 32	Kleinrivier	B	+t/+l	S	X
	Pn 36	Klerksdorp	B/C	-l	SClLm	X
	Pn 34	Nagtwagt	B/C	-l	SLm	X
	Pn 33	Oewer	B/C	-l	SLm	X
	Pn 16	Ouwerf	A/B	+l	SClLm	X
	Pn 30	Papiesvlei	B	+t/-l	LmS	X
	Pn 14	Pinedene	A/B	+l	SLm	X

Table 3.1 (continued)

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

Soil Form	Code	Soil Series	SCS Group -ing	SCS Adjust- ment Factor	Typical Text- ural Class	Inter- flow Poten- tial
STERK- SPRUIT	Ss 17	Driebaden	D		SCl	X
	Ss 21	Graafwater	D		LmS	X
	Ss 25	Grootfontein	D		LmS	X
	Ss 20	Halseton	D		LmS	X
	Ss 24	Hartbees	D		SLm	X
	Ss 12	Ruacana	D		S	X
	Ss 22	Silwana	D		S	X
	Ss 23	Stanford	D		SLm	X
	Ss 26	Sterkspruit	D		SClLm	X
	Ss 16	Swaerskloof	D		SClLm	X
	Ss 11	Tina	D		LmS	X
	Ss 14	Toleni	D		SLm	X
SWARTLAND C/D	Sw 12	Breidbach	D	-t	Cl	X
	Sw 21	Broekspruit	C/D		SCl	X
	Sw 32	Hogsback	D	-t	Cl	X
	Sw 40	Malakata	C/D		SCl	X
	Sw 41	Nyoka	C/D		SCl	X
	Sw 42	Omdraai	D	-t	Cl	X
	Sw 22	Prospect	D	-t	Cl	X
	Sw 10	Reveillie	C/D		SClLm	X
	Sw 30	Rosehill	C/D		SClLm	X
	Sw 11	Skilderkrans	C/D		SCl	X
	Sw 31	Swartland	C/D		SCl	X
	Sw 20	Uitsicht	C/D		SClLm	X
TAMBAN- KULU C	Tk 10	Fenfield	C		SClLm	X
	Tk 20	Loshoek	C		SClLm	X
	Tk 21	Masala	C/D	-t	SCl	X
	Tk 11	Tabankulu	C/D	-t	SCl	X
VALS- RIVIER C/D	Va 31	Arniston	C/D		SCl	X
	Va 32	Chalumna	C	-t	Cl	X
	Va 21	Craven	C/D		SCl	0
	Va 30	Herschel	C/D		SClLm	X
	Va 12	Lilydale	D	-t	Cl	0
	Va 41	Lindley	C/D		SCl	X
	Va 22	Marienthal	C	-t	Cl	0
	Va 42	Sheppardvale	D	-t	Cl	X
	Va 10	Sunnyside	C/D		SClLm	0

Table 3.1 (continued)

Soil Form	Code	Soil Series	SCS Group -ing	SCS Adjust- ment Factor	Typical Text- ural Class	Inter- flow Poten- tial
VALS- RIVIER (contd)	Va 40	Valsrivier	C/D		SClLm	X
	Va 11	Waterval	C/D		SCl	0
	Va 20	Zuiderzee	C/D		SClLm	0
VILA- FONTES A/B	Vf 45	Blombosch	A/B		SLm/SClLm	XX
	Vf 23	Blythdale	A/B		SLm/SClLm	XX
	Vf 31	Brenton	A/B		LmS	XX
	Vf 24	Chantilly	A/B		CLm/SClLm	XX
	Vf 44	Dassenhoek	A/B		SLm/SClLm	XX
	Vf 21	Fairbreeze	A/B		LmS/SCLm	XX
	Vf 43	Geelbek	A/B		SLm/SClLm	XX
	Vf 11	Hudley	A/B		LmS	XX
	Vf 22	Klaarwater	A/B		LmS/SClLm	XX
	Vf 34	Knysna	A/B		SLm	XX
	Vf 40	Kransduinen	A/B		LmS/SClLm	XX
	Vf 20	Matigulu	A/B		LmS/SClLm	XX
	Vf 41	Mazeppa	A/B		LmS/SClLm	XX
	Vf 35	Meulvlei	A/B		SLm	XX
	Vf 10	Moreland	A/B		LmS	XX
	Vf 14	Moyeni	A/B		SLm	XX
	Vf 25	Nhamacala	A/B		SLm/SClLm	XX
	Vf 33	Rheebok	A/B		SLm	XX
	Vf 30	Sedgefield	A/B		LmS	XX
	Vf 32	Swinton	A/B		LmS	XX
	Vf 13	Tinley	A/B		SLm	XX
	Vf 42	Vallance	A/B		LmS/SClLm	XX
	Vf 15	Vilafontes	A/B		SLm	XX
	Vf 12	Zeekoe	A/B		LmS	XX
WASBANK C	Wa 12	Burford	C		SClLm	XX
	Wa 13	Endicott	C/D	-t	SCl	XX
	Wa 30	Hamman	B/C	+t	S	XX
	Wa 10	Hoopstad	B/C	+t	LmS	XX
	Wa 11	Kromvlei	C		SLm	XX
	Wa 20	Rondevlei	B/C	+t	LmS	XX
	Wa 31	Sandvlei	B/C	+t	SClLm	XX
	Wa 22	Warrick	C		SClLm	XX
	Wa 21	Wasbank	C		SLm	XX
	Wa 32	Winterveld	C		SClLm	XX

Soil Form	Code	Soil Series	SCS Group -ing	SCS Adjust- ment Factor	Typical Text- ural Class	Inter- flow Poten- tial
WESTLEIGH C	We 10	Chinde	B/C	+t	LmS	X
	We 32	Davel	C		SClLm	X
	We 22	Devon	C		SClLm	X
	We 20	Kosi	B/C	+t	LmS	X
	We 30	Langkuil	B/C	+t	S	X
	We 31	Paddock	B/C	+t	SLm	X
	We 12	Rietvlei	C		SClLm	X
	We 13	Sibasa	D	-t	SCl	X
	We 11	Westleigh	C		SLm	X
	We 21	Witsand	C		SLm	X
WILLOW- BROOK D	Wo 21	Chinyika	D		SCl	0
	Wo 10	Emfuleni	D		SClLm	0
	Wo 20	Sarasdale	D		SClLm	0
	Wo 11	Willowbrook	D		SCl	0

Table 3.2a Runoff Curve Numbers for selected agricultural, suburban and urban land uses

LAND USE	TREATMENT/PRACTICE/DESCRIPTION	HYDROLOGICAL CONDITION	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	Poor	72	77	81	85	88	90	91
	Straight row	Good	67	73	78	82	85	87	89
	Planted on contour	Poor	70	75	79	82	84	86	88
	Planted on contour	Good	65	70	75	79	82	84	86
	Conservation structures	Poor	66	70	74	77	80	81	82
	Conservation structures	Good	62	67	71	75	78	80	81
Garden and			45	56	66	72	77	80	83
truck crops	Straight row	Good	68	71	75	79	81	83	84
Small grain	Straight row	Poor	65	71	76	80	84	86	88
	Straight row	Good	63	69	75	79	83	85	87
	Planted on contour	Poor	63	69	74	79	82	84	85
	Planted on contour	Good	61	67	73	78	81	83	84
	Planted on contour - winter rainfall region	Good	63	66	70	75	78	80	81
	Conservation structures	Poor	61	67	72	76	79	81	82
	Conservation structures	Good	59	65	70	75	78	80	81
Close seeded legumes or Rotational meadow	Straight row	Poor	66	72	77	81	85	87	89
	Straight row	Good	58	65	72	75	81	84	85
	Planted on contour	Poor	64	70	75	80	83	84	85
	Planted on contour	Good	55	63	69	74	78	81	83
	Conservation structure	Poor	63	68	73	77	80	82	83
	Conservation structure	Good	51	60	67	72	76	78	80
Sugarcane	Straight row: trash burnt	-	43	55	65	72	77	80	82
	Straight row: trash mulch	-	45	56	66	72	77	80	83
	Straight row: limited cover	-	67	73	78	82	85	87	89
	Straight row: partial cover	-	49	60	69	73	79	82	84
	Straight row: complete cover	-	39	50	61	68	74	78	80
	Planted on contour: limited cover	-	65	70	75	79	82	84	86
	Planted on contour: partial cover	-	25	46	59	67	75	80	83
	Planted on contour: complete cover	-	6	14	35	59	70	75	79
Pasture or veld (range)	-	Poor	68	74	79	83	86	88	89
	-	Fair	49	61	69	75	79	82	84
	-	Good	39	51	61	68	74	78	80
	Planted on contour	Poor	47	57	67	75	81	85	88
	Planted on contour	Fair	25	46	59	67	75	80	83
	Planted on contour	Good	6	14	35	59	70	75	79
Irrigated pasture		Good	35	41	48	57	65	68	70
Meadow		Good	30	45	58	65	71	75	81
Woods		Poor	45	56	66	72	77	80	83
		Fair	36	49	60	68	73	77	79
		Good	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	Good	39	44	53	61	66	69	71
Forests/ plantations	Humus depth 25 mm; Compactness:	compact	52	62	72	77	82	85	87
		moderate	48	58	68	73	78	82	85
		loose/friable	37	49	60	66	71	74	77
	Humus depth 50 mm; Compactness:	compact	48	58	68	73	78	82	85
		moderate	42	54	65	70	75	78	81
		loose/friable	32	45	57	62	67	71	74
	Humus depth 100mm; Compactness:	compact	41	53	64	69	74	77	80
		moderate	34	47	59	64	69	72	75
		loose/friable	23	37	50	56	61	64	67
	Humus depth 150mm; Compactness:	compact	37	49	60	66	71	74	77
		moderate	30	43	56	61	66	69	72
		loose/friable	18	33	47	52	57	61	65
Urban/suburban land uses	Open spaces, parks, cemeteries	Good (75% + grass cover)	39	51	61	68	74	78	80
		Fair (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 500m^2	65% impervious	77	81	85	88	90	91	92
	1000m^2	38% impervious	61	69	75	80	83	85	87
	1350m^2	30% impervious	57	65	72	77	81	84	86
	2000m^2	25% impervious	54	63	70	76	80	83	85
	4000m^2	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

Table 3.2b Runoff Curve Numbers for conservation tillage (after Rawls and Richardson, 1983)

LAND USE	COVER TREATMENT OR PRACTICE	HYDROLOGICAL CONDITION	RUNOFF CURVE NUMBERS BY HYDROLOGICAL SOIL GROUP A	B	C	D
Fallow	Straight row		77	86	91	94
	Straight row + conservation tillage	Poor*	75	84	89	92
	Straight row + conservation tillage	Good°	74	83	87	90
Row crops	Straight row	Poor	72	81	88	91
	Straight row	Good	67	78	85	89
	Straight row + conservation tillage	Poor*	71	79	86	89
	Straight row + conservation tillage	Good°	64	75	82	85
	Planted on contour	Poor	70	79	84	88
	Planted on contour	Good	65	84	82	86
	Planted on contour + conservation tillage	Poor*	69	78	83	87
	Planted on contour + conservation tillage	Good°	64	74	80	84
	Conservation structures	Poor	66	74	80	82
	Conservation structures	Good	62	71	78	81
	Conservation structures + conservation tillage	Poor*	65	73	79	81
	Conservation structures + conservation tillage	Good°	61	70	76	79
Small grains	Straight row	Poor	65	76	84	88
	Straight row	Good	63	75	83	87
	Straight row + conservation tillage	Poor*	64	74	82	86
	Straight row + conservation tillage	Good°	60	72	80	84
	Planted on contour	Poor	63	74	82	85
	Planted on contour	Good	61	73	81	84
	Planted on contour + conservation tillage	Poor*	62	73	81	84
	Planted on contour + conservation tillage	Good°	60	72	79	82
	Conservation structures	Poor	61	72	79	82
	Conservation structures	Good	59	70	78	81
	Conservation structures + conservation tillage	Poor*	60	71	78	81
	Conservation structures + conservation tillage	Good°	58	69	76	79

* Less than 20 % of the surface is covered with residue (less than 800 kg/ha for row crops or 350 kg/ha for small grain).

° More than 20 % of the surface is covered with residue (more than 850 kg/ha for row crops or 350 kg/ha for small grain).

Table 3.2c Runoff Curve Numbers for use with LANDSAT Data (Jackson and Rawls, 1981)

Land Cover Category	Curve Numbers for Hydroloical Soil Group A	B	C	D
Agriculture	63	69	77	82
Open Space	36	60	73	78
Forest	25	55	70	77
Disturbed Land	72	82	88	90
Residential	61	76	84	88
Paved	98	98	98	98
Commercial-Industrial	84	88	90	93

Table 3.3 Listing of relevant information on rainfall stations representing 712 climatic zones in southern Africa

ZONE	STATION NUMBER	LAT (MINUTES)	LONG (MINUTES)	LAT (DEG&MIN)	LONG (DEG&MIN)	ELEV (M)	START YEAR	END YEAR	LEN*	MAP (MM)	STATION NAME
1*	020719B	2039	1104	3359	1824	763	1908	1984	30		TABLE MTN DISA HEAD
2	020689	2039	1103	3359	1823	655	1906	1984	63	1282.1	TABLE MTN WOODHEAD
3	020716	2036	1105	3356	1825	107	1906	1965	47	736.8	TABLE MTN TAMBOER
4	004702	2052	1104	3412	1824	76	1951	1984	28	596.4	KOGELFONTEIN
5	021130	2020	1115	3340	1835	42	1918	1967	36	366.9	PHILADELPHIA
6	021055	2035	1112	3355	1832	15	1906	1984	69	472.5	CAPE TOWN MAITLAND
7	021260	2030	1119	3350	1839	152	1900	1984	72	605.1	DURBANVILLE (POL)
8	021655	2036	1132	3356	1852	122	1878	1984	90	711.8	STELLENBOSCH (TNK)
9	006065	2044	1143	3404	1903	564	1927	1984	47	1605.9	NIEWEBERG (BOS)
10	005880	2050	1141	3410	1901	277	1926	1973	33	1067.3	MORNING STAR
11	005612	2053	1132	3413	1852	533	1955	1984	27	1258.9	STEENBRAS NO.2
12	005771	2061	1136	3421	1856	21	1953	1984	25	1104.8	BETTYS BAY
13	006167	2057	1146	3417	1906	402	1938	1983	40	931.3	HIGHLANDS (BOS)
14	006192	2051	1146	3411	1906	262	1924	1984	53	659.5	LEBANON (BOS)
15	006332	2042	1152	3402	1912	335	1932	1984	47	778.7	RUSTFONTEIN
16	006031	2041	1142	3401	1902	1372	1972	1984	11	2962.5	JONKERSHOEK(DISA)
17	022116	2036	1144	3356	1904	274	1920	1961	37	1838.0	DRIEFONTEIN (BOS)
18	022113	2033	1144	3353	1904	223	1919	1984	55	818.2	LA MOTTE (BOS)
19	021823	2023	1138	3343	1858	125	1878	1984	97	855.9	PAARL (TNK)
20	041417	2007	1124	3327	1844	183	1877	1984	91	450.3	MALMESBURY (TNK)
21	AWS0027	1997	1122	3317	1842	170	1931	1982	51	393.0	HOOGGELEE
22	040604	1984	1101	3304	1821	37	1907	1984	68	314.2	HOPEFIELD (POL)
23	040653	2004	1103	3324	1823	244	1891	1984	70	472.4	THE TOWERS
24	040035	1985	1082	3305	1802	6	1912	1984	56	230.6	LANGEBAAN (POL)
25	020866	2036	1109	3356	1829	40	1850	1984	126	625.3	ROYAL OBSERVATORY
26	106408	1909	1094	3149	1814	12	1951	1984	22	184.4	DORINGBAAI
27	084059	1949	1112	3229	1832	15	1936	1984	37	266.1	REDELINGHUYS (POL)
28	062444	1975	1126	3255	1846	229	1879	1984	87	464.5	PIKETBERG (POL)
29	062379	1969	1123	3249	1843	550	1940	1982	26	838.5	HELDERVUE
30	041871	1981	1140	3301	1900	137	1914	1984	31	460.9	PORTERVILLE (MUN)
31	041713	2003	1134	3323	1854	128	1937	1983	36	647.6	RIEBEEK KASTEEL (MUN)
32	042227	1997	1149	3317	1909	165	1877	1984	93	470.6	TULBAGH (POL)
33	022004	2015	1141	3335	1901	185	1931	1984	48	607.0	WELBEDACHT
34	022038	2018	1143	3338	1903	185	1904	1984	77	748.0	VRUGBAAR
35	022368	2017	1154	3337	1914	260	1932	1977	42	998.4	SWARTVLEI
36	022521	2021	1159	3341	1919	225	1900	1984	73	589.4	RAWSONVILLE (POL)
37	022504	2034	1157	3354	1917	400	1932	1984	46	719.2	WELGEGUND
38	022539	2040	1158	3400	1918	350	1924	1984	54	614.3	VILLIERSDORP
39	007699	2049	1193	3409	1953	162	1932	1984	39	417.6	BLYDSKAP
40	006733	2053	1166	3413	1926	244	1877	1984	83	528.3	CALEDON (POL)
41	006527	2057	1159	3417	1919	213	1918	1984	58	493.1	TUSSENBEIDE
42	006415	2065	1154	3425	1914	24	1935	1984	42	637.5	HERMANUS (MUN)
43	006836	2067	1167	3427	1927	15	1925	1984	46	528.4	STANFORD (SKL)
44	006612	2053	1161	3413	1921	122	1920	1984	47	378.7	BOONTJIESKRAAL
45	003032	2072	1202	3432	2002	91	1875	1984	103	466.5	BREDASDORP (POL)
46	002885	2085	1200	3445	2000	12	1911	1984	57	470.8	ZOETENDALS VALLEI
47	007595	2066	1192	3426	1952	101	1924	1971	31	318.1	MIERKRAAL
48	008470	2059	1218	3419	2018	168	1933	1984	44	384.0	PLAATJES KRAAL
49	024146	2036	1206	3356	2006	120	1925	1983	53	266.8	BONNIEVALE (SKL)
50	022759	2019	1166	3339	1926	221	1880	1984	104	263.4	WORCESTER (TNK)
51	023678	2028	1193	3348	1953	183	1877	1984	95	322.1	ROBERTSON (TNK)
52	023674	2025	1193	3345	1953	375	1927	1984	52	496.7	DASSIESHOEK
53	023602	2012	1192	3332	1952	1128	1942	1984	33	272.7	SOUTRIVIER
54	042280	1990	1151	3310	1911	400	1953	1984	27	954.9	REMHOOGTE
55	042802	2002	1164	3322	1924	540	1932	1984	45	378.8	AGTERFONTEIN
56	042581	1991	1160	3311	1920	1030	1932	1984	43	650.4	BOKVELDSKLOOF

Table 3.3 (continued)

ZONE	STATION NUMBER	LAT (MINUTES)	LONG (MINUTES)	LAT (DEG&MIN)	LONG (DEG&MIN)	ELEV (M)	START YEAR	END YEAR	LEN	MAP (MM)	STATION NAME
57	085112	1943	1143	3223	1903	1120	1908	1984	59	683.9	ALGERIA (BOS)
58	084558	1938	1129	3218	1849	408	1926	1984	52	498.8	ELANDSFONTEIN
59	084701	1931	1134	3211	1854	91	1869	1984	93	207.1	CLANWILLIAM (POL)
60	085112	1943	1143	3223	1903	1120	1908	1984	59	683.9	ALGERIA (BOS)
61	063718	1978	1166	3258	1926	1066	1925	1975	36	377.9	EXCELSIOR
62	085309	1929	1152	3209	1912	338	1898	1984	78	220.9	MERTENHOF
63	044050	2000	1202	3320	2002	774	1886	1984	53	219.6	TOUWSRIVIER (SAR)
64	045134	1994	1235	3314	2035	896	1878	1984	60	155.9	MATJIESFONTEIN
65	087186	1926	1207	3206	2007	1384	1933	1984	49	370.2	AGTERKOP
66	109785	1895	1197	3135	1957	1055	1928	1984	47	166.4	BO-DOWNES
67	138041	1871	1292	3111	2132	1219	1913	1984	63	155.5	GORAAS
68	089385	1945	1273	3225	2113	1650	1934	1984	44	293.5	RHENOSTERVLEI
69	066027	1977	1231	3257	2031	1320	1925	1984	46	277.7	OUMURE
70	067074	1964	1263	3244	2103	1094	1932	1984	38	175.0	ANYSRIVIER
71	068010	1960	1291	3240	2131	732	1910	1984	62	135.1	MERWEVILLE (POL)
72	045611	1992	1251	3312	2051	649	1901	1984	60	114.6	LAINGSBURG (MUN)
73	044765	1995	1226	3315	2026	1064	1899	1975	65	269.1	PIETER MEINTJIES
74	046058	2009	1261	3329	2101	411	1920	1984	50	183.0	BUFFELSVLEI
75	024101	2022	1204	3342	2004	375	1931	1966	28	173.1	MIDDLEVOETPAD
76	025162	2023	1236	3343	2036	494	1919	1975	48	129.8	BELLAIR DAM
77	025414	2034	1244	3354	2044	375	1925	1984	57	279.5	BARRYDALE (POL)
78	025599	2039	1250	3359	2050	433	1898	1984	73	1016.7	STRAWBERRY HILL
79	026510	2040	1277	3400	2117	305	1936	1984	45	638.8	GARCIA (BOS)
80	008782	2042	1227	3402	2027	143	1888	1984	81	742.8	SWELLENDAM (TNK)
81	009365	2045	1244	3405	2044	311	1944	1984	24	528.8	VAN REENENS CREST
82	009783	2044	1258	3404	2058	98	1920	1984	54	454.7	BLACKDOWN
83	011132	2052	1296	3412	2136	168	1924	1984	52	438.4	ALBERTINIA (POL)
84	011617	2057	1310	3417	2150	20	1937	1984	35	362.7	DIE EILAND
85	012393	2044	1333	3404	2213	12	1900	1984	72	509.7	GREAT BRAK RIVER
86	028536	2036	1337	3356	2217	297	1925	1984	56	645.2	KLEINFONTEIN
87	028415	2035	1334	3355	2214	457	1919	1984	56	1030.6	JONKERSBERG (BOS)
88	028775	2035	1346	3355	2226	510	1954	1984	27	961.5	WITFONTEIN (BOS)
89	028407	2027	1334	3347	2214	411	1926	1984	50	241.6	GROOTDOORNRIVIER
90	027302	2012	1301	3332	2141	228	1877	1984	91	192.5	CALITZDORP (POL)
91	046479	2010	1276	3330	2116	549	1878	1984	96	318.1	LADISMITH (TNK)
92	028335	2015	1332	3335	2212	315	1878	1984	94	242.2	OUDTSHOORN (TNK)
93	047716	2006	1314	3326	2154	579	1928	1984	50	423.6	KRUISRIVIER
94	048051	2001	1322	3321	2202	1800	1950	1984	33	718.7	DEWETSVLEI (BOS)
95	047801	2001	1315	3321	2155	1140	1972	1984	11	520.7	KLIPHUISVLEI (BOS)
96	048043	1993	1322	3313	2202	602	1877	1984	86	165.4	PRINCE-ALBERT (TNK)
97	068857	1967	1319	3247	2159	549	1881	1984	79	118.8	LEEU GAMKA (SAR)
98	091288	1938	1330	3218	2210	847	1912	1984	61	183.0	GRANTHAM
99	114505	1913	1336	3153	2216	1402	1925	1982	51	182.4	DRIEFONTEIN
100	090673	1933	1313	3213	2153	1049	1912	1954	37	167.6	RIETVLEI
101	090196	1936	1297	3216	2137	1049	1912	1984	41	171.2	TAFELBERG
102	091782	1922	1347	3202	2227	1536	1933	1978	42	240.6	ROSEDENE
103	091763	1933	1346	3213	2226	1600	1912	1984	58	300.9	PAARDEKRAAL
104	115324	1914	1360	3154	2240	1339	1916	1957	34	183.4	HILLCREST
105	094167	1937	1416	3217	2336	963	1927	1984	52	246.9	SARELSRIVIER
106	093314	1934	1391	3214	2311	1003	1890	1984	82	217.0	BAKENSRUG
107	050785	1985	1407	3305	2327	719	1928	1974	39	157.7	VOLSTRUISLEEGTE
108	071264	1974	1389	3254	2309	771	1915	1984	50	183.9	RIETBRON (MUN)
109	069559	1969	1339	3249	2219	792	1925	1984	56	165.8	LAMMERKRAAL
110	049050	2000	1352	3320	2232	732	1910	1984	69	186.3	KLAARSTROOM (POL)
111	049372	1992	1360	3312	2240	832	1912	1984	58	130.6	RONDAWEL
112	049562	2003	1369	3323	2249	914	1913	1970	52	146.3	MATJESVLEI

Table 3.3 (continued)

ZONE	STATION NUMBER	LAT (MINUTES)	LONG (MINUTES)	LAT (DEG&MIN)	LONG (DEG&MIN)	ELEV (M)	START YEAR	END YEAR	LEN	MAP (MM)	STATION NAME
113	030219	2020	1388	3340	2308	730	1878	1979	88	312.9	UNIONDALE (TNK)
114	028771	2031	1347	3351	2227	610	1924	1984	54	476.8	HEROLD (POL)
115	028838	2038	1347	3358	2227	229	1877	1984	105	880.0	GEORGE
116	014063	2043	1383	3403	2303	15	1880	1984	61	728.8	KNYSNA (TNK)
117	030265	2035	1389	3355	2309	680	1890	1984	77	1145.4	BUFFELSNEK (BOS)
118	030446	2035	1395	3355	2315	361	1931	1984	48	856.6	KRANSBOS (BOS)
119	031507	2038	1427	3358	2347	229	1896	1984	76	1115.0	LOTTERING (BOS)
120	031438	2028	1425	3348	2345	570	1925	1977	42	523.7	KRAKEELRIVIER
121	030493	2021	1397	3341	2317	1080	1912	1974	54	422.0	DE HOOP
122	032275	2015	1450	3335	2410	378	1927	1979	45	297.3	ZANDVLAKTE
123	052590	2000	1461	3320	2421	427	1892	1984	81	237.8	STEYTLERVILLE (MAG)
124	073377	1967	1453	3247	2413	838	1920	1978	45	224.9	STOCKDALE
125	052571	1981	1460	3301	2420	567	1900	1983	76	253.1	KLIPPLAAT (SAR)
126	096101	1931	1474	3211	2434	850	1888	1984	90	279.0	ROODEBLOEM
127	095395	1925	1454	3205	2414	1341	1927	1984	51	484.7	HOUD CONSTANT
128	096094	1924	1474	3204	2434	1137	1920	1984	58	407.0	GROOTHOEK
129	094578	1928	1430	3208	2350	1378	1888	1984	77	331.1	DE KRUIS
130	119082	1912	1473	3152	2433	1315	1885	1984	81	359.0	NIEU-BETHESDA (POL)
131	073871	1951	1470	3231	2430	613	1890	1984	75	276.3	KENDREW ESTATES
132	053432	1992	1484	3312	2444	555	1926	1983	55	248.8	EENSTROOM
133	034121	2011	1505	3331	2505	320	1926	1984	55	251.6	ADOLPHSKRAAL
134	033871	2012	1501	3332	2501	550	1927	1984	47	467.6	TIERHOEK
135	034405	2025	1514	3345	2514	637	1929	1984	40	609.8	TRIGKOP (BOS)
136	034052	2032	1502	3352	2502	80	1912	1979	55	512.0	LOERIE (SAR)
137	017452	2042	1487	3402	2447	140	1878	1984	79	684.3	HUMANSDORP (POL)
138	016484	2045	1457	3405	2417	115	1941	1978	33	951.9	KLIPDRIFT
139	034231	2031	1508	3351	2508	360	1929	1984	53	755.3	LONGMORE (BOS)
140	035209	2039	1537	3359	2537	50	1884	1958	59	647.3	DRIFT SANDS (BOS)
141	034762	2022	1526	3342	2526	168	1914	1984	58	492.7	UITENHAGE SPRINGS
142	036605	2014	1580	3334	2620	274	1920	1977	55	585.3	LONGVALE
143	054293	2003	1510	3323	2510	214	1885	1982	49	326.1	GLENCONNOR (POL)
144	056139	1999	1565	3319	2605	274	1877	1984	79	415.4	ALICEDALE
145	055410	2001	1544	3321	2544	594	1924	1984	39	737.5	ZUURBERG (BOS)
146	056709	1999	1583	3319	2623	546	1881	1984	71	607.7	FIR GLEN
147	076567	1977	1549	3257	2549	518	1877	1970	78	314.8	MIDDLETON (SAR)
148	076555A	1965	1549	3245	2549	579	1898	1984	62	412.3	COOKHOUSE (SAR)
149	076133	1963	1535	3243	2535	739	1877	1984	91	615.6	SOMERSET EAST (TNK)
150	075784	1954	1527	3234	2527	975	1927	1984	52	343.4	GROOTVLAKTE
151	075759	1959	1526	3239	2526	900	1927	1984	51	414.8	BUFFELSFONTEIN
152	097427	1927	1515	3207	2515	1295	1920	1977	54	364.4	LORRAINE
153	120838	1918	1529	3158	2529	980	1922	1977	40	308.1	FORTUINPLAAS
154	121275	1895	1540	3135	2540	1265	1914	1984	65	346.7	KAREEFONTEIN
155	098595	1945	1550	3225	2550	869	1916	1984	60	319.6	LABORARE
156	099229	1939	1568	3219	2608	1326	1891	1984	77	483.5	CHEVIOT FELLS
157	099301	1921	1572	3201	2612	1212	1933	1978	41	390.8	ALDERSYDE
158	099622	1941	1581	3221	2621	1550	1907	1984	70	658.1	VENTNOR
159	077522	1962	1578	3242	2618	599	1891	1984	75	428.2	ADELAIDE (POL)
160	057048A	1998	1592	3318	2632	533	1877	1984	84	703.3	GRAHAMSTOWN (TNK)
161	036642	2022	1582	3342	2622	191	1919	1984	61	919.6	ALEXANDRIA (BOS)
162	036729	2019	1585	3339	2625	183	1885	1984	86	642.3	ALEXANDRIA (POL)
163	058192	1992	1627	3312	2707	290	1878	1983	86	506.8	PEDDIE (MAG)
164	078296	1977	1600	3257	2640	511	1938	1984	39	473.2	MERINO
165	078227	1967	1598	3247	2638	436	1877	1984	94	513.4	FORT BEAUFORT (TNK)
166	078879	1960	1620	3240	2700	1006	1899	1984	76	1074.1	WOLFRIDGE (BOS)
167	100293	1943	1600	3223	2640	1463	1949	1984	33	537.6	HEX PLANTATION
168	100779	1949	1616	3229	2656	1387	1914	1984	57	592.6	ROCKFORD

Table 3.3 (continued)

ZONE	STATION NUMBER	LAT (MINUTES)	LONG (MINUTES)	LAT (DEG&MIN)	LONG (DEG&MIN)	ELEV (M)	START YEAR	END YEAR	LEN	MAP (MM)	STATION NAME
169	122806	1916	1587	3156	2627	1227	1885	1984	89	447.1	WAVERLEY
170	123654	1914	1612	3154	2652	1067	1884	1979	76	523.5	QUEENSTOWN (TNK)
171	101097	1927	1624	3207	2704	887	1881	1984	81	460.1	TYLDEN (SAR)
172	102542	1922	1669	3202	2749	831	1889	1978	68	512.3	TSOMO (POL)
173	101447	1947	1635	3227	2715	994	1932	1984	48	427.7	THOMAS RIVER (POL)
174	101804	1945	1647	3225	2727	1067	1887	1984	78	758.0	QACU (BOS)
175	079490	1960	1637	3240	2717	991	1885	1984	82	1023.7	ISIDINGE (BOS)
176	079251	1961	1629	3241	2709	646	1886	1982	77	632.0	KIESKAMAHOEK (POL)
177	080143	1973	1655	3253	2735	500	1892	1984	62	673.5	BERLIN (SAR)
178	058334	1984	1632	3304	2712	162	1932	1973	21	383.9	LINE DRIFT
179	059243	1983	1659	3303	2739	189	1926	1984	46	788.5	SILVERDALES
180	080569	1979	1669	3259	2749	158	1919	1984	54	839.0	UMZONIANA (RSV)
181	103570	1950	1699	3230	2819	480	1889	1984	73	968.5	KENTANI (BOS)
182	080072	1962	1652	3242	2732	713	1877	1984	72	763.2	KEI ROAD (POL)
183	103230	1940	1688	3220	2808	560	1889	1984	79	603.0	BUTTERWORTH (TNK)
184	102369	1930	1663	3210	2743	1137	1920	1983	48	862.5	MBULU (BOS)
185	125150	1920	1655	3200	2735	914	1894	1983	69	654.6	COFIMVABA (TNK)
186	102762	1932	1677	3212	2757	1060	1889	1984	85	686.6	NQAMAKWE (TNK)
187	103886	1936	1710	3216	2830	590	1889	1983	79	1025.1	WILLOWVALE (TNK)
188	104762	1932	1736	3212	2856	80	1901	1984	72	1125.4	CWEBE
189	127833	1913	1738	3153	2858	564	1923	1984	58	997.5	WILO (BOS)
190	127298	1918	1721	3158	2841	655	1892	1984	82	701.0	ELLIOTDALE (TNK)
191	106512	1892	1098	3132	1818	53	1938	1984	32	102.5	KOEKENAAP (IRR)
192	213129	1779	1025	2939	1705	20	1951	1983	30	75.9	GROOTMIS (SKL)
193	213888	1788	1050	2948	1730	457	1933	1982	46	119.2	KOMAGGAS
194	214670	1780	1073	2940	1753	940	1878	1984	101	215.7	SPRINGBOK (TNK)
195	186139	1819	1085	3019	1805	1448	1885	1984	65	376.3	KAMIESBERG
196	157874	1834	1080	3034	1800	250	1885	1952	47	134.0	GARIES (POL)
197	131639	1869	1101	3109	1821	360	1925	1983	51	154.0	NUWERUS (POL)
198	131767	1878	1109	3118	1829	210	1957	1977	19	104.7	GROOTGRAAFWATER
199	107396	1896	1124	3136	1844	110	1885	1984	76	147.8	VANRHYNSDORP (TNK)
200	107318	1909	1121	3149	1841	604	1933	1984	44	360.1	PUTS
201	133050	1880	1142	3120	1902	782	1914	1984	59	466.7	CLOUDSKRAAL
202	133202	1882	1147	3122	1907	719	1908	1984	51	339.9	NIEUWOUDVILLE (POL)
203	108311	1901	1151	3141	1911	640	1923	1984	54	233.1	LOKENBURG
204	133344	1875	1152	3115	1912	396	1924	1950	19	117.6	DOORNRIVIER
205	134378	1878	1183	3118	1943	820	1923	1984	46	206.8	GROOT TOREN
206	247242	1742	1149	2902	1909	450	1878	1981	77	74.6	PELLA
207	280351	1731	1182	2851	1942	835	1938	1984	44	93.8	SKUITKLIP
208	110512	1894	1218	3134	2018	1039	1934	1984	44	129.1	DIEPDRIFT
209	251430	1747	1269	2907	2109	884	1938	1984	45	150.4	N'ROUGAS SUID
210	194323	1823	1331	3023	2211	1064	1880	1983	76	153.6	GANNAPAN
211	166755	1835	1347	3035	2227	1164	1912	1984	54	198.6	OORLOGSHOEK
212	252894	1763	1321	2923	2201	1029	1924	1984	52	190.8	BRAKBOSCHPOORT
213	167665	1834	1373	3034	2253	1134	1903	1984	71	222.3	VOSBURG
214	140020	1880	1351	3120	2231	1400	1933	1984	43	191.1	REITFONTEIN
215	141329	1889	1394	3129	2314	1273	1913	1983	53	227.8	BIESJESFONTEIN
216	142805	1885	1437	3125	2357	1417	1877	1984	100	324.8	RICHMOND C/K (TNK)
217	142153	1863	1416	3103	2336	1292	1916	1984	62	271.1	LEKKERVLEI
218	226327	1797	1421	2957	2341	1021	1906	1984	70	251.1	STRYDENBERG (POL)
219	198836	1826	1468	3026	2428	1356	1878	1983	94	331.1	PHILIPSTOWN (TNK)
220	143784	1864	1467	3104	2427	1390	1878	1984	77	319.8	HANOVER (POL)
221	143598	1888	1460	3128	2420	1500	1893	1983	71	268.0	MIDDLEMOUNT
222	119315	1904	1481	3144	2441	1700	1907	1984	69	418.3	GORDONVILLE
223	120338	1898	1511	3138	2511	1180	1885	1984	78	347.2	TAFELBERG HALL
224	145310	1870	1512	3110	2512	1490	1929	1984	53	389.3	GROENVLEI

Table 3.3 (continued)

ZONE	STATION NUMBER	LAT (MINUTES)	LONG (MINUTES)	LAT (DEG&MIN)	LONG (DEG&MIN)	ELEV (M)	START YEAR	END YEAR	LEN	MAP (MM)	STATION NAME
225	146588	1878	1550	3118	2550	1500	1877	1984	82	425.5	STEYNSBURG
226	172163	1843	1506	3043	2506	1372	1877	1984	95	395.5	COLESBERG (TNK)
227	201020	1821	1531	3021	2531	1484	1905	1984	66	405.4	ORANJE
228	174093	1834	1565	3034	2605	1294	1927	1984	51	484.0	CLIFTON VALE
229	228567	1798	1490	2958	2450	1265	1909	1984	69	369.2	TEVREDENHEID
230	230810	1800	1557	3000	2557	1509	1906	1984	62	408.5	LILLYDALE
231	203043	1813	1592	3013	2632	1407	1882	1984	60	510.0	SMITHFIELD (MUN)
232	202505	1825	1578	3025	2618	1298	1932	1984	43	403.1	EBENHAEZER
233	174550	1841	1578	3041	2618	1387	1884	1984	85	473.1	ELLESMERE
234	176015	1845	1621	3045	2701	1497	1930	1984	53	571.3	PAARDEFONTEIN
235	148083	1884	1594	3124	2634	1753	1916	1984	60	557.3	MARSHMOOR
236	147654	1884	1582	3124	2622	1591	1889	1984	72	526.4	MOLTENO (MUN)
237	122071	1902	1564	3142	2604	1478	1914	1984	65	415.4	SMOORDRIF
238	123063	1893	1593	3133	2633	1349	1885	1984	87	479.6	STERKSTROOM (POL)
239	148517	1867	1608	3107	2648	1612	1879	1984	83	530.8	JAMESTOWN (POL)
240	149204	1885	1628	3125	2708	1661	1915	1984	59	642.7	CLARKS SIDING
241	124402	1902	1634	3142	2714	1027	1885	1983	89	574.2	LADY FRERE (TNK)
242	125432	1902	1665	3142	2745	1158	1923	1984	50	1085.6	NOMADAMBA (BOS)
243	125880	1900	1680	3140	2800	914	1890	1983	69	788.8	ENGCOBO (TNK)
244	150085	1885	1653	3125	2733	1353	1886	1984	73	695.6	IDA
245	150620	1880	1671	3120	2751	1446	1906	1984	66	718.7	ELLIOT (SAR)
246	177178	1858	1656	3058	2736	1656	1884	1984	91	586.3	BARKLY EAST (TNK)
247	176372	1843	1633	3043	2713	1632	1887	1984	70	751.3	LADY GREY (POL)
248	177552	1843	1669	3043	2749	1900	1926	1984	55	810.6	FUNNYSTONE
249	176631A	1832	1642	3032	2722	1455	1900	1974	64	640.0	STERKSPRUIT (TNK)
250	203657	1827	1613	3027	2653	1588	1911	1984	64	621.7	MIDDELPLAATS
251	232895	1795	1620	2955	2700	1524	1915	1984	57	577.0	SWEETWATER
252	233239	1800	1628	3000	2708	1539	1924	1984	49	681.3	LADYSDALE
253	177184	1834	1657	3034	2737	1596	1899	1976	61	743.4	BLIKANA
254	207337	1807	1722	3007	2842	1981	1895	1979	21	949.1	QACHASNEK
255	207108	1818	1713	3018	2833	1463	1942	1972	27	747.6	ADE
256	179353	1853	1721	3053	2841	1298	1926	1984	49	974.0	ETWA (BOS)
257	151604	1864	1701	3104	2821	1250	1891	1984	68	741.0	MACLEAR (MAG)
258	151623	1884	1700	3124	2820	1338	1922	1978	41	637.3	HOPEFIELD
259	126724	1894	1706	3134	2826	948	1901	1984	60	1157.1	BAZIYA (BOS)
260	126082	1912	1683	3152	2803	1103	1920	1984	50	1039.0	NKOBONGO (AGR)
261	127426	1896	1725	3136	2845	777	1944	1984	36	609.4	OWEN DAM
262	128040	1900	1742	3140	2902	655	1916	1984	63	806.4	NGQELENI (TNK)
263	152475	1885	1744	3125	2904	1143	1919	1984	49	1204.6	NQADU HEIGHTS (BOS)
264	152468	1878	1726	3118	2846	914	1923	1984	44	561.3	TSOLO (MAG)
265	180030	1860	1741	3100	2901	1154	1924	1984	50	746.6	PAPANE (BOS)
266	152482	1861	1726	3101	2846	1066	1919	1984	52	970.0	CENGCANE (BOS)
267	178881	1842	1710	3042	2830	1364	1891	1984	75	686.4	MOUNT FLETCHER (TNK)
268	179344	1845	1723	3045	2843	1728	1926	1983	53	1099.0	COLWANA (BOS)
269	179790	1840	1737	3040	2857	1463	1923	1984	50	895.7	TSHATSHENI (BOS)
270	207560	1820	1729	3020	2849	1463	1892	1984	64	675.1	MATATIELE (TNK)
271	208635	1806	1762	3006	2922	2150	1916	1984	54	843.3	BEN LOMOND
272	209039	1810	1772	3010	2932	1466	1901	1984	60	1131.8	INSIKENI (BOS)
273	AWS0219	1834	1754	3034	2914	1463	1924	1982	58	742.8	PALMIET
274	180722A	1834	1766	3034	2926	1289	1882	1980	72	672.8	KOKSTAD (TNK)
275	180439	1849	1756	3049	2916	1118	1914	1984	56	918.2	INSIZWA (BOS)
276	180648A	1849	1762	3049	2922	1052	1949	1984	32	713.2	MOUNT AYLIFF (TNK)
277	180712	1852	1766	3052	2926	1515	1914	1984	60	1055.5	TONTI (BOS)
278	153631	1861	1762	3101	2922	1039	1916	1984	55	1173.9	TABANKULU (BOS)
279	153875	1865	1770	3105	2930	838	1900	1984	62	856.4	FLAGSTAFF (TNK)
280	154142	1882	1775	3122	2935	594	1909	1984	51	1032.0	LUSIKISIKI (TNK)

Table 3.3 (continued)

ZONE	STATION NUMBER	LAT (MINUTES)	LONG (MINUTES)	LAT (DEG&MIN)	LONG (DEG&MIN)	ELEV (M)	START YEAR	END YEAR	LEN	MAP (MM)	STATION NAME
281	154354	1884	1782	3124	2942	518	1914	1984	57	1485.9	NTSUBANE (BOS)
282	182535	1855	1818	3055	3018	65	1907	1984	63	1113.2	BUSHY VALES
283	181073	1846	1776	3046	2936	1212	1914	1984	60	914.7	FORT DONALD (BOS)
284	181664	1835	1793	3035	2953	850	1920	1970	45	759.2	HARDING (TNK)
285	209766	1816	1796	3016	2956	732	1885	1980	74	680.3	UMZIMKULU (TNK)
286	210002	1801	1800	3001	3000	1192	1913	1984	38	804.6	SUMMERFORD
287	210397	1807	1814	3007	3014	747	1919	1953	26	624.1	LEENANE
288	210826	1816	1829	3016	3029	579	1923	1984	48	843.2	SAWOTI
289	182430	1840	1815	3040	3015	535	1951	1984	32	797.5	MINNEHAHA
290	183005	1835	1831	3035	3031	70	1904	1984	61	989.6	KLOOFEND
291	SUG0107	1825	1840	3025	3040	15	1920	1984	65	1052.5	SEZELA
292	240269	1799	1839	2959	3039	610	1919	1979	50	956.5	NEWLANDS
293	244405	1755	1064	2915	1744	884	1879	1984	81	142.6	STEINKOPF (POL)
294	276072	1722	1053	2842	1733	245	1952	1984	30	48.7	VIOOLSDRIFT
295	280772	1733	1195	2853	1955	910	1933	1984	49	126.6	BLADGROND
296	283098	1719	1263	2839	2103	775	1918	1983	60	153.6	GEELKOP
297	284008	1719	1291	2839	2131	914	1899	1983	77	199.3	THORNLEA
298	319882	1692	1350	2812	2230	1149	1932	1977	36	247.6	NOKANNA
299	320348	1698	1362	2818	2242	1368	1893	1984	67	331.0	DUNMURRAY
300	320359	1708	1365	2828	2245	1204	1919	1948	20	247.7	LA DAUPHINE
301	253648	1758	1342	2918	2222	930	1912	1981	64	227.3	KOEGASBRUG
302	255202	1762	1388	2922	2308	960	1901	1984	63	234.8	NUWEJAARSKRAAL
303	287441	1731	1396	2851	2316	1332	1883	1984	71	300.0	GRIQUATOWN (TNK)
304	321110	1700	1384	2820	2304	1294	1917	1984	62	332.8	POSTMASBURG (POL)
305	358268	1679	1416	2759	2336	1600	1934	1984	42	402.8	SMOUSPOORT
306	322071	1691	1413	2811	2333	1460	1914	1984	57	387.1	DANIELSKUIL
307	322172	1700	1415	2820	2335	1515	1923	1984	52	354.5	SILVERSTREAMS
308	322329	1709	1420	2829	2340	1419	1919	1984	57	375.1	PAPKUIL
309	288528	1728	1428	2848	2348	1173	1919	1984	61	322.2	TWEEFONTEIN
310	288416	1736	1424	2856	2344	1085	1928	1983	49	280.0	KALKDAM
311	227054	1795	1442	2955	2402	1140	1925	1984	53	291.9	PERDEPUT
312	227368	1779	1453	2939	2413	1067	1884	1977	65	266.8	ORANGE RIVER (SAR)
313	257655	1765	1462	2925	2422	1210	1914	1983	59	307.6	BELMONT (POL)
314	258182	1742	1478	2902	2438	1114	1914	1984	52	360.2	MODDERRIVIER (POL)
315	290032	1712	1472	2832	2432	1105	1884	1984	68	391.7	BARKLY WEST (TNK)
316	323649	1700	1462	2820	2422	1021	1885	1980	85	406.9	NEWLANDS
317	360512	1653	1487	2733	2447	1113	1898	1983	61	446.7	TAUNG (POL)
318	324607	1687	1491	2807	2451	1181	1911	1984	60	422.4	WARRENTON (MUN)
319	325471	1702	1517	2822	2517	1280	1920	1984	56	376.1	BORDEAUX
320	291245	1715	1509	2835	2509	1261	1929	1978	44	436.1	LEEUFONTEIN
321	290560	1730	1490	2850	2450	1166	1917	1984	56	399.2	BENFONTEIN
322	258458	1748	1486	2908	2446	1128	1885	1984	70	381.6	JACOBSDAL (POL)
323	258380	1760	1483	2920	2443	1201	1913	1975	57	256.7	WATERVAL WES
324	229737	1787	1526	2947	2526	1387	1890	1983	60	421.2	JAGERSFONTEIN
325	260030	1770	1532	2930	2532	1292	1919	1984	54	352.6	STEEUNMEKAAR (POL)
326	231279	1779	1570	2939	2610	1414	1906	1984	73	487.1	REDDERSBURG (POL)
327	293106	1726	1564	2846	2604	1266	1925	1984	53	471.5	FLORISBAD
328	259727	1747	1525	2907	2525	1251	1905	1984	64	432.1	PETRUSBERG (POL)
329	291148	1737	1505	2857	2505	1161	1908	1984	60	396.0	PERDEBERG (SAR)
330	325877	1688	1530	2808	2530	1274	1924	1984	51	495.6	HERTZOGVILLE (POL)
331	327257	1697	1569	2817	2609	1320	1905	1984	60	499.0	BULTFONTEIN (SKL)
332	293792	1722	1587	2842	2627	1393	1905	1984	59	548.4	BRANDFORT (MAG)
333	293700	1720	1584	2840	2624	1356	1916	1981	52	475.4	AARDOORNS
334	261722	1742	1584	2902	2624	1311	1905	1984	68	543.8	MAZELSPOORT DAM
335	231076	1786	1563	2946	2603	1362	1913	1956	27	353.9	TOELOOP
336	232275	1775	1600	2935	2640	1541	1905	1984	67	589.9	DEWETSDORP (POL)

Table 3.3 (continued)

ZONE	STATION NUMBER	LAT (MINUTES)	LONG (MINUTES)	LAT (DEG&MIN)	LONG (DEG&MIN)	ELEV (M)	START YEAR	END YEAR	LEN	MAP (MM)	STATION NAME
337	232823	1783	1618	2943	2658	1472	1914	1984	62	585.1	WATERFORD
338	263567	1767	1638	2927	2718	1573	1917	1984	57	639.3	CONVAMORE
339	263014	1754	1621	2914	2701	1609	1936	1983	43	713.5	HEATHFIELD
340	263041	1751	1622	2911	2702	1585	1906	1984	67	610.4	TWEESPRUIT
341	295139	1730	1625	2850	2705	1417	1925	1975	46	506.9	SKIMPERSVLEI
342	295001	1711	1621	2831	2701	1433	1886	1984	67	565.9	WINBURG (POL)
343	364322	1672	1601	2752	2641	1341	1906	1984	58	502.1	ODENDAALSRUS
344	329215	1685	1628	2805	2708	1417	1907	1984	54	548.0	VENTERSBURG (MAG)
345	366117	1677	1654	2757	2734	1524	1923	1984	49	619.9	STEYNSRUS (MUN)
346	330098	1688	1654	2808	2734	1541	1913	1983	50	529.7	TREKPAD
347	365855	1664	1649	2744	2729	1455	1912	1975	55	477.2	RIENZI
348	330199	1699	1657	2819	2737	1433	1905	1983	57	622.1	SENEKAL (AGR)
349	295558	1728	1639	2848	2719	1539	1911	1984	70	671.8	FLORA
350	263792	1752	1649	2912	2729	1593	1905	1984	58	711.8	LADYBRAND (SKL)
351	264022	1760	1652	2920	2732	1585	1936	1983	37	797.1	BOTSABELO
352	297300	1740	1690	2900	2810	1829	1937	1963	23	1006.1	PONTMAIN
353	296682	1732	1673	2852	2753	1600	1905	1984	67	741.4	FICKSBURG (TNK)
354	331058	1708	1682	2828	2802	1835	1908	1969	57	790.1	OVERDENE
355	330421	1681	1665	2801	2745	1580	1913	1984	62	684.6	ROODEPOORT
356	367768	1668	1706	2748	2826	1640	1904	1984	70	692.4	REITZ
357	331068	1688	1681	2808	2801	1646	1907	1984	58	677.9	KAALLAAGTE
358	331740	1700	1705	2820	2825	1753	1913	1982	59	705.1	SPITSKRANS
359	298301	1711	1721	2831	2841	1768	1912	1984	62	825.0	OLDENBURG
360	FOR0002	1740	1753	2900	2913	1974	1949	1971	23	1510.8	CATHEDRAL PEAK 2
361	266646	1766	1732	2926	2852	2133	1932	1983	20	531.6	OVERBURY
362	236521	1781	1728	2941	2848	1829	1932	1983	34	464.9	MASHAI
363	AWS0243	1770	1770	2930	2930	1584	1959	1982	24	1375.9	DUART,HIMEVILLE
364	237471	1792	1756	2952	2916	1745	1935	1984	44	1194.1	BERGVIEW
365	238132	1783	1776	2943	2936	1577	1924	1984	55	936.1	SNOWHILL
366	238595	1796	1790	2956	2950	1433	1923	1955	29	1266.6	XUMENI
367	239472	1792	1816	2952	3016	884	1916	1984	57	1032.7	RICHMOND-NATAL
368	238636	1776	1792	2936	2952	1539	1927	1984	56	982.1	IMPENDLE (POL)
369	AWS0032	2021	1173	3341	1933	245	1970	1982	12	1030.2	EENDRAG
370	268441	1761	1785	2921	2945	1585	1925	1984	44	976.1	EAST MESHLYN
371	299357	1737	1752	2857	2912	1463	1936	1984	41	1300.0	CATHEDRAL PEAK
372	AWS0250	1750	1792	2910	2952	1520	1909	1982	73	882.7	LOWLAND
373	268845	1745	1800	2905	3000	1371	1925	1984	53	729.4	GLENIFFER
374	AWS0331	1737	1789	2857	2949	1020	1903	1982	80	725.8	ESTCOURT
375	299900	1741	1769	2901	2929	1167	1927	1984	53	910.8	HEARTSEASE
376	299008	1720	1742	2840	2902	1280	1927	1984	50	998.6	CLIFFORD CHAMBER
377	299614	1724	1761	2844	2921	1130	1930	1984	45	740.9	BERGVILLE (MAG)
378	AWS0233	1718	1767	2838	2927	1220	1935	1982	47	707.8	VENTERSLAAGER
379	298871	1712	1740	2832	2900	1768	1925	1984	55	766.3	BOSCHKLOOF
380	332103	1693	1714	2813	2834	1715	1924	1983	47	656.6	SKALKIE
381	333226	1696	1748	2816	2908	1631	1882	1984	55	619.8	HARRISMITH (TNK)
382	369238	1678	1748	2758	2908	1769	1906	1984	66	694.5	BUCKLAND DOWNS
383	406658	1648	1794	2728	2954	1654	1930	1983	49	1006.1	LAINGSNEK
384	334174	1704	1777	2824	2937	1219	1914	1984	54	850.0	MOORSIDE
385	301692	1713	1825	2833	3025	1158	1918	1975	44	762.9	RESIDENCE
386	301795	1725	1827	2845	3027	594	1926	1984	45	644.8	TUGELA FERRY (MAG)
387	334825	1695	1798	2815	2958	1167	1914	1984	54	908.5	BALBROGIE
388	335250	1691	1809	2811	3009	1295	1933	1984	47	794.5	GLENCOE (MUN)
389	335746	1707	1825	2827	3025	1524	1920	1979	45	711.8	HELPMEKAAR (POL)
390	336016	1696	1831	2816	3031	1113	1945	1975	23	673.8	RIVER VIEW
391	336283	1693	1841	2813	3041	1341	1924	1984	55	769.7	NQUTU (TNK)
392	337006	1686	1863	2806	3103	975	1940	1984	41	651.7	GOEDGELOOF

Table 3.3 (continued)

ZONE	STATION NUMBER	LAT (MINUTES)	LONG (MINUTES)	LAT (DEG&MIN)	LONG (DEG&MIN)	ELEV (M)	START YEAR	END YEAR	LEN	MAP (MM)	STATION NAME
393	337143	1703	1865	2823	3105	1301	1928	1984	48	871.4	BABANANGO (POL)
394	302699	1719	1853	2839	3053	1524	1939	1984	38	1583.8	QUDENI (BOS)
395	302699	1719	1853	2839	3053	1524	1939	1984	38	1583.8	QUDENI (BOS)
396	337628	1708	1880	2828	3120	1006	1937	1984	38	851.8	MTONJANENI
397	302320	1731	1841	2851	3041	863	1913	1982	50	612.4	NADI
398	301795	1725	1827	2845	3027	594	1926	1984	45	644.8	TUGELA FERRY (MAG)
399	270544	1744	1849	2904	3049	1140	1928	1984	51	1095.8	BOSCOMBE
400	AWS0230	1749	1838	2909	3038	980	1935	1982	47	888.4	CROWES PLACE,SEV
401	AWS0314	1762	1818	2922	3018	1075	1921	1982	61	1187.1	HAWKESTONE,HOWIC
402	AWS0195	1772	1817	2932	3017	1067	1914	1982	68	874.7	CEDARA AGR RES STN
403	270119	1770	1834	2930	3034	960	1932	1984	48	998.3	WINDY HILL NO.2
404	240073	1783	1833	2943	3033	762	1914	1984	56	681.3	CAMPERDOWN
405	AWS0326	1796	1819	2956	3019	810	1937	1982	45	892.5	LITTLE HARMONY
406	SUG0133	1796	1830	2956	3030	732	1964	1984	21	894.6	MID-ILLOVO
407	240716	1796	1854	2956	3054	115	1919	1984	52	897.7	UMLAAS WATERWORK
408	240891	1791	1860	2951	3100	91	1871	1984	113	1013.5	DURBAN-BOTANICAL
409	240564	1787	1846	2947	3046	671	1923	1984	54	858.4	INTAKE
410	271099	1750	1864	2910	3104	533	1923	1984	52	1079.6	MAPUMULO (TNK)
411	SUG0016	1761	1878	2921	3118	33	1920	1984	65	974.6	GLENDHOW MILL
412	270722	1742	1856	2902	3056	1050	1932	1984	50	940.6	GLEN ELAND
413	SUG0013	1734	1878	2854	3118	587	1932	1984	51	1061.7	ENTUMENI MILL
414	272121	1742	1895	2902	3135	55	1912	1984	56	1014.1	GINGINDLOVU
415	304446	1737	1905	2857	3145	12	1916	1984	55	1161.1	MTUNZINI (MAG)
416	AWS0158	1727	1895	2847	3135	152	1911	1971	61	604.5	UMTATA
417	304283	1722	1900	2842	3140	122	1923	1972	38	765.6	KWA-YAYA
418	304681	1731	1913	2851	3153	55	1922	1971	34	1332.3	PORT DURNFORD
419	304822	1722	1918	2842	3158	30	1916	1984	52	1083.6	KULU HALT
420	SUG0145	1724	1906	2844	3146	153	1912	1984	73	940.9	EMPANGENI WEST
421	337795	1694	1888	2814	3128	777	1916	1984	65	765.6	MAHLABATINI (MAG)
422	374264	1674	1899	2754	3139	841	1916	1984	59	895.5	NONGOMA
423	339352	1702	1932	2822	3212	76	1928	1984	49	882.4	KANGELA
424	SUG0150	1711	1928	2831	3208	46	1924	1984	60	973.7	ETEZA
425	305308	1718	1931	2838	3211	30	1932	1984	47	1387.0	KWA-MBONAMBI (BOS)
426	339538	1708	1938	2828	3218	8	1929	1984	46	1094.7	ULOA
427	387240	1650	1208	2730	2008	850	1922	1984	50	145.3	NOENIEPUT (POL)
428	423044	1605	1202	2645	2002	792	1907	1984	66	169.2	RIETFONTEIN (POL)
429	390155	1623	1297	2703	2137	900	1936	1979	35	178.9	TOTSPLAAS
430	427083	1613	1323	2653	2203	925	1933	1984	46	261.9	VANZYLSRUS (POL)
431	392148	1650	1358	2730	2238	1190	1926	1984	53	338.0	WINTON
432	356712	1673	1375	2753	2255	1190	1912	1984	59	375.0	SMYTHE
433	358263	1672	1419	2752	2339	1600	1932	1983	46	460.4	CLARKSDALE
434	393566	1646	1398	2726	2318	1463	1956	1984	27	479.8	WHITEBANK-MILL
435	468210	1590	1447	2630	2407	1231	1923	1984	52	394.9	FIELDEN
436	467487	1568	1427	2608	2347	1135	1898	1983	58	322.6	MOROKWENG (POL)
437	506386	1557	1483	2557	2443	1147	1913	1964	33	378.8	LOGAGING
438	468456	1567	1456	2607	2416	1135	1954	1977	21	474.6	PALMVELD
439	468318	1576	1451	2616	2411	1185	1913	1984	64	444.6	PALMYRA
440	469459	1569	1486	2609	2446	1175	1911	1979	58	416.3	MOSITA
441	394574	1624	1430	2704	2350	1295	1930	1984	47	419.4	BOTHITHONG
442	432387	1618	1484	2658	2444	1190	1886	1984	65	463.4	VRYBURG (POL)
443	396454	1623	1486	2703	2446	1188	1915	1963	41	427.6	TIERKLOOF (SKL)
444	396284	1633	1480	2713	2440	1170	1918	1984	60	455.1	MADRID
445	395855	1635	1469	2715	2429	1338	1920	1957	30	325.2	COMPTON RANCH
446	359304	1654	1451	2734	2411	1400	1932	1984	47	429.2	REIVILO
447	361736	1665	1522	2745	2522	1219	1934	1984	42	454.4	MOIRTON
448	361832	1673	1528	2753	2528	1245	1930	1984	50	437.2	KALKPOORT

Table 3.3 (continued)

ZONE	STATION NUMBER	LAT (MINUTES)	LONG (MINUTES)	LAT (DEG&MIN)	LONG (DEG&MIN)	ELEV (M)	START YEAR	END YEAR	LEN	MAP (MM)	STATION NAME
449	398177	1647	1536	2727	2536	1271	1911	1984	67	489.6	ZEVENFONTEIN
450	361760	1660	1526	2740	2526	1222	1910	1974	49	403.9	PALMIETFONTEIN
451	433804	1614	1527	2654	2527	1330	1903	1984	61	467.7	POORTJIE
452	434236	1616	1538	2656	2538	1395	1930	1984	51	486.0	KLIPSPRUIT
453	433791	1601	1527	2641	2527	1350	1922	1984	53	514.4	DELAREYVILLE (MUN)
454	433512	1593	1517	2633	2517	1380	1914	1978	53	472.8	BRANDWAG
455	470196	1576	1507	2616	2507	1220	1903	1982	67	492.1	SETLAGODI (POL)
456	433301	1591	1511	2631	2511	1365	1911	1959	39	399.9	BOSRAND
457	471259	1579	1539	2619	2539	1365	1929	1984	53	550.9	SILVERTON
458	472281	1569	1570	2609	2610	1477	1903	1978	69	602.3	LICHTENBURG (MUN)
459	434888	1609	1560	2649	2600	1475	1911	1984	60	542.6	OTTOSDAL (POL)
460	398876	1626	1558	2706	2558	1415	1910	1984	60	522.7	ROOIPOORT
461	398556	1636	1549	2716	2549	1343	1906	1984	68	512.5	HOLLOWAYSRUST
462	399208	1648	1567	2728	2607	1286	1927	1983	47	492.0	DRIEKOPPIES
463	363651	1671	1582	2751	2622	1325	1924	1984	51	448.5	WESSELSBRON (MUN)
464	399419	1649	1574	2729	2614	1250	1906	1957	30	545.1	KOMMANDODRIF
465	400203	1644	1597	2724	2637	1280	1905	1984	51	526.4	BOTHAVILLE (MUN)
466	400647	1637	1612	2717	2652	1384	1930	1984	51	597.0	BOVENLANDSPLAATS
467	399662	1622	1583	2702	2623	1379	1910	1983	68	548.4	SYFERFONTEIN
468	435735	1606	1585	2646	2625	1478	1904	1983	55	585.7	HARTBEESFONTEIN
469	436495	1605	1607	2645	2647	1356	1920	1984	59	600.6	BEATRIX
470	435721	1591	1585	2631	2625	1433	1917	1980	54	558.7	KAFFERSKRAAL
471	472730	1570	1586	2610	2626	1505	1918	1959	34	480.5	WELGEVONDEN
472	474198	1579	1627	2619	2707	1500	1913	1984	70	641.0	ZAMENKOMST
473	473416	1586	1604	2626	2644	1372	1910	1971	55	483.6	KLIPPLAATDRIFT
474	474255	1575	1630	2615	2710	1470	1903	1984	71	581.4	KLERKSKRAAL (POL)
475	475056	1586	1652	2626	2732	1606	1908	1971	54	656.3	LEEUWPOORT
476	437517	1597	1638	2637	2718	1365	1924	1984	51	611.5	KLIPDRIFT
477	436855	1605	1619	2645	2659	1372	1904	1984	63	626.7	BRAKSPRUIT (AGR)
478	437383	1613	1633	2653	2713	1393	1929	1982	47	645.0	TIERFONTEIN
479	436747	1617	1615	2657	2655	1317	1922	1984	52	609.2	BUSHY BAND
480	401407	1638	1634	2718	2714	1344	1925	1984	55	536.0	MIDDELWEG
481	365400	1660	1635	2740	2715	1344	1913	1978	62	593.0	KROONSTAD (PARKS)
482	366529	1668	1668	2748	2748	1564	1924	1982	55	656.4	KISMET ESTATE
483	365731	1661	1646	2741	2726	1420	1913	1984	54	546.5	WELTEVREDE
484	367066	1656	1683	2736	2803	1661	1925	1984	53	599.1	LANQUEDOC
485	403054	1644	1682	2724	2802	1612	1925	1984	51	691.3	SCHOONGEZICHT
486	401798	1638	1648	2718	2728	1381	1915	1984	61	586.9	DUNKELD
487	402788	1628	1677	2708	2757	1550	1919	1984	57	614.9	OORSPRONG-OOS
488	439389	1620	1692	2700	2812	1485	1922	1984	55	562.2	ORANJEVILLE (SKL)
489	437660	1620	1643	2700	2723	1408	1906	1984	64	667.7	VREDEFORT (SKL)
490	438716	1616	1674	2656	2754	1457	1915	1984	52	645.4	RIETFONTEIN
491	437834	1614	1648	2654	2728	1403	1904	1984	62	584.6	PARYS (MUN)
492	438315	1606	1661	2646	2741	1417	1916	1984	61	699.1	BARRAGE (RWB)
493	439396	1596	1694	2636	2814	1510	1920	1984	53	688.1	SCHIKFONTEIN
494	475717	1587	1674	2627	2754	1568	1925	1983	48	631.8	DOORNKUIL
495	475736	1576	1675	2616	2755	1615	1907	1984	71	688.7	KLIPSPRUIT (PUR)
496	476433	1573	1695	2613	2815	1622	1903	1984	70	701.4	BOKSBURG (MUN)
497	475611	1571	1672	2611	2752	1701	1904	1984	64	809.7	DURBAN ROODEPOOR
498	475881	1571	1680	2611	2800	1747	1898	1984	74	819.4	JHB-BRAAMFONTEIN
499	476396	1566	1694	2606	2814	1652	1904	1964	39	684.5	KEMPTON PARK (SAR)
500	477309	1569	1721	2609	2841	1548	1907	1984	64	691.3	DELMAS (POL)
501	477762	1574	1736	2614	2856	1585	1920	1984	56	665.8	STREHLA
502	440157	1597	1716	2637	2836	1664	1913	1984	68	721.3	RIETBULT
503	439769	1609	1706	2649	2826	1560	1904	1984	54	613.7	BEERLAAGTE
504	440885	1605	1739	2645	2859	1545	1909	1984	65	698.8	SANDBAKEN

Table 3.3 (continued)

ZONE	STATION NUMBER	LAT (MINUTES)	LONG (MINUTES)	LAT (DEG&MIN)	LONG (DEG&MIN)	ELEV (M)	START YEAR	END YEAR	LEN	MAP (MM)	STATION NAME
505	441270	1620	1749	2700	2909	1504	1927	1984	49	636.2	GOEDGEVONDEN
506	404316	1636	1721	2716	2841	1591	1908	1984	65	544.2	DUNEDIN
507	368634	1654	1732	2734	2852	1628	1909	1984	52	730.6	WOUDZICHT
508	369284	1664	1750	2744	2910	1859	1931	1984	49	656.6	ROCCO
509	406607	1627	1791	2707	2951	1690	1906	1984	69	772.5	RIETPOORT
510	370834	1674	1799	2754	2959	1189	1915	1973	46	841.8	BALLENGLEICH
511	370430	1661	1785	2741	2945	1603	1914	1954	23	556.5	DOORNHOEK
512	405295A	1646	1750	2726	2910	1704	1916	1984	59	690.8	VREDE (MUN)
513	406221	1631	1779	2711	2939	1754	1913	1983	64	697.1	PAARDEKOPPLAAS
514	405753	1623	1767	2703	2927	1618	1903	1962	40	730.9	EARLRIDGE
515	441261	1612	1750	2652	2910	1603	1917	1984	55	679.9	JONKERSDAM
516	442068	1601	1773	2641	2933	1622	1906	1977	56	655.1	HENDRIKSPAN (SKL)
517	515234	1554	1748	2554	2908	1530	1922	1975	41	717.1	CLEWER (SAR)
518	479545	1565	1790	2605	2950	1648	1910	1979	59	645.1	KARINA
519	442853	1602	1799	2642	2959	1667	1948	1984	32	726.5	GOEDEHOOP
520	442867	1616	1799	2656	2959	1710	1904	1984	66	717.6	ROLFONTEIN
521	444176	1617	1835	2657	3035	1359	1929	1983	50	910.6	VLAKKLOOF ESTATE
522	407639	1628	1822	2708	3022	1311	1929	1984	53	767.3	GROOT RIETVLEI
523	AWS0261	1663	1840	2743	3040	1370	1948	1982	34	1036.3	VRYHEID
524	371579	1659	1820	2739	3020	1219	1916	1984	58	739.9	UTRECHT (TNK)
525	370486	1656	1788	2736	2948	1515	1924	1984	48	785.1	LOSKOP
526	371706	1666	1825	2746	3025	1265	1927	1984	53	695.9	WAAIHOEK
527	372361	1651	1844	2731	3044	1190	1926	1984	34	901.2	MARTHINUSDRIFT
528	408798	1638	1857	2718	3057	1042	1924	1984	51	824.7	ZAAIPLAATS
529	373080	1670	1863	2750	3103	1371	1921	1972	29	1102.4	LANGKRANS
530	373058	1679	1862	2759	3102	1000	1913	1984	44	849.0	GLUCKSTADT (POL)
531	373680	1670	1883	2750	3123	1268	1923	1984	52	1517.9	NGOMI (BOS)
532	373485	1655	1877	2735	3117	1265	1914	1984	58	787.0	LOUWSBURG (MAG)
533	409375	1634	1873	2714	3113	895	1904	1984	62	761.8	BERGPLAATS
534	409460	1630	1876	2710	3116	983	1915	1983	56	744.8	DWALENI
535	444746	1617	1855	2657	3055	1189	1911	1964	27	741.5	BLESBOKSPRUIT
536	445100	1600	1864	2640	3104	1030	1909	1984	65	854.5	MANKAYANE
537	481239	1588	1838	2628	3038	1558	1924	1984	52	877.4	BROADHOLM
538	480520	1569	1816	2609	3016	1774	1909	1953	29	762.4	FAIRVIEW
539	518088	1558	1834	2558	3034	1124	1911	1984	59	812.1	BADPLAAS (POL)
540	482357	1587	1872	2627	3112	720	1919	1984	45	1120.4	MC CREEDY
541	446136	1606	1895	2646	3135	325	1920	1963	33	858.4	SINGCENI
542	483426	1566	1905	2606	3145	250	1916	1984	53	680.0	SWAZILAND RANCH
543	SUG0155	1645	1891	2725	3131	290	1940	1984	45	675.2	PONGOLA
544	374402	1662	1904	2742	3144	457	1931	1984	46	550.4	ZILVERHOUT
545	447446	1616	1935	2656	3215	64	1919	1984	53	628.0	NDUMU
546	SUG0153	1684	1939	2804	3219	30	1924	1984	61	756.4	HLUHLUWE
547	448450	1620	1965	2700	3245	30	1914	1978	45	869.0	MAPUTU (POL)
548	411353	1640	1933	2720	3213	61	1959	1983	25	548.2	MAMFENE
549	410878	1628	1920	2708	3200	707	1919	1984	56	824.4	INGWAVUMA (TNK)
550	483695	1565	1914	2605	3154	256	1945	1984	31	784.6	VUVULAND
551	545499	1519	1549	2519	2549	1181	1943	1984	31	560.7	GOPANE
552	508261	1551	1539	2551	2539	1277	1898	1980	58	557.1	MAFEKING (TNK)
553	508428	1538	1544	2538	2544	1347	1919	1976	43	490.6	JAGERSFONTEIN
554	509078	1548	1563	2548	2603	1463	1910	1964	48	601.9	NOUPOORT
555	508649	1549	1551	2549	2551	1408	1915	1984	45	603.9	SLURRY
556	508825	1545	1558	2545	2558	1423	1904	1984	68	542.5	OTTOSHOOP (POL)
557	545626	1527	1552	2527	2552	1280	1904	1976	55	583.3	DINOKANA
558	546314	1514	1571	2514	2611	1076	1919	1984	57	579.1	BOTATABOOMEN
559	585056	1495	1562	2455	2602	1158	1930	1984	43	534.9	GROOTPOORT
560	585528	1488	1578	2448	2618	1105	1910	1965	39	566.5	VLEISFONTEIN

Table 3.3 (continued)

ZONE	STATION NUMBER	LAT (MINUTES)	LONG (MINUTES)	LAT (DEG&MIN)	LONG (DEG&MIN)	ELEV (M)	START YEAR	END YEAR	LEN	MAP (MM)	STATION NAME
561	586545	1475	1609	2435	2649	963	1932	1983	47	493.8	ENGELAND
562	672748	1439	1615	2359	2655	856	1905	1984	66	443.8	CUMBERLAND (POL)
563	630556	1456	1639	2416	2719	998	1933	1984	39	486.7	GROENVLEI (SKL)
564	631011	1451	1652	2411	2732	991	1922	1984	49	515.8	HOPEWELL
565	586441	1491	1605	2451	2645	1082	1907	1976	47	550.7	GANSVLEI
566	587668	1478	1645	2438	2725	950	1920	1963	36	600.3	MEBANI
567	586341	1482	1601	2442	2641	975	1940	1984	40	549.5	BRUSSELS
568	548165	1515	1627	2515	2707	1143	1908	1984	64	638.3	PILANESBERG (POL)
569	546412	1522	1575	2522	2615	1146	1904	1984	54	632.6	ENZELBERG
570	509759	1539	1589	2539	2629	1201	1910	1984	63	604.9	TWYFELSPOORT
571	510433	1543	1605	2543	2645	1341	1924	1984	54	676.1	DOORNKOM
572	510410	1550	1604	2550	2644	1484	1924	1977	38	629.7	DOORNPOORT
573	510712	1552	1614	2552	2654	1553	1911	1984	52	678.7	KOSTER (POL)
574	511120	1559	1623	2559	2703	1525	1911	1984	59	597.7	DWARSFONTEIN
575	511467	1547	1636	2547	2716	1204	1924	1984	51	732.0	HEX KRANTZ
576	511310	1540	1631	2540	2711	1332	1914	1975	50	732.7	DONKERHOEK-RAINH
577	511672	1542	1641	2542	2721	1152	1928	1984	53	643.0	KLIPFONTEIN
578	512280	1540	1660	2540	2740	1120	1928	1984	45	681.8	KAREEPOORT (IRR)
579	512602	1533	1671	2533	2751	1131	1929	1984	50	633.7	MAMAGALIESKRAAL
580	512613	1543	1671	2543	2751	1143	1905	1984	55	671.3	HARTBEESPOORT DA
581	513345	1545	1692	2545	2812	1371	1912	1984	69	714.9	PRETORIA-BURGERS
582	512481	1531	1667	2531	2747	1134	1923	1984	57	617.5	MAMOGALESKRAAL
583	548747	1527	1645	2527	2725	1021	1910	1982	64	587.8	KAFFERSKRAAL
584	549130	1511	1655	2511	2735	960	1925	1984	43	550.9	VAALKOP
585	588385	1495	1664	2455	2744	1113	1912	1984	59	634.6	LEEUPOORT
586	588230	1490	1658	2450	2738	1548	1933	1984	38	764.0	STERKFONTEIN
587	589670	1480	1702	2440	2822	1234	1913	1984	45	596.2	ELANDSPOORT
588	588721	1472	1675	2432	2755	1250	1917	1984	53	661.3	RANKINS PASS
589	631131	1454	1655	2414	2735	980	1937	1978	22	516.5	DIAMANT
590	631596	1466	1670	2426	2750	1524	1913	1980	53	743.4	STERKFONTEIN
591	631520	1450	1668	2410	2748	1021	1904	1953	31	567.9	HERMANUSDOORNS
592	674207	1437	1658	2357	2738	994	1939	1984	38	477.8	STERKFONTEIN
593	632274	1444	1690	2404	2810	1463	1935	1984	38	607.9	DORSET
594	633393	1444	1722	2404	2842	1204	1916	1984	56	653.4	ZAAIPLAATS
595	632297	1467	1690	2427	2810	1250	1911	1974	41	612.2	BOEKENHOUTSKLOOF
596	633503	1463	1727	2423	2847	1128	1912	1969	38	664.1	RIETFONTEIN
597	590307	1479	1720	2439	2840	1105	1917	1984	51	628.7	NYLSVLEY
598	590106	1486	1713	2446	2833	1143	1908	1953	34	589.0	VARKENSKUIL
599	589628	1498	1701	2458	2821	1103	1907	1979	59	626.6	ROODEKUIL
600	590028	1499	1711	2459	2831	1052	1906	1984	64	571.2	ILLAWARRA
601	551281	1511	1720	2511	2840	978	1924	1984	46	592.2	ROOIKOP
602	514010	1540	1711	2540	2831	1433	1904	1984	71	695.8	PREMIER MINE
603	513382	1552	1693	2552	2813	1469	1916	1984	53	688.4	IRENE
604	514618	1549	1731	2549	2851	1387	1905	1984	60	698.9	WILGERIVIER (SAR)
605	515732	1542	1765	2542	2925	1402	1911	1977	40	704.9	BOTSABELO (SKL)
606	553009	1510	1771	2510	2931	978	1919	1959	29	679.7	WELTEVREDE
607	552247	1507	1749	2507	2909	939	1952	1984	29	633.2	KUILSRIVIER (IRR)
608	634566	1466	1759	2426	2919	935	1941	1984	34	482.3	VOLOP
609	634084	1463	1742	2423	2902	1070	1911	1980	55	512.4	KALKFONTEIN
610	634417	1467	1754	2427	2914	945	1922	1984	52	555.6	UITZICHT
611	634131	1451	1744	2411	2904	1219	1904	1984	65	584.7	PLANKNEK
612	678776	1436	1796	2356	2956	1393	1903	1984	56	857.5	HAENERTSBURG (POL)
613	635763	1452	1795	2412	2955	950	1938	1984	40	423.2	GROOTFONTEIN
614	635554	1454	1789	2414	2949	823	1948	1984	31	410.1	MALIPSDRIF (POL)
615	592615	1486	1792	2446	2952	1402	1929	1984	44	549.9	JANE FURZE HOSPITAL
616	592474	1495	1786	2455	2946	1570	1906	1984	53	636.8	NEBO

Table 3.3 (continued)

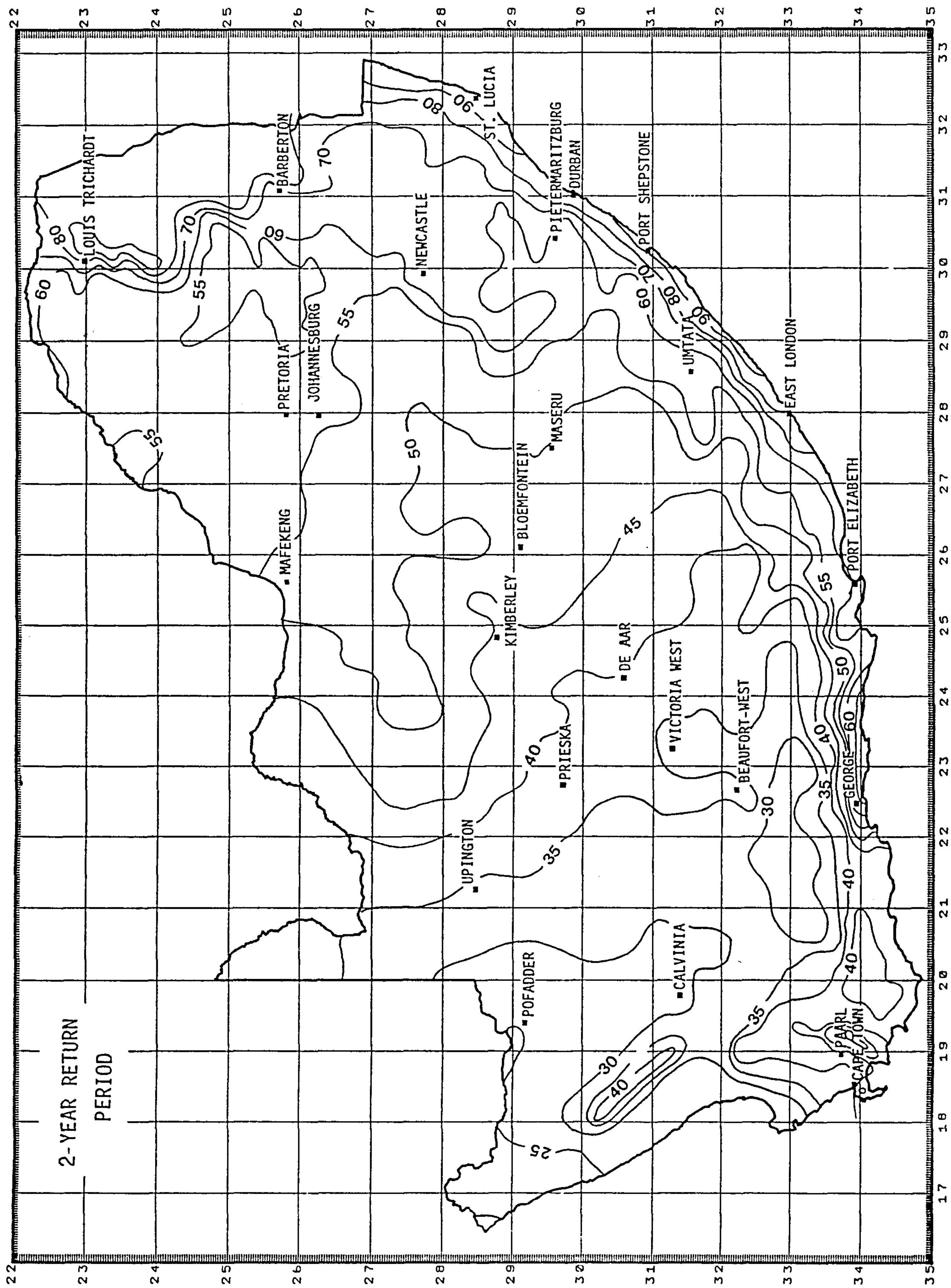
ZONE	STATION NUMBER	LAT (MINUTES)	LONG (MINUTES)	LAT (DEG&MIN)	LONG (DEG&MIN)	ELEV (M)	START YEAR	END YEAR	LEN	MAP (MM)	STATION NAME
617	516554	1544	1789	2544	2949	1707	1905	1984	61	689.8	ROODEPOORT
618	AWS0445	1545	1780	2545	2940	1638	1913	1974	61	764.2	GEMSBOKFONTEIN
619	516708	1548	1794	2548	2954	1789	1904	1981	54	700.6	WONDERFONTEIN
620	517430	1540	1815	2540	3015	1536	1903	1984	52	781.4	MACHADODORP
621	517762	1542	1826	2542	3026	1844	1919	1984	53	919.4	WELTEVREDEN
622	517877	1537	1830	2537	3030	1048	1905	1959	34	703.5	AIRLIE (SAR)
623	554175	1525	1806	2525	3006	2030	1906	1984	55	816.2	DULLSTROOM (SAR)
624	554786	1506	1827	2506	3027	1366	1904	1984	52	670.8	LYDENBURG (POL)
625	593419	1499	1814	2459	3014	1408	1909	1984	58	687.6	MARTENSHOOP (POL)
626	593586	1487	1821	2447	3021	820	1927	1978	39	493.1	DE GROOTBOOM
627	593126	1476	1805	2436	3005	975	1924	1984	53	606.8	MAANDAGSHOEK
628	636518	1448	1818	2408	3018	840	1920	1984	52	1022.8	SCHELM
629	679290	1430	1810	2350	3010	700	1927	1984	45	943.1	TZANEEN (POL)
630	680059	1440	1831	2400	3031	670	1906	1970	28	653.5	LEYDSDORP
631	637609	1448	1852	2408	3052	390	1927	1984	44	461.1	INYOKO
632	557712	1522	1914	2522	3154	168	1938	1984	38	599.2	KROKODILBRUG
633	595161	1481	1866	2441	3106	549	1924	1984	48	784.7	CHAMPAGNE (NAF)
634	594457	1477	1846	2437	3046	1219	1906	1983	59	659.9	ELANDSFONTEIN
635	594217	1477	1838	2437	3038	1036	1919	1978	49	534.0	NOOITGEDACHT
636	554885	1514	1830	2514	3030	1740	1947	1984	33	910.2	KAFFERVOETPAD (BOS)
637	594383	1493	1843	2453	3043	1630	1949	1984	25	809.7	MORGENZON (BOS)
638	594444	1495	1846	2455	3046	1240	1907	1984	54	955.3	PILGRIMS REST (POL)
639	594539	1499	1849	2459	3049	1360	1914	1984	57	1513.5	MAC MAC (BOS)
640	594806	1496	1857	2456	3057	945	1935	1984	46	1263.3	WILGEBOOM (BOS)
641	595110	1490	1864	2450	3104	880	1905	1984	57	1028.2	BOSBOKRAND (POL)
642	556898	1530	1890	2530	3130	310	1938	1984	41	615.4	MALELANE
643	555878	1508	1860	2508	3100	1042	1929	1984	48	1148.1	WITWATER (BOS)
644	555441	1520	1843	2520	3043	1030	1915	1984	44	930.3	RIETVALLEI
645	518186	1536	1836	2536	3036	961	1922	1984	48	837.6	VLAKPLAATS
646	518367	1537	1844	2537	3044	1424	1924	1984	40	971.6	COETZEESTROOM
647	518455	1535	1846	2535	3046	1606	1903	1984	47	1496.7	KAAPSEHOOP
648	555567	1527	1850	2527	3050	706	1905	1984	62	833.4	ALKMAAR
649	556143	1523	1865	2523	3105	859	1927	1979	42	798.4	THE KNOLL
650	556088	1529	1862	2529	3102	579	1930	1984	42	735.2	MAYFERN
651	518859	1548	1857	2548	3057	853	1910	1984	66	780.8	OORSCHOT
652	518589	1550	1850	2550	3050	1396	1934	1984	40	1090.6	NELSHOOGTE (BOS)
653	518886	1547	1860	2547	3100	715	1911	1984	61	661.4	CARMICHAEL (TNK)
654	519732	1542	1884	2542	3124	1097	1922	1984	43	1710.1	KAMHLABANE
655	SUG0030	1537	1892	2537	3132	366	1919	1984	63	887.8	KAALRUG
656	520589	1549	1910	2549	3150	248	1922	1984	50	649.9	FIG TREE
657	596647	1487	1912	2447	3152	244	1935	1984	42	541.2	TSOKWANE
658	717595	1404	1641	2324	2721	810	1925	1984	42	423.3	STOCKPORT (POL)
659	718409	1399	1664	2319	2744	780	1930	1977	36	350.3	RUSTENBURG NO.51
660	762532	1372	1698	2252	2818	914	1937	1984	44	365.1	DROEVLEI
661	763313	1363	1722	2243	2842	780	1949	1979	25	417.4	GROENDRAAI
662	808139	1340	1745	2220	2905	589	1954	1975	18	329.8	VERGENOEG
663	764161	1361	1746	2241	2906	843	1930	1984	48	377.0	ALLDAYS (POL)
664	765253	1363	1779	2243	2939	673	1962	1984	21	426.6	SANDOW
665	720727	1387	1735	2307	2855	1502	1915	1978	42	557.1	KGATALALA
666	721197	1397	1747	2317	2907	962	1919	1977	53	455.5	BOCHUM
667	675182	1412	1687	2332	2807	855	1908	1984	63	434.9	VILLA NORA (POL)
668	675125	1415	1685	2335	2805	894	1932	1978	37	471.5	AUTHORITEIT
669	675117	1437	1685	2357	2805	1294	1919	1983	53	540.3	DERDEKRAAL
670	676237	1437	1718	2357	2838	988	1941	1984	38	516.8	VERDOORNSDRAAI
671	676705	1425	1734	2345	2854	1082	1925	1976	47	488.5	SWERWERSKRAAL
672	677562	1432	1760	2352	2920	1280	1912	1951	32	546.5	BIESJESPOL

Table 3.3 (continued)

ZONE	STATION NUMBER	LAT (MINUTES)	LONG (MINUTES)	LAT (DEG&MIN)	LONG (DEG&MIN)	ELEV (M)	START YEAR	END YEAR	LEN	MAP (MM)	STATION NAME
673	678023	1433	1771	2353	2931	1371	1918	1984	56	482.0	BROADLANDS
674	677259	1429	1748	2349	2908	1295	1920	1984	53	425.9	BERGZICHT
675	678144	1436	1775	2356	2935	1277	1906	1984	67	435.9	KALKFONTEIN
676	678883	1422	1800	2342	3000	828	1913	1964	40	515.5	RAMATOELLASKLOOF
677	722082	1402	1774	2322	2934	1000	1923	1984	52	387.4	LEGKRAAL
678	678722	1412	1795	2332	2955	1189	1926	1984	45	615.6	DRIEFONTEIN
679	723080	1402	1803	2322	3003	1073	1927	1984	38	754.2	SETALI
680	723055	1406	1802	2326	3002	1119	1904	1964	46	1076.7	DOORNBOOM
681	723070	1390	1804	2310	3004	875	1903	1984	44	689.8	ELIM (HOSP)
682	722614	1394	1792	2314	2952	1023	1920	1984	56	481.3	ZWARTRANDJES
683	722497	1398	1787	2318	2947	1103	1926	1978	48	404.8	ROUWPUT
684	722571	1382	1790	2302	2950	950	1908	1984	69	610.1	VERSAMELHOEK
685	764899	1380	1770	2300	2930	1306	1934	1954	18	598.2	VENTERSDORP
686	722721	1381	1795	2301	2955	1030	1913	1984	64	792.8	GROBLERSPLAAS
687	766324	1374	1812	2254	3012	823	1931	1984	42	462.1	SILOAM SENDINGST
688	765707	1367	1794	2247	2954	731	1922	1984	54	334.4	JULIANA
689	765007	1357	1772	2237	2932	728	1926	1965	33	245.6	BANDUR
690	808253	1333	1748	2213	2908	525	1965	1984	18	403.3	PONTDRIFT (POL)
691	766842	1352	1829	2232	3029	580	1954	1983	28	293.1	FOLONHODWE
692	812567	1347	1879	2227	3119	213	1925	1984	50	427.7	PAFURI
693	768011	1361	1861	2241	3101	472	1924	1984	29	645.4	PUNDA MILIA
694	766837	1377	1828	2257	3028	762	1904	1984	61	1056.1	SIBASA
695	723182	1382	1807	2302	3007	1215	1948	1984	31	1570.3	SHEFEERA
696	766480	1380	1816	2300	3016	1341	1923	1984	45	1821.8	ENTABENI (BOS)
697	723155	1384	1808	2304	3008	853	1923	1984	48	895.0	GOEDEHOOP (BOS)
698	723338A	1388	1812	2308	3012	706	1923	1984	52	785.9	DRIEFONTEIN
699	723231	1401	1809	2321	3009	710	1922	1984	49	596.6	BONTFONTEIN
700	723793	1392	1826	2312	3026	654	1950	1984	32	765.1	TABAANS
701	723113	1402	1805	2322	3005	1054	1949	1984	33	905.7	VOORSPOED (BOS)
702	680225	1427	1839	2347	3039	464	1932	1984	44	542.9	BLACK HILLS
703	679156	1416	1806	2336	3006	689	1924	1979	41	513.3	MOOKETSI (SAR)
704	678680	1430	1793	2350	2953	1477	1953	1984	25	607.4	MASEALAMA
705	679164	1424	1806	2344	3006	895	1913	1984	55	1277.9	WESTFALIA
706	678805	1434	1797	2354	2957	1447	1923	1978	39	1140.0	WELTEVREDEN
707	679268	1438	1807	2358	3007	950	1938	1984	29	1275.9	MONAVEIN
708	679532	1432	1818	2352	3018	530	1924	1983	53	784.7	LETABA ESTATES
709	679221	1422	1808	2342	3008	869	1906	1982	61	1016.2	DUIWELSKLOOF (MUN)
710	679339	1420	1813	2340	3013	950	1913	1947	21	709.8	MOOIPLAAS
711	680439	1429	1845	2349	3045	504	1923	1965	27	485.6	PLATVELD
712	680821	1420	1858	2340	3058	345	1944	1984	32	446.0	MAHALE

* LEN designates the number of years of complete record used.

Figure 3.1 Expected maximum one-day rainfall in southern Africa for selected return periods



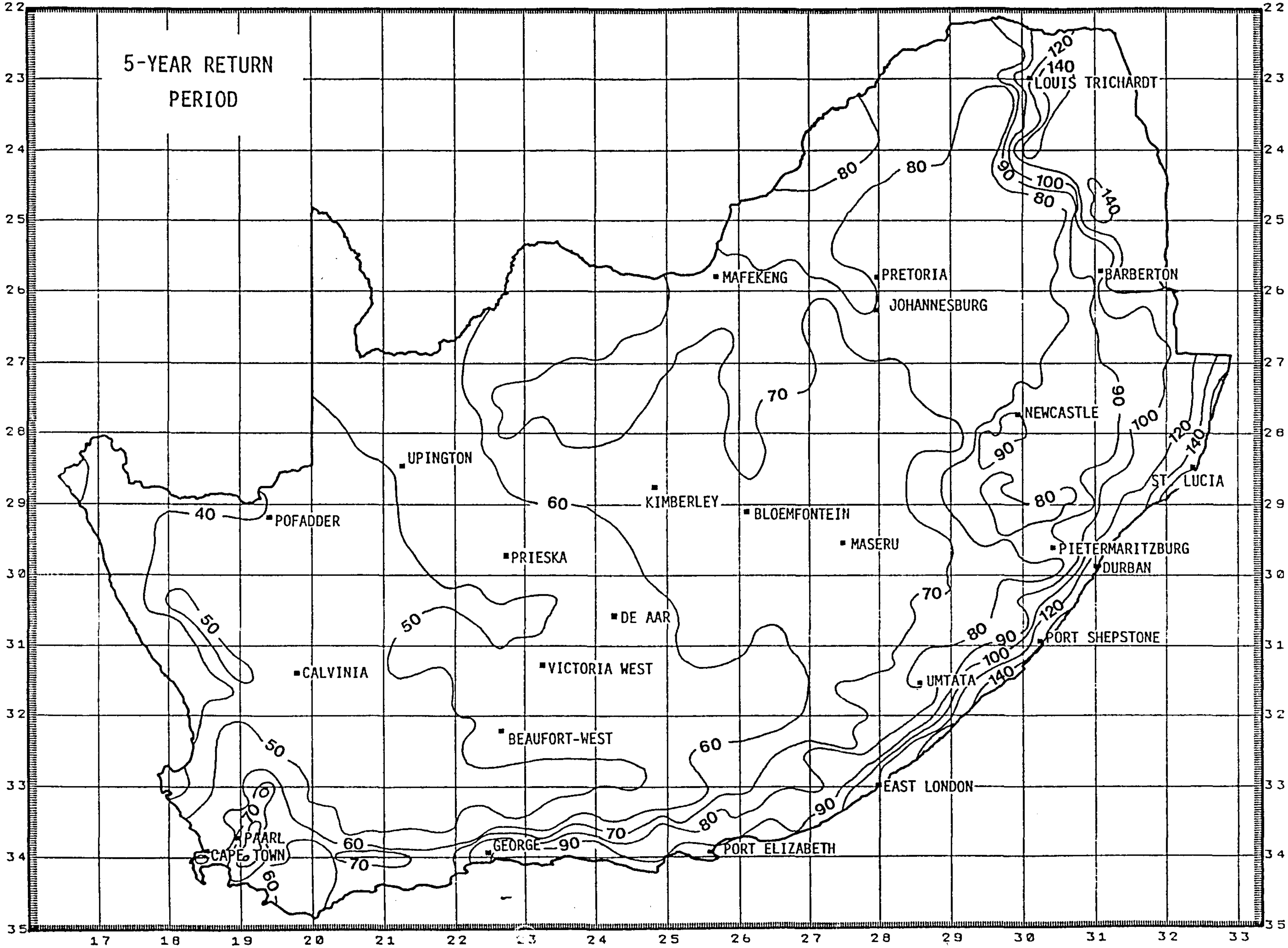


Figure 3.1 (continued)

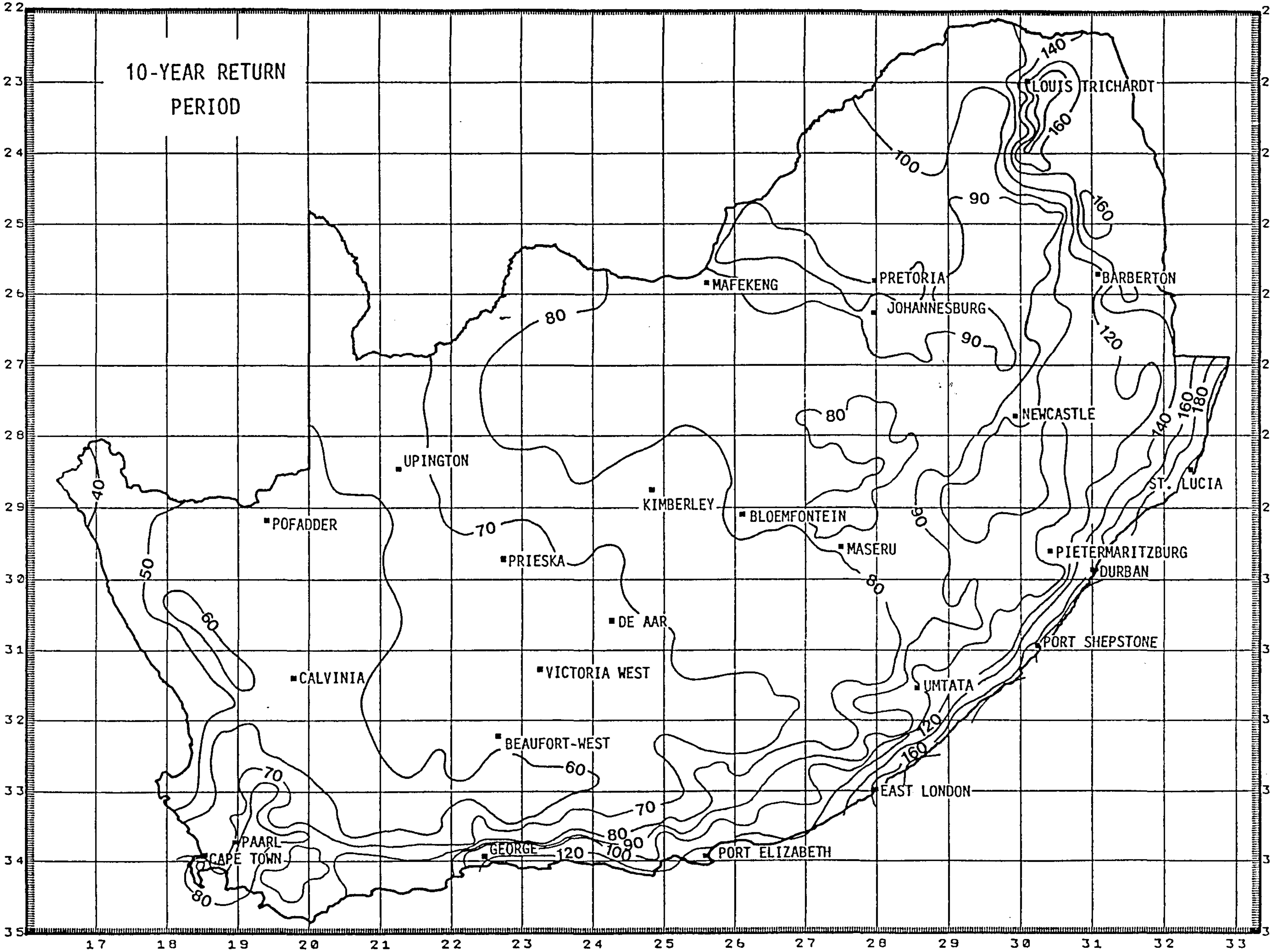
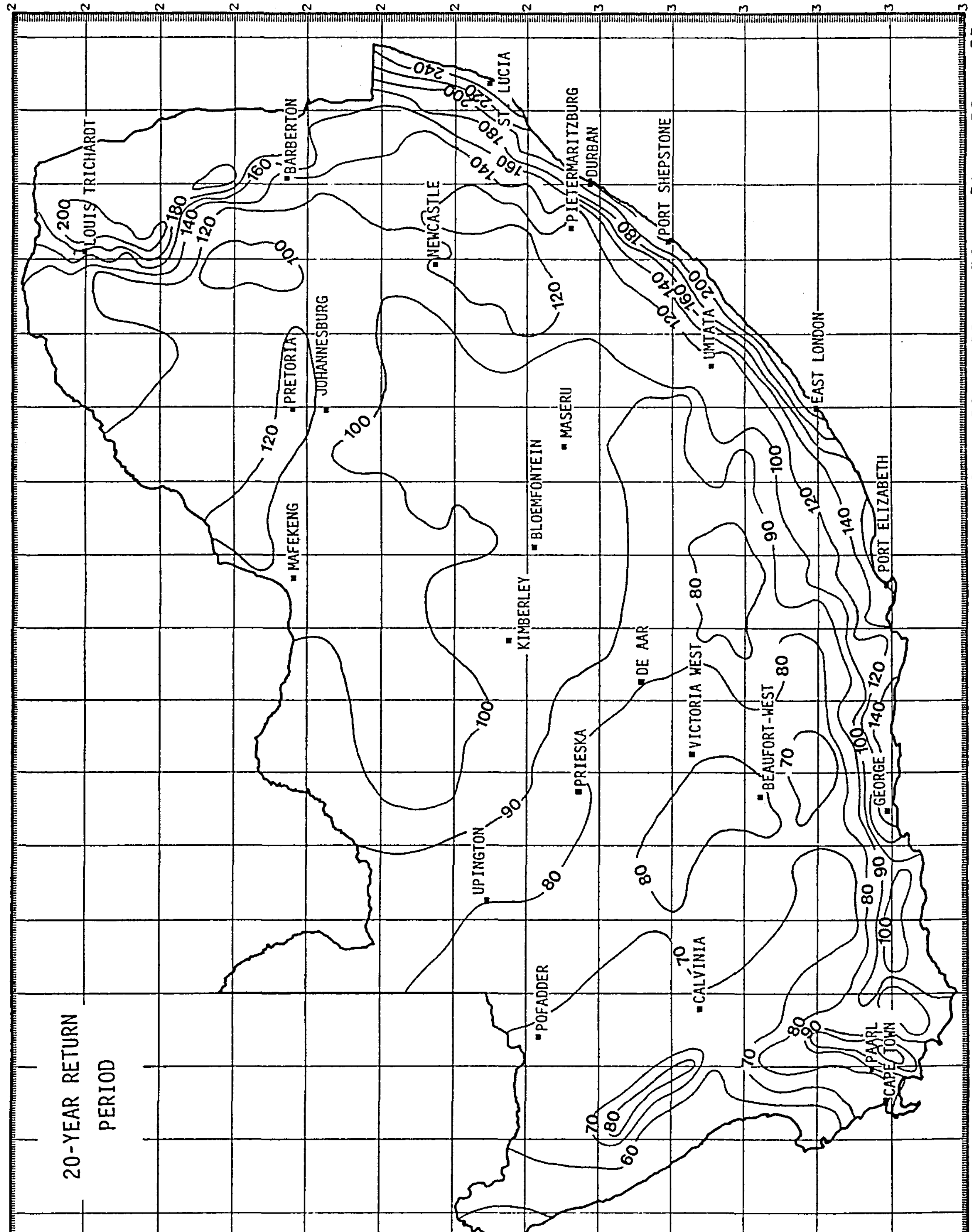


Figure 3.1 (continued)

Figure 3.1 (continued)



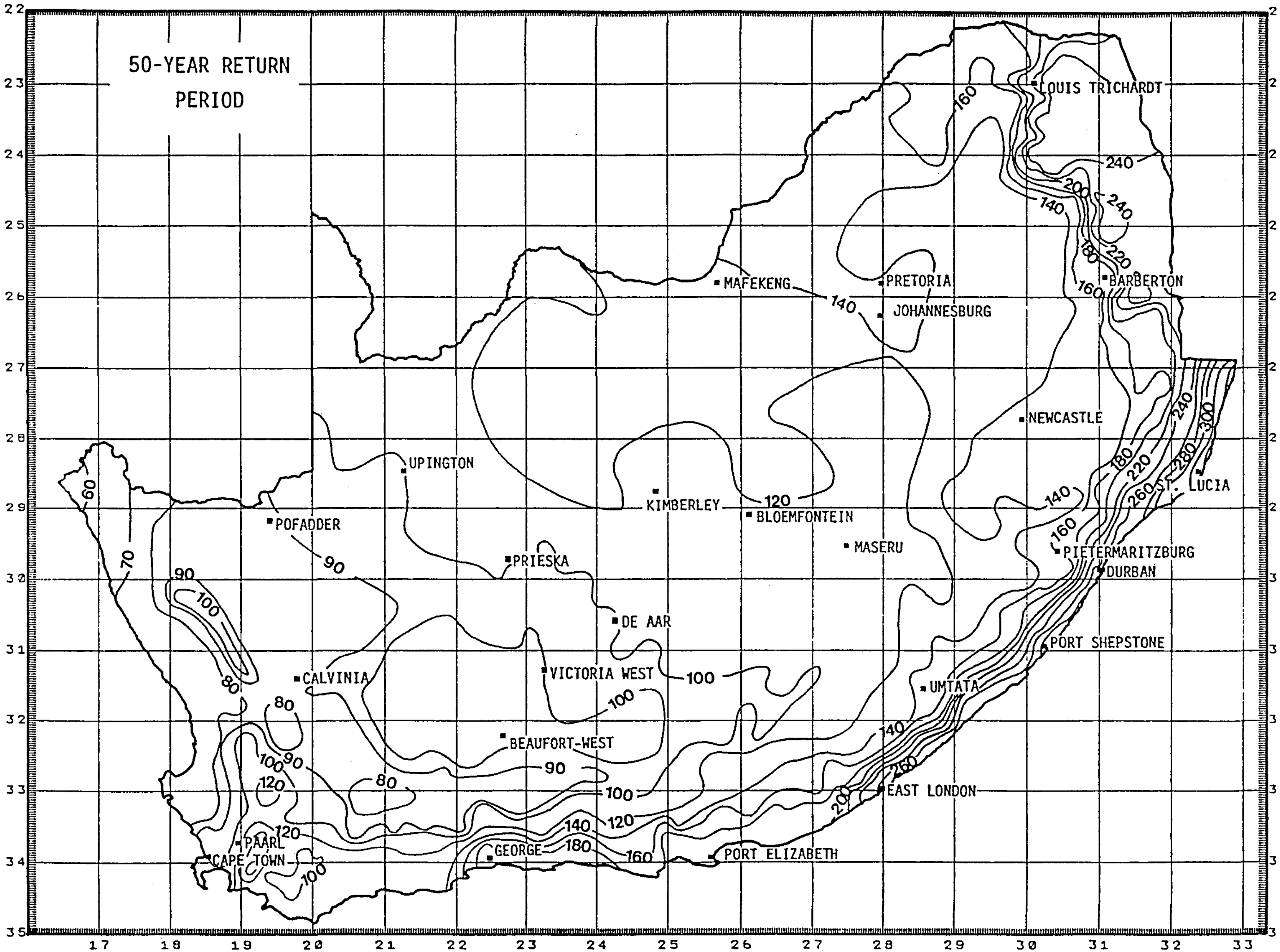


Figure 3.1 (continued)

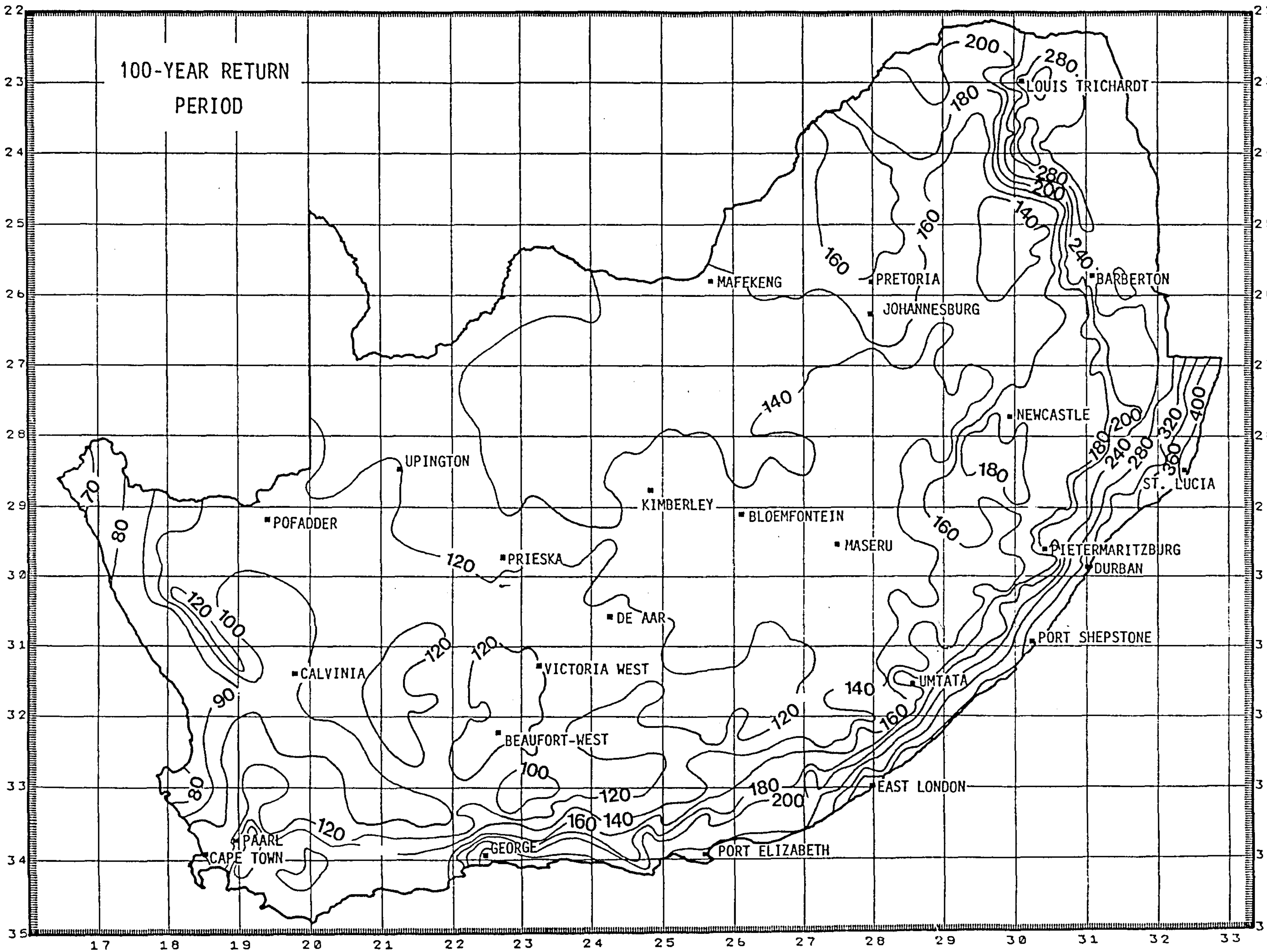
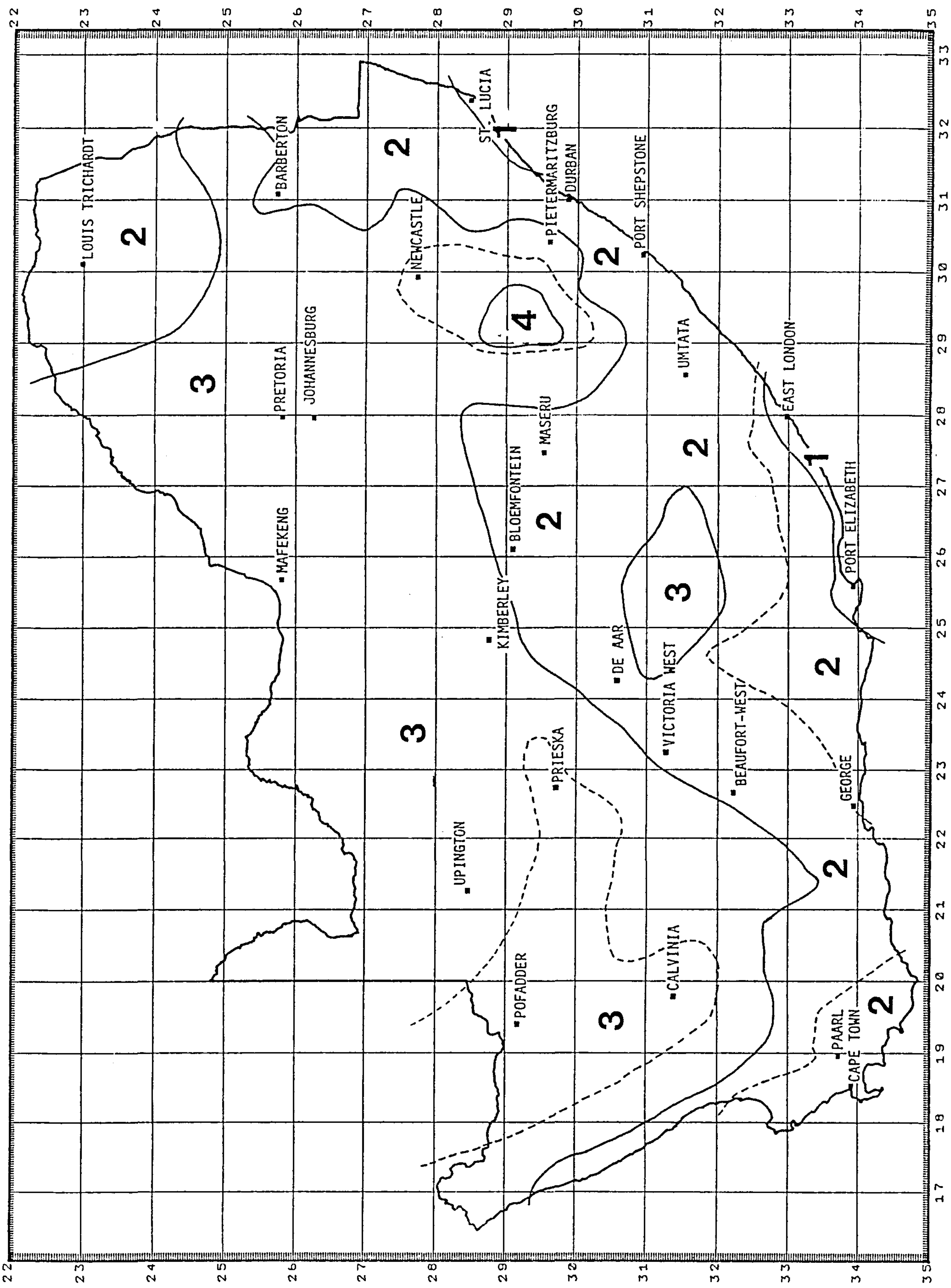


Figure 3.1 (continued)

Figure 3.2 Regionalisation of synthetic rainfall distributions in southern Africa (after Weddepohl, 1988)



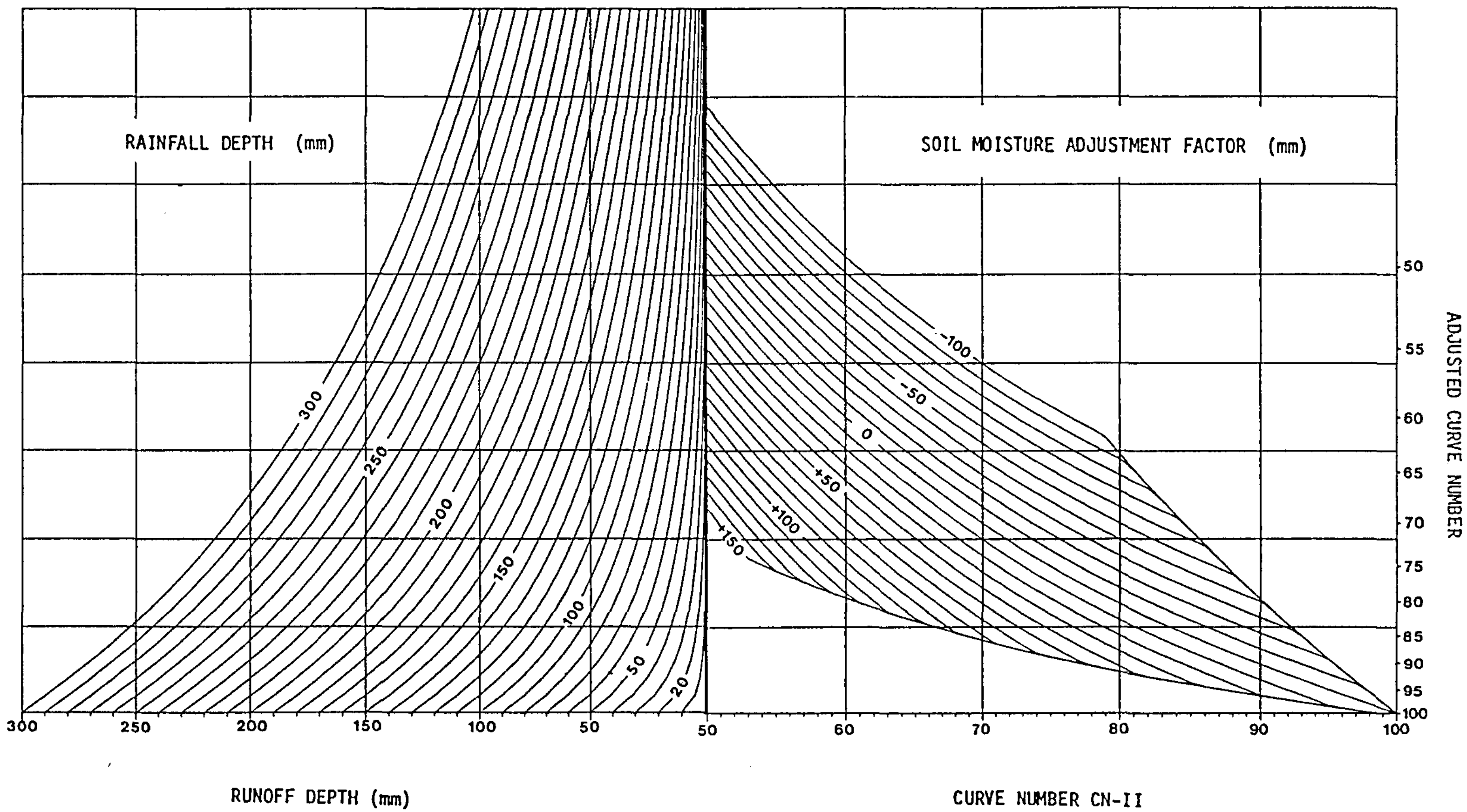


Figure 3.3 Nomograph for adjustment of CN by Hawkins' method and solution to estimated runoff depth

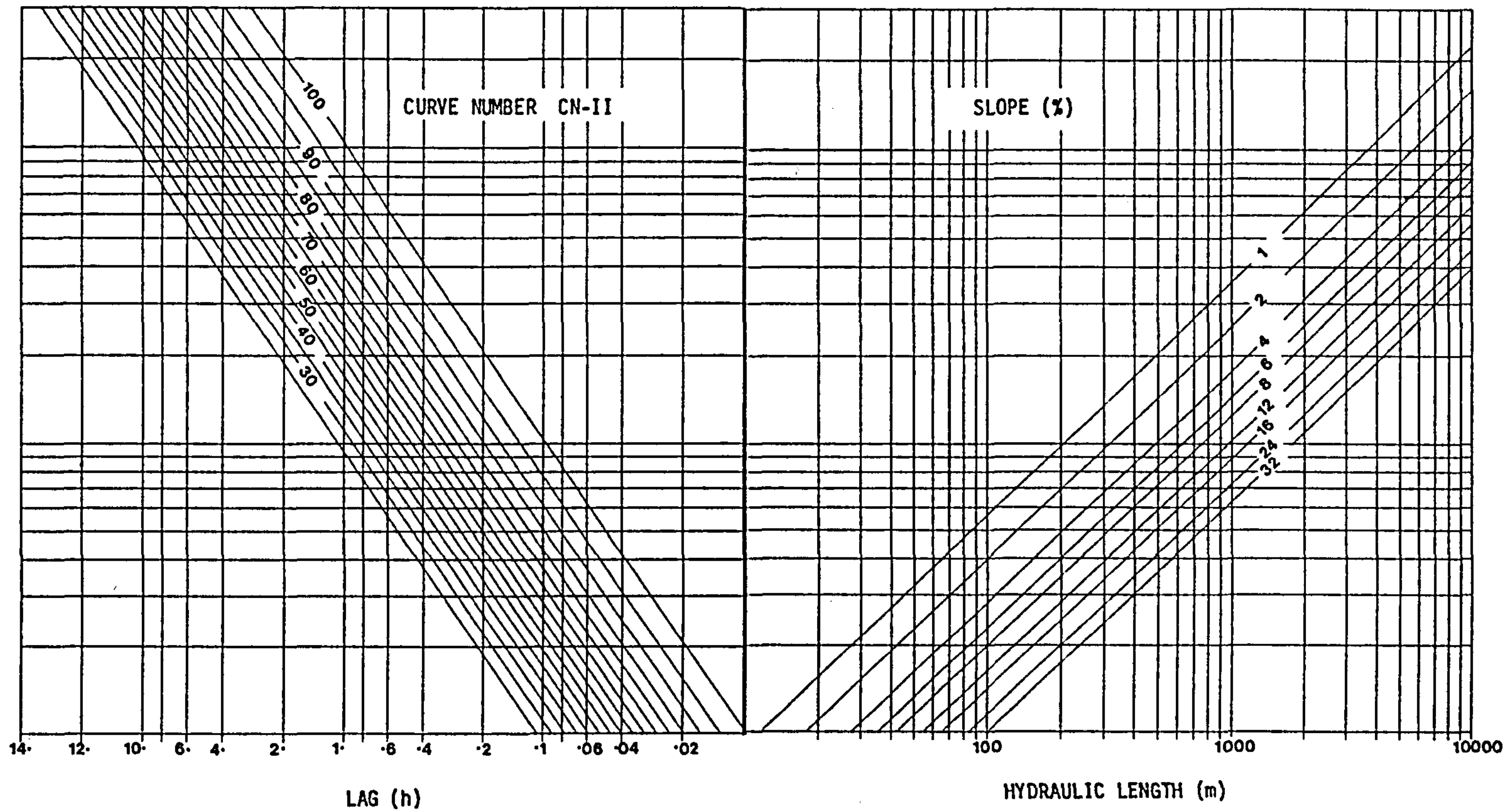


Figure 3.4 Nomographic solution to catchment lag by the original SCS equation

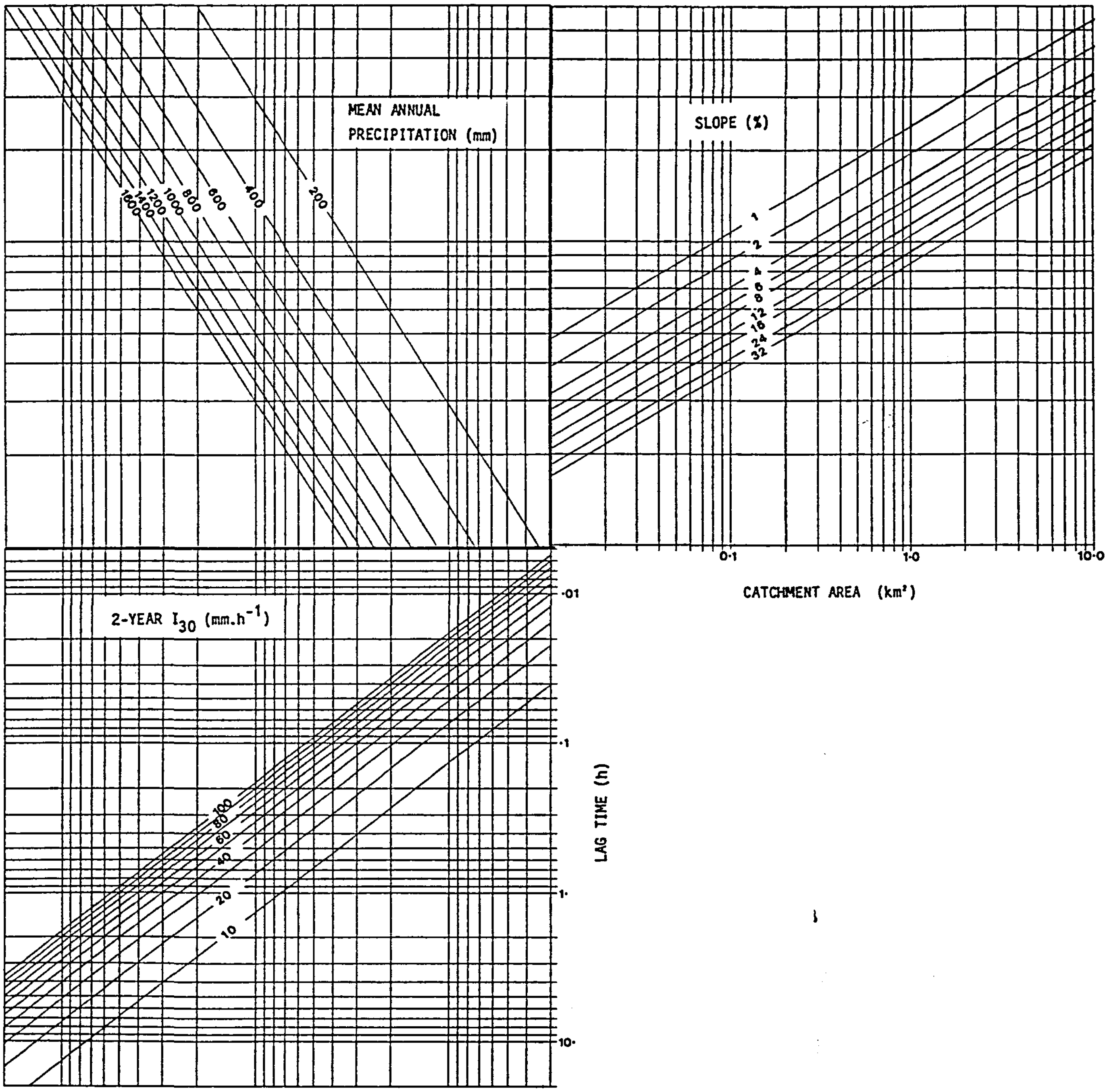


Figure 3.5 Nomographic solution to catchment lag by the Schmidt-Schulze equation

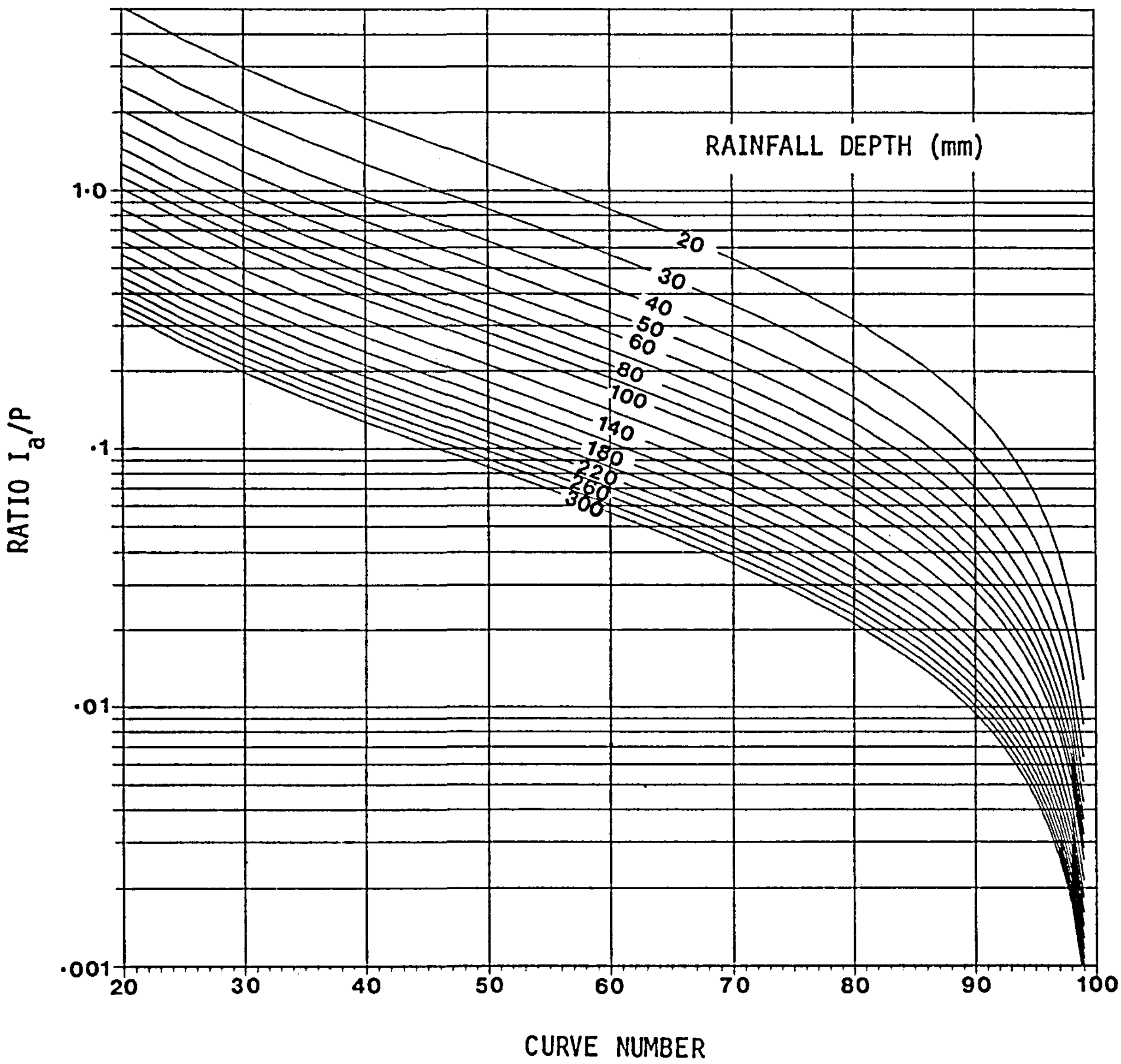


Figure 3.6 Nomographic solution to I_a/P (Method 1)

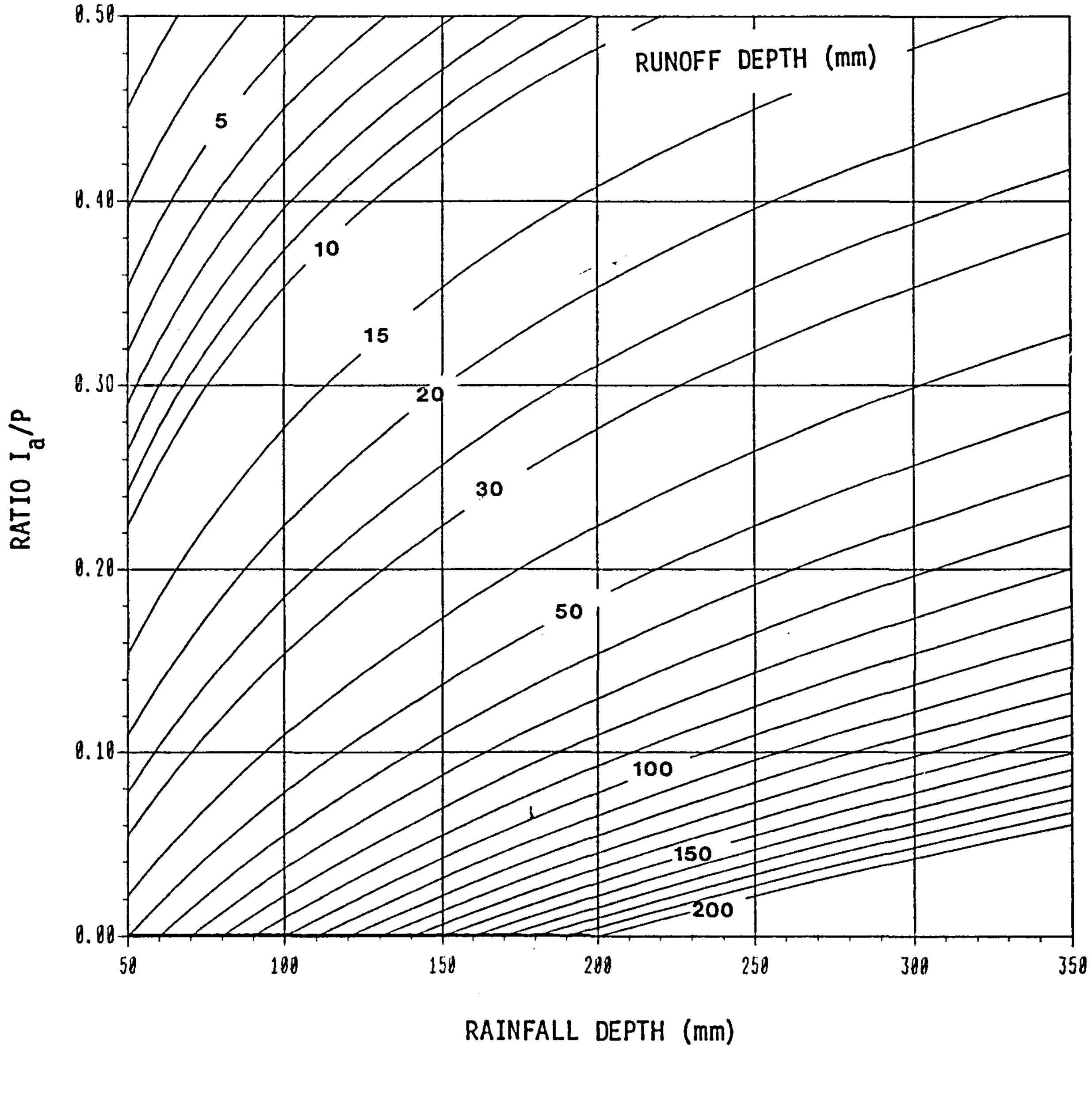
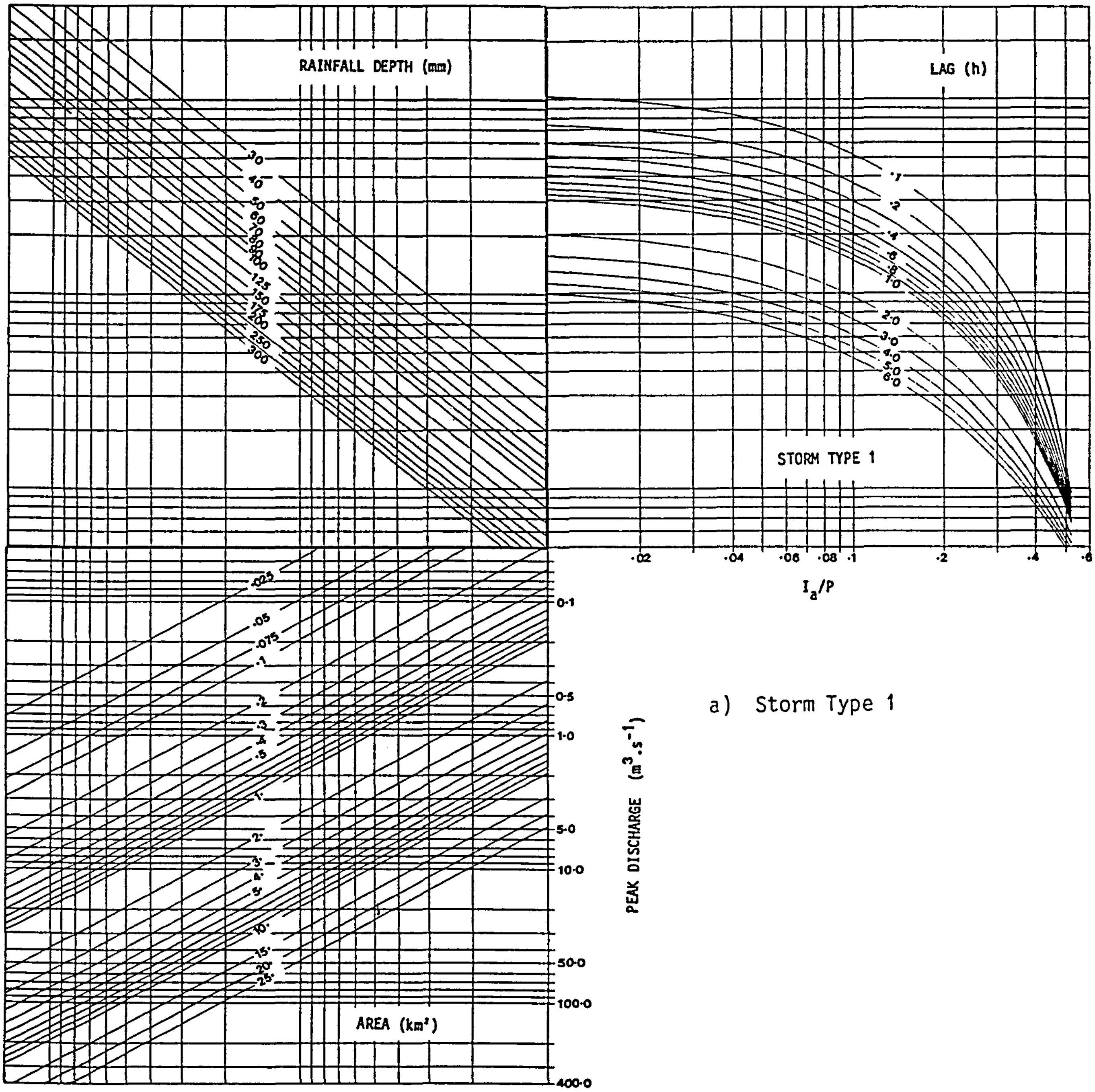
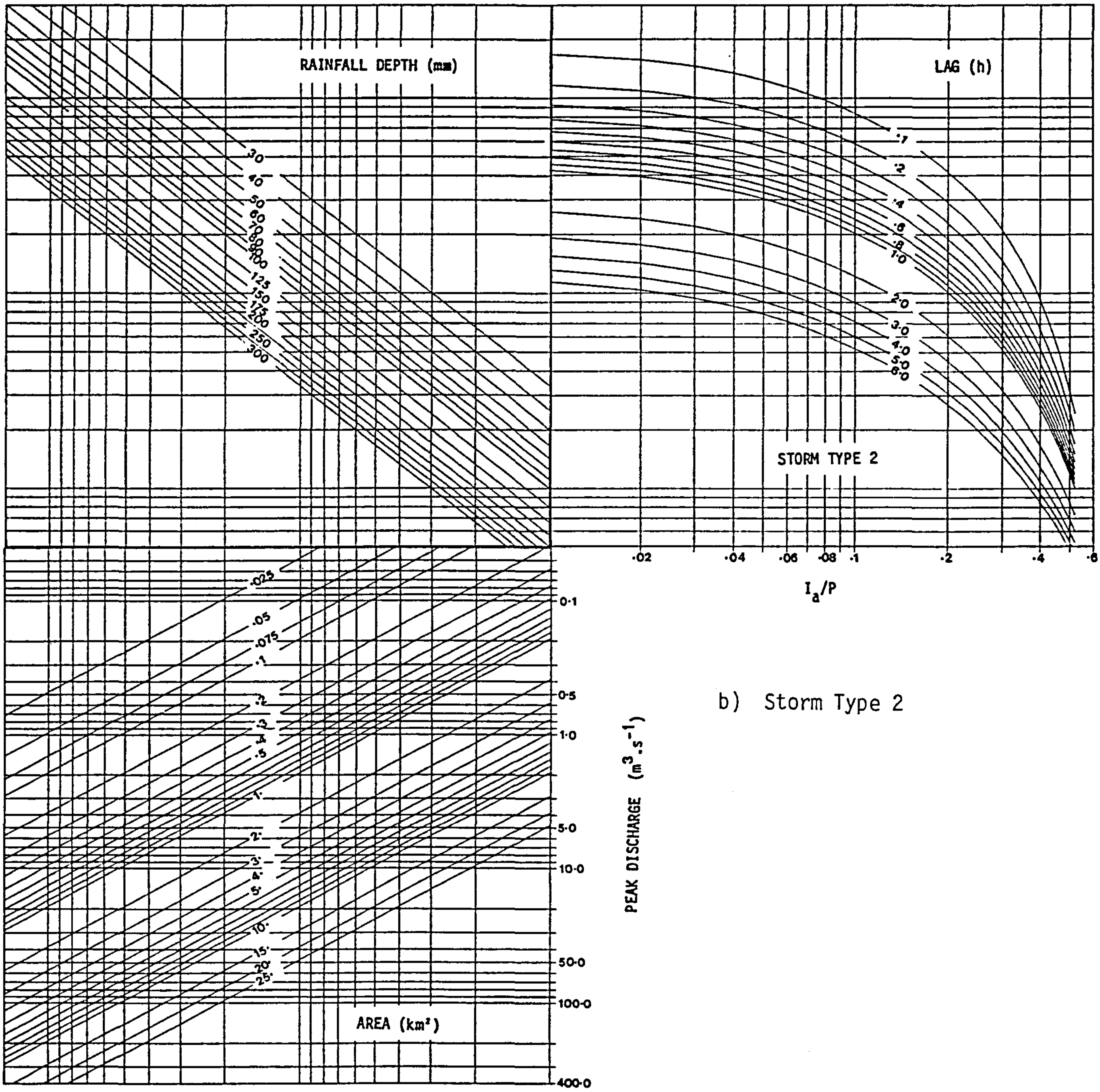


Figure 3.7 Nomographic solution to I_a/P (Method 2)



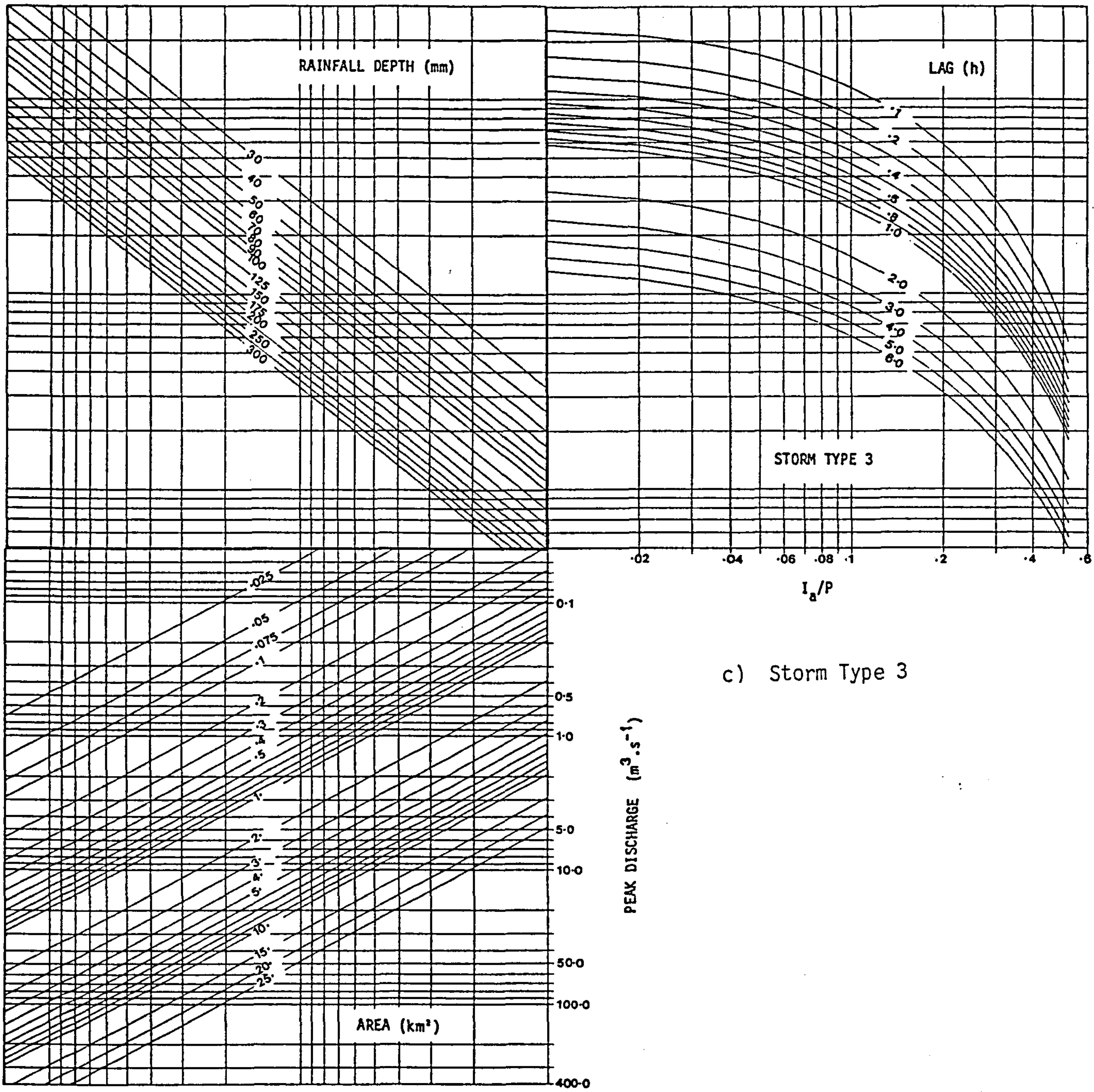
a) Storm Type 1

Figure 3.8 Nomographic solution to estimated peak discharge



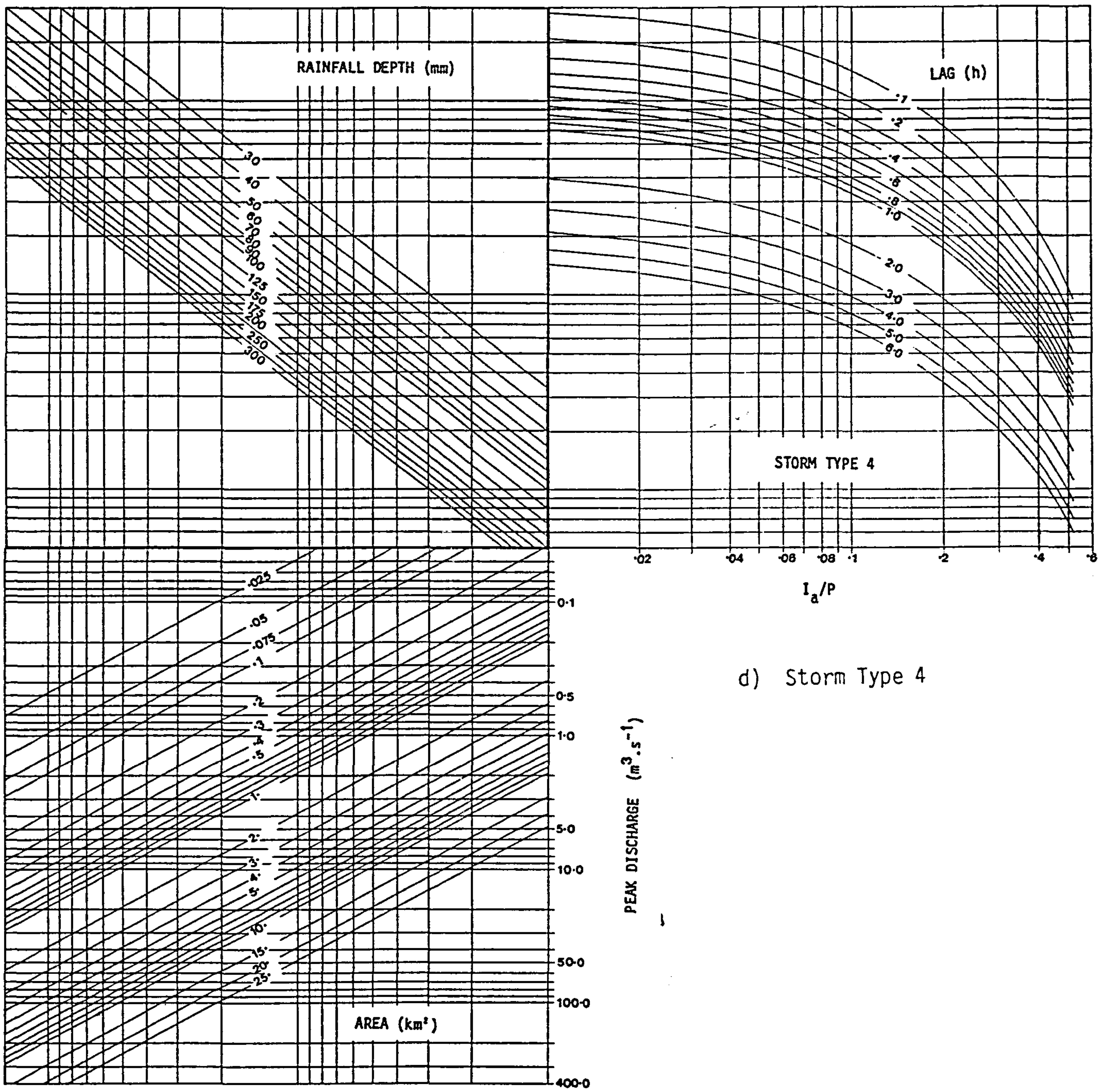
b) Storm Type 2

Figure 3.8 (continued)



c) Storm Type 3

Figure 3.8 (continued)



d) Storm Type 4

Figure 3.8 (continued)

Figure 3.9 Climatic zones used for evaluating moisture status
(See separate fold-out map)

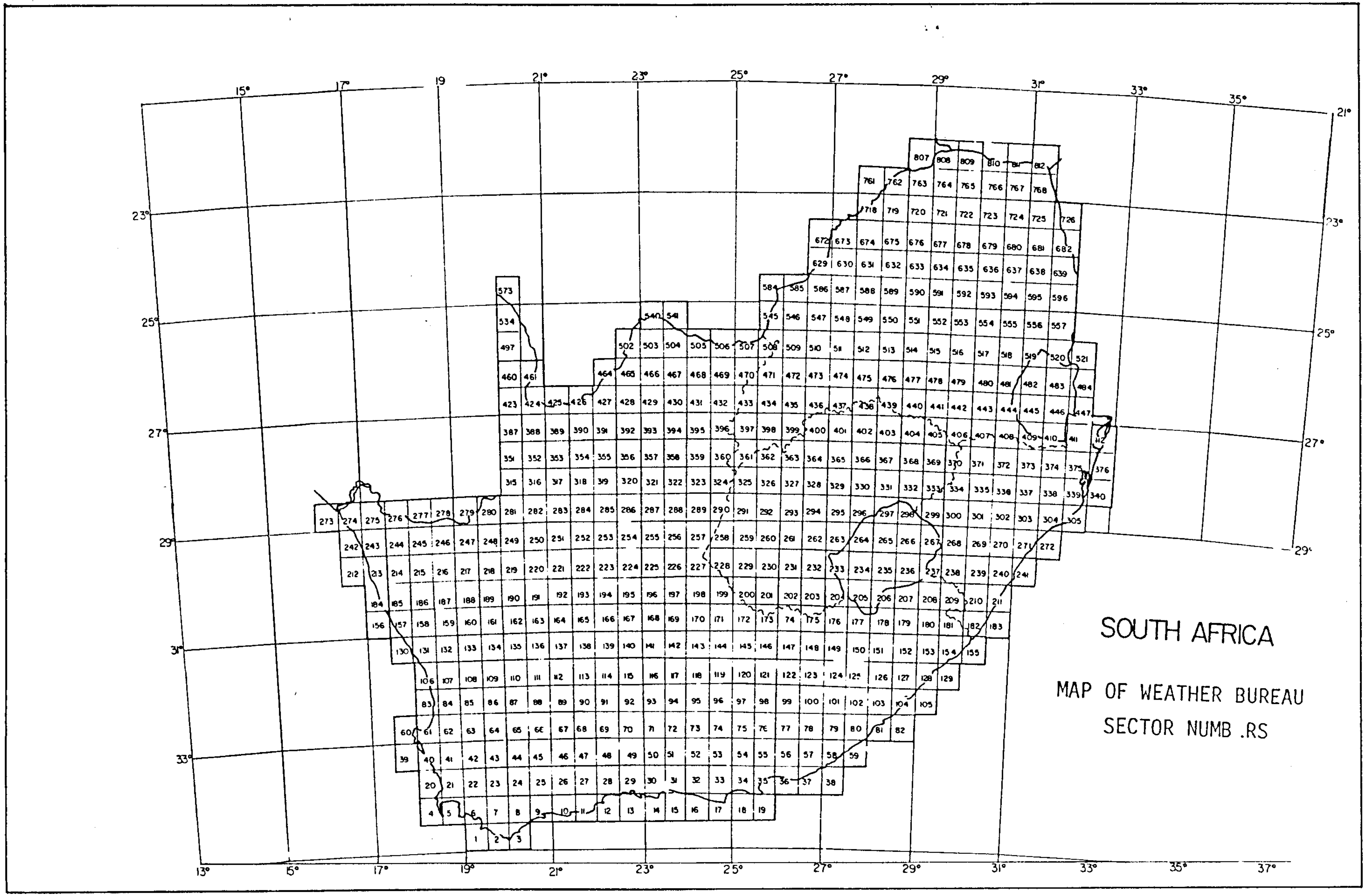
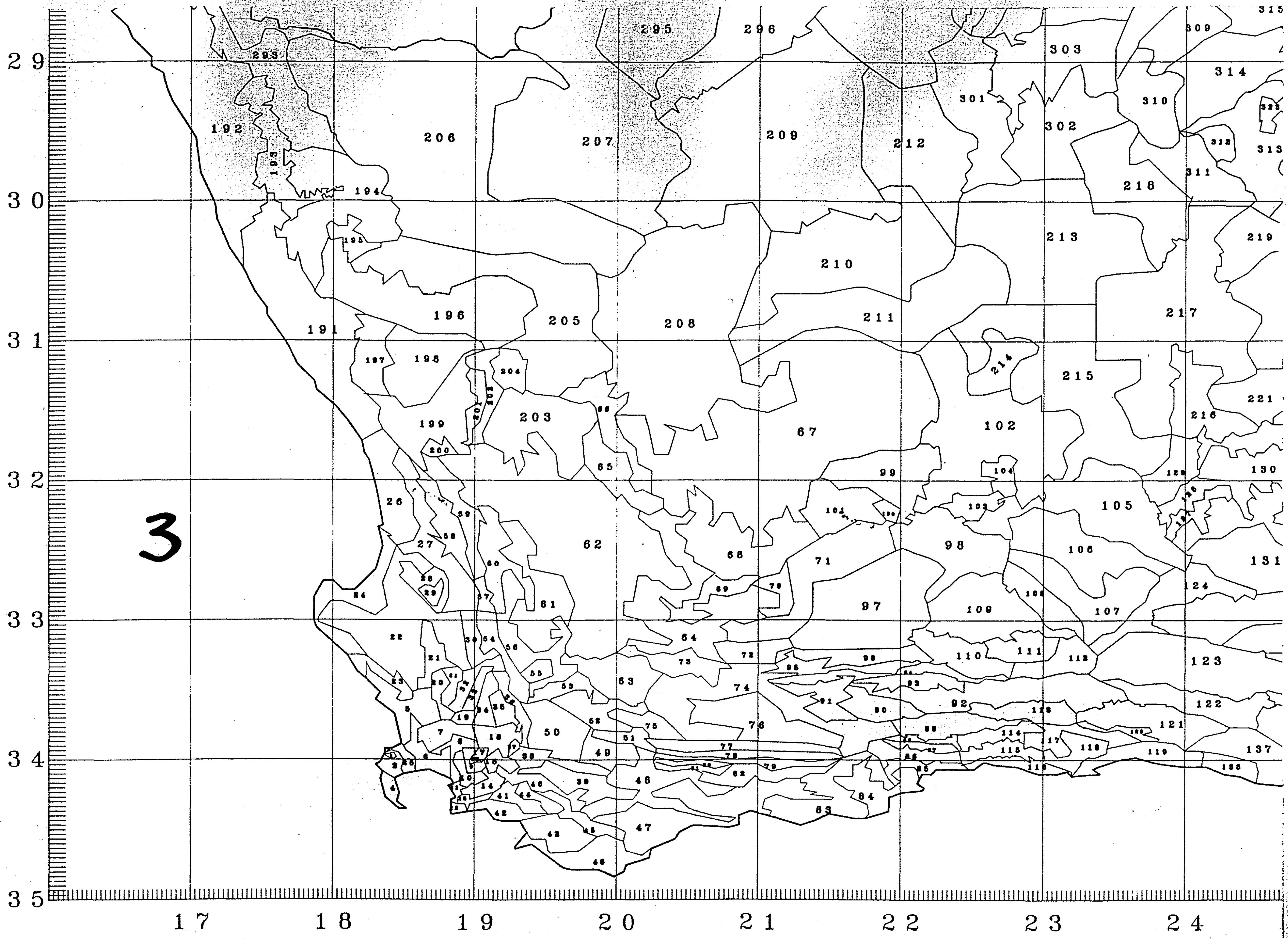


Figure 3.10 Map of Weather Bureau sector numbers



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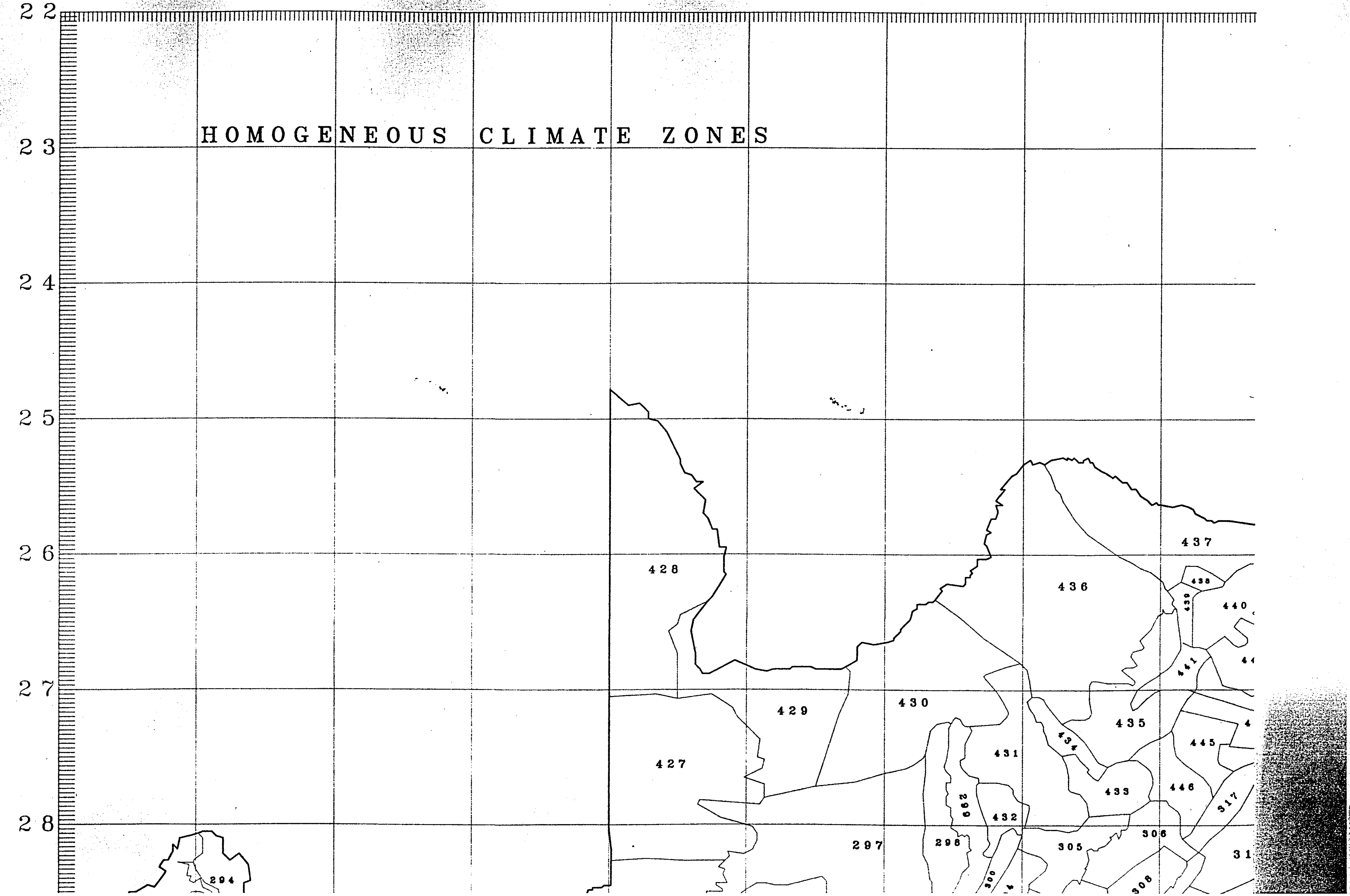
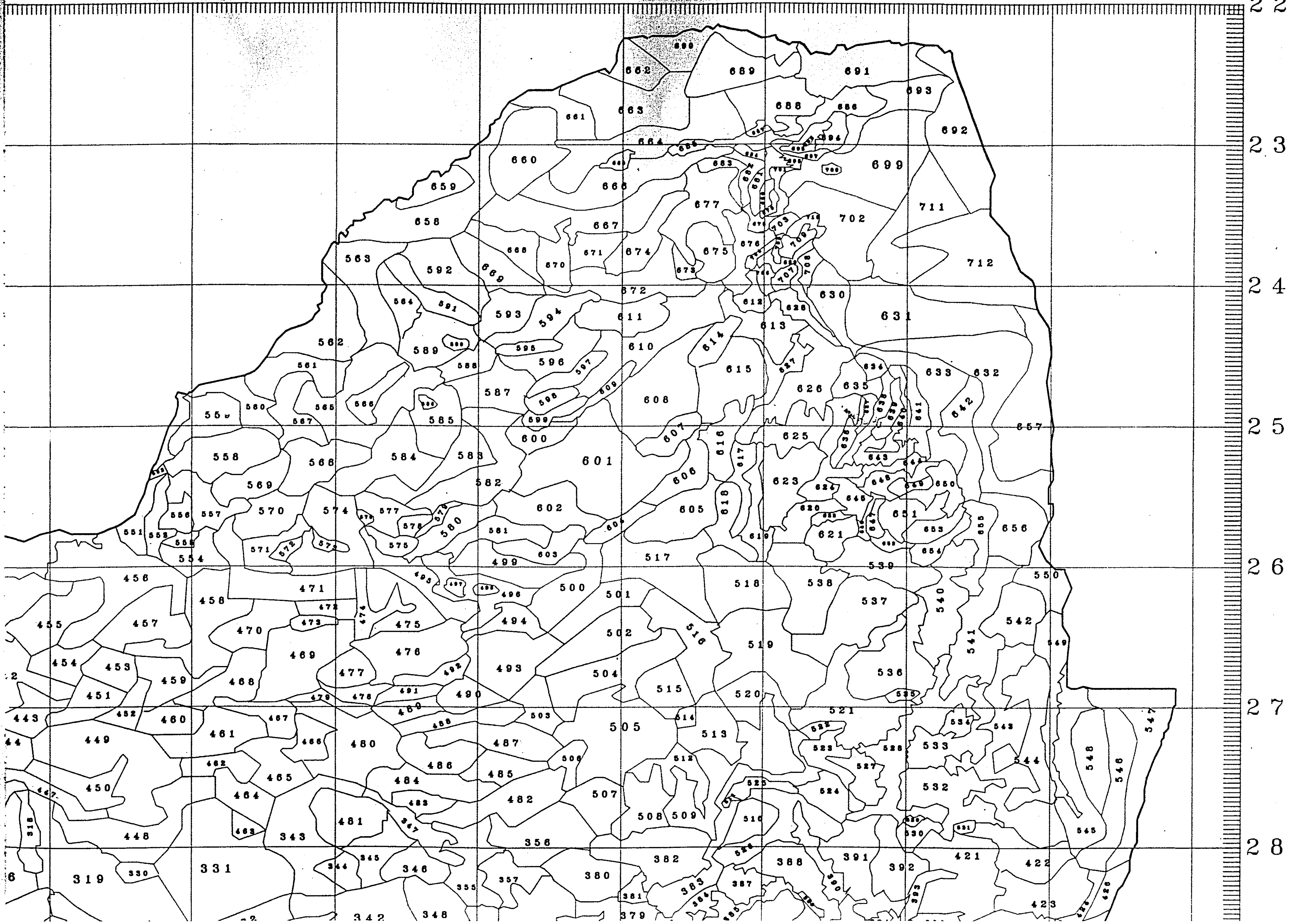
HOMOGENEOUS CLIMATE ZONES

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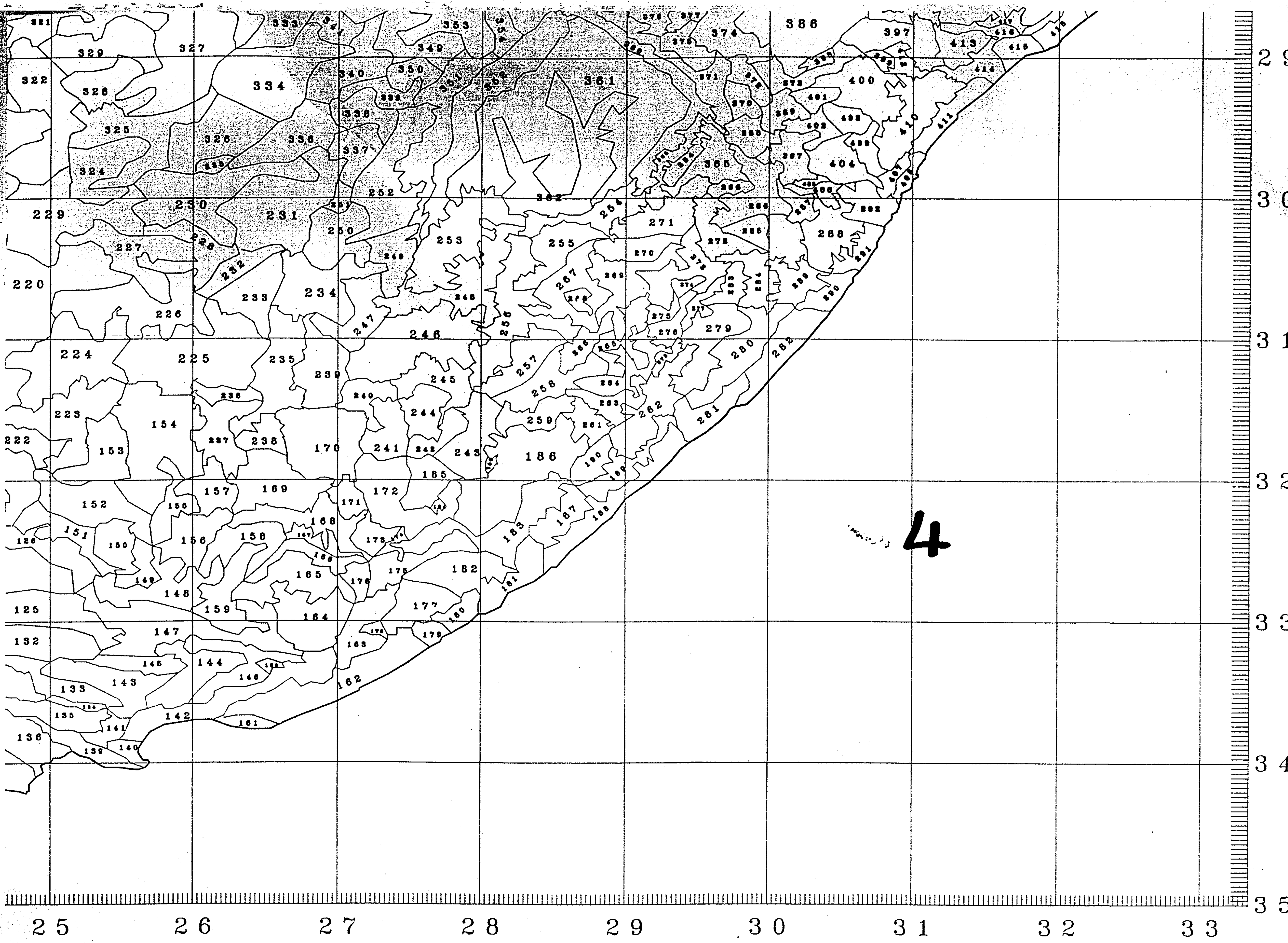

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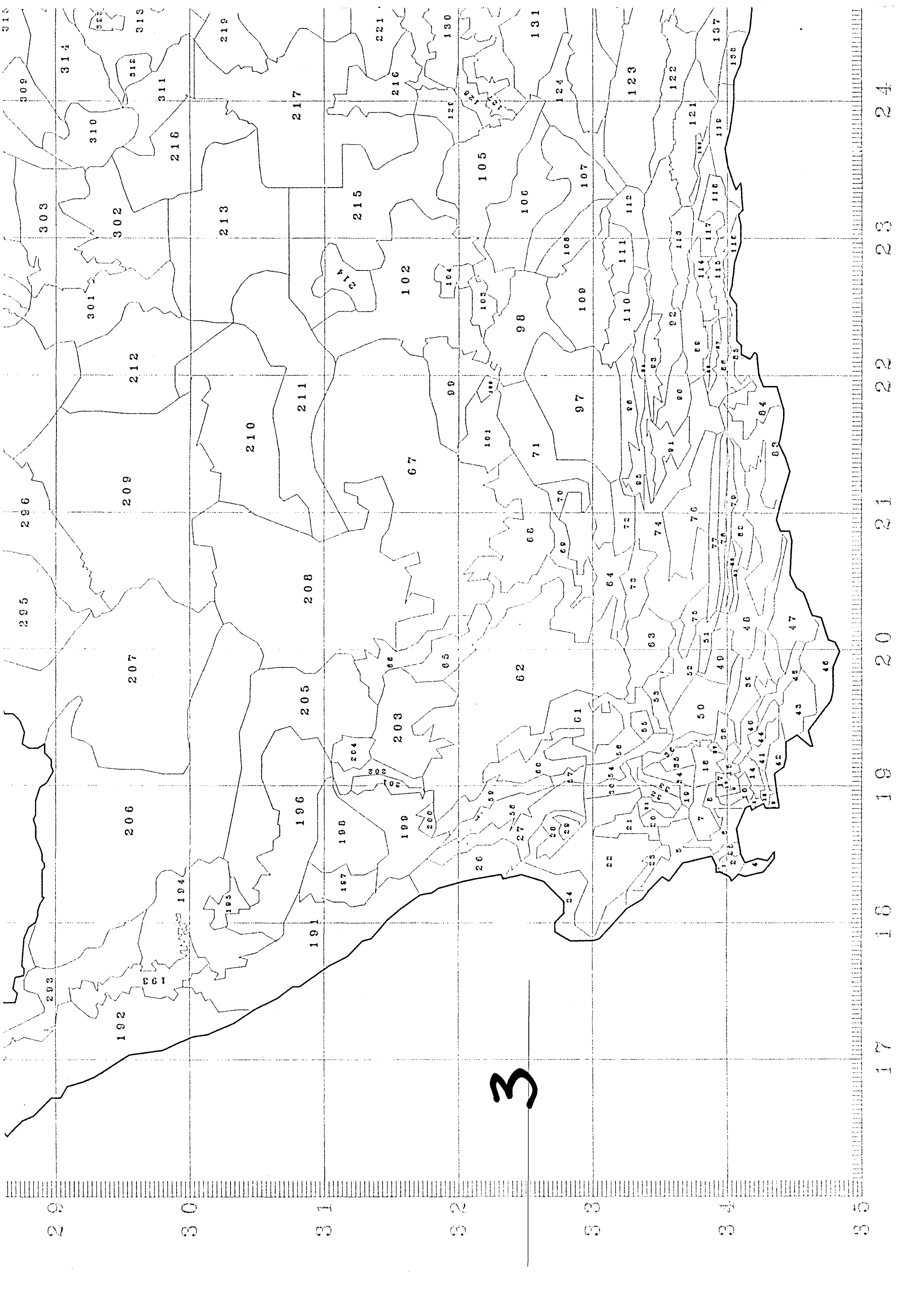

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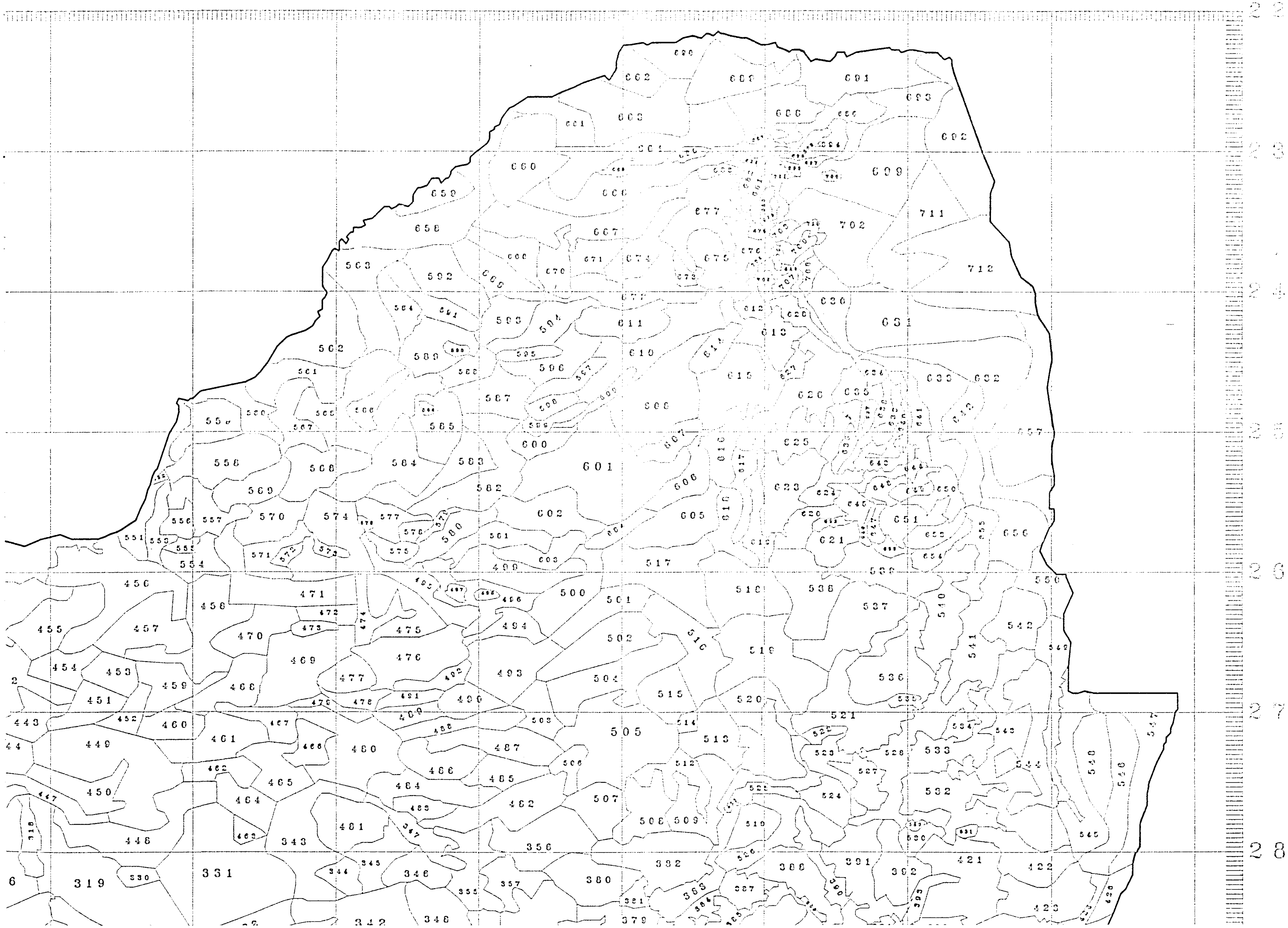

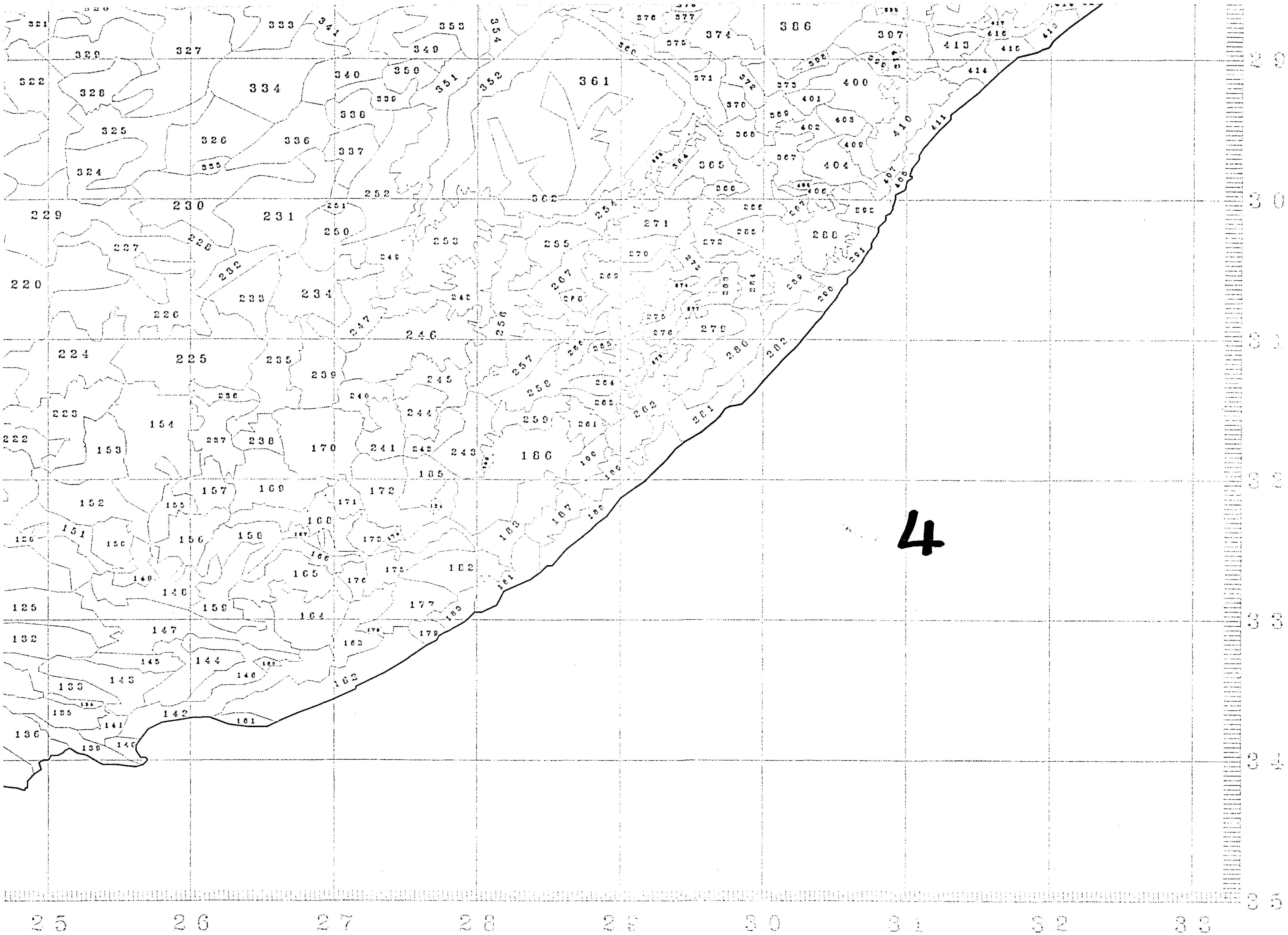

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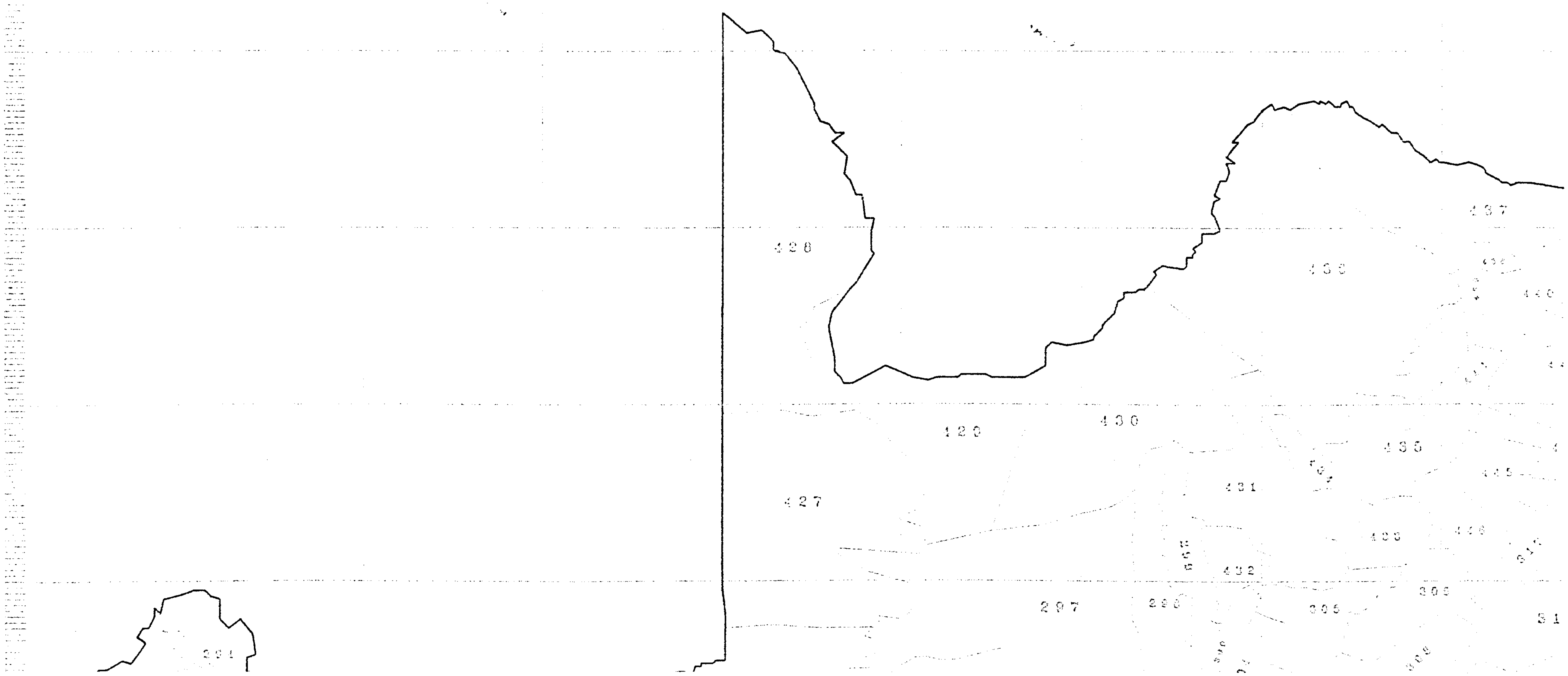
HOMOGENEOUS CLIMATE ZONES



South African Water Law Review Process

The Philosophy and Practice of Integrated Catchment Management:

Implications for Water Resource Management in South Africa

Department of Water Affairs and Forestry

and

Water Research Commission

WRC Report No TT 81/96

1996

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FOREWORD

South Africa is a semi-arid country whose scarce water resources are not equitably distributed in geographical terms. The Department of Water Affairs and Forestry has recognized that naturally occurring water can only be effectively and efficiently managed within a river basin or catchment area. Thus, the Department recognizes and accepts that an integrated catchment management approach is necessary in South Africa.

This approach will help to achieve a balance between the interdependent roles of resource protection and resource utilization. However, our situation is complicated by the facts that provincial and other political or administrative boundaries often divide catchments, and that inter-basin transfers allow water to cross catchment boundaries.

Water and the management and development of water resources are regarded as the responsibility of the National Government, in particular the Department of Water Affairs and Forestry, as these functions are not specified as functional areas in Schedules 4 and 5 of the Constitution, which sets out the legislative competencies of provinces.

The sustainable protection, utilisation and management of South Africa's water resources must be based on sound principles of natural resource management. This means that the Department's responsibilities with regard to protection of the resource relate to the management of all aspects of water quantity, water quality and the physical and structural characteristics of the resource. It is also important to understand that land, water and air quality degradation, together with their subsequent impacts on land and water users, cannot easily be separated or managed independently of one another. Therefore, co-ordinated planning and action is required at all levels, from national government through provincial authorities to local authorities and communities, as well as individual landowners and water users.

This need to link together the activities and priorities of many different agencies and Government departments is reflected in the several initiatives which are currently underway in South Africa. These initiatives include the development and application of Strategic Environmental Assessment protocols, as well as the initiation of Integrated Pollution Control principles and practices.

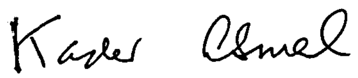
The role of central government in integrated catchment management must be one of leadership, aimed at facilitating and co-ordinating the development and transfer of skills, and assisting with the provision of technical advice and financial support, to local groups and individuals. Where specific areas of responsibility fall outside the mandate of a single government department, appropriate institutional arrangements are needed to ensure effective inter-departmental collaboration. In this process, individual landholders and communities are recognized as competent partners. Where these individuals may lack the necessary skills for full participation, the lead agencies must take responsibility for assisting with their development and application.

As custodian of our water resources, the Department of Water Affairs and Forestry also plays a leading role in the development of guidelines and procedures for water resource management. The Department is also responsible for ensuring that the needs of water users can be met, in perpetuity. Here, the often controversial issue of water allocation to different water users is based on the principles of social equity and justice.

Responsibility and accountability must accompany any statutory power to manage a catchment. The successful execution of such responsibility requires appropriate levels of skills, expertise and judgement. Thus it is essential that government agencies at national and provincial level should provide leadership which will help to co-ordinate the development and implementation of appropriate policies and strategies, facilitate negotiation and conflict resolution processes, provide technical advice and financial support, and transfer skills to catchment organizations.

The Department recognized the importance of drawing on the water resource management experiences of other nations in order to develop the best possible practical approaches for South Africa. This need prompted the Water Research Commission and the Department jointly to initiate a project which reviewed local and overseas experiences and put forward suggestions as to how the Department should incorporate the principles of integrated catchment management in its management of the country's water resources. The joint project, which also benefited from a financial contribution from the Finnish Development Corporation, culminated in the production of this discussion document.

The Department has accepted that the principles of integrated catchment management form an important central component of the comprehensive review of South Africa's Water Law that is now in progress. Nevertheless, the Department recognises that many of the procedures and practices of integrated catchment management are still evolving. This is a discussion document which records our current thinking and I therefore wish to use this opportunity to invite anyone who wants to contribute to further development of our approaches to water resource management in South Africa to comment on the issues that have been described. Your comments and/or proposals should be sent to The Director: Water Quality Management, Department of Water Affairs and Forestry, Private Bag X313, Pretoria 0001. Fax number (012) 323-0321.



Professor Kader Asmal, MP
Minister: Department of Water Affairs & Forestry

December 1996

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THE PHILOSOPHY AND PRACTICE OF INTEGRATED CATCHMENT MANAGEMENT : IMPLICATIONS FOR WATER RESOURCE MANAGEMENT IN SOUTH AFRICA

1. PREFACE

The Department of Water Affairs & Forestry has recognized that naturally occurring water usually can be effectively and efficiently managed only within a river basin or catchment area, because of the need to manage, or at least account for, all aspects of the hydrological cycle. Thus, the Department recognizes and accepts that an integrated catchment management (ICM) approach will be adopted in South Africa (DWAF, 1986).

This approach is seen to facilitate the achievement of a balance between the interdependent roles of resource protection and resource utilization. However, the situation is complicated by the facts that provincial and other political or administrative boundaries often divide catchments, and that inter-basin transfers allow water to cross catchment boundaries.

However, despite the recognition of water as a strategic national resource which is not equitably distributed in geographic terms, water resource management has not yet been defined as a national function in the Constitution. Water and the management and development of water resources are regarded as the responsibility of the National Government, in particular the Department of Water Affairs & Forestry, as these functions are not specified as functional areas in Schedules 4 and 5 of the Constitution, which sets out the legislative competencies of provinces.

Against this background, it is important to recognize that a water resource includes not only the water but also the structural components (morphology, riparian and instream habitat) and the biotic components of the aquatic ecosystem. The resource is an ecological system, the sustainability of which is to a large extent dependent on the ecological interactions between the physico-chemical attributes and the biotic attributes of the resource.

Therefore, it follows that protection, utilisation and management of the resource must be based on ecological principles. This means that the Department's responsibilities with regard to protection of the resource relate to the management of the water quantity, water quality and physical and structural characteristics of the resource, so as to provide an appropriate abiotic template which will ensure the integrity of the biotic component of the resource.

On the basis of these management responsibilities, a water resource can be defined as follows (DWAF, 1996).

- A water resource includes the three components of habitat (sediments, instream and riparian), aquatic biota and water, as well as the physical, chemical and ecological processes which link these components of the aquatic environment.

It is also important to recognize that land and water degradation, together with their subsequent impacts on land and water users, cannot easily be separated or managed independently of one another. This implies that co-ordinated planning and action is required at all levels, from national government through provincial authorities to individual landowners.

The role of central government in ICM should be one of leadership, aimed at facilitating and co-ordinating the development and transfer of skills, and assisting with the provision of technical advice and financial support, to local groups and individuals. Where specific areas of responsibility fall outside the mandate of a single government department, appropriate institutional arrangements are required to ensure effective inter-departmental collaboration.

At a lower level in this process, individual landholders and communities must be recognized as competent partners. Where these individuals may lack the necessary skills for full participation, the lead agencies must take responsibility for assisting with their development and application.

Five basic principles for effective ICM can be defined. These are:

- A systems approach which recognizes the individual components as well as the linkages between them, and addresses the needs of both the human and natural systems.
- An integrated approach, rather than a comprehensive approach, in which attention is directed towards key issues of concern identified by all stakeholders in the process.
- A stakeholder approach which recognizes the importance of involving individual citizens and landowners, as well as government agencies, in a participatory process to define all decisions around the conservation and use of natural resources which affect their lives.

- A partnership approach which promotes the search for common objectives, and defines the roles, responsibilities and accountabilities of each agency and individual who participates in the process of decision making.
- A balanced approach where close attention is given to decisions designed to achieve a sustainable blend of economic development, protection of resource integrity, whilst meeting social norms and expectations.

A basic tenet of ICM is that responsibility and accountability must accompany any statutory power to manage a catchment. Clearly, successful execution of such responsibility requires appropriate levels of skills, expertise and judgement. Thus it is essential that government agencies at national and provincial level should provide strong leadership which will help to co-ordinate the development and implementation of ICM policies and strategies, facilitate negotiation and conflict resolution processes, provide technical advice and financial support, and transfer skills to catchment organizations.

The concepts embodied within the term Integrated Catchment Management (ICM) contain the critical central issues on which water resource management is based. Accordingly, it is essential that there is a clear understanding of the meanings that are given to each of the three issues and the ways in which they are applied, namely: "catchment", "integrated" and "management". These issues are outlined, individually, below:

1.1 Catchment

The Water Law Principles support the idea that effective management of water resources encompasses management of the entire hydrological cycle. The hydrological cycle includes water in all its aspects:

- atmosphere (quantity, quality and distribution of precipitation, including rain, hail, dew and snow);
- subsurface water, including water in soil moisture storage and groundwater reservoirs;
- surface water (rivers, lakes, wetlands, impoundments);
- estuarine zone;
- coastal marine zone.

A river basin boundary would be that which includes water in all aspects of the hydrological cycle, through precipitation, into subsurface storage and along drainage lines, to the sea. The land area included in a river basin should include land through or over which water moves, and land on which human activities or disturbances create impacts which affect the quantity, quality or distribution of water in any of the aspects of the hydrological cycle.

A river basin could be made up of several catchments, either contiguous or nested within each other, which would cover the hydrological cycle from precipitation, through or over land to surface drainage lines which converge to a single point, at which the water exits to another catchment or to the sea. Again, the land area of the catchment includes the land through or over which that water flows, and/or the land from where impacts can be generated which affect quantity, quality or distribution of water.

1.2 Integrated

A catchment is a living ecosystem, which means that it is a large, interconnected web of land, water, vegetation, structural habitats, biota and the many physical, chemical and biological processes which link these. This is different from the more engineering-related idea of a set of components in series or parallel or a combination of these, linked at clearly defined points by clearly defined processes. Such a situation could exist, for example, where complex water transfer systems such as the Lesotho Highlands Water Project have been constructed.

A true systems approach means recognising that a disturbance made at a place in the system will be translated to other parts of the system. Sometimes the effect on another part of the system may be indirect, and may be damped out due to natural resilience to disturbance; sometimes the effect will be direct, significant and may increase in degree as it moves through the system.

For example: the effects of land use, such as urban development, may cause changes in the quality of surface water resources. Degradation of water quality due to urban development, with its associated runoff pollution and treated wastewater discharges, may lead to impacts on other land uses downstream, such as irrigation. If the impacts on irrigation are negative, and lead to reduced agricultural returns, this may then lead to adverse economic impacts on the original urban development.

An integrated approach to catchment management entails:

- seeing the catchment and the associated water as one system, using the sense of the word system as discussed above;

- acknowledging both the direct and indirect effects that actions in one part of the system, whether the land, water or atmospheric aspects, may have on other parts;
- ensuring that actions taken by an agency or responsible body in one part (land, water or atmosphere) of the catchment are not taken in isolation from, or in conflict with, the actions of other agencies;
- ensuring that actions are taken with due attention to the needs of other stakeholders in the catchment who may be affected, either directly or indirectly, by such actions.

1.3 Management

If the idea of a catchment as an integrated system is accepted, in the sense described above, then management of the catchment would entail the planning and execution of actions designed to maintain the system at a particular agreed status (of water quantity, quality and distribution), within an accepted range of variability and reliability.

Management actions could be focused on land, to constrain the impacts of land-based activities on water resources, as well as on the water itself, to ensure adequate storage, distribution and rehabilitation where necessary. Typically, stakeholders would have participated in the debate around preferred sequences of actions and their consequences. The selected series of management actions would then be documented as a catchment management plan which required the formal approval of the Minister of Water Affairs. Responsibility for implementation of the catchment management plan could rest with a legally constituted catchment authority that represented the interests of all stakeholders.

A catchment management plan would include a set of numerical and/or narrative water environment objectives, which would be derived such that the agreed status of the catchment water resources can be maintained. The plan would cover management of land-based impacts as well as the management of the water in the catchment; responsibility for management actions may be devolved to various agencies, authorities or individual stakeholders.

2. BACKGROUND INFORMATION

2.1 Introduction

The ability of all nations or societies to develop and prosper is tied directly to their ability to properly develop, utilize, protect and sustain their water resources. Ultimately, the achievement of these objectives is dependent on the implementation of an appropriate management system that ensures the long-term sustainability of both the water resources and the uses that are made of them.

In this context, well-managed water resources allow industrial development, transportation of goods, agricultural production, protection of public health, enhancement of recreational opportunities and production of energy, whilst environmental degradation is minimized. Therefore, one of the highest priorities of all countries should be the development and maintenance of the most effective and efficient water resource management systems that are possible.

Competing demands for equitable access to, and sustained use of, water resources can often result in acrimonious disputes and even open conflict. This is particularly evident in the more arid regions of the world which experience frequent water shortages, and where key water resources (such as rivers) cross or coincide with political boundaries. Therefore, another important goal of water resource management is to ensure that conflicts between different users are resolved or minimized.

The scarcity and variability of the available water resources in South Africa, coupled with the country's need for economic growth and development, as well as social upliftment, presents water resource managers with a number of significant challenges. The situation is further complicated by the deterioration in the quality of South Africa's water resources as a result of both past and current developments.

More recently, sweeping socio-economic and political changes have occurred in South Africa. Previous "command and control" approaches to water resources management, imposed unilaterally from a central government body, are no longer widely accepted by the general public. People now feel a growing need to participate in, and contribute to, decision making processes, partly due to their lack of trust in previous delivery systems. Related to this, it has become evident that the end users of any resource development project need to be closely involved in both the planning and management aspects to ensure that their concerns are taken into account and they get appropriate delivery of the resource.

Whilst people should accept responsibility and accountability for participation in water resource management issues, it is necessary for the Department to be capable of taking up the responsibility for leadership and guidance, rather than control. As a consequence, water resource management processes need to become more people-oriented, rather than being dominated by technical considerations as in the past.

2.2 Current developments

The growing complexity of the situation, and the scale of the problems that need to be addressed as a matter of urgency, require the development and implementation of new approaches by South African water resource managers. It will be essential that these new approaches incorporate a detailed understanding of the resources available as well as the needs and aspirations of the user communities. Technical, economic, social, political, legal and environmental considerations will have to be taken into account in the management process. This is only possible if a systems approach is followed which integrates engineering skills, socio-economic concerns, and environmental constraints within a multi-disciplinary decision-making process.

In a given area, each component of the hydrological cycle is influenced by, or influences, other components in the cycle; none can be viewed in isolation. Water resources therefore need to be administered and managed in a way that recognizes the entire hydrological cycle as an indivisible continuum. This requires an increased appreciation of the individual roles and interactions between atmospheric precipitation, evaporation, infiltration, seepage, runoff and erosion.

Similarly, each use that is made of a particular water resource also influences, or is influenced by, the actions of all other water uses. Therefore, it is important to recognize the requirements of individual water uses, the value of each alternative use of water, and the consequences of not being able to meet some or all of these requirements. Effective water resource management thus requires the simultaneous integration of all relevant factors, processes and uses within a single system.

In the context of water resources, the river basin or catchment is now widely accepted as the best management unit which will enable this to be achieved. However, the definition of a water resource does not include the land area of the catchment. Whilst it is recognized that land-based activities impact on water resources, these can be managed through co-operation with the relevant authorities within the framework of an integrated catchment management system.

An integrated catchment management (ICM) approach implies that water and associated land resources will be managed in harmony so as to gain the full benefits of multipurpose use and to co-ordinate the activities of various agencies and other bodies involved in water resource utilization and protection.

A number of overseas countries have accepted and adopted ICM as the most practical approach to water resource management. Over several years, these countries have implemented very similar water resource management strategies and, despite some significant differences in their processes of public participation and in the day-to-day implementation of operational management functions, some significant successes have been achieved along with some failures.

It is important to note that these approaches to water resource management did not occur overnight but were the result of many years of research, testing and learning in the field. In the case of most European countries, for example, their water resource management practices have evolved over several centuries. Therefore, it must be realized that ICM is an evolutionary process; one that has already started in South Africa but needs to be driven more urgently and systematically.

It is clearly unnecessary for South African water resource managers to duplicate this long-term evolutionary process. Rather, it is more appropriate that we should learn from the overseas experiences and adopt only those components of the process which are likely to be successful in a South African context.

2.3 The issue of sustainability

The process of water resource management involves managing the complex inter-relationships and interactions between ecological systems, land use activities and water which control and characterize the water resource. The people who use the resource, as well as the people and institutions who are responsible for developing and managing the resource, have to be included in the process. Current international trends towards policies of "sustainable development" and "sustainable resource management" reflect a growing commitment to the principle of stewardship at all levels of strategic and operational management (MacKay *et al.*, 1996). The principle of stewardship implies a responsibility to consider the welfare, needs and aspirations of the current generation, without prejudicing those of future generations.

The Draft Principles put forward to guide the revision of Water Law in South Africa make several references to the need for sustainability (DWAF, 1996a). Accordingly, it is accepted that the principles of sustainability will form the basis for water resource management in South Africa.

There are many definitions of sustainability, both in terms of the development or utilization of a resource, and in terms of maintaining the integrity of a resource. Whilst each definition reflects the particular viewpoint of the author of the definition, they almost always share a common theme, namely: that utilization or development of the resource should be regulated such that the characteristics and integrity of the resource in question are protected and maintained within agreed limits.

In the context of water resources, the concept of sustainable resource use is one where, with effective management, the rate of resource withdrawal, use, consumption or depletion should always be balanced (or preferably exceeded) by the rate of resource replenishment. In the process, the selected and agreed characteristics of the resource (e.g. water quality, biological diversity, degree of resilience to external disturbance or change) should also be maintained.

The general principle that the development and use of water and other natural resources should take place in a manner which ensures sustainability of the resource has become one of the central objectives of international natural resource and environmental policy since 1980. Clearly, sustainable development should not be confused with zero growth. Rather, it entails achieving a balance or compromise between protecting the ecological resource base and allowing economic growth to take place through a rational and carefully managed use of the available resources. This does not imply merely setting limits on economic activity in the interests of preserving the environment, but is instead an approach to development which emphasizes the fundamental importance of open participation and equity within the economic system.

Sustainable development can be defined in broad terms as development which meets the needs of the present without compromising the ability of future generations to meet their own aspirations and needs. Four recurring elements comprise the key concepts embodied in sustainable development:

- the need to take into consideration the needs of present and future generations;

- the acceptance of limits placed upon the level of use and exploitation of natural resources, on the grounds that this is the only way to protect the capability of the resource for use and exploitation in the long-term;
- the role of equity principles in the allocation of rights and obligations, which also imply that the access to, and use of a resource, made by one user must take into account these needs of other users; and
- the need to ensure that environmental considerations are integrated into economic and other development plans and that development needs are taken into account in setting environmental objectives.

Sustainable development of water resources implies the adoption, in an iterative fashion, of three successive steps in water management:

- *identification* of the system characteristics, which involves the specification of the characteristic features of the water resource system relevant to the different problems encountered. These features consist of the bio-physical, economic, social and environmental characteristics of the system;
- *prediction* of the behaviour of the system, which corresponds to determining how the system will respond to certain actions taken by man, (including pollution discharges into water bodies, urbanization, changes in agricultural practices, the building of works and structures which confine or condition the behaviour of water resources within the system, implementation of management actions); and
- *management* of the system, which involves selection and implementation of the best strategy to attain certain objectives, where management decisions are based on the previous steps of identification and prediction.

2.4 Purpose of this document

This document forms an important part of the background information required by the Department of Water Affairs & Forestry for its comprehensive review of South Africa's Water Law. The usefulness of the ICM approach has been accepted as fact and the Department intends to continue with, and refine, its current initiatives in implementing ICM throughout South Africa.

The document has been written primarily for water resource managers within the Department of Water Affairs & Forestry. It aims to provide these managers with an up-to-date and concise overview of the variety and complexity of the issues which affect and control ICM. The scope of this document is described in **Section 3.2**.

Whilst this document focuses mainly on water resource management issues, a number of other concerns, such as land use management and institutional arrangements, are also examined because they impact on water resources and influence management decisions. The final report from this study will serve as a basis for linking together the different water resource management functions within the Department and will also form the background for additional policy development.

3. BACKGROUND TO THE PRESENT STUDY

During 1993 and 1994, staff of the CSIR's Division of Water Technology conducted several studies on catchment management processes and undertook visits to Australia, the USA and the United Kingdom to evaluate overseas experience in a variety of water resource issues, including ICM. This was followed by interactions with other Australian, American and British practitioners, where additional insights were obtained as to their respective approaches and the successes achieved.

In response to the growing demand for clarity as to the nature of ICM and how it could be applied successfully in South Africa, the Water Research Commission (WRC) launched a one year desk-top study in 1995 to draw together and evaluate appropriate overseas experience. This study was designed to provide an overview of current approaches and offer suggestions as to which of those practices could be applied in South Africa. This study would also provide a strategic overview of the directions for any additional South African research which should be conducted on different aspects of ICM.

Also in 1995, the Department of Water Affairs & Forestry initiated a comprehensive review of the country's water law, with the aim of drafting a new Water Act that is consistent with the new constitution and the Water Law Principles. This process includes a significant emphasis on wide public participation in identifying and rectifying past inadequacies. A central component of this water law review is the acknowledged need to manage the country's water resources on the basis of economic, social and environmental sustainability. Therefore, the principles of ICM are important in the water law review process.

At the request of the Department of Water Affairs & Forestry, the WRC agreed to expand the study on overseas practices to include an evaluation of current South African practices and to identify the essential links with other water resource management functions. Funding for the WRC study was supplemented by the

Department and the study was designed to proceed in parallel with a number of other law review initiatives launched by the Department.

The present study therefore focuses on the principles and practices of ICM, both locally and overseas. The study aims to provide a concise overview of the current thinking and experience on the best ways in which to implement an ICM approach to water resources management. This will allow the Department of Water Affairs & Forestry to select appropriate options which could form the basis for management decisions and legislation relating to the implementation of ICM in South Africa. The overall objective of this process is to ensure that South Africa's water resources are managed on a sustainable basis.

3.1 Approach followed in this investigation

Given the constraints of the relatively short time frame of the study, the project has been focused on the compilation and interpretation of information produced by local and overseas agencies and individuals. No attempt has been made to invent or put forward new approaches. It was considered appropriate to concentrate on the successes and failures that have been experienced and, wherever possible, to identify the factors responsible for such success or failure. Accordingly, the following approach was adopted:

- Overseas visits were undertaken to selected institutions in Australia, the United Kingdom and the USA, in order to meet individuals responsible for water resource management issues and involved in the planning and implementation of ICM plans and actions.
- Verbal discussions and written communications were exchanged with overseas specialists who have been, or still are, responsible for the development of catchment management policies and plans.
- Personal and telephonic interviews were conducted with South African water resource managers and practitioners, including key staff within the Department and water boards, as well as consultants engaged in the production of reports on a variety of catchment studies. Verbal discussions took place over an extended period from January 1993 and were supplemented by personal interviews and interactive discussions at workshops and symposia.
- A wide variety of documents and electronic information from international sources was retrieved via the Internet.

- Copies of study reports and policy documents were obtained from local and overseas institutions and agencies. The information in these documents was then critically reviewed to assess its usefulness.
- Personal interviews were conducted with water resource managers and strategic planners within the Department of Water Affairs & Forestry.

3.2 The scope of this report

The report arising from this investigation has been designed primarily to meet the information needs of water resource managers within the Department of Water Affairs & Forestry. This document has therefore been structured to provide a systematic review of the philosophy and practice of ICM, followed by a series of suggestions and recommendations for implementation in South Africa.

This report outlines the philosophy and practice of ICM, with a particular focus on the South African situation and our requirements. The existing situation in South Africa is examined and possible reasons for the successes or failures that have been achieved to date are highlighted. Much of the information contained in this report is based on an evaluation of the appropriateness and possible applicability of overseas experience (Australia, United Kingdom, United States of America, Europe, Africa) to the South African situation.

The core concepts contained within the ICM approach are examined, together with the processes and institutional arrangements required for success. The report evaluates and comments on the ways in which a flexible ICM process links together all of the different stakeholders, helps to identify critical issues, and then directs appropriate attention to these issues. The interplay between environmental, social and economic issues is emphasized, together with the institutional, practical, legal and information requirements that are necessary for success. An important component of this report is the brief overview of the need for proper institutional arrangements; this has been designed to complement the more detailed, parallel studies on institutional structures conducted by Mr Andrew Tanner of Ninham Shand Inc.

This report synthesizes the local and international information on ICM. Specific references to individuals and literature sources have largely been omitted from the main text of the document. Instead, a full list of the individuals consulted and the written materials studied is included in the list of references.

A detailed review of Australian approaches to water resource management has been compiled by Dr H.M. MacKay. Her entire report has been attached as an appendix to this document. A searchable run-time version of her references plus notes has been made available to the Department on diskette, together with copies of all the published references consulted.

4. THE DEPARTMENT OF WATER AFFAIRS & FORESTRY

4.1 The role of the department

The water resources of South Africa are recognized as a critically important national asset (DWAF, 1986). Accordingly, they must be managed effectively and efficiently so as to bring maximum long-term benefit to the country as a whole. The Department of Water Affairs & Forestry (DWAF) is recognized as the custodian of these resources and has a national responsibility to ensure that both the basic (survival) needs of the people are met, together with those additional needs for water required to sustain the current needs of users and the anticipated growth in the national economy.

The role of the Department in relation to the water sector can be segmented into two distinct, but closely related, functional areas:

- Providing equitable access to the resource to ensure optimal economic and social development, including access to water and sanitation services for all citizens. This is the Department's main priority and takes precedence over any economic development objectives; and
- Managing the resource, as well as the demands made on the resource, both to protect the resource and to ensure sustainable and equitable use by current and future generations. This is reflected in the Department's mission statement of "ensuring some for all, ... forever".

The Department has an important leadership role and responsibility to set in place national strategies for long-term water resource management. The Department provides leadership, technical guidance and a resource management framework, based on important principles such as minimum standards, environmental protection, waste minimization. Provincial governments and local authorities are expected to address local and regional issues and to take appropriate responsibility for decisions within this management framework.

4.2 Relationship to other institutions and organizations

Within the Department, overall responsibility for water resource development and management has been segmented into several line function Directorates for increased efficiency. There is also some devolution of responsibility to regional offices of the Department who are responsible for implementing national policies in managing the water resources within their areas of jurisdiction.

The water resource management functions and responsibilities of the Central Government and the nine Provincial Governments are closely inter-linked and have been clearly defined. Provincial Governments share the responsibility for assuring service provision, specifically through the promotion of effective local government. Water Boards and Irrigation Boards represent the Department and also form a link between the Department (Central Government) and Local Government through their provision of bulk water supply services where there is an economic advantage to be gained from regional service provision. The overall relationships between the different levels of functional responsibility are summarized in **Figure 1**.

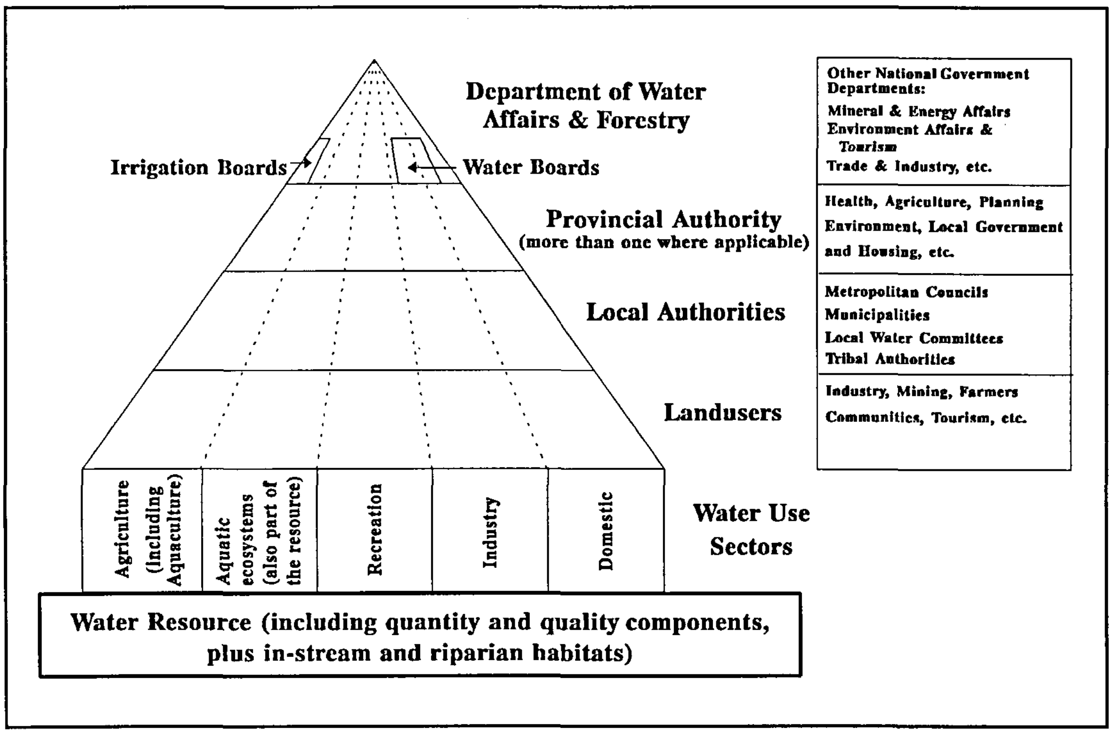

Figure 1: Diagrammatic representation of the inter-relationships between the different levels of stakeholders and functional responsibilities involved in water resource management and utilization in South Africa. (Adapted from a diagram provided by Mr JLJ van der Westhuizen of the Department of Water Affairs & Forestry).

Water Boards and Irrigation Boards act as agents on behalf of the Department of Water Affairs & Forestry. Their areas of operation often extend beyond provincial boundaries and they undertake important parts of the water resource service provision on behalf of the Department (DWAF, 1995).

Tribal authorities who enforce traditional laws relating to water resource use and allocation in certain designated areas, have largely been excluded from participation in water resource management to date. The empowerment and involvement of this group will in future form an important component of South Africa's overall water resource management strategy (DWAF, 1996a).

The importance of close collaboration and cooperation between the Department and Provincial Governments is clear, given their joint interest in the development of the capacity of local government to provide water supplies and sanitation services on an equitable and efficient basis. Provincial Water Liaison Committees have been established to ensure effective formal communication and liaison between the department and the Provincial governments. In addition, the Minister of Water Affairs & Forestry has been empowered to establish statutory Local Water Committees (LWCs). These LWCs will undertake the task of local water and sanitation provision until effective local government structures have been formed.

In addition to the Department of Water Affairs & Forestry, several other government departments control issues which impact directly and indirectly on water resource management. For example, the Department of Agriculture is responsible for agricultural activities and soil conservation, the Department of Water Affairs & Forestry is custodian of water quantity and water quality issues, and the Department of Environmental Affairs and Tourism controls conservation-related issues. Clearly, each of these areas of responsibility can and does influence the temporal and spatial availability and quality of water within a river system. The need to manage these issues co-operatively becomes further complicated where different government departments have delegated differing levels of management responsibility to provincial and local government levels.

4.3 Historical development of catchment management

During the 1980's, the Department of Water Affairs & Forestry (DWAF) adopted an integrated management approach to address various catchments in the former Eastern and Northern Transvaal provinces. The Department commissioned several detailed investigations which attempted, with varying degrees of success, to assess the quantity and quality of available water resources, identify the needs of different water use sectors, predict likely future developments and develop holistic approaches and plans for water resource management in the catchments of concern.

Each successive catchment study built upon the experience gained in earlier investigations and identified a number of common needs or issues of concern. These included:

- the need to improve processes of public participation, including clear definition of the roles and responsibilities of all participants;
- the need to develop appropriate institutional structures which could facilitate communication, promote information sharing at all levels, assist in the decision making process, and allow the definition of clear responsibilities and accountabilities for implementation;
- the need to involve all water users in the planning and implementation phases of water resource management; and
- the need for the Department to take responsibility for leadership and the provision of technical guidance and a management framework for water resource management.

The theoretical aspects of these investigations provided a solid basis for understanding many of the technical, environmental and engineering-related complexities involved in managing water resources on a catchment basis. However, one of the major shortcomings of these early studies was the fact that they consisted largely of technical inventories and did not include public participation in the development and acceptance of water resource management plans with defined goals, objectives, strategies and time schedules.

As a result, the actual process of managing water resources on the ground did not meet people's expectations and centralized "command and control" approaches continued to operate without adequate stakeholder support. This led to widely-held public perceptions that the Department was unsuccessful in managing the country's water resources.

More recently, however, the situation in a few catchments and sub-catchments (e.g. the Wilderness Lakes area, upper Olifants River catchment, and the Sand, Vet, Jukskei and Mgeni catchments) has changed due to the incorporation of wider public participation in catchment forums and in the development of catchment management plans. This represents a major improvement in the public perception of the

Department's capabilities. In these recent examples, the public participation process has led to a widespread sense of "ownership" of the process amongst all participants, a better understanding of the complex issues that need to be dealt with, and greater appreciation of the needs of other stakeholders.

Perhaps the most visible problem area identified in the earlier catchment studies was that resource managers, engineers, scientists and the general public all had different levels of understanding of the precise meaning of ICM and lacked a shared vision and agreement as to how this could be achieved effectively. In turn, the problem was accentuated by a lack of appropriate institutional arrangements and the virtual absence of suitable mechanisms to facilitate interactions between water user groups and the Department's water resource managers. Conflicts still arose between water user groups competing for the same scarce resources and management remained relatively narrowly focused on meeting the demands of water supply to domestic, agricultural and industrial users.

Since the late 1980's, water resource managers have increasingly emphasized the urgency of meeting the growing demands of water users from a scarce resource. The problem was compounded by the fact that both the availability of the resource and its quality or fitness for designated uses had steadily diminished. They advocated that this could only be achieved through holistic approaches which balanced economic, social and environmental concerns and strove to assure sustainability of both the water resource and the use made of the resource. This triggered a number of investigations directed at resolving inter-sectoral conflicts around the use of water, and the development of public participation mechanisms to ensure the wider involvement of all participants in selecting appropriate management strategies.

5. THE CONCEPTUAL BASIS OF ICM

The conceptual basis of ICM relies on recognition that the different components of the hydrological cycle are intimately linked to one another, and each component is affected by changes in every other component. Therefore, they cannot be managed effectively as separate or disconnected units.

The core concepts embodied within ICM are often difficult to promote without an unambiguous terminology. The confusion has arisen principally because many terms have been used inconsistently, have been given extended meanings or have been misapplied. Care is therefore needed when ICM is applied.

5.1 The catchment as a basic management unit

A catchment area is the drainage basin of a river, and its boundaries are demarcated by the points of highest altitude in the surrounding landscape. It is adjoined by other catchments and its geographical area covers all of the land which drains into one river system, from its source to its estuary.

Much of the rainfall or precipitation falling on to a catchment is lost to the atmosphere by evapotranspiration; the remainder enters the surface as ground water or flows along stream and river channels as surface water. Within a catchment, surface and unconfined ground water flows are dominated by gravitational drainage from the catchment divide or watershed to the mouth of the river. Flows are usually unidirectional, through and over hillslopes to streams and along the channel system to the river mouth or estuary. The speed with which water moves through and over a catchment is dependent on the topography and geology of the catchment, whilst the characteristics of the geology, soils, vegetation and land use within the catchment contribute impurities to the water and alter its quality.

The physical, chemical and biological characteristics of the river system change progressively and cumulatively along its length as the water is altered by land use, runoff, water abstractions and effluent discharges. These processes of change link the different components into an integrated system which includes not only the water and biota in the river system, but also all of the human activities and natural processes in the catchment which affect the quantity and quality of the water. All of these features need to be taken into account when the water resource is managed.

The sustainable management of a catchment's water resource becomes extremely difficult if responsibility for this is fragmented by organizational, administrative and political boundaries. It is important to recognize the catchment as a single management unit and to streamline the structures and functions of bodies responsible for its management.

5.2 What is ICM ?

The term "Integrated Catchment Management" (ICM) represents a systems approach to the management of natural resources, in particular water resources, within the bounds of a geographical unit which is based on the catchment area of a single river system. This approach allows clear segmentation of river systems into logical or functional management units (catchments and sub-catchments) which can then be linked together into an overall management plan for an entire river basin.

In its widest possible sense, ICM recognizes the need to integrate all environmental, economic and social issues within a river basin (or related to a river basin) into an overall management philosophy, process and plan. This is aimed at deriving the optimum possible mix of sustainable benefits for future generations and the communities in the area of concern, whilst protecting the natural resources which are used by these communities and minimizing possible adverse social, economic and environmental consequences. In its ideal form, this is a shift away from narrowly focused management of a single resource such as water or soil.

General acceptance and implementation of ICM is often hampered by differences in people's understanding as to exactly what is meant by the term ICM. This is largely due to the fact that ICM has three aspects, namely it is a philosophy, a process and a product. There is not always a clear consensus that these three characteristics are all part of ICM; indeed, many management approaches still attempt to focus solely on the more technical aspects of the process or product functions of ICM.

- ICM provides a **philosophy** which underpins sound natural resource management, and which is based on a consideration of whole natural systems, and a recognition that systems respond to disturbance or utilization as just that: systems, not as individual components in isolation from each other;
- ICM provides a **process** for engaging the community and government, in a "people-oriented" partnership which is designed to achieve better natural resource management at the local catchment level, and which takes account of the needs and aspirations of the whole community; and
- the ICM process results in a **product** or ICM strategy which can be implemented on the ground. This is a regional-scale strategy and management plan which incorporates environmental, social and economic considerations and is based on a set of development objectives which are identified jointly by the community and government. The identification of development objectives centres on identifying and acknowledging the environmental constraints of an area; these are the environmental or resource capacities that must be protected, otherwise all capacity to meet user needs may be lost. The management plan also provides a unifying central guide for implementation on the ground.

Whether ICM approaches are local or international in scope, all contain a common objective, namely: to ensure equitable and sustained use of the available natural resources through a shared development and management effort. This is aimed at working across political jurisdictions and involving in the decision making process all those constituencies which either place demands on the resources or cause impacts on the resources.

In practice, the ICM approach is most often used to provide a logical framework within which the water resources of a region or country can be managed. This is important in countries where different environmental systems and natural resource units have been artificially segmented and allocated to different political jurisdictions.

Catchment, or river basin-wide, approaches to the development and management of water resources have proven highly successful and are gaining greater prominence worldwide. This is due to their inherent effectiveness in budgeting and balancing the quantity and quality of the water resources available against the uses and demands made of them. This success has been responsible for the creation of management organizations on an international scale to manage the water resources of large river and lake systems shared by several countries.

Despite the fact that the concept of effective water resource management by means of ICM is relatively new in South Africa, many of the individual processes and approaches contained within the concept are widely understood and accepted. However, there has been a noticeable lack of success in our ability to integrate all these processes and functions into a coherent whole. Nevertheless, since the social and scientific basis of the ICM concept is inherently sound and the approach has been shown to work well in many other areas with similar types of problems to those experienced here, it is the only logical option to use in South Africa.

However, it is important to remember that the power of change-amplifying and change-reducing mechanisms within a catchment, and within nature in general, are such that human interventions need to be undertaken with a large measure of caution. We cannot always be confident that our interventions will produce the intended outcomes. This has direct implications for catchment management and has given rise to three important principles, namely:

- An *integrated or systems approach* is required to properly assess and link together the processes and actions which cause bio-physical and ecological change in catchment systems;

- An *adaptive management* approach is needed, which responds to changes in information regarding catchment conditions and knowledge of associated processes, and allows corresponding adjustments to management actions and strategies, according to the understanding gained by observing the effects of management; and
- Social organization for catchment management needs to be based on *an active partnership approach and joint strategic planning* so as to achieve outcomes which are acceptable to all participants and which will allow sustained use of the water resource.

5.3 Critical success factors for effective water resource management

Overseas experience has shown that effective and efficient water resource management based on ICM approaches can be characterized by four critical success factors or principles. These are described separately below.

5.3.1 An integrated approach to strategic planning and resource assessment

Typically, ICM must follow a systems approach to water resource management. This involves consideration of the whole natural system and all its linkages, including both natural and human systems and their inter-relationships. The management unit should encompass linkages between components and will usually consist of the whole catchment or another similar geographical unit such as a sub-catchment.

Policies, plans and actions must be linked together within a framework which maps out the strategically important development objectives and priorities for the management of the water resource and its catchment. At the same time, these activities must also ensure that the water resource is protected so that it can continue to sustain the uses made of the water. Important elements of this process are:

- *Objectives* for managing the suite of environmental values or beneficial uses of the water resource (e.g. protection of aquatic ecosystems, provision of safe supplies of water for domestic, industrial, recreational and agricultural use) must be drawn up and integrated into a coherent management plan;
- *Management options* which can directly or indirectly influence environmental outcomes within the system, and which may have complementary or synergistic benefits (e.g. wastewater treatment and wetland rehabilitation) must be designed and incorporated into a defined plan of action; and

- Consensus must be reached by all stakeholders regarding *co-ordinated action plans* for different aspects of water resource management by central, provincial and local government, industry, land user and community organizations.

An integrated or systems approach is required for appropriate assessment of the diverse, interacting components of catchment processes and resource management actions which impact on the water resource and the overall state of the catchment. The emphasis here should primarily be on technical aspects, though the economic and resource value implications of catchment conditions and management actions are also directly relevant. Key elements of the integrative process include:

- *Analysis* of aspects of the catchment system (e.g. water quality, streamflow and riparian conditions) which affect relevant values or uses of the water resource;
- *Assessment* of the prevailing environmental, economic and social values, together with the values arising from beneficial uses of the water resource and the related impacts of management actions; and
- *Monitoring* of environmental conditions and related socio-economic factors that are influenced by those organizations and groups responsible for implementing management actions and activities.

Following the assessment of specific values and impacts within a systems framework which helps to integrate these diverse issues, the overall merits of alternative combinations of technical activities and implementation actions should be evaluated. This integrated evaluation will assist in the identification of decision options which optimize or balance social, economic and environmental values with respect to:

- finding a sustainable balance at local and regional levels between resource use and resource conservation;
- reversing the adverse impacts of land uses on the status of the water resources and on other land and water uses, as well as preventing adverse impacts of proposed new land uses;
- achieving effective co-ordination and integration of water and other natural resource policies to focus on common goals and objectives at a catchment level;
- focusing planning and management actions and activities at a sensible regional and local scale which is strongly related to natural systems, and which can better accommodate local and regional community needs and desires, as well as national objectives;

- promoting the efficient use of public and private economic and other resources;
- ensuring an equitable distribution of costs and benefits amongst all stakeholders;
- defining the roles, responsibilities and accountabilities of each individual involved in implementation of the management plan; and
- ensuring the effectiveness of management actions in achieving desired outcomes.

5.3.2 Institutional arrangements for social and economic optimization

One of the most important factors in successful implementation of the ICM approach has been the development of institutional approaches that are appropriate to the needs of each situation. Different countries have created a wide variety of specific institutional structures to accommodate local resource or hydrological landscapes, demographic situations, specific management approaches and political situations. Whilst the broad principles remain the same, none of these institutional structures can easily be taken and imposed, without modification or customization to suit local circumstances, onto the situation in a different region or country. Nevertheless, the broad principles can be transferred and adapted successfully to a new situation.

From a systems perspective, there are a number of different levels of involvement of individuals, communities, institutions and government. Each level has its appropriate range of roles, responsibilities, functions and needs. For each of these levels to be able to operate efficiently and effectively, the levels immediately above and below it also need to operate effectively and within the scope of their respective roles and responsibilities.

A detailed evaluation of the types of institutional structures that will be required to ensure that ICM will work effectively and efficiently, in a South African context, are addressed in a separate study which is being undertaken by Mr Andrew Tanner of Ninham Shand.

5.3.3 An active partnership approach

Collaboration and the attainment of consensus amongst key stakeholder interests, either those affected by use of the water resource or those responsible for management action, is essential in order to generate credibility, commitment and co-operation. This approach recognizes that all government agencies, as well as non-governmental organizations and individuals, have important roles in identifying common objectives and creating a shared vision. This helps to ensure a balanced approach in which the needs of the three components, namely: people, economic development and the environment are considered, together with any requirement for resource protection, when pursuing and achieving sustainable development at both regional and local scales.

In this process it is vitally important to ensure that appropriate processes, procedures and mechanisms are defined and accepted for mediation, reaching consensus and resolving conflicts. All of these issues need to be incorporated into the overall catchment management plan. It is also important to emphasize that this process should not be seen as a "threat" to existing decision makers. Instead, the incorporation of local objectives, local knowledge, increased local ownership and commitment to action should improve the effectiveness and success of water resource management.

5.3.4 Adaptive management processes

Overseas experience has shown that it is essential that the management process followed in ICM be flexible. This will allow continuous optimization of resource allocation (people, equipment and funding), whilst at the same time being effective enough to promote the overall goal of sustainable water resource use under continuously changing environmental, social and economic circumstances. The process evolves progressively so that individual and institutional learning is enhanced and can be incorporated into adaptations to structures, approaches and processes. Similarly, the catchment management plan must be flexible enough so that action strategies and programmes can be modified, when required, as the plan is implemented.

A flexible management framework is needed to guide staged implementation of action programmes, taking account of resource availability, developing knowledge, changing catchment conditions and on-going evaluations of effectiveness. The action strategies need to be adapted as experience of the effects of catchment management activities is accumulated, beginning with experimental or trial interventions where little knowledge of cause-effect relationships is available.

5.3.5 An effective catchment management plan

For management to be effective and successful, it must set out agreed policies and strategies, provide leadership to all participants, define roles and responsibilities, be able to communicate effectively with all participants, and be able to mobilize sufficient human, technical and financial resources to undertake the tasks at hand. In the context of water resource management, the management dimension requires a particularly broad-based appreciation of the need to attain a balance between protection of the water resource and meeting the varied needs of stakeholders.

The overall framework for water resource management is formed by national and provincial resource management policies which set out issues of national strategy and resource management principles. Within this framework, regional and local issues and concerns must be aligned consistently with national and provincial goals. Ideally, this requires that catchment management operates as part of a formal process of water resource management, which is supervised and guided by the Department of Water Affairs & Forestry. The Department would therefore be responsible for defining and approving the specific requirements for water resource management within each specific catchment or sub-catchment. This would normally take the form of Ministerial approval for a catchment management plan.

Whilst a formal catchment management plan is a prerequisite for effective water resource management on a catchment basis, the mere existence of formal documentation is insufficient. An effective catchment management plan must address the typical management aspects of: planning, co-ordination, implementation or operation, and monitoring, as well as control and auditing of the management process, plus feedback to stakeholders.

The typical components of a catchment management plan address the following management issues:

- *planning*:
  - who initiates and documents the process;
  - who funds any investigations which may be necessary;
  - who participates in the planning process and how are they selected for participation;
  - what institutional arrangements are required to facilitate interactions with stakeholders and ensure that the requirements of resource equity are met; and
  - who reviews and approves the plan.

- *implementation*
  - who is responsible for the necessary legislation in the different levels of national, provincial and local government;
  - who funds the implementation process;
  - who authorizes and directs the implementation process; and
  - what mechanisms are available to resolve potential conflicts amongst stakeholders.
- *operation*
  - what are the different lines of authority and responsibility;
  - who funds the different activities; and
  - who ensures that resources are applied effectively and efficiently.
- *auditing and control*
  - who undertakes the necessary monitoring;
  - what information is reported and to whom is it reported;
  - who evaluates the information and what are the criteria used for evaluation; and
  - who responds or reacts to the information, and how are they required to respond under given scenarios.
- *feedback to stakeholders*
  - who is responsible for communicating with stakeholders;
  - what types of information must be communicated; and
  - what form must this communication take, and how often should the information be communicated.

5.4 An appropriate management framework

To develop and manage water resources effectively, it is necessary that a balance be achieved between the legitimate competing demands placed on the resource. At the same time, interference with the natural hydrological cycle, and the disruption of ecological processes, should be minimized since these are critically important to the sustainability of the resource. Whilst this is relatively simple in concept, it is far more difficult to achieve this balance in practice. Indeed, a failing with many water resource management strategies worldwide is that, whilst they are able to adequately represent the correct aspirations for management of the resource, they are often unable to deliver the product on the ground to the satisfaction of the end-users. This is most often due to the fact that the end-users, or the people who are most affected by the management decisions, have not been adequately involved in the decision-making process.

Even when a single water resource system is located within a single political jurisdiction, the different uses made of the water often lead to conflicts amongst water users. In situations where water resources are scarce and under increasing pressure to be utilized, conflict is unlikely to be avoided. However, through appropriate processes of information sharing, stakeholder education and open negotiation, disputes and conflict situations can usually be resolved. Here, consensus can be achieved in negotiation situations through exploring alternative options for water use and allocation.

The concept of "national objectives" for water resource protection or maintenance of water resource quality should form the basis, or highest level of authority, in dispute cases. In addition, there would also need to be appropriate institutional systems involving the courts, as well as other dispute resolution techniques, to resolve those situations where consensus cannot be reached through negotiation. Clearly, conflict analysis and management are therefore key activities in water resource management.

The use of catchment management plans and strategies which have been developed by community-based or other publicly accepted participation processes will help to resolve potential conflicts through fostering a better understanding of the positions, aspirations, needs and vulnerabilities of each stakeholder. This process tends to alter the focus of negotiation and discussion away from the primary *goals* of the management plan, to one which is concerned with *how the goals will be decided and achieved*. Conflict can be reduced or resolved if the focus is placed rather on *how people decide* on the goals. World wide there is evidence that people do not support decisions in which they feel they have not been able to have some influence or participation.

Water resource management can be defined as the systematic use of a set of technical and non-technical measures and activities designed to ensure the effective and efficient management of water resources. The primary goal of water resource management must be to optimize the relationship between the capacity of the available resources to provide sustainable services, such as water of a given quantity and quality (which must be protected) because it is required to meet basic human needs, and utilization of the resource, including consumptive and non-consumptive uses and waste disposal.

The need to protect the water resource in perpetuity whilst at the same time ensuring sustained and effective utilization of the resource can be considered to be conflicting management functions. Whilst this is often true, sustained utilization of the water resource is only possible if the level of protection afforded to the resource is adequate. This balance can only be achieved when there is good interactive dialogue between all parties so that their needs, capabilities and concerns are clearly understood at all stages of the process.

6. SUMMARY OF CURRENT APPROACHES TO ICM

Throughout the world, a variety of technical, economic and management approaches have been adopted in attempts implement ICM so as to manage water resources on a sustainable basis. Whilst many of these approaches have shown varying degrees of success, there have also been several notable failures. It is therefore important that South African water resource managers take careful cognisance of the overseas experience in their development of new ICM approaches for South Africa. Accordingly, the available information on ICM experiences to date has been reviewed to evaluate those principles, strategies and processes which would form an appropriate basis for implementing ICM in South Africa.

6.1 South African approaches

Over the past two decades, the widespread and growing concern over South Africa's scarce water resources has been accompanied by a growing awareness of the complexity of the processes and interactions required to manage these resources so that they can sustain the growing demands made on them. Since the early 1980's water resource managers within the Department of Water Affairs & Forestry have come to realize and accept that effective water resource management requires an integrated approach based on logical hydrological units. It was considered appropriate that these units should be whole river basins or catchments.

However, it was also clear that very little information was available which would allow the development of catchment-wide water resource management approaches based on ICM. This prompted the Department to initiate several major catchment studies which were designed to:

- obtain information on the physical, chemical and ecological characteristics of the water resources available within each catchment;
- identify and quantify the specific catchment processes and activities which affect the spatial and temporal distribution of these water resources;

- quantify the existing and future demand for water, by each water use sector, including specific requirements for water quantity, water quality and the timing of these requirements;
- identify those individuals, institutions and organizations which should be consulted or involved in decisions around water resource allocations; and
- define appropriate management strategies and actions which could help to alleviate the effects of frequent droughts, resolve conflicts associated with water allocations and inter-basin transfers, and comply with international agreements around shared water resources.

The Department then intended to develop a catchment management plan for each catchment which, when implemented, would help to ensure the equitable distribution of water resources between different water use sectors. It was anticipated that a suitable "catchment authority" would then be created to undertake the day-to-day management of water resources within each catchment. This "catchment authority" would represent each water use sector in the catchment and would be responsible for executing the management plan under Departmental supervision.

In theory, this new approach represented a radical change from previously exclusive "command and control" practices which were applied in a centralized manner. Here, the Department focused primarily on the national development of water resources, followed by the management of water allocations and the control of point sources of pollution.

The Department's new approach was very comprehensive in terms of the number and variety of issues that were investigated. Similarly, the Department clearly realized the need to integrate all of these issues into a single coherent assessment and management plan. However, this was seldom achieved in practice. Instead, the various issues were addressed individually and management actions tended to focus on the compilation of lists of problem areas and on the collection, transformation and presentation of data. Very little attention was paid to the processes linking and controlling interactions between different components, and the level of true stakeholder participation was relatively low. In addition, very little attention was given to the development of action plans to address the problem areas which were identified.

Overseas experience has shown that one of the major difficulties in being able to effectively implement an ICM approach in practice is usually a lack of appropriate experience and inadequate involvement of all stakeholders in a catchment. In the absence of appropriate guidelines or handbooks, and lacking experience in participative catchment management, the Department's water resource managers have had to undergo a rapid learning experience whilst continuing with their more traditional water resource management activities. This usually resulted in limited acceptance of the Department's goals and strategies by those stakeholders who may have been excluded from the process.

In addition, the relatively narrow segmentation of functions and responsibilities between different Government departments, and the lack of effective inter-Departmental collaboration, had the result that many land use activities which affect water resources and water quality were outside the influence of the Department of Water Affairs & Forestry. This confined the Department's focus purely to that of water resource management. Since there was no co-ordinated administrative or management system which allowed the catchment processes and activities which affect water resources to be addressed, the process was often ineffective.

Within the Department, the lack of shared understanding of exactly what ICM really is, or could be, resulted in a rather *ad hoc* approach which focused on specific hydrological issues, water quality modelling on a small scale and assessments of the impacts of effluent discharges. For example, the introduction and implementation of systems analysis techniques enabled water supply and risk to be evaluated stochastically on a regional or whole catchment basis. Whilst this helped to alleviate many water supply problems, it largely ignored the critical issue of the flow and water quality requirements of aquatic ecosystems.

The Department's water resource managers were fully aware that the existing institutional structures and legal framework were inadequate to deal with the complexity of water resource management. Similarly, the Department accepted the need to ensure that the process would accommodate previously neglected environmental issues, and would be able to adapt to the changing political, social and economic needs of South African society. It is anticipated that the current review of South Africa's Water Law will address these critical issues and the new legislation will provide a more suitable and practical legal support for the necessary institutional frameworks.

The absence of suitable institutional structures and the presence of an inappropriate legal framework also prevented adequate involvement of the public in decisions around the wider socio-economic implications of development and resource management actions. In many cases, the public were informed on an *ad hoc* basis of impending management actions rather than being involved in a participatory management system based on shared responsibility and joint decision-making.

This was made worse in those situations where the general public either did not understand the issues at stake or were unable to participate properly, either because they were uncertain as to their roles and responsibilities or because they lacked appropriate information. At the same time, continued rapid and uncontrolled urbanization and development, coupled with inadequate provision of water supply and sanitation systems, has led to over-exploitation of our water resources. Overall, therefore, the ICM approach to water resource management cannot be considered to have been successfully implemented on a large scale in South Africa.

However, in a few situations, (e.g. the Wilderness Lakes area, the upper Olifants River sub-catchment, and the Sand-Vet, Nkongolwana and Mgeni catchments), water resource managers have been able to ensure that most, if not all, the parties concerned have been widely involved in the decision-making process. In each of these situations, the participants have accepted that the ICM approach is at least partially successful and it is now in the process of formal implementation. Such successful applications could in future be used as a foundation for the design of improved institutional structures and communication processes elsewhere.

6.2 Australian approaches

6.2.1 Separation of commercial and non-commercial water sectors

The functions of water supply and sanitation provision are being separated from the non-commercial function of catchment and waterway management, unless it is more practical not to do so on a local basis. Water authorities and supply boards are being regionalized (for greater efficiency and economy of scale) and commercialised (as opposed to privatised). The supply agencies thus become bulk users of water and/or effluent dischargers, and are subject to the same licensing procedures as other catchment stakeholders or impacters.

Metropolitan water supply agencies will be allocated a bulk water entitlement, which they in turn allocate to domestic and industrial consumers. Rural water boards will further partition their bulk entitlement to agricultural and rural domestic users. Legally defensible water entitlements will be granted to the environment. Bulk water entitlements will be tradable, at real market-related prices.

6.2.2 Catchment and waterway management

Catchment and waterway management remains the responsibility of the Environmental Protection Agency (EPA) and relevant government departments, such as Water Resources, Agriculture, Environment. Management attention is focused primarily on identifying, controlling and remediating land use activities which have impacted, or are impacting, on water resources.

Impacts in catchments can broadly be grouped into:
- point sources;
- diffuse sources and the impacts of land use or land degradation; and
- degradation of the instream and riparian environment.

Point source discharges are subject to control by the EPA, who issue works approvals (permits). The criteria for discharge to the water environment are generally site-specific, though subject to certain minimum industry or State standards. Criteria would be based on receiving environment objectives for the local area in question. In many catchments, these objectives would have been set after negotiation amongst stakeholders, through a catchment board or committee.

Land use impacts and degradation of the instream environment might be related to industrial or urban development, which would be subject to control by the EPA or a government department. Where land use impacts arise from agricultural or forestry practices, then a much stronger emphasis is placed on community-based management and action.

6.2.3 Community involvement in land and water management

The most urgent and potentially damaging issues facing the rural Australian sector are salinization and nutrient enrichment of water resources. Salinization arises from two principal causes:
- dryland salinity, which is related to the clearing of deep-rooted forests for agriculture or commercial wood harvesting; and
- irrigation salinity, which occurs when irrigation leads to a rise in the water table, bringing very saline groundwater to the land surface.

Nutrient enrichment is a result of leaching of agricultural fertilisers, discharge of sewage effluents, runoff from agricultural land, and uncontrolled access to water bodies by stock animals. In such cases, water resources management is very closely tied to land management. The problems can only be solved by changes in land use practices at a very local level.

The lead government agency, which may be a department responsible for water resources, environment or agriculture, usually takes the lead in identifying problems through monitoring. The lead agency then plays a critical role in initiating discussions with stakeholders in the catchment and establishing a catchment committee or board, which is representative of the interest in the catchment. The committee, under the guidance of the lead government agency, will usually begin by focusing on a priority problem, such as salinity or algal blooms. Again with guidance and technical support from a number of government agencies, the committee will develop long term objectives, a strategy and an action plan for dealing with the problem.

The initial focus on a priority problem creates cohesion in the group, and ensures that people get involved because they have a real interest in the outcome. As capacity is developed in the committee or group, they can then go on to address other issues in the catchment through the same process, and again with support from the government agencies.

The EPA and supporting government agencies provide the committees with a broader context for development of catchment plans: the objectives and plan for the catchment do need to fit within wider state and national interests. Once the objectives and plan have been developed, statutory support is provided by the EPA, who gazette the objectives, responsibilities and roles of the various agencies and stakeholders in a State Environment Protection Policy paper (SEPP). The SEPPs are catchment-specific, and subject to review every ten years or so. The EPA or a delegated agency is responsible for monitoring and assessing progress towards the achievement of objectives.

The catchment committees are formally constituted bodies, but have very little statutory power themselves: enforcement is still the role of EPA or a government department. The committees have more of a planning function. The lead government agencies provide a very strong "extension service", in their role of technical guidance and support. They may also provide funding for initial scientific/technical investigations, and for the running costs incurred by the committee (such as travel, secretariat).

The extent of the initial priority problem or issue may determine the extent of responsibility which is taken up by a catchment committee, and also the geographical boundaries of responsibility. These are fairly flexible. Sub-catchment committees can later be coordinated under a larger catchment committee or forum.

Once an action plan has been developed, it then remains for individual landowners to implement the relevant land use practices (such as replanting deep-rooted trees, installing drainage, irrigation management). Here the Australian approach is to rely on voluntary compliance, rather than centralized "command and control". It is considered that voluntary compliance, as a form of self-regulation, is more acceptable in Australian society, and also more cost-effective, since fewer resources are required to monitor and enforce compliance.

Self-regulation is admittedly not 100 % successful, but is widely encouraged through community groups such as Greening Australia and Landcare. National Landcare appears to be the key to achieving success in changing land use practices: farmers or groups can apply for grant funding or tax incentives to assist them in implementing on-farm management which complements the catchment plan. Excellent technical and educational support is also provided. (Urban Landcare is now in the early stages of development).

6.2.4 Lessons for South Africa

The fact that statutory power remains in the hands of a government agency may help to prevent misuse of that power to promote local interests above provincial or national interests. That, and the emphasis on extension and supporting services supplied by government agencies, may be a valuable lesson for South Africa, at least in so far as rural or undeveloped catchments are concerned.

If catchment authorities are granted statutory powers, then along with that power goes responsibility and accountability. To discharge responsibility adequately requires expertise, skill and judgement. Whether South Africa has, at the present time, sufficient expertise and skill at the local level, which can be utilised in catchment authorities, is very doubtful. The model of catchment committees with strong planning functions, supported by government agency personnel providing technical guidance, facilitation, statutory and regulatory support may be more resource- and cost-efficient at this stage of our development.

The implications of this model are that:

- the Regional offices of the Department and other relevant government departments would need to have the necessary expertise, not only in technical issues, but also in facilitation and extension services;
- collaboration and liaison between different government departments, both at national and provincial level, would need to be improved; and
- legislation promulgated by the various government departments should be complementary and focused on resource management.

6.3 North American (USA) Approaches

6.3.1 Introduction

This review is based on the results of an Internet search. The search was focused on the home pages of selected institutions which are involved in catchment management, in order to collect information on the structure, role and functions of such bodies. In additions, the USEPA National Library catalogue was searched for useful references, and these have been included in a bibliography as **Appendix 2**. The information obtained was fairly general in nature, and limited to a few key catchments. However, the references provided can be used as a guide for additional more detailed investigation and follow-up.

6.3.2 The watershed approach

Description of the Watershed Approach

The implementation of a so-called Watershed Approach in the USA is equivalent to the adoption of integrated catchment management in countries such as Australia and the United Kingdom. Presently, this approach is, as in many other countries, focused on protection and management of the quality of natural resources in a river basin. Catchment-based bodies have been set up to manage the major regulated rivers of the USA, and this is discussed in a separate section.

The Clean Water Act and Safe Drinking Water Act, which were passed more than 20 years ago in the USA, have led to significant progress in protecting and restoring the quality of water resources. These Acts were focused on the control of point source discharges from industry and from domestic sewage treatment works. As control of pollution from such point sources has improved, the persistent problems of non-point sources, sewer overflows and habitat degradation have required more attention.

In order to deal effectively with non-point sources and habitat degradation, it was considered necessary to adopt a watershed-based planning and management approach. Therefore, for the last five years, government departments, agencies and local authorities have all adapted their policies to reflect a watershed-based planning. The watershed approach is being applied nationally, in all the activities of the related agencies and authorities, such as those involved in agriculture, forestry, conservation and development. The USEPA (Office of Water) plays a key role in implementing the watershed approach, providing technical guidance, financial support to community groups, co-ordination and partnerships between interested parties and government agencies, and regulatory support.

The watershed approach is made up of three key components:

- a geographic focus, where the watershed boundaries, including groundwater recharge areas, are used as the primary unit for planning any activities which are related to the utilisation and management of natural resources;
- the development and use of sound scientific data, tools and techniques to inform the planning and management process; and
- partnerships and stakeholder involvement in designing and implementing goals for the watershed.

The USEPA Office of Water (Wetlands, Oceans and Watersheds Program) can be contacted at any time for up-to-date information. Their home page address is: **http://www.epa.gov/OW/**

Implementation of the Watershed Approach

A number of states are now implementing formal watershed planning approaches, and in particular this is being applied in the synchronisation of permitting on a watershed basis. For example, in Massachusetts, the state-wide Watershed Protection Approach was implemented in 1993. Under this policy, water quality monitoring and assessment, water abstraction permitting, non-point source control and point source permitting were all synchronised at the watershed scale. The regional USEPA office collaborated in this by realigning the schedules for permits, so that all permits in a watershed will expire and be reissued at the same time. The intention of this is to allow more options for assessing and implementing the most effective controls on both point sources and non-point sources, depending on the impacts of these pollution sources on water bodies.

In the state of Georgia, legislative authority was granted in 1992 to the Georgia Department of Natural Resources Environmental Protection Division (GAEPD), to guide the state-wide development and implementation of the River Basin Management Planning Approach. This approach provides a planning framework for developing management strategies to "reduce pollution, enhance aquatic habitat, and provide dependable water supplies".

The state was divided into 14 major river basins, and a five-year cycle of planning and management was introduced. By late 1996, the first management plans should be drafted. Georgia's approach is similar to that followed in Australia, in requiring significant public involvement. A committee of stakeholders is appointed in each river basin, to assist with development of a management plan. The stakeholders represent interests such as landowners, agriculture, forestry, local government, concerned citizens and special interest groups. Staff of the GAEPD serve on the technical planning teams to provide co-ordination, guidance and continuity.

The management cycle has 12 steps, from setting up the stakeholder committee and basin team, resource assessment, setting of objectives, development of strategies, through to drafting of a management plan, review and implementation of the plan. It has been recognised that the River Basin Management Planning Approach will mature as all partners learn from the process. Issues which are not dealt with adequately in the first management cycle can be addressed in the next cycle.

In Utah, the Department of Environmental Quality is responsible for developing programmes to control or prevent pollution. Their Division of Water Quality has been identified as the lead agency for implementing the new Watershed Approach Framework. The emphasis here is on better co-ordination of existing management programs, and more direct involvement of citizens in protecting and managing watersheds.

As in Georgia, the state has been divided into watershed management units, and a five-year planning cycle has been established. Stakeholders will be involved in defining and implementing plans, and activities such as support of ongoing projects, issuing of permits and voluntary best management practices, will be co-ordinated within the strategy for a specific watershed.

A very useful information resource for accessing examples of watershed management plans, related to development of plans as well as implementation, is the California Watershed Projects Inventory. Watershed projects in California are mostly community and government agency partnerships for rehabilitation and management. The reports on the various watershed projects show how community-based advisory groups are established, to work together with government agencies to solve localised watershed problems.

Issues addressed include water quality, environmental quality, land use impacts and soil erosion. Various reports can be accessed through this web page, including:

- watershed management plans (small and large scale);
- conservation planning efforts (species and habitat);
- co-ordinated resource management planning;
- wetlands restoration and enhancement;
- riparian restoration and enhancement;
- native plant revegetation projects; and
- mining reclamation programmes and regulatory compliance.

The home page address of the Inventory is:
http://ice.ucdavis.edu/California_Watershed_Projects_Inventory/

6.3.3 Management of regulated rivers and shared river basins

Many of the larger rivers of the USA are shared between two or more States, and may be shared across international boundaries. In addition, many of the larger rivers are highly regulated, and have been so for much if this century, in some cases. The purposes for regulation include hydroelectric power generation, navigation, provision of irrigation water, and water storage facilities for urban supply.

Institutional models for basin management at this scale vary. In some cases, such as the Tennessee River, an independent commercialised authority, much like the South African water board, manages and operates the river for its primary business purpose. In the case of the Tennessee Valley Authority (TVA), whose primary purpose is to generate and supply hydropower, this authority may also have a water quality management and habitat management function assigned to it. The TVA must consult with stakeholders, in order to manage the river so as to best meet the needs of all users, within the constraints of the primary purpose of power generation.

In the Colorado Basin, the water is shared amongst several states of the USA, as well as Mexico. Compacts and treaties dating back to 1922 have been used to apportion the use of waters in the Colorado Basin. Management of water resources in the Colorado Basin is a constant challenge due to the demand for water which frequently exceeds the available supply, or the agreed portion, in this arid area.

Strategies for water resources management in the Colorado Basin are described in the Annual Operating Plan for Colorado River Reservoirs, and the report on the Colorado River Decision Support System, both of which are available on the web page belonging to the US Bureau of Reclamation, which is responsible for water and power management in the Lower Colorado. The address of this home page is:
http://www.lc.usbr.gov/~g4000/index.html

In a shared river basin such as the Colorado, the general institutional model resembles that used in the Murray-Darling Basin in Australia. A Basin Commission is set up which represents the interests of the states and water users to whom water has been legally apportioned. This Commission then makes decisions on river management, operation and water allocation, within the framework of state and national law, and any treaties or compacts which have been signed. The actual day-to-day management may be undertaken by a government agency, such as the US Army Corps of Engineers, the USGS, the US Bureau of Reclamation, or state government departments. Sometimes an executive office is established which can carry out delegated river management functions, such as the Ohio River Valley Water Sanitation Commission, which is an interstate water pollution control agency for the Ohio Basin.

The Great Lakes International Joint Commission (GLIJC) is a good example of an international authority which manages a very large shared drainage basin. The GLIJC was set up under the 1909 Boundary Waters Treaty, in order to manage the lakes and rivers of the basin for the benefit of citizens of the USA and Canada. Three Commissioners are appointed by the USA and three by Canada. Their role is to set broad policy guidance for basin management, and to provide impartial judgements in resolving any conflicts which might arise. A number of advisory and regulatory agencies, including a Great Lakes Regional Office of the GLIJC, have been set up to administer and implement management strategies.

Information on the GLIJC, and on treaties and agreements such as the Great Lakes Water Quality Agreement, can be found on the Great Lakes Information Network home page at: **http://www.great-lakes.net/**

6.3.4 USEPA information related to watershed management

The On-Line Library Catalogue of the National Library of the USEPA was searched for useful references relating to watershed management. The search parameters included policy on watershed management, examples of actual watershed management plans and reports, laws and agreements relating to management of shared watersheds, as well as strategies for watershed management (more technical in nature). The search was limited to documents published after 1980 (for law and agreements), and after 1985 (for watershed management). The results of the literature search are provided in **Appendix 2**.

All the documents listed in **Appendix 2** are available from the USEPA. Copies can be requested by electronic mail, addressed to: **water@epamail.epa.gov**

6.4 United Kingdom approaches

Recent developments and changes in the institutions involved in water resource management in the United Kingdom have resulted in the National Rivers Authority (NRA) and Her Majesty's Inspectorate of Pollution becoming part of the Environment Agency (EA). This now means that all the processes and functions of environmental protection, management and regulation can be matched to catchment boundaries and controlled largely by a single authority.

It is anticipated that this will lead to more effective protection of the environmental and ecological aspects of catchment processes, and to more efficient regulation of environmental impacts. However, much of the planning and decision-making is undertaken by the government agency on behalf of the communities involved in the area of concern; therefore, this is more of a "top-down" model.

The process is likely to be very effective as long as the regulatory agency has sufficient personnel with adequate expertise, and the appropriate technical and financial resources are available. Also, in contrast with the situation in South Africa, allocation of water is a problem only in certain areas of Britain, since the country, in the main, is not water-scarce. This feature, coupled with the considerable degree of trust shown towards regulatory authorities by the general public, has reduced the need for stakeholders to participate actively or have close involvement in the decision making process.

The development of approaches to ICM in the UK is still in the early stages, which may explain why public participation in actual decision making is relatively limited. A formal process of Catchment Management Planning has been adopted by the regulatory agency: the catchment management plan which is a result of this process, is intended to establish a long-term vision for individual river catchments; to balance conflicting uses and identify actions needed by government agencies and stakeholders; to promote effective and proactive planning to prevent future environmental damage and to provide lasting solutions to environmental problems. The focus is very much on protection of the general environment of the catchment, although long term water resources planning and development was also formerly a responsibility of the NRA.

The Catchment Management Planning process has several steps:

1. A multi-functional Catchment Management Planning Working Group is set up, consisting of NRA (or EA) members to give managerial and technical support to the planning process.
2. Current and potential catchment uses and activities are identified; liaison with other groups and organisations is informal, and limited to data collection and issue identification.
3. The Working Group identifies environmental objectives (water quantity, water quality, physical features) which are necessary for each of the catchment uses to be supported.
4. The current water quantity, quality and physical status of the catchment is reviewed, and compared to the objectives. Concerns and potential problem areas are identified, and management options to address these are put forward by the Working Group.
5. A Catchment Management Planning Consultation Report is produced, outlining the vision for the catchment, objectives, current status and options for management and/or rehabilitation. The consultation report is used as the basis for both internal and external consultation and discussion.
6. A Catchment Management Action Plan is drawn up which takes into account the issues and comments raised during the consultation process. The Action Plan outlines clearly the actions and timetable required to meet the objectives, and who is responsible for implementation. This responsibility will probably be shared by several agencies, stakeholder groups and organisations.

Examples of Action Plans which were made available by the then NRA reflect not only the fairly early stage of development of ICM in the UK, but also that the need for planning of new economic development is much less urgent than in South Africa. The Action Plans largely consist of lists of regulatory and auditing activities to be undertaken by the NRA and other responsible agencies. While this kind of plan would be extremely useful in South Africa for regulating, managing and keeping track of environmental and water quality aspects in catchments, it does not adequately address the need for proactive planning of economic development which matches the constraints of the natural resource base.

The current UK approach has high requirements for competent administration, infrastructure, technical skills and funding at central and regional government levels. These features make it difficult to implement this system in South Africa simply on the basis of our limited skilled human resources. In addition, the South African constitution reflects the active desire of communities to have a more active and significant role in making decisions about critical natural resources such as water, than this approach allows at its current stage of development.

6.5 French approaches

All water-related issues in France are considered to be part of the responsibility of the Minister of Environment, and are dealt with under the auspices of the Department's Water Directorate. Water is considered to be an important natural resource and aquatic ecosystems are important and worthy of protection. The Ministry determines all water policy and supervises the implementation of these policies by local representatives. In each political and administrative district, local responsibilities have been delegated to the Prefect or administrative head of the district. In turn, the prefect appoints a Basin Co-ordinator for Water Administration to oversee the process. Currently, two sets of legislation (which were promulgated on 16 December 1964 and 3 January 1992) control all water-related activities in the country.

The French water legislation is based on five main principles:

- the unity of surface and underground water resources;
- water must be managed within the context of drainage basins;
- water management must be integrated to include all activities which influence the quantity and quality of the water;
- there must be financial solidarity between all categories of water users (people who abstract water as well as effluent dischargers); and
- the need to ensure close collaboration between all parties and agencies involved in, or associated with, water management.

The French approaches to water resource management have recognized the importance of focusing on the natural drainage basin of each river and its tributaries. Accordingly, the country has been divided into six major drainage basins, whose boundaries cross local and provincial political boundaries. Within each of the six drainage basins, a Drainage Basin Committee and a Drainage Basin Agency have been set up to deal with all issues related to water.

Each Drainage Basin Committee acts as a "mini parliament", and determines how best to address local and regional water problems in the river basin, within the context of national policies. Its decisions are then enacted by the appropriate Drainage Basin Agency. The Basin Committees often have over 100 members, composed of representatives drawn, in approximately equal proportions, from three main groups. These are:

- user groups (industry, land owners, effluent dischargers, etc.);
- representatives of the local departments, regions, cities and towns; and
- representatives of the French State, appointed by the Ministry.

The six Basin Agencies, (called Water Agencies since 1991), are public institutions which operate under the auspices of the Ministry of the Environment. Each Water Agency is an executive tool of the Committee and implements policies decided by the latter. Each Agency is controlled by a board of directors consisting of elected officials, water users, effluent dischargers, and State representatives appointed by each Basin Committee. They are financially autonomous, and thus able to address and support operations required to resolve water supply and water pollution problems.

Each Agency draws up a five-year plan for the development of water resources and for pollution control. Implementation of this plan is financed by taxes or levies collected from water users and effluent dischargers. These levies or taxes are in proportion to the quantity of water abstracted or the quantity and quality of effluent discharged, respectively.

The main objectives addressed by each Water Agency are the following:

- control of all forms of water pollution;
- the restoration of surface and groundwater quality where this may be required;
- preservation of aquatic ecosystems;
- the development, protection and distribution of the water resource to meet fully all uses as and when required, and to ensure drinking water supply;
- preservation of water flows and the prevention of flooding; and

- the provision of adequate water supplies for agriculture, fishing, leisure and all other legally permitted human activities.

The institutional features of the French approach seem to be relatively cumbersome when compared with other overseas approaches to water resource management. However, the basic concepts are similar to those of other countries and work well within their national context.

6.6 Other African approaches

6.6.1 Introduction

Elsewhere in Africa, considerable attention and rhetoric have been focused on the issue of water resource management and, in particular, integrated catchment management. Inevitably, much of the attention has been directed towards resolving the complex issues of large shared river basins (e.g. the Nile, Zambezi, Okavango, Kunene and Orange rivers) and inter-basin water transfers. Unfortunately, very limited success has been achieved to date in attempts to resolve these issues. The respective debates and negotiations have been particularly intense and often highly acrimonious in those regions where water resources are scarce or where civil war prevails (e.g. Sudan, Uganda and Ethiopia in the upper Nile River basin; Angola in the upper catchments of the Kunene and Okavango rivers).

Several international aid agencies have made concerted attempts to facilitate multi-national negotiations and agreements on shared water resources. Perhaps the best-known African examples are those of the Nile and the Zambezi rivers. Many of these international attempts have focused on the development of regional water balances and a variety of predictive modelling techniques have been used to examine different water allocation scenarios. However, due to the inherent political, economic and social instability of several of these basin countries, very little has been achieved beyond the development of conceptual plans. Therefore, it is unlikely that these attempts will succeed until each country is able to participate in the debate as an equal partner, and there are sufficient skilled personnel available plus the required technical and financial resources.

In some southern African countries, (e.g. Namibia and Zimbabwe), there is good appreciation that the ICM approach offers the most effective solution to water resources management. However, the degree to which the principles of ICM are applied differs between them.

6.6.2 Namibia

In the case of Namibia, many water resource managers consider that there are too few perennial surface water resources to justify the application of this approach throughout the country. The only perennial rivers, (Kunene, Okavango, Zambezi and Orange), are located on the country's borders and are shared with other basin states, not all of whom share Namibia's problems of water scarcity. Each of these shared river basins are administered by Joint Permanent Technical Commissions, where each basin state is represented.

In the case of the Okavango River, for example, a tripartite organization called the Okavango River Basin Commission (OKACOM) has been formed by Namibia, Botswana and Angola. This organization aims to oversee water resource management within the entire river basin. Because this organization is still in the early stages of formalization, it has not yet undertaken any formal management activities. Elsewhere in Namibia, no formal catchment management authorities have yet been constituted, though water supply activities have begun to be commercialized through the formation of a parastatal organization called Namwater. This organization will function very similarly to a South African Water Board.

Nevertheless, the ICM approach has been used to good effect within Namibia, for example in the ephemeral westward-flowing rivers which drain through the Namib Desert to the Atlantic Ocean. Here, the ICM approach provides a valuable framework for defining the needs of users and selecting appropriate management options. In the case of the Central Namib State Water Scheme (CNSWS), demands on the groundwater resources from three different ephemeral river systems (the Kuiseb, Swakop and Omaruru rivers) can be carefully balanced to minimize environmental degradation.

6.6.3 Zimbabwe

In Zimbabwe, water resource management is a responsibility of the central government, specifically the Ministry of Lands and Water Resources, and includes both surface and groundwater resources. The responsible Minister has delegated authority to regulate and supervise the exercise of water allocation rights and the control of water quality to a number of River Boards. The primary objectives of these Boards are to exploit and conserve the water resources of the(ir) specified area with the object of:

- securing their proper use and development;
- providing in both the short- and long-term, adequate water supplies on the most economic basis; and
- ensuring the efficient distribution of water supplies in order that the economic development of the area may be promoted, facilitated and expedited in the National interest.

Catchment Boards and River Boards are found in many areas of Zimbabwe but their areas of jurisdiction do not cover all of the country, all people holding water rights, all catchments or all commercial farmers. The legislation <u>allows</u> the formation of River Boards but does not make them compulsory. Therefore, it is only those people who have a critical interest in the day-to-day management of water who have formed boards in these areas - these are inevitably the larger commercial farmers who use over 80 % of the managed water in Zimbabwe. Given the important need to manage irrigation water on a day-to-day basis, the activities of River Boards can therefore be said to be acting on the basis of water use efficiency and the self-interest of the participating landowners and irrigators.

The enabling legislation in Zimbabwe refers only to River Boards, even though most established River Boards represent a section of river, stream or tributary which is only part of a catchment. Of the River Boards in operation, there is great variability in size, efficiency and effectiveness. In some parts of the country several River Boards have formally grouped themselves together to form a higher body, a Catchment Board, to manage a catchment or part of a catchment; this activity is allowed by the River Board regulations and legislation.

However, none of the areas of responsibility of these Catchment Boards actually covers an entire catchment. In addition, there are no formal mechanisms or processes which can be used to facilitate participation and negotiation amongst stakeholders. In some cases, River Boards could not be formed because of a lack of agreement amongst interested and concerned participants as to who should represent specific interest groups.

A Regional Water Authority (RWA) has been formed to assist with the development and management of water resources and agricultural potential in the south-eastern region of Zimbabwe. However, despite owning and operating water supply dams, and possessing its own water rights, most commercial farmers operate independently of the RWA. In addition, the RWA is restricted in its ability to manage its own water in that virtually all of the water it manages is committed by long-term agreements to specific users.

The overall impression gained of water resource management in Zimbabwe is one of fragmented and divided responsibilities in which there is little or no co-ordination at regional or national level. Whilst some individual landowners may benefit from the actions River Boards, these do not function in a manner which is conducive to either efficient or effective water resource management. In conclusion, the Zimbabwe River Boards example is one which South Africa would do well to avoid.

7. CONCLUSIONS

Based on the information gained from local and overseas sources, several pertinent comments can be made regarding the level of commitment and types of arrangements that would be required to implement an ICM approach in South Africa. Clearly, whatever approaches appear to be applicable, the Department's objectives for adopting ICM will influence the type of ICM approach which is eventually implemented in South Africa. Two possible objectives are addressed below.

7.1 Objectives for ICM implementation

7.1.1 Devolution of authority and responsibility

If the Department's objective is to devolve more of the day-to-day management function down to local level in order to relieve pressure on the available manpower resources at central government level, then it may be more appropriate to set up statutory catchment boards with the power to raise levies, issue permits for discharge and abstraction, and enforce permit conditions.

The advantages of this are that responsibility, accountability and authority are held at the catchment level, and this is in line with the philosophy of the present government. Real decision making can then take place at a catchment level, assuming the catchment boards are structured so that all stakeholders are represented.

However, the disadvantages of this model probably outweigh the advantages:

- the appropriate expertise, experience and judgement are not likely to be available within stakeholder communities at a catchment level, nor is it likely that South Africa could, in the short- to medium-term, find sufficient skilled people to be employed to carry out the executive and management functions of the boards.
- the activities and administration of the boards would probably have to be financed from the local tax base, possibly with additional support from central or provincial government. Sufficient funding may not always be available.
- given that many of South Africa's river catchments are shared across provincial boundaries, and that inter-basin transfers are common, there will be a good deal of administrative effort required in co-ordination. Also, the participation by local, provincial and national priorities will need to be balanced. This may be problematic if authority for water allocation is devolved to individual catchments or even individual province level.

7.1.2 Improved resource management

If the objective is to improve the long term management and protection of water resources, then the Australian or British models would probably serve as the best basis for implementing ICM in South Africa. However, it is important to remember that they are two fundamentally different models.

The British model has very high requirements for centralized control, administration, infrastructure, skills and funding at central and regional government levels. This would make it very difficult to implement in South Africa because of our limited skilled human resources. The South African constitution presents an additional problem in the way in which it reflects the desire of communities to have a more active and significant role in decision-making about natural resources.

An alternative approach to ICM which draws on the positive aspects of the Australian models seems to show the most promise for South Africa. The Australian approach relies on active community and stakeholder participation in natural resources management and decision making, within a framework of guidance and support from government agencies at state and federal level.

However, a perceived disadvantage of the Australian model may be that ICM is seen as a long-term process, where implementation is a gradual and slow process of learning, negotiation, planning and action. In addition, the Australian model would need to be adapted to deal with the complex and sensitive water allocation decisions which have to be made in South Africa.

The advantages of the Australian models are that planning and actions are community-based. All stakeholders play an active role in management, from the institutional level down to the individual landholder level. Broad policies and objectives for water resources management can still be set at central government level, and these serve as a framework within which catchment communities can make their own decisions about how the resources are allocated and managed.

The Australian models require the following:

- a core of skilled personnel at central and regional government levels, to initiate, facilitate, assist and guide catchment community groups through the process of ICM;
- access to technical support through scientific and engineering strategies for assessing and dealing with resource management issues;
- greatly improved collaboration between the government departments and agencies involved in resource management. This may be facilitated through the adoption by all relevant government departments of an umbrella national policy towards ICM;
- long term commitment of funds and personnel to support each of the catchment community groups.
- policy support and guidance from central government level so that water resources management decisions are made on a consistent basis throughout the country.

Clearly, if ICM is to succeed in South Africa, there must be a far wider acceptance of the need to properly empower people so that they can participate in a transparent decision-making process. This will require a dramatic change in attitude and approach, both amongst the general public and from our water resource managers. At this crucially important time in the history of South Africa, we have the unique opportunity to facilitate this change as an integral part of the socio-economic reconstruction and development of our society. However, ICM will not succeed if the approach is not supported by suitable legal, institutional and administrative frameworks. Unfortunately, this will take both time and money to accomplish as we are still at an early stage in the development phase.

8. RECOMMENDATIONS FOR THE FUTURE

Ideally, South Africa should look at a gradual shift from a situation where ICM is regulated and controlled by central and regional government levels (as in Britain), but still with some stakeholder consultation, to the community-based self-regulatory approach towards which Australia seems to be moving. This would allow sufficient time for learning and the development of an appropriate skills base: the country could then expand ICM from the present relatively small core of skilled people at central and regional government level. This would also allow us to take the best learning from the different models used in other countries, and apply it in a logical and structured manner as we develop ICM towards its ideal.

On the ground, this could take the form of identifying priority catchments, and working initially with a catchment forum, or some similar participatory organisation. The forum could be gradually developed into a catchment committee, taking more responsibility and accountability as local capabilities are developed and enhanced. The next step could be the development and constitution of a catchment board or authority, whose legal, executive and fund-raising status would depend on the needs of the local situation.

Some specific recommendations can be made on the basis of overseas experience in ICM and our current state of knowledge. These are:

1. The Department should spend enough time on developing a sound policy basis for ICM in South Africa. The policy process needs to involve not only the Department as the regulatory and water management agency, but also representatives from other government departments and agencies whose responsibilities are related to water resources allocation and management, as well as other stakeholder groups.

2. The Department should consider the development of a national "umbrella" policy, to which all relevant government departments could subscribe. The intention of this would be to ensure commitment to ICM and collaboration from all the agencies at national, provincial and local level. Inter-department co-ordination on resource management issues at national, provincial and local level should be supported as a matter of policy.

3. The lead agencies involved in ICM should ensure long-term commitment to providing the right personnel to develop and implement national ICM policy

at the catchment level. This should be supported by parallel commitments to provide long-term funding to policy implementation. Perhaps the best location for personnel who are involved in setting up catchment community groups and guiding the planning process, would be at regional level within the Department of Water Affairs & Forestry.

4. The Department should minimise the introduction of detailed new legislation on ICM at this time, or at least until there is a wider shared vision of the way in which ICM should proceed in South Africa. In addition, the ICM philosophy is founded on flexibility and adaptability. Legislation and regulation should follow the ICM process, rather than attempt to lead it too strongly.

5. Ideally, the new Water Act should contain sufficient enabling legislation to allow an appropriate catchment management body (a forum, committee or board) to be set up within a catchment. This would allow lead agencies to:
   - facilitate the development of appropriate frameworks for catchment management plans;
   - allow the regulatory agency to enforce permit conditions and aspects of the management plan; and
   - set up appropriate consensus-seeking and conflict resolution mechanisms.

6. The revised Water Act should allow the Minister to issue regulations on a catchment-specific basis, regarding:
   - the geographical boundaries of a catchment;
   - resource management objectives for the catchment;
   - the nature of the process of developing a catchment management plan;
   - agency and stakeholder responsibilities for implementation;
   - authority, accountability and legal status of the catchment board or committee;
   - conflict resolution processes;
   - monitoring, auditing and reporting requirements and responsibilities; and
   - the time scale and process for review of regulations.

7. In order to ensure successful implementation of ICM approaches, there should be a clear long-term commitment from government to support ICM with financial and manpower resources.

8. Clear policy guidance will be required on the use in ICM of instruments such as: water quality guidelines, effluent emission standards and permits, environmental impact assessments.

9. REFERENCE MATERIALS USED

The individuals consulted and the published information examined during the execution of this investigation are listed below. The individuals are listed in alphabetical order whilst the published references are listed in alphabetical order and then in chronological order for subsequent articles by the primary author.

9.1 Personal communications and interviews

Dr V. Alavian, Vice-President: Rankin International Engineering Consultants, Knoxville, Tennessee, USA.

Professor A. Arthington, Director: Centre for Catchment and In-stream Research, Griffith University, Nathan Campus, Brisbane, Queensland, Australia.

Dr B.A. Banninck, Principal Scientist, Rijksinstituut voor Volksgezondheid en Milieuhygiene, Bilthoven, Holland; (Manager of the RIVM Nairobi Office).

Mr G. Bateman, NRA South Western Region, UK.

Dr G.A. Best, Principal Freshwater Scientist, Clyde River Purification Board, Glasgow, Scotland.

Mr D.J. Blackmore, Chief Executive: Murray-Darling Basin Commission, Canberra, Australia.

Professor A. Bouzaher, Head: Resource and Environmental Policy, Centre for Agricultural and Rural Development, Iowa State University, Ames, Iowa.

Professor C.M. Breen, Programme Manager: Kruger National park Rivers Research Programme, and Director: Institute for Natural Resources, University of Natal, Pietermaritzburg.

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APPENDIX 1

MANAGEMENT OF WATER RESOURCES IN AUSTRALIA

Report to

Water Research Commission

and

Department of Water Affairs and Forestry
(Water Law Review: Institutional Arrangements Task Team)

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CONTENTS

MANAGEMENT OF WATER RESOURCES IN AUSTRALIA

1. INTRODUCTION

1.1 Background to the Australian Study

Australia is a country which, over the last two hundred years, has built an economic foundation on the development and commercial utilisation of natural resources, primarily land, forests and water, before beginning to strengthen their manufacturing and resource beneficiation industries. Much of Australia is water-scarce, with great variability in the distribution of water. The generally semi-arid climate is similar to that of southern Africa. Hence we can expect that Australia has faced, or is presently facing, many of the same issues as South Africa does, in relation to the development, utilisation and management of natural resources.

A study visit was undertaken in 1994 to identify key issues in natural resources management in Australia, with the intention of finding out how similar these issues were to those facing South Africa, and what learning could be gained from comparing the approaches used in the two countries. The Australian situation was assessed within a framework which covered, broadly:

- *issues* - the most significant current issues being dealt with in Australia, in the context of natural resources management;
- *policy* - current and developing policies for addressing these significant issues;
- *legislation* - key legislation which facilitates (or constrains) the sound management of natural resources;
- *institutional arrangements* - the roles, responsibilities and interactions between the agencies, authorities and government departments involved in natural resources management, including the interactions between the Federal and various State governments;
- *implementation* - how the policy and legislation is translated into practical action plans, and how these actions are being undertaken. This includes the development of scientific and technical support systems, but also, and most importantly, addresses the role of communities and individuals in implementation of national, state and regional policy and legislation. The study included an investigation of community-based programs such as Landcare, Salt Action and Waterwatch; the establishment of catchment co-ordinating committees for addressing land and water management issues; the role of lead government agencies in initiating and supporting community-based programs.

Melbourne, in the state of Victoria, was used as the geographical base for the study. This was principally because, among the Australian states and territories, Victoria has the longest history of policy and legal support for the protection and management of natural resources. Their Environment Protection Act of 1970[1] gave the basis for the establishment of the Victoria Environmental Protection Authority (VEPA), and for co-operation between the relevant government departments in integrated management of natural resources. Experience gained in implementation has allowed the policy, legislation and institutional functions to be reviewed and optimised over the years. The Water Studies Centre of Monash University provided an ideal base from which to work, due to the close proximity to most state government central offices, and the availability of library facilities.

The Australian states each tend to follow slightly different approaches to management of natural resources. Although recent agreements[2] have led to closer collaboration between the Commonwealth Government in Canberra and the states, each state still retains a considerable degree of autonomy in decision making. From Melbourne, visits were made to Queensland, Western Australia and Canberra to investigate the policy, legislation, institutional and practical aspects of resource management.

The scope of the study included the management of agricultural land, forests and water resources. All of these three are closely linked in Australia, since the most significant issues related to water resources management arise primarily from the impacts of forestry or agricultural practices, although industrial and domestic effluents and urban developments are also of concern.

For the purposes of this report, we have focused on water resources management, specifically the development and implementation of integrated catchment management approaches. In many of the examples discussed, forestry and agriculture have been used to illustrate the development and application of systems for the optimal integrated management of land and water on a catchment basis. As far as possible, the policy, legislation, institutional structures and community-based programs which make up these management systems are identified and critically reviewed.

1.2 Study Methodology

The study method was based on personal interviews with:

- people in each government department dealing with land, water and forestry resources;
- people in VEPA and the Commonwealth EPA (CEPA);

- key people in water authorities, including Melbourne Water, the Murray-Darling Basin Commission and the Water Authority of Western Australia;
- people involved in the initiation and implementation of community programs, specifically Landcare and Waterwatch;
- scientists and researchers involved in development of supporting technical information and scientific understanding, including the Land and Water Resources Research and Development Corporation (LWRRDC) and various Co-operative Research Centres;
- community representatives involved in the activities of catchment management committees.

Discussions with these interviewees were based on the study framework of identifying the key issues, policy, legislation, institutional functions and implementation related to natural resources management. In each case, these interviewees were asked for referrals to other key people, and were also requested to provide documentation or references to documentation which would support the study.

It is a tribute to all of these Australians that no request for an interview was ever refused, and that everyone interviewed gave of their time generously and often on more than one occasion, since it was sometimes necessary to follow up on certain issues; that everyone interviewed was willing to openly discuss the issues from their perspective, and how their roles and responsibilities contributed to the management of natural resources; and that a large amount of documentation was provided freely, which has formed an important information resource for this study. Dr Jane Doolan and Ms Patricia Geraghty of the Department of Conservation and Natural Resources in Victoria, and Dr Phil Price of LWRRDC deserve special mention and thanks.

1.3 Structure of this Report

Current reforms in the Australian water sector are progressing towards an eventual separation of the commercial functions of water supply and sewerage services, and the non-commercial function of waterway management. Therefore this report is presented in three main sections:

- firstly, a brief discussion of current reforms related to water supply functions, and the changing role of water supply agencies. This is relevant to waterway and catchment management in so far as commercialised water supply agencies will now be more clearly identified with other land users and bulk users of water, through the implementation of new legislation regarding tradable water entitlements.

- Secondly, a discussion of integrated catchment and waterway management, which will remain the responsibility of state agencies or those to whom authority is delegated by the state government.
- Thirdly, sections outlining some lessons from the Australian experience of ICM, which may be useful for South Africa, and some points for discussion as part of the Water Law Review process.

Because of the comprehensive nature of the study, and also because there are so many related aspects of land and water management, this report is intended to serve more as a broad overview. Rather than incorporating all the detail here, the report should provide guidance for further investigation of specific aspects. In the general discussion of catchment and waterway management, the framework of issues, policy, legislation, institutions and implementation will be followed.

The reader in search of more detailed information will be referred to the relevant documents, or to people in Australia who can assist with queries. Almost all of the documents cited in this report are available, and will be archived at the main library of the Department of Water Affairs & Forestry in Pretoria. One of the supporting products of the study is a keyword-searchable database of these documents, with reference information and brief summary notes on the content of each.

2. THE COMMERCIAL WATER SECTOR

The Australian water industry has assets of $80 billion but in commercial terms relative to land values, the return on these assets is very poor. In order to promote economic development, the real cost of water to agricultural, industrial and domestic consumers has often been subsidised(3). This has led to the situation where water, although recognised as being a scarce and valuable resource, has not always been treated as such in a financial sense.

The current trend in Australia is towards commercialisation of water supply functions, with the objectives of providing a more efficient and effective service, but also of achieving some degree of cost recovery in a real-market situation(4,5). The reform of the water industry in Victoria is discussed here as an example.

The promulgation of the 1989 Water Act in Victoria signalled an attitudinal change of the State Government towards integrated resource management based on modern economic, social and environmental principles. The Act represents a marked shift from the view that water is a plentiful resource for all to take for granted, to the prevailing reality that water is a scarce resource which requires wise and efficient management.[6,3]

Superimposed on new and existing legislation is the Victorian Government's desire to corporatise the institutions which manage water resources, and make them more autonomous and financially accountable. The underlying philosophy of the State Government is to open up the water sector to market forces, particularly competition.[3]

Victoria's water supply sector can be divided into three primary sub-sectors, and each of these are discussed separately:

- the Melbourne metropolitan area;
- outer Melbourne and peri-urban areas;
- rural areas.

2.1 Water Supply in the Melbourne Metropolitan Area

The sole responsibility for bulk harvesting and supply of drinking water, removal of sewerage, urban drainage, trade disposal, and parks waterways and catchment management for the Melbourne metropolitan area lay until recently with Melbourne Water. Melbourne Water is a "State Government Owned" company, which operates under the Water Act 1989, the Melbourne and Metropolitan Board of Works Act 1958, Melbourne Water Corporation Act 1992, Catchment and Land Protection Act 1994[7] and the State Owned Enterprises Act. Proposed reforms to Melbourne Water include[3]:

- separating core commercial activities of water, sewerage and drainage services for which returns can be expected, from non-commercial activities such as management of parks and waterways;
- issuing Melbourne Water with an operating licence which will legally require it to deliver its core functions of water, sewerage and drainage services, and require these services to meet standards and be price-regulated;
- restructuring the accounting system to introduce three main catchment based water distribution businesses within Melbourne Water i.e. competition generated by internal comparisons;
- contracting out services like water and sewerage maintenance, survey and mapping, cafeteria, geotechnical and insurance to private industry;
- allowing a private company to build, own and operate the Yan Yean drinking water treatment plant which then sells treated water i.e. Melbourne Water

buys treated water rather than pays to treat the water itself. This allows Melbourne Water to focus on its core business of supplying water;

- implementing a user-pays pricing structure for consumers so that the more one uses, the more one pays;
- privatisation of assets, although Melbourne Water will continue to be Government owned (for now).

The planning handbook *Water Victoria: The Next 100 Years*[8], proposed three possible scenarios for taking Victoria into the next century in relation to water resource management.

The scenario which incurs the least cost to the environment, and to the government and consumer, is to make water a tradable commodity. There is also the option of treating low quality water or sewerage to provide potable water in the future. Water is presently allocated by the State Government, but this system has not always operated efficiently, and has been conducive to mismanagement of both land and water[4]. The National approach to water reform is set up water markets within which water entitlements can be bought and sold, and in which the environment has a legal entitlement. This approach will eventually underpin how the water sector, including Melbourne Water[10], operates in the future. A separate discussion on tradable water entitlements, and the development of policy and legislation in this respect, can be found in section 2.1.4 below.

2.2 Water Supply to Outer Melbourne

The same services which Melbourne Water was supplying to the Melbourne area were provided by over 100 different water authorities to the outer Melbourne or peri-urban area. The underlying thrust of the reform for this sector is to make water services more catchment oriented rather than local region oriented.

All of the legislation which applies to Melbourne Water and the Melbourne area also applies to this sector. The main mechanism for facilitating the reforms is to amalgamate the authorities, reducing the number from 83 to 17 regional water supply authorities,[6] (catchment-based as far as is practical). Benefits should flow on from economies of scale and more co-ordinated management. Essentially the same principles of separating core business from non-commercial functions apply to this sector also, and it is expected that the new Catchment and Land Protection legislation[7] will provide for management of the land and water resources.

2.3 Water Supply in Rural Areas

The Rural Water Corporation, which is now a statutory authority or a Government managed institution, has responsibility for supplying irrigation, agricultural, stock and rural domestic water to the rural areas of Victoria. The Corporation had relied on cross-subsidies to finance the provision of water supply to rural areas, but substantial reform is intended to improve efficiency in this sector also. The Rural Water Corporation now operates under the Water (Rural Water Corporation) Act 1992. The proposed reforms[(6)] include:

- having a small central corporation providing strategic direction and fiscal guidance while driving the change process;
- having five regional organisations, based on physical water systems, each with a Regional Management Board, which will provide the full range of wholesale and retail water services;
- having technical and business support services provided by service companies open to market competition;
- making up the shortfall in revenue by restructuring, debt forgiveness in exchange for Government owned equity, revenue from new sources, increased charges and a government subsidy over an adjustment period;
- setting up semi-independent service companies;

Activities such as water quality monitoring, floodplain management and licensing of works are no longer the responsibility of the Rural Water Corporation, but will be the responsibilities of VEPA, Department of Conservation and Natural Resources and the proposed Catchment Boards.

2.4 Tradable Water Entitlements and Water Accounting

Under the Water Act 1989, the State Government or "Crown" has the ultimate legal control and right over all surface and groundwater in Victoria. The Crown allocates water to water authorities such as Melbourne Water and the Rural Water Corporation, who then partition and allocate water to consumers.

In Victoria, a task force examined ways to convert existing water rights to "bulk entitlements". There are attenuated and non-attenuated entitlements to water. Non-attenuated (NA) entitlements derive from a percentage of the source i.e. dam or reservoir, whereas attenuated (A) entitlements derive from volumetric abstractions from a water network, mostly at the point of delivery. A water authority which operates in a headwater or catchment would have NA bulk entitlements, whereas an authority downstream who must take water from a stream or river would operate under an A entitlement for example, by using a licence system. The details of such a system can be found in additional references.[9,11,12,13]

It is expected that this approach will cost less in both environmental and economic terms because future growth and development will be sustained through reallocation of existing stores of water and not by building more dams and diversions. It is, however, important that water rights be precisely specified and that the total entitlements allocated do not add up to more than 100 % of available water.

The principal objectives of implementing Bulk Water Entitlements are:
- to provide authorities with a clearly defined property right to water;
- to provide authorities with flexibility to manage within their entitlements;
- to provide a basis for sharing limited water resources;
- to facilitate water trading between user groups;
- to allow specific entitlements for environmental purposes.

In order for the system to be successful, Bulk Water Entitlements must be:
- explicit in defining where or from which source the water will be abstracted;
- exclusive to the authority to which the water has been granted;
- tradable in part or in total to other authorities;
- enforceable by law through proper monitoring and policing.

To support the system of entitlements, a form of water accounting is likely to be necessary. The water accounting system presently used in the Murray-Darling Basin, where several states are granted water entitlements from a shared water resource, is described in greater detail in additional documentation.[14]

Under the system of tradable entitlements, legal entitlements can be made to the aquatic environment. In some cases, these entitlements may need to be bought back from users by the State, and reallocated to the environment. In cases of new water developments, the entitlement to the environment would be allocated on the basis of representations made by environmental managers (such as the relevant government departments, the VEPA, National Parks or Catchment Boards).

3. CATCHMENT AND WATERWAY MANAGEMENT

Approaches to integrated catchment management differ from State to State in Australia, but are generally all in early stages of development, and show different degrees of implementation and formalisation, as well as differing levels of success in meeting objectives. A comprehensive review of integrated catchment management processes in Australia was carried out by the Australian Research Centre for Water in Society[15] in 1993, and several recommendations were made in that report which would be relevant for the South African situation.

This section covers descriptions of different approaches to integrated catchment management in Australia, focusing primarily on the management of land use impacts on water resources. There is a strong emphasis on the role of private landholders in integrated catchment management in Australia, but the principles described here can be applied to the management of publicly held land, and of land uses which generate point source effluent discharges (such as industry and urban development).

The section begins with an overview of the key catchment issues of concern in Australia, and then the different State approaches are dealt with in separate sub-sections. The role of National Landcare in integrated catchment management is covered in a separate section.

3.1 Key Issues in Land and Water Management

The key issues of concern which have led to the need for integrated management of water resources and the land areas which impact on them are similar to issues of concern in South Africa. The issues are listed below. In some cases, more detail is given in the following sub-sections:

- dryland salinity
- irrigation-induced salinity
- nutrient enrichment
- soil erosion and sediment discharge into surface waters
- degradation of riparian and instream habitat
- river regulation for irrigation and supply purposes
- discharge of point source effluents to surface waters (industrial and domestic effluents).

3.1.1 Salinity

Many areas of Australia are underlain by extremely saline groundwater reservoirs. Salinisation, or the accumulation of salts in water and soil, occurs naturally over time. When it results from natural geological processes such as weathering, it is referred to as primary salinisation. Land and water salinisation due to human activities is known as secondary salinisation. A further distinction can be made between the types of secondary salinisation. Dryland salinity is a result of water table rise due to accelerated recharge form non irrigated land as opposed to irrigation salinity where the water table rises due to accelerated recharge from irrigated land. Even though the results are the same, distinguishing between the two types of salinity is useful in as much as it distinguishes between two different types of land use and thus different management options. Dryland salinity may also include non-water table related "dry scald" where top soil is lost, exposing a naturally saline sub-soil.

It is now well established that the unprecedented clearing of deep-rooted native vegetation and replacement with shallow rooted perennial grasses and annual crops is the principal cause of secondary dryland salinity in Australia. Overgrazing and the changed frequency and timing of fire also contribute to dryland salinity. In addition to the degradation of the land is the concomitant degradation of surface water by salts being washed off the land and by salinisation of groundwater discharge into streams. There is also the problem of downstream siltation and flooding.

Even though the consequences of land clearing have been obvious in Australia since the early 1900's, land continues to be cleared and legislation has been required, in order to control the rate of land degradation. The states now have mixes of tenure, land use, and land management arrangements.[16,17,18,19,20,21] These include various forms of clearing controls, tax incentives and deductions, state and federal grants for projects, and public awareness and education about the benefits of native vegetation. State-wide controls regulating the broadscale clearing of native vegetation for agriculture have recently been introduced in South Australia and Victoria.

There is a considerable amount of legislation controlling vegetation clearing, housed in various State and Federal departments, which does make matters complicated. However, there are no legislative impediments which would deter landowners from planting deep-rooted trees if they so desired, and such activities are supported through programmes such as Landcare and Greening Australia. The co-ordination of such activities should be done on a catchment basis, and hence salinity management has often formed the initial catalyst for broader integrated catchment management processes to begin.

The Land and Water Resources Research and Development Corporation (LWRRDC) provides the national leadership and co-ordinating role for research and funding of salinity management throughout Australia.

3.1.2 Nutrient enrichment

Nutrient enrichment of surface waters is a significant concern in Australia. Recent massive algal blooms in the Murray-Darling and in many other rivers and reservoirs have led to the adoption of strategies for nutrient load reduction. Although point source discharges contribute to the problem, it is considered that enhanced control of non-point sources on a catchment basis should lead to improvements in water quality. The Federal Government has published recommendations for nutrient management, which include recommendations on the roles of government agencies and landholders.[22]

In Victoria, the recently passed Catchment and Land Protection Act 1994[7] provides the legislative framework to support the implementation of improved catchment management plans. One aspect of improved catchment management is the Victorian Nutrient Management Strategy[23] which is designed to provide the policy and planning framework necessary to address eutrophication.

Programmes for controlling nutrient pollution might include a mixture of regulatory (i.e. licensing releases into a stream and planning approvals), market based approaches (i.e. tradable effluent permits) and educational initiatives (i.e. Landcare, Waterwatch). Examples of catchment plans focused on nutrient management include stormwater management in the Murray-Darling Basin[24], nutrient management in the Peel-Harvey system[25], reservoir management plans for Candowie and Lance Creek[26].

Mechanisms for control of diffuse nutrient pollution would be applied in a co-ordinated manner through the several responsible government agencies, within the context of an agreed catchment management plan, and include:

- managing fertiliser application;
- maintaining vegetation cover to reduce soil and nutrient runoff;
- preventing stock access to a water body;
- better management of riparian zones;
- regulating irrigation drainage;
- using wastewater for irrigation; and
- retaining effluent from intensive animal industries on land.

Measures for reducing nutrient pollution from point sources include:

- removing or reducing phosphorus in detergents;
- treatment of domestic sewerage;

- retaining effluent in holding basins and wetlands which assimilate some of the nutrients, and allow particulate matter to settle out;
- diverting effluent to land i.e. to plantations;
- not allowing septic tanks to discharge into rivers and streams; and
- providing gross pollutant traps in storm drains before the stormwater reaches waterways.

3.1.3 Degradation of riparian and instream habitat

The degradation of riparian and instream habitat leads to damage to ecosystem health, which in turn can cause water quality problems in surface water resources. Typical concerns related to riparian and instream degradation are:

- removal of vegetation by stock, agriculture, recreation, human development and erosion;
- weeds and vermin infestation, i.e. blackberries and willows;
- increased salinity in rivers adversely affecting existing riparian vegetation and revegetation;
- vandalism of fences;
- loss of ecological niches; and
- loss of landscape, cultural and recreation values.

In Victoria, the river frontages are administered and managed by DCNR who license river frontages to private landowners for grazing and agriculture. However, Management Committees can be set up to take the managerial responsibility. Some landowners own river frontage but rarely the bed and banks of a river. One approach being tested in Victoria is to delegate responsibility of management to a local river management authority which retains river frontage revenue and uses it for frontage management programs[27].

Suggested management options include:

- regulation of weir operation, where possible, to mimic natural flow conditions. This could involve prolonging the rates of rise and fall by staging operations to offset the rapid changes typical of the regulated river;
- control of the effects of grazing on riparian vegetation through fencing off of certain areas;
- license fees which reflect the true value of river frontages;
- reduction of license fees to encourage the landowner to undertake river frontage rehabilitation works; and
- planning controls.

3.1.4 Point source discharges

Point source discharges are licensed and regulated by a government agency, usually the State EPA. In Victoria, the VEPA, under the Environment Protection Act 1970[1], issues a "works approval" (equivalent to a discharge permit) for an industry, which covers emissions to the water, air or land environments[28].

Discharge standards are set in the context of the receiving water environment objectives for a particular river or river reach. These objectives would have been decided by the catchment committee or board, with guidance from the VEPA and other government agencies.

There is a strong emphasis by both Federal and State EPA on encouraging cleaner production and waste minimisation, through the use of economic incentives and awareness programmes.[29,30,31,32]

3.2 Approaches to Integrated Catchment Management

3.2.1 Broad policy support for integrated catchment management

Integrated management of land and water is supported by several other national and State policies in Australia. Umbrella policies which give a context and impetus to integrated catchment management include:

- the National Conservation Strategy. Examples of Victoria's initiatives under this policy are available[33,34,35];
- the National Strategy for Ecologically Sustainable Development[36], and the associated recommendations for sectoral development[37];
- the National Soil Conservation Program[38];
- policies of the Agricultural and Resource Management Council of Australia and New Zealand (ARMCANZ);
- policies and guidelines of the Australian and New Zealand Environment and Conservation Council (ANZECC).

Frameworks for implementation of umbrella policy, on a national basis, include:

- the National Water Quality Management Strategy[39], which provides policy guidance for drawing up water quality management plans, setting water quality objectives, controlling the impacts of diffuse and point sources, and initiating integrated catchment management[40,41,42,43];

- the national Decade of Landcare Plan[44] and National Landcare programmes[45] (discussed in more detail in a separate sub-section).

3.2.2 Integrated catchment management in Victoria

Integrated catchment management in Victoria is probably further advanced, in terms of planning and action, than in the other states. Salinity management has formed the focus for development of integrated catchment management strategies in Victoria.

Integrated catchment management in the broader context has developed from this single-issue basis to address much wider aspects of land and water management. This natural evolution from a single-issue focus to a more integrated process has allowed the development of learning, skills, capability and the willingness to take responsibility for land and water management, both in government agencies and amongst members of the community.

Initially, technical approaches to salinity management and the control of land and water degradation through salinisation were imposed from the "top-down" by government, but this was not successful[15], and hence Victoria has moved to an approach which emphasises active local community involvement in drawing up land and water management plans.

Legislation to support integrated catchment management has developed in response to perceived needs, as experience was gained in the planning and implementation process. The recent Catchment and Land Protection Act[7] represents the first significant step towards a legislative framework for integrated catchment management in Victoria. The Act will allow the integration of other policies, on issues such as salinity, nutrients and soil conservation. It is intended to support:

- the establishment of institutional arrangements which allow local planning and action;
- a process of community-based planning and review to identify priorities, co-ordinate activities and allow the assessment of progress;
- the application of incentives to promote sustainable land and water use.

A State Catchment and Land Protection Council has been established, to act as an advisory body to the government on the management of natural resources, to ensure co-ordination between community and government agencies, and the new Catchment and Land Protection Boards, and to provide guidance and specialist advice. These Boards will include representatives of major resource users and landholders, local government and people with knowledge and experience in resource management issues. The Boards will be allocated financial support by government, to fulfil administrative and executive functions.

The primary activity of such a Catchment Board would be to ensure co-ordination between the various groups involved in land and water management, and to carry out a planning function. Catchment boundaries are not specifically defined in the Act, but will be proclaimed by the Minister for Natural Resources. The boundaries will be catchment-based, but will also depend on common issues and community structures.

The lead government agencies (DCNR, Department of Agriculture and Rural Water Corporation) take responsibility for initiating and implementing integrated catchment management. Members from one or more of these agencies assist in the identification of problems, through monitoring, and in the facilitation and establishment of community-based groups. These groups then play a major role in developing catchment management plans focused on the priority issues (such as salinity or nutrients). The plans would include objectives, options for control and programmes of action, and would be developed within the context of state-wide objectives for land and water management. It is interesting to note that despite almost constant restructuring of the civil service in Victoria, the facilitation and support function in integrated catchment management remains strong. This is possibly due to the good collaboration between personnel of various agencies.

A participatory modelling approach which has been tested with considerable success is Adaptive Environmental Assessment and Management (AEAM)[(46,56)]. This approach, for problem identification, prioritisation and development of management action plans, shows promise for application in South Africa.

The involvement of the VEPA in planning and advising catchment community groups ensures that local interests do not conflict with regional or state interests, and the VEPA provides the regulatory and statutory authority necessary for implementation of the management plans[(47,48)]. Once the plan and the objectives are approved, the VEPA issues a State Environment Protection Policy (SEPP), essentially a gazette designating the catchment area and different reaches, listing beneficial uses and environmental values, describing the water and environment quality objectives for a catchment, and the responsibilities of various agencies and groups[(49,50)]. Permits or approvals for development are then issued by the VEPA on the basis of these objectives. A SEPP is reviewed periodically, with the same level of stakeholder involvement in assessing progress, reviewing objectives, and developing a new management plan if necessary.

Implementation of the catchment management plan is supported financially by the government, through the use of grant funding or economic incentives such as tax relief. Individual landholders or community groups can apply for funding from National Landcare to undertake rehabilitation or land management activities.

The generally successful development of ICM approaches in Victoria seems to have been achieved by allowing natural progress from single priority issues to broader management, by focusing on community-based planning processes, and by avoiding the premature imposition of potentially restrictive legislative frameworks. However, the role of the lead government agencies in facilitating (rather than driving) the ICM process is absolutely critical, as is the provision of adequate manpower and financial support for the process.

3.2.3 Integrated catchment management in New South Wales

The information on integrated catchment management in New South Wales is based on an Australian review[15].

New South Wales passed a Catchment Management Act in 1989, which gave formal structure and a statutory basis for ICM. The lead government agency in this respect is the Department of Conservation and Land Management. Administration of the Act is the responsibility of the Minister of Land and Water Conservation. The objectives of the Act are to ensure the co-ordination of policies, programmes and initiatives related to resource management, and to further good working relationships between government and communities.

Currently, there are three main institutional levels:

- Local action groups (usually Landcare groups) which address common issues of concern related to land and water resources;
- Regional Catchment Management Committees which co-ordinate integrated catchment management policies and programmes at a regional or river basin level. These bodies prepare regional strategies, co-ordinate funding for management and rehabilitation activities, and also serve as a forum for co-ordination of agency roles. Membership is voluntary, the majority of representation is from catchment stakeholders. If considered necessary, Catchment Management Trusts can be established by the Minister. These

bodies can then levy rates within a "catchment contribution area"; they must submit corporate plans, strategies and programmes to government for approval.

- The State Catchment Management Co-ordinating Committee provides central co-ordination. The committee includes representatives from the community, from Catchment Management Committees, industry, environmental groups, local government and state government agencies. It is responsible to the Minister of Land and Water Conservation on rural issues, and to the Minister of the Environment on urban issues.

Some problems have been identified with the implementation of integrated catchment management in New South Wales. In particular, it is considered that there is insufficient technical support and guidance at a local level: agency staff are over-stretched and cannot give sufficient attention to the community groups. Funding becomes a problem when too many Catchment Management Committees request statutory Trust status. The general feeling is that if the State wishes to devolve the responsibility for environmental management to a regional or local level, then adequate manpower and financial resources must be provided.

3.2.4 Integrated catchment management in Queensland

An integrated catchment management implementation programme began in Queensland in 1990, as part of the Natural Resources Management Programme. At the time, one of the issues of concern was the potential impact of pollutants derived from agricultural practices on the Great Barrier Reef ecosystem. No new legislation was introduced at that time, since it was considered that existing legislation gave sufficient basis for integrated catchment management. Most of the state functions related to integrated catchment management and Landcare are within the Department of Primary Industries.

The approach to integrated catchment management is based on common understanding of issues between stakeholders, on acceptance of individual responsibility for land and water management, and on voluntary changes in land and water use practices.

Five pilot studies were established, of which the Johnstone River was one. These studies have provided valuable learning for future implementation of integrated catchment management on a larger scale in Queensland. The Johnstone River is discussed here as an example (Merrin, personal communication).

A Catchment Co-ordinating Committee was established, representing major stakeholder groups and government agencies. A Catchment Co-ordinator was appointed by the Department of Primary Industries, who provide financial and administrative support for the Catchment Office. One of the most important responsibilities of the Co-ordinator is to oversee a comprehensive resource assessment of the catchment. The Catchment Office also acts as a link between the public, the Committee and government agencies, and develops educational and promotional material related to integrated catchment management.

The Co-ordinating Committee held public meetings and workshops with groups and agencies in the catchment, to identify the issues of concern in the catchment. These issues included water quality, management of the river system and estuarine and coastal areas, loss of habitat in the catchment, and the maintenance of agricultural viability.

The Committee provided a forum for debate on these issues, prioritisation of the issues, and the development of integrated catchment management strategies. Since there was no single clear issue of concern on which to focus initially, the identification and prioritisation of key issues was a difficult and lengthy process (Merrin, personal communication). Technical Advisory Groups were appointed, who produced discussion papers on specific issues. These were used in the development of a strategic plan for catchment management. The strategic plan identifies what actions and programmes are to be implemented, who is responsible, and the time frame for implementation.

The Committee and the Co-ordinator have worked with existing regional and local agencies, to facilitate their involvement in planning and implementation. One important objective was to draw up a memorandum of understanding between the Catchment Committee and resource management agencies, to clarify and assign responsibilities for implementation of management plans in the future. Without formal legislative support, implementation relies on the goodwill of all parties involved. Problems have occurred in gaining support from state or central government for catchment plans, due to the lack of close involvement of these agencies in the planning process.

The involvement of local government is considered to be a key factor in successful integrated catchment management in Queensland, since this can provide a local focus, and co-ordination with local strategic and economic development plans.

At a state level in Queensland, a Catchment Management Co-ordinating Committee co-ordinates and provides advice and support for Catchment Management Committees. The State Committee also reviews proposed catchment plans.

3.2.5 Integrated catchment management in Western Australia

In Western Australia, integrated catchment management is also still in the process of evolution. The major concerns related to land and water management included the extensive clearing of native bush for agriculture, eutrophication of surface water bodies, salinisation of land and water, soil erosion and degradation(51). Existing legislation allowed for the establishment of Land Conservation Districts, in which concerned landholders could, having identified the boundaries, request the Minister of Agriculture to appoint a Land Conservation Committee. However, this was not sufficient to prevent continuing degradation of natural resources.

In 1989, the state government issued a policy on integrated catchment management which stated that integrated catchment management should:

- include co-ordinated planning, use and management of water, land, vegetation and other natural resources on a river or groundwater catchment basis;
- involve landowners and local communities at all stages from identification of issues to planning and implementation;
- provide a co-ordinated government approach to complex resource management issues.

No new legislation was introduced to formalise integrated catchment management, since it was considered that existing legislation amongst the various government agencies was sufficient, and that improved co-ordination would be more effective. Integrated catchment management processes and structures have developed through learning and trial. Mitchell and Hollick(51) give a detailed review of the problems and successes associated with the development of integrated catchment management in Western Australia.

At a local level, Community Catchment Groups are being established, on a priority catchment basis, and these are the main mechanism for stakeholder involvement. Representation includes major stakeholder groups, local government and supporting government agencies. The Blackwood Community Catchment Group is a good example(52,53). The lead government agency, in this case the Office of Catchment Management, facilitates and guides the group through the process of identifying and prioritising issues, and developing a management plan(54), which includes objectives and a programme of action. In the case of the Blackwood catchment, funding has been granted by National Landcare to support the establishment of a secretariat and the appointment of a full-time catchment co-ordinator. Initially there was a lack of clarity and agreement on whether groups such as this would be only advisory bodies or whether they would be involved in making management decisions.

At state level, an inter-departmental committee, the Integrated Catchment Management Co-ordinating Group, deals with inter-agency implications, co-ordination of policies and collaboration. Representation is entirely from government agencies, and the Group is responsible to the Minister for the Environment. Responsibilities include:

- guidelines for financing of multi-agency initiatives;
- recommendations on government funding for integrated catchment management;
- review of legislation and institutional arrangements for implementation of integrated catchment management;
- consideration of appropriate power-sharing amongst stakeholders;
- research needs;
- development of performance indicators at state and catchment levels.

The Office of Catchment Management supports the Group's activities, taking a proactive role in the facilitation and implementation of integrated catchment management.

It has taken some time to arrive at a wider understanding of the process and products of integrated catchment management in Western Australia, but there is general agreement that the critical elements of the process are[(51)]:

- setting the boundaries; delineating catchment areas, including groundwater;
- identifying the environmental limits of different parts of the catchment environment, in particular very sensitive components;
- working closely with the local catchment community to see what objectives they have for development, and comparing these with environmental limits, and also the aspirations of the state-wide community, where appropriate;
- developing strategies to meet the objectives, primarily at the local level;
- encouraging community self-monitoring to measure changes and progress;
- involving the wider community, both in setting objectives and as a resource for labour, money and expertise; and
- auditing progress at the local and state level.

Although some notable successes have been achieved, such as planning for management of the Peel-Harvey system[25,55], the Blackwood catchment, and the Perth coastal region[56,57], the lack of legislation sometimes led to difficulties in clearly delineating the responsibility and authority of various government departments. Much of the success has been due to the intensive, long-term involvement of personnel of the lead government agencies in facilitating and establishing catchment groups, and the value of this contribution must not be under-estimated.

Recent recommendations for further implementation of integrated catchment management in Western Australia[51] are that integrated catchment management must be given credibility as a state policy through explicit political, administrative and financial commitment. The state government should publicly endorse integrated catchment management, issue a revised policy, and instruct chief executive officers of state departments and agencies to include integrated catchment management as a key component in their corporate plans and programmes.

It was also recommended that a three-year programme be established, with committed funding, to provide direction and specific objectives for advancement of integrated catchment management on a state-wide basis. The Integrated Catchment Management Co-ordinating Group should include representation from non-government groups. The role, power and authority of Community Catchment Groups in planning and decision-making must be clarified.

3.2.6 Integrated catchment management in the Murray-Darling Basin

The Murray-Darling Basin covers 1.06 million km^2, and a significant proportion of Australia's agricultural production is located within this area. The Murray-Darling river system runs through four different states: New South Wales, Victoria, South Australia and Queensland. Significant areas of the Basin are degraded as a result of land practices, water abstraction and discharges.[64] Typical problems include soil erosion, land and water salinisation, soil acidification and eutrophication of surface waters. In order to manage the natural resources of the Basin, a co-ordinated approach from the various state governments and national government is required. Similar problems arise in South Africa, where many river basins are shared across political or administrative boundaries, and the development of integrated management of the Murray-Darling Basin holds some lessons for this country.

New South Wales, Victoria and South Australia signed a water sharing agreement in 1914, and this has stood largely unchanged for the better part of the century.

However, the need to manage land and water quality led to the signing of the Murray-Darling Basin Agreement in 1988.[14] The objective of this agreement, between three states and the federal government, was to facilitate joint management of the Basin and its natural resources. This promotes the integration of policies and programs at political and bureaucratic levels, rather than simply at local or regional levels[65].

The management structure of the Murray-Darling Basin consists of:

- at the highest level, a Ministerial Council, who set broad policy on those issues requiring common action by member states. Council members are Ministers from the signatory governments, representing the land, water and environment departments. The charter of the Murray-Darling Basin Ministerial Council is to "promote and coordinate effective planning and management for the equitable, efficient and sustainable use of the land, water and environmental resources of the Murray-Darling Basin".
- The executive functions of management are carried out by the Murray-Darling Basin Commission, who see themselves as being accountable for the state of the natural resources in the Basin (Blackmore, personal communication). The Commission is made up of two representatives from each government, usually the heads of the departments which are responsible for land, water and environmental management.
- The Office of the Commission, situated in Canberra, provides technical support, undertakes operation of works, planning, investigations and technical programmes. The Office, which consists of about 40 people, is funded jointly by the signatory governments.
- A Community Advisory Committee represents regional, special and community interests. The role of this Committee is to advise the Ministerial Council on policy directions and regional issues.

Water sharing among the Basin states is now facilitated through a system of continuous water accounting. This provides the necessary water security for each state, but allows flexibility in the way in which they use their water allocations.

The salinity and drainage strategy[66] has been developed to manage the serious problems of land and water salinisation on a basin scale. Each member state is allocated tradable salt credits. Within their salt load allocation, each state may then develop strategies which best balance the needs of river protection with the needs for land management and drainage.

Most land in the Murray-Darling Basin is held by private owners, and hence implementation of any catchment management plan relies heavily on community commitment, involvement, knowledge and resources.[67] As part of the community participation program, Communities of Common Concern (CCCs) have been set up around the Basin (about 750 Landcare groups exist so far). These CCCs address issues of local concern, according to local priorities, within the framework of the management objectives for the Basin as a whole.

The size, function and responsibility of the CCCS is flexible, in order to deal with the different local issues. The role of the CCCs is to identify issues and problems, to develop plans for solving problems or managing land and water on a local basis, and to implement these plans. Government support for the CCCs is in the form of education, policy and legislative frameworks, research, funding, monitoring and review of plans.

3.3 The Role of National Landcare in Catchment Management at Community Level

National Landcare in Australia plays an important role in co-ordinated planning and in the implementation of plans for land and water management. The Landcare movement encourages the establishment of strong partnerships between government agencies and communities, and the development of Landcare has useful lessons which could be applicable for ICM in South Africa.

In the face of long-standing problems of land degradation, such as salinisation and soil erosion, small community Landcare groups were formed on a voluntary basis, under the guidance of conservation-oriented agencies, in the early 1980s. However, the extent of serious land degradation, and the substantial losses in agricultural production as a result of land degradation, as well as the consequent damage to natural resources, led to a joint submission to the Federal Government in 1989 by the National Farmers' Federation and the Australian Conservation Foundation[63], for the establishment of a national land management program.

This submission outlined a plan for setting up Landcare groups on a national basis, with co-ordination and support from national and state governments. The principles of the submission included:

- that partnerships for land management and rehabilitation should be formed, on a no-blame basis, rather moving forward from that time with a national approach;

- that it was necessary to have political support from all parties, and long term commitment to a partnership between government, landowners, communities and also aboriginal people living on tribal lands;
- that a regulatory approach would be discouraged in favour of a long term but voluntary approach to solving problems of land degradation.

The program of action for establishing National Landcare included several steps:

1. The setting up of local Landcare groups, on a priority basis. These should be integrated with existing community groups, and should be representative of all land users (including representation from users or managers of public lands). Although the groups should be encouraged to become self-funding as soon as possible, government support initially should include funding for secretariat and co-ordination functions, administration and communication. An amount of A$2500 per year, for each group, was proposed to assist the groups in their initial stages.
2. The development of property plans, for management of private land in a way that would be consistent with catchment or regional plans.
3. Technical support structures for information dissemination and training, direct government funding of projects and training programs.
4. Tax rebates for the cost of works established as part of approved land management plans.
5. Incentives for conservation farming practices.
6. Administrative support from the state in developing and approving plans.
7. National assessment of priority land degradation areas.
8. Development of legislation to support land management, as appropriate.
9. Education and awareness programs aimed at both rural and metropolitan residents.

National Landcare developed from being focused primarily on agricultural land, to encompassing broader principles of management of natural resources. This arose naturally because of the link between land and water processes within catchments: land practices were often dependent on the state of water resources, yet land practices also influenced the state of water resources. Several other related programs were amalgamated under the National Landcare umbrella, which encouraged the "whole systems" approach to natural resources management. These programs included the National Soil Conservation Program, the Federal Water Resources Assistance Program, Save the Bush, One Billion Trees and the Murray-Darling Basin Natural Resources Management Strategy.[59]

The principal components of National Landcare are:

- Community Landcare groups. These are local groups, representative of land users, who are responsible for planning, promoting and implementing land and water rehabilitation programs. In the larger context, the role of the groups is also to generate commitment to sustainable natural resource use at a local level. Approximately 20% of farmers are now involved in Landcare groups or group activities.
- The State component. State governments are responsible for strategy development, for integration of Landcare strategies with economic development planning, for funding and action.
- The National component. National government is responsible for monitoring, evaluation and review of Landcare activities; for policy development, investigation and trials, communication and awareness, and dissemination of information.
- A National Landcare Facilitator, whose role is to encourage collaboration between the states in monitoring and evaluation, to develop strategies to improve the effectiveness of Landcare groups, to ensure liaison, communication and awareness, and to develop proposals for future directions in Landcare.(62)
- The National Decade of Landcare Plan(61), the objective of which is to manage natural resources so as to improve their productivity and to enhance their ability to support economic development.
- City Landcare, which aims to broaden awareness of land use and catchment management amongst urban dwellers. Objectives include improvement of the environment in urban areas, and establishment of links between urban and rural Landcare groups.(58)
- Links to many other community programs such as Waterwatch(60), and research programs such as the river health initiatives.

Landcare is intended to provide incentives and a framework at local level for understanding problems, identifying and acquiring the information and skills to develop practical, locally-suited solutions to problems of natural resources management. The philosophy and ideas on which Landcare has been based could be very valuable for implementation of ICM at a community level.

One of the primary reasons for the phenomenal success and growth of Landcare in Australia has been that Landcare is not politically oriented in any way. There is widespread support for the principles and activities of Landcare across all political groups, and within all government departments (Farley, personal communication). The Federal government has provided commitment and financial support, and has undertaken to review all policies and programs so that they are consistent with Landcare objectives, and so that economic development meets the requirements for protection and management of the natural resource base.

A recommendation has been made[62] that in the future, a resource economics approach should be applied, to investigate the costs and benefits of implementing natural resources management or rehabilitation plans, against the costs of degradation of the natural resource base. This would form the basis for determining an appropriate level of national and state expenditure on programs such as Landcare.

4. SUMMARY OF AUSTRALIA'S EXPERIENCE

4.1 Separation of Commercial and Non-Commercial Water Sectors

The functions of water supply and sanitation provision are being separated from the non-commercial function of catchment and waterway management, unless it is more practical not to do so on a local basis. Water authorities and supply boards are being regionalised (for greater efficiency and economy of scale) and commercialised (as opposed to privatised). The supply agencies thus become a bulk users of water and/or dischargers, subject to the same licensing procedures as other catchment stakeholders or impacters. Metropolitan water supply agencies will be allocated a bulk water entitlement, which they in turn allocate to domestic and industrial consumers. Rural water boards will further partition their bulk entitlement to agricultural and rural domestic users. Legally defensible water entitlements will be granted to the environment. Bulk water entitlements will be tradable, at real market-related prices.

Catchment and waterway management remains the responsibility of the EPA and relevant government departments, such as Water Resources, Agriculture, Environment.

4.2 Catchment and Waterway Management

Impacts in catchments can broadly be grouped into:

- point sources;
- diffuse sources and the impacts of land use or land degradation; and
- degradation of the instream and riparian environment.

The most urgent and potentially damaging issues facing the rural Australian sector are salinisation and nutrient enrichment of water resources. Salinisation arises from two principal causes:

- dryland salinity, which is related to the clearing of deep-rooted forests for agriculture or commercial wood harvesting;
- irrigation salinity, which occurs when irrigation leads to a rise in the water table, bringing very saline groundwater to the land surface.

Nutrient enrichment is a result of leaching of agricultural fertilisers, discharge of sewage effluents, runoff from agricultural land, and uncontrolled access to water bodies by stock animals. In such cases, water resources management is very closely tied to land management. The problems can only be solved by changes in land use practices at a very local level.

Point source discharges are subject to control by the EPA, who issue works approvals (permits). The criteria for discharge to the water environment are generally site-specific, though subject to certain minimum industry or State standards. Criteria would be based on receiving environment objectives for the local area in question. In many catchments, these objectives would have been set after negotiation amongst stakeholders, through a catchment board or committee.

Land use impacts and degradation of the instream environment might be related to industrial or urban development, which would be subject to control by the EPA or a government department. Where land use impacts arise from agricultural or forestry practices, then a much stronger emphasis is placed on community-based management and action.

A lead government agency, which may be a department responsible for water resources, environment or agriculture, usually takes the initiative in identifying problems through monitoring. The lead agency then plays a critical role in initiating discussions with stakeholders in the catchment and establishing a catchment committee or board, which is representative of the interest in the catchment.

The committee, under the guidance of the lead government agency, will usually begin by focusing on a priority problem, such as salinity or algal blooms. Again with guidance and technical support from a number of government agencies, the committee will develop long term objectives, a strategy and an action plan for dealing with the problem. The initial focus on a priority problem creates cohesion in the group, and ensures that people get involved because they have a real interest in the outcome. As capacity is developed in the committee or group, they can then go on to address other issues in the catchment through the same process, and again with support from the government agencies.

The EPA and supporting government agencies provide the committees with a broader context for development of catchment plans: the objectives and plan for the catchment do need to fit within wider state and national interests. Once the objectives and plan have been developed, statutory support is provided by the EPA, who gazette the objectives, responsibilities and roles of the various agencies and stakeholders in a State Environment Protection Policy paper (SEPP). The SEPPs are catchment-specific, and subject to review every ten years or so. The EPA or a delegated agency is responsible for monitoring and assessing progress towards the achievement of objectives.

The catchment committees are formally constituted bodies, but have very little statutory power themselves: enforcement is still the role of EPA or a government department. The committees have more of a planning function. The lead government agencies provide a very strong "extension service", in their role of technical guidance and support. They may also provide funding for initial scientific/technical investigations, and for the running costs incurred by the committee (such as travel and secretariat).

The extent of the initial priority problem or issue may determine the extent of responsibility which is taken up by a catchment committee, and also the geographical boundaries of responsibility. These are fairly flexible. Sub-catchment committees can later be co-ordinated under a larger catchment committee or forum.

Once an action plan has been developed, it then remains for individual landowners to implement the relevant land use practices (such as replanting deep-rooted trees, installing drainage, irrigation management). Here the Australian approach is to rely on voluntary compliance, rather than "command and control". It is considered that voluntary compliance, as a form of self-regulation, is more acceptable in Australian society, and also more cost-effective, since fewer resources are required to monitor and enforce compliance.

Self-regulation is admittedly not 100 % successful, but is widely encouraged through community groups such as Greening Australia and Landcare. National Landcare appears to be the key to achieving success in changing land use practices: farmers or groups can apply for grant funding or tax incentives to assist them in implementing on-farm management which complements the catchment plan. Excellent technical and educational support is also provided. (Urban Landcare is now in the early stages of development).

5. IMPLICATIONS FOR INTEGRATED CATCHMENT MANAGEMENT IN SOUTH AFRICA, BASED ON AUSTRALIAN EXPERIENCE

5.1 General Principles

Some general principles related to integrated catchment management can be distilled from the Australian experience[15]. The most important is that land and water degradation, and the subsequent impacts on land and water users, usually transcend property boundaries. This means that co-ordinated planning and action is required at all levels, from national government to the individual. The most important principles are:

- Institutional arrangements, the structure and role of catchment committees must be flexible, allowing for varying social structures and issues.
- The government's role in integrated catchment management in Australia tends to remain within the co-ordination of skills and skills transfer, provision of technical advice and support, and provision of funding for local groups or individuals.
- Technical and scientific experts must recognise landholders and stakeholders as competent partners in resource management.
- Successful implementation of ICM depends on sound long term relationships, goodwill and trust amongst the people and agencies involved. Restructuring of government agencies and promulgation of legislation will never be sufficient to ensure success. Long term continuity and commitment from lead agencies is also essential.
- Adequate financial and human resources must be provided on a long-term basis, or else integrated catchment management cannot be implemented successfully.
- The catchment community should be defined by a common interest or a clear environmental variable such as soil type. For land use action, catchment communities can be defined in social terms rather than necessarily in geographic or hydrological terms.
- Expectations and goals must be defined in realistic short to medium terms, but integrated catchment management must be recognised as a long term process, requiring continuity of support from government agencies.

Mitchell and Hollick set out suggested building blocks for integrated catchment management, and it is worth quoting them here in full[51].

"The building blocks for integrated catchment management should be:

1. A systems approach, in which attention is directed toward both human and natural systems, their component parts, and the inter-relationships among those parts. To be consistent with this approach, the management unit should be the one that highlights linkages. This will often, but not automatically, lead to the catchment or river basin being the appropriate planning and management unit.
2. An integrated approach rather than a comprehensive approach, in which attention is directed to key issues and variables identified through consultation with stakeholders and to the linkages among key issues and variables. In contrast, in the comprehensive approach, attention is given to all issues and variables.
3. A stakeholder approach, in which it is recognised that citizens and non-government groups should be able to participate in decisions about what ought to be, what can be, and what will be for an area.
4. A partnership approach, in which it is recognised that state agencies, local government organisations and individuals each have a role. This requires a search for common objectives, decisions at the outset about the relative roles and powers of state agencies, local governments and citizens, and identification of mechanisms that will be used to make decisions when conflicts arise.
5. A balanced approach, in which attention is directed to weighing concern about enhancing economic development, protecting the integrity of natural systems, and satisfying social norms and values."

5.2 Implications for Integrated Catchment Management in South Africa

The general model for integrated catchment management as practised in Australia rests heavily on the acceptance of individual or group responsibility by communities, with as little "top-down" governance as possible. This model works for the management of impacts of land use, for both private and public land. Integrated catchment management in Australia relies on not decoupling land resources management from water resources management. This would be difficult to implement fully in South Africa while so many inter-agency and inter-department boundaries exist, at national and provincial levels, and while there is considerable fragmentation of responsibility for natural resources management. The lack of consistent national and regional policy in South Africa also adds to the problem.

The Australian model would be applicable for water quality management on a catchment basis in South Africa, but may well fail when there is a need to resolve issues of water allocation, whether these are directly linked to water quality issues or not. Water allocation is a politically sensitive issue, at various levels, and it may be that a catchment management system based on partnership and consensus-seeking will not be adequate for water allocation decisions in South Africa at this time. The responsibility, accountability and authority for water allocation, in the context of implementation of integrated catchment management, need to be carefully considered.

The trend in Australia is to separate water supply functions from catchment and waterway management functions. Water supply agencies are seen as bulk users of water. The future role of water boards and irrigation boards in integrated catchment management in South Africa must be clarified. Conflict of interest is likely if commercialised or corporatised water supply agencies, as primary resource users, are also entrusted with responsibilities related to the development, allocation and management of resources. They can, however, provide certain technical functions such as operation of works, monitoring of resources and demand, education, communication and awareness programmes.

The fact that, in Australia, statutory and regulatory power remains primarily in the hands of a government agency may help to prevent misuse of that power to promote local interests above provincial or national interests. That, and the emphasis on extension and supporting services supplied by government agencies, may be a valuable lesson for South Africa, at least in so far as rural catchments are concerned.

If catchment authorities are granted statutory powers, then along with that power goes responsibility and accountability. To discharge responsibility adequately requires expertise, skill and judgement. Whether South Africa has, at the present time, sufficient expertise and skill at the local level, which can be utilised in catchment authorities, is very doubtful. The model of catchment committees with strong planning functions, supported by government agency personnel providing technical guidance, facilitation, statutory and regulatory functions may be more resource- and cost-efficient at this stage of our development.

The Australian model for catchment community groups is dependent on a high level of skill in the lead government agencies, especially in facilitation, co-ordination, negotiation and provision of technical advice. These skills would need to be available in the regional office of DWAF and related government departments. Capability would be required at national level to co-ordinate integrated catchment management policy and approaches, to provide support, funding, skills transfer and training.

An issue which has not been resolved in Australia will also need to be addressed in South Africa, and that is the constitutional right of an individual landholder to manage his land freely, versus protection of the public good.

5.3 Discussion Points for Development of Legislation Options

The following are intended to serve as points of departure for discussion on adoption of an integrated catchment management model which is similar to that used in Australia:

1. The introduction of new legislation, new agency structures or prescriptive institutional arrangements should be minimised at this stage, since we are still in the early stages of a learning process, and because the integrated catchment management philosophy is founded on flexibility and adaptability. Legislation and regulation should follow the integrated catchment management process, rather than attempt to lead it too strongly.

2. The revised Water Act should allow the Minister to issue regulations on a catchment-specific basis, regarding
   - the geographical boundaries of a catchment,
   - resource management objectives for the catchment,
   - the nature of the process of developing a catchment management plan,
   - agency and stakeholder responsibilities for implementation,
   - authority, accountability and legal status of the catchment board or committee,
   - conflict resolution processes,
   - monitoring, auditing and reporting requirements and responsibilities, and
   - the time scale and process for review of regulations.

3. An umbrella national policy on integrated catchment management should be considered, which is supported by all appropriate government departments, and which is incorporated in the planning functions of all departments and agencies at national and regional level. Inter-department co-ordination on resource management issues at national, provincial and local level should be supported as a matter of policy.

4. In order to ensure successful implementation of integrated catchment management approaches, there should be a clear long-term commitment from

government to support integrated catchment management with financial and manpower resources.

5. Clear policy guidance will be required on the use in integrated catchment management of instruments such as water quality guidelines, emission standards, environmental impact assessments.

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APPENDIX 2

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Water Research Commission

and

Department of Water Affairs and Forestry
(Water Law Review: Institutional Arrangements Task Team)

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Year Published: 1995
Report Number: EPA 841-R-95-003

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Main Title: Watershed protection a statewide approach.
Publisher: U.S. EPA, Office of Wetlands, Oceans, and Watersheds.
Year Published: 1995
Report Number: EPA 841-R-95-004

Accession Number: 231829
Main Title: Why watersheds?
Publisher: U.S. Environmental Protection Agency, Office of Water.
Year Published: 1996
Report Number: EPA800-F-96-001

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Main Title: Watershed protection approach 1993/94 activity report.
Publisher: U.S. Environmental Protection Agency, Office of Water.
Year Published: 1994
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Publisher: U.S. Environmental Protection Agency,
Year Published: 1994
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Main Title: Texas Rural Water Quality Network Project : challenge of the colonias, small community wastewater management in the Lower Rio Grande Valley.
Corporate Author: Texas. Dept. of Agriculture.; National Demonstration Water Project (U.S.)
Publisher: Texas Dept. of Agriculture : National Demonstration Water Project,
Year Published: 1986

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Main Title: Water resources for the future : Michigan's action plan.
Corporate Author: Great Lakes and Water Resources Planning Commission.
Publisher: The Commission
Year Published: 1987

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Corporate Author: Great Lakes and Water Resources Planning Commission.
Publisher: The Commission
Year Published: 1987

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Main Title: Water resources for the future Michigan's draft action plan.
Corporate Author: Great Lakes and Water Resources Planning Commission.
Publisher: The Commission
Year Published: 1987

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Main Title: Analysis of Regional Lake Water Quality Patterns: Implications for Lake Resource Management in Minnesota.
Personal Author: Heiskary, S.A.; Wilson, C.B.; Larsen, D.P.
Corporate Author: Corvallis Environmental Research Lab., OR.; Minnesota Pollution Control Agency, Roseville., Division of Water Quality.
Year Published: 1987
Call Number: PB87-188157
Report Number: EPA/600/D-87/010

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Main Title: Statement of policy and by-laws 1988-1989.
Corporate Author: Interstate Conference on Water Policy.
Publisher: Interstate Conference on Water Policy
Year Published: 1989

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Main Title: Water values and markets emerging management tools : a special report.
Publisher: Freshwater Foundation / Freshwater Society
Year Published: 1986

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Main Title: Water resources for the future Michigan's action plan.
Publisher: Great Lakes and Water Resources Planning Commission
Year Published: 1987

Accession Number: 159522
Main Title: Progress in the National Estuary Program: Report to Congress.
Corporate Author: Environmental Protection Agency, Washington, DC., Office of Marine and Estuarine Protection.
Year Published: 1990
Call Number: PB91-168385
Report Number: EPA/503/9-90/005

Accession Number: 166731
Main Title: Water resources in Pennsylvania availability, quality, and management.
Publisher: Pennsylvania Academy of Science
Year Published: 1990

Accession Number: 173590
Main Title: EPA/State management conference agreement
Corporate Author: Galveston Bay National Estuary Program.
Publisher: s.n.
Year Published: 1989

Accession Number: 182165
Main Title: U.S.-Canada transboundary resource issues
Year Published: 1986

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Main Title: Protecting the Nation's Wetlands, Oceans, and Watersheds: An Overview of Programs and Activities.
Corporate Author: U.S. EPA, Washington, DC., Office of Wetlands, Oceans and Watersheds.
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Call Number: PB93-105609
Report Number: EPA/840/S-92/001

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Main Title: Coordinating water resources in the federal system the groundwater-surface water connection.
Personal Author: Blomquist, William A.
Publisher: U.S. Advisory Commission on Intergovernmental Relations
Year Published: 1991
Report Number: A-118

Accession Number: 184240
Main Title: Water resources people and issues interview with
Gilbert F. White.
Personal Author: White, Gilbert F.
Publisher: Office of History, U.S. Army Corps of Engineers
Year Published: 1992

Accession Number: 185804
Main Title: Tribal water utility management
Publisher: United States Environmental Protection Agency, Office of Water
Year Published: 1993
Report Number: EPA 812-B-93-005

Accession Number: 187830
Main Title: Regional Nonpoint Source Program Summary.
Personal Author: Edwards, R.; Partee, G.; Fleming, F.
Corporate Author: Environmental Protection Agency, Chicago, IL., Water Div.
Year Published: 1992
Call Number: PB93-169134
Report Number: EPA/910/9-91/035

Accession Number: 192911
Main Title: National Estuary Program Guidance. Comprehensive Conservation and Management Plans: Content and Approval Requirements.
Corporate Author: Environmental Protection Agency, Washington, DC., Office of Water.
Publisher: Oct 92
Year Published: 1992
Call Number: PB93-217172
Report Number: EPA/842/B-92/002

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Main Title: Institutional arrangements for areawide water resources management planning in the Washington DC region under the Federal Water Pollution Control Act amendments of 1972
Personal Author: Lieber, Harvey.
Corporate Author: University of the District of Columbia. Water Resources Research Center.
Publisher: Water Resources Research Center, University of the District of Columbia

Year Published:	1980
Accession Number:	?
Main Title:	Groundwater quality protection policies for the Rocky Mountain Region and the nation : transcript of a conference.
Corporate Author:	Environmental and Energy Study Institute.; Colorado Water Resources Research Institute.
Publisher:	Colorado Water Resources Reseach Institute, Colorado State University,
Year Published:	1986
Accession Number:	221359
Main Title:	EPA Nonpoint Source Strategy.
Corporate Author:	Environmental Protection Agency, Washington, DC., Office of Water.
Publisher:	Feb 85
Year Published:	1985
Call Number:	PB95-194379
Accession Number:	164018
Main Title:	General Proceedings and Action Agendas from the U.S. Environmental Protection Agency's National Leadership Conference on Building Public-Private Partnerships. Held in Washington, DC. on October 26, 1988.
Corporate Author:	Environmental Protection Agency, Washington, DC., Resource Management Div.
Year Published:	1989
Call Number:	PB91-219584
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Main Title:	Public participation and remedial action plans an overview of approaches, activities and issues arising form RAP coordinator's forums.
Publisher:	International Joint Commission, Great Lakes Regional Office,
Year Published:	1990
Accession Number:	216050
Main Title:	Working for Clean Water: An Information Program for Advisory Groups. Public Participation. Citizen Handbook.
Corporate Author:	Pennsylvania State Univ. Capitol Campus, Middletown.;Environmental Protection Agency, Washington, DC. Office of Water.
Year Published:	1995
Call Number:	PB95-157244
Accession Number:	221207
Main Title:	Working for Clean Water: An Information Program for Advisory Groups. 1. Citizen Handbooks.
Personal Author:	Stoltzfus, L.C.
Corporate Author:	Ohio State Univ., Columbus. SMEAC Information Reference Center.; Environmental Protection Agency, Washington, DC. Office of Water.
Year Published:	1995
Call Number:	PB95-156048
Accession Number:	221208
Main Title:	Working for Clean Water: An Information Program for Advisory Groups. Role of Advisory Groups. Citizen Handbook.
Corporate Author:	Pennsylvania State Univ. Capitol Campus, Middletown. Inst. of State and Regional Affairs.;Environmental Protection Agency, Washington, DC. Office of Water.
Year Published:	1995
Call Number:	PB95-156055

Accession Number:	221214
Main Title:	Working for Clean Water: An Information Program for Advisory Groups. Public Participation. Instructor Guide.
Personal Author:	Buskirk, E.D.; Auker, D.
Corporate Author:	Pennsylvania State Univ. Capitol Campus, Middletown. Inst. of State and Regional Affairs.; Environmental Protection Agency, Washington, DC. Office of Water.
Year Published:	1995
Call Number:	PB95-156113

Section 2 : Examples of Watershed Management Plans

Accession Number:	82553
Main Title:	Western branch river subbasin low flow management framework plan /
Personal Author:	Heicher, David W.
Publisher:	Susquehanna River Basin Commission,
Year Published:	1989

Accession Number:	129348
Main Title:	Waimea-Paauilo watershed, Hawaii County, Hawaii watershed plan and environmental assessment.
Publisher:	U.S. Dept. of Agriculture, Soil Conservation Service
Year Published:	1989

Accession Number:	131335
Main Title:	Salinity control on BLM-administered public lands in the Colorado River Basin a report to Congress.
Corporate Author:	United States Bureau of Land Management.
Publisher:	The Bureau
Year Published:	1987

Accession Number:	133622
Main Title:	Water resources Corps of Engineers' drought management of Savannah River projects; report to the honorable Butler Derrick, House of Representatives.
Corporate Author:	United States. General Accounting Office.
Publisher:	The Office
Year Published:	1989

Accession Number:	150714
Main Title:	Clean Lakes Program Phase 2 Project. Report for Lake Le-Aqua-Na Stephenson County, Illinois.
Corporate Author:	Illinois State Environmental Protection Agency, Springfield. Div. of Water Pollution Control.
Year Published:	1990
Call Number:	PB91-123323
Report Number:	IEPA/WPC/90-296

Accession Number:	159207
Main Title:	Buffalo-Trempealeau River water quality management plan
Corporate Author:	Wisconsin. Dept. of Natural Resources.
Publisher:	The Department
Year Published:	1991

Accession Number:	161742
Main Title:	Manitowoc River Basin water quality management plan a five-year plan to enhance and protect our water resources.
Corporate Author:	Wisconsin. Dept. of Natural Resources.
Publisher:	Dept. of Natural Resources
Year Published:	1991

Accession Number:	163426
Main Title:	Lower Chippewa River Basin water quality management plan
Corporate Author:	Wisconsin. Dept. of Natural Resources.
Publisher:	The Department
Year Published:	1989

Accession Number:	167946
Main Title:	Watershed Nitrogen Management: Upper Potomac River Basin Case Study.
Personal Author:	Groffman, P.M.; Jaworski, N.A.
Corporate Author:	Environmental Research Lab., Narragansett, RI.; Rhode Island Univ., Narragansett.; Chesapeake Research Consortium, Inc., Baltimore, MD.
Year Published:	1990
Call Number:	PB92-108083
Report Number:	EPA/600/D-91/233; ERLN-1255

Accession Number:	169043
Main Title:	Upper Susquehanna subbasin low flow management framework plan.
Personal Author:	Heicher, David W.
Publisher:	Susquehanna River Basin Commission,
Year Published:	1991

Accession Number:	190360
Main Title:	Massachusetts Bays program progress 1990.
Publisher:	Massachusetts Bays Program
Year Published:	1990

Accession Number:	192641
Main Title:	Regulatory Effectiveness Study for the Armand Bayou Coastal Preserve.
Personal Author:	Mitchell, G.; Windsor, D.
Corporate Author:	Galveston Bay National Estuary Program,, Austin, TX.; Jesse H. Jones Graduate School of Administration, Houston, TX.; Environmental Protection Agency, Washington, DC.
Year Published:	1991
Call Number:	PB93-205680
Report Number:	GBNEP-13

Accession Number:	192642
Main Title:	Regulatory Effectiveness Study for the Christmas Bay Coastal Preserve.
Personal Author:	Mitchell, G.; Windsor, D.
Corporate Author:	Galveston Bay National Estuary Program,, Austin, TX.; Jesse H. Jones Graduate School of Administration, Houston, TX.; Environmental Protection Agency, Washington, DC.
Year Published:	1991
Call Number:	PB93-205698
Report Number:	GBNEP-14

Accession Number:	196490
Main Title:	Chesapeake Bay Executive Council Directive: Fish Passage Goals.
Corporate Author:	Environmental Protection Agency, Annapolis, MD. Chesapeake Bay Program.
Year Published:	1993
Call Number:	PB94-110152

Accession Number:	199070
Main Title:	Water quality standards for salinity, Colorado River system final report.
Publisher:	The Forum
Year Published:	1993

Accession Number:	204860
Main Title:	Watershed Planning in the Albemarle-Pamlico Estuarine System. Report 1. Annual Average Nutrient Budgets.
Personal Author:	Dodd, R.C.; McMahon, G.; Stichter, S.
Corporate Author:	Research Triangle Inst., Research Triangle Park, NC. Center for Environmental Analysis; Geological Survey, Raleigh, NC.;North Carolina Dept. of Environment,

	Health, and Natural Resources, Raleigh. Albemarle-Pamlico Estuarine Study.; Environmental Protection Agency, Washington, DC.
Year Published:	1992
Call Number:	PB94-173366
Report Number:	APES-4873-03; APES-92-10

Accession Number:	204972
Main Title:	Comprehensive Environmental Management Plan for the Currituck Sound Drainage Basin: Background Investigations.
Personal Author:	Rideout, R.R. ;
Corporate Author:	North Carolina Dept. of Environment, Health, and Natural Resources, Raleigh. Albemarle-Pamlico Estuarine Study; North Carolina State Univ. at Raleigh. Dept. of Forestry.; Environmental Protection Agency, Washington, DC.
Year Published:	1990
Call Number:	PB94-181625
Report Number:	APES-90-19

Accession Number:	205025
Main Title:	North Carolina's Estuaries: A Pilot Study for Managing Multiple Use in the State's Public Trust Waters.
Personal Author:	Clark, W.F.; Edgerton, C.R.
Corporate Author:	North Carolina State Univ. at Raleigh. Sea Grant Coll. Program.;North Carolina Dept. of Environment, Health, and Natural Resources, Raleigh. Albemarle-Pamlico Estuarine Study.
Year Published:	1990
Call Number:	PB94-183530
Report Number:	APES-90-10

Accession Number:	205731
Main Title:	Ground-water management plan
Corporate Author:	Susquehanna River Basin Commission.
Publisher:	Susquehanna River Basin Commission
Year Published:	1993

Accession Number:	206322
Main Title:	Restoration of the Anacostia River the report to Congress.
Publisher:	Printed by the U.S. Environmental Protection Agency for the Chesapeake Bay Program
Year Published:	1992
Report Number:	CBP/TRS 79/92

Accession Number:	210640
Main Title:	1994 Columbia River Basin Fish and Wildlife Program overview.
Publisher:	Northwest Power Planning Council
Year Published:	1994

Accession Number:	210679
Main Title:	Evaluation of watershed quality in the Minnesota River basin
Personal Author:	Arthur, John W.
Publisher:	Environmental Research Laboratory - Duluth, Office of Research and Development, U.S. Environmental Protection Agency
Year Published:	1994
Report Number:	EPA/600/R-94/143

Accession Number:	210902
Main Title:	Seeking an integrated approach to watershed management in the South Platte Basin October 27-28, 1993, University Park Holiday Inn, Fort Collins, Colorado.

Publisher: Colorado Water Resources Research Institute, Colorado State University
Year Published: 1993

Accession Number: 210903
Main Title: Defining ecological and sociological integrity for the South Platte River Basin
Publisher: Colorado Water Resources Research Institute
Year Published: 1993

Accession Number: 211513
Main Title: Water availability, use, and estimated future water demand in the upper Duck River basin, middle Tennessee
Personal Author: Hutson, Susan S.
Publisher: U.S. Dept. of the Interior, U.S. Geological Survey
Year Published: 1993

Accession Number: 211831
Main Title: Environmental Management Program for the Hampton Roads Virginia Portion of the Albemarle-Pamlico Estuarine Watershed.
Corporate Author: Hampton Roads Planning District Commission, VA.; North Carolina Dept. of Environment, Health, and Natural Resources, Raleigh. Albemarle-Pamlico Estuarine Study.; Environmental Protection Agency, Research Triangle Park, NC.; National Estuary Program.
Year Published: 1993
Call Number: PB95-106811
Report Number: A/P-92-19; APES-92-19

Accession Number: 211837
Main Title: Watershed Planning in the Albemarle-Pamlico Estuarine System. Report 6 - Use of Information Systems for Developing Subbasin Profiles.
Personal Author: Dodd, R.C.; Cunningham, P.A.; Curry, R.J.; Stichter, S.J.
Corporate Author: Research Triangle Inst., Research Triangle Park, NC.; North Carolina Dept. of Environment, Health, and Natural Resources, Raleigh. Albemarle-Pamlico Estuarine Study.; Environmental Protection Agency, Research Triangle Park, NC.; National Estuary Program.
Year Published: 1993
Call Number: PB95-109484
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Accession Number: 213251
Main Title: Opportunities for action an evolving plan for the future of the Lake Champlain Basin : pollution prevention, control & restoration plan : draft.
Publisher: Lake Champlain Basin Program
Year Published: 1994

Accession Number: 215900
Main Title: River and Watershed Planning: The San Luis Rey River Case Study.
Personal Author: Micheli, E.
Corporate Author: California Univ., Berkeley.; Corvallis Environmental Research Lab., OR.
Year Published: 1994
Call Number: PB95-155826
Report Number: EPA/600/R-94/213

Accession Number: 219586
Main Title: Integrated watershed management in the South Platte Basin status and practical implementation : October 26-27, 1994, Ramkota Inn, Greeley, Colorado.
Publisher: Colorado Water Resources Research Institute, Colorado State University,
Year Published: 1994

Accession Number: 223377
Main Title: Report on the Potomac River Watershed Visions Project.
Corporate Author: Potomac River Watershed Visions Project.
Publisher: Interstate Commission on the Potomac River Basin
Year Published: 1994

Accession Number: 226393
Main Title: Monitoring Program to Assess Environmental Changes in Tampa Bay, Florida.
Personal Author: Squires, A.; Janicki, A.; Heimbuch, D.; Wade, D.; Wilson, H.
Corporate Author: Coastal Environmental, Inc., St. Petersburg, FL.; Tampa Bay National Estuary Program, St. Petersburg, FL.
Year Published: 1994
Call Number: PB95-260907
Report Number: TBNEP-T-92-02; TBNEP-02-93

Accession Number: 229515
Main Title: Controlling salinity in the Colorado River Basin
Publisher: s.n.
Year Published: 1989

Accession Number: 233384
Main Title: National Water-Quality Assessment Program the upper Tennessee River Basin.
Personal Author: Hampson, Paul S.
Publisher: U.S. Dept. of the Interior, U.S. Geological Survey
Year Published: 1995

Accession Number: 233441
Main Title: Merrimack Project a cooperative effort of the United States Environmental Protection Agency, the Commonwealth of Massachusetts, the state of New Hampshire.
Publisher: U.S. Environmental Protection Agency, Office of Water
Year Published: 1995
Report Number: EPA 820-R-95-004

Accession Number: 75346
Main Title: Voluntary basinwide water management : South Platte River Basin, Colorado
Personal Author: Caulfield, Henry P.
Corporate Author: Colorado Water Resources Research Institute.
Publisher: The Institute
Year Published: 1987

Accession Number: 122579
Main Title: Initial remedial action plan for the Rouge River basin.
Corporate Author: Southeast Michigan Council of Governments.
Year Published: 1987

Accession Number: 122788
Main Title: Remedial action plan for the Rouge River Basin draft.
Corporate Author: Southeast Michigan Council of Governments.
Publisher: The Council
Year Published: 1988

Accession Number: 159253
Main Title: Upper Wisconsin River northern sub-basin water quality management plan prepared by the Wisconsin Dept. of Natural Resources.
Corporate Author: Wisconsin. Dept. of Natural Resources.
Publisher: The Department
Year Published: 1991

Accession Number: 161742
Main Title: Manitowoc River Basin water quality management plan a five-year plan to enhance and protect our water resources.
Corporate Author: Wisconsin. Dept. of Natural Resources.
Publisher: Dept. of Natural Resources
Year Published: 1991

Accession Number: 163426
Main Title: Lower Chippewa River Basin water quality management plan.
Corporate Author: Wisconsin. Dept. of Natural Resources.
Publisher: The Department
Year Published: 1989

Accession Number: 167857
Main Title: Chester river basin water quality management plan.
Publisher: Dept. of Health and Mental Hygiene
Year Published: 1987

Accession Number: 167946
Main Title: Watershed Nitrogen Management: Upper Potomac River Basin Case Study.
Personal Author: Groffman, P.M.; Jaworski, N.A.
Corporate Author: Environmental Research Lab., Narragansett, RI.; Rhode Island Univ., Narragansett.; Chesapeake Research Consortium, Inc., Baltimore, MD.
Year Published: 1990
Call Number: PB92-108083
Report Number: EPA/600/D-91/233; ERLN-1255

Accession Number: 168603
Main Title: Water resources Corps' management of ongoing drought in the Missouri River Basin : report to Congressional requesters.
Corporate Author: United States. General Accounting Office.
Publisher: The Office
Year Published: 1992
Report Number: GAO/RCED-92-4 B-241794

Accession Number: 192727
Main Title: Clark-Fork-Pend Oreille Basin Water Quality Study: A Summary of Findings and a Management Plan.
Corporate Author: Environmental Protection Agency, Seattle, WA. Region X.
Year Published: 1993
Call Number: PB93-208148
Report Number: EPA/910/R-93/006

Accession Number: 222969
Main Title: Water quality information on salinity control projects in the Colorado River Basin : statement of James Duffus, III, Director, Natural Resources Management Issues, Resources, Community, and Economic Development Division, before the Subcommittee on Water and Power Resources, Committee on Resources, House of Representatives.
Personal Author: Duffus, James.
Publisher: The Office
Year Published: 1995

Accession Number: 120001
Main Title: Cape Cod Aquifer Management Project (CCAMP).
Personal Author: Zoto, G.A.; Gallagher, T.

Corporate Author:	Environmental Protection Agency, Boston, MA. Region I.; Geological Survey, Boston, MA. Water Resources Div.; Massachusetts Dept. of Environmental Quality Engineering, Boston.; Cape Cod Planning and Economic Development Commission, Barnstable, MA.
Year Published:	1988
Call Number:	PB89-106298
Report Number:	EPA/901/3-88/006
Accession Number:	121377
Main Title:	Cape Cod Aquifer Management Project (CCAMP) : Institutional Recommendations.
Corporate Author:	Massachusetts Dept. of Environmental Quality Engineering, Boston.; Environmental Protection Agency, Boston, MA. Region I.; Geological Survey, Boston, MA. Water Resources Div.; Cape Cod Planning and Economic Development Commission, Barnstable, MA.
Year Published:	1988
Call Number:	PB89-140024
Accession Number:	121660
Main Title:	Cape Cod Aquifer Management Project (CAMP). Executive Summary.
Corporate Author:	Environmental Protection Agency, Boston, MA. Region I.; Geological Survey, Boston, MA. Water Resources Div.; Massachusetts Dept. of Environmental Quality Engineering, Boston.; Cape Cod Planning and Economic Development Commission, Barnstable, MA.
Year Published:	1988
Call Number:	PB89-155782
Report Number:	EPA/901/3-88/003
Accession Number:	132588
Main Title:	Chesapeake Bay Annual Workplan, 1989.
Corporate Author:	Environmental Protection Agency, Annapolis, MD. Chesapeake Bay Program.
Year Published:	1989
Call Number:	PB89-237788
Accession Number:	133639
Main Title:	Federal land management Chandler Lake land exchange not in the government's best interest : report to the Chairman, Subcommittee on Water and Power Resources, Committee on Interior and Insular Affairs, House of Representatives.
Corporate Author:	United States. General Accounting Office.
Publisher:	The Office
Year Published:	1989
Report Number:	GAO/RCED-90-5 B-229232
Accession Number:	139968
Main Title:	Lake Union and Ship Canal water quality management program background report.
Corporate Author:	Land Use & Transportation Project (Seattle, Wash.)
Publisher:	The Project
Year Published:	1986
Accession Number:	153368
Main Title:	Water resources management plan for Fresno-Clovis urban & northeast Fresno County
Publisher:	The County
Year Published:	1986
Accession Number:	153972
Main Title:	Revised workplan for the proceedings on the San Francisco Bay/Sacramento-San Joaquin Delta estuary.

Corporate Author: California. State Water Resources Control Board.
Publisher: The Board
Year Published: 1989

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Main Title: Water resources Corps' management of 1990 flooding in the Arkansas, Red, and White River basins : briefing report to the Honorable David Pryor, U.S. Senate.
Corporate Author: United States. General Accounting Office.
Publisher: General Accounting Office
Year Published: 1991
Report Number: GAO/RCED-91-172BR B-243956

Accession Number: 182194
Main Title: Water resources Corps of Engineers management of 1986 flooding in northeastern Oklahoma : briefing report to the Chairman, Subcommittee on Environment, Energy, and Natural Resources, Committee on Government Operations, House of Representatives.
Corporate Author: United States. General Accounting Office.
Publisher: The Office
Year Published: 1987

Accession Number: 188318
Main Title: Framework for Characterization. (Revised Final Report March 1992).
Personal Author: Ramsay, M.; Boynton, W.; Clark, P.
Corporate Author: Tampa Bay Regional Planning Council, St. Petersburg, FL.;Tampa Bay National Estuary Program, St. Petersburg, FL.
Year Published: 1992
Call Number: PB93-191237
Report Number: T-91-01; TBNEP-01-92

Accession Number: ?
Main Title: Economic Characterization of the Albemarle-Pamlico Comprehensive Conservation andManagement Plan.
Personal Author: Chazal, J.; Peck, L.G.; Cox, V.; Smutko, L.S.
Corporate Author: Resource Analytics Inc., Raleigh, NC.;North Carolina Dept. of Environment, Health, and Natural Resources, Raleigh. Albemarle-Pamlico Estuarine Study.;Environmental Protection Agency, Research Triangle Park, NC. NationalEstuary Program.
Year Published: 1993
Call Number: PB95-104055
Report Number: APES-93-16

Accession Number: 211818
Main Title: Public Attitudes Toward Water Quality and Management Alternatives in the Albemarle-Pamlico Estuarine System. Phase 2 Report.
Personal Author: Hoban, T.; Clifford, W.
Corporate Author: North Carolina State Univ. at Raleigh. Dept. of Sociology.; North Carolina Dept. of Environment, Health, and Natural Resources, Raleigh. Albemarle-Pamlico Estuarine Study.; Environmental Protection Agency, Research Triangle Park, NC. National Estuary Program.
Year Published: 1992
Call Number: PB95-105425
Report Number: NCSU-89-6; APES-PR-92-13; APES-92-13

Accession Number: 212128
Main Title: Chesapeake Bay Basinwide Toxics Reduction Strategy Reevaluation Report. Executive Summary.

Corporate Author: Environmental Protection Agency, Annapolis, MD. Chesapeake Bay Program.
Year Published: 1994
Call Number: PB95-136453

Accession Number: 212359
Main Title: Long Island Sound Study: Summary of the Comprehensive Conservation and Management Plan, July 1994.
Corporate Author: Environmental Protection Agency, Washington, DC. Office of Wetlands, Oceans and Watersheds.; New York State Dept. of Environmental Conservation, Albany. Div. of Marine Resources; Connecticut Dept. of Environmental Protection, Hartford.
Year Published: 1994
Call Number: PB95-137865
Report Number: EPA/842/S-94/001

Accession Number: 230612
Main Title: Chesapeake Bay Habitat Restoration: A Framework for Action.
Corporate Author: Environmental Protection Agency, Annapolis, MD. Chesapeake Bay Program.
Year Published: 1995
Call Number: PB96-144274
Report Number: CBP/TRS-140/95; EPA/903/R-95/015

Accession Number: 3686
Main Title: Ohio River Basin comprehensive survey - main report and development program formulation. Communication from the Chairman, United States Water Resources Council, transmitting the Council's report on a comprehensive program for water and related land use in the Ohio River Basin, pursuant to Public law 89-80.
Corporate Author: U.S. Water Resources Council.; U.S. Congress. House. Committee on Interior and Insular Affairs.
Publisher: U.S. Govt. Print. Office
Year Published: 1971

Accession Number: 95701
Main Title: River Basin Management Post-Audit and Analysis.
Personal Author: Wilkinson, John M.
Corporate Author: Little (Authur D.) Inc., Cambridge, Mass.
Year Published: 1900
Call Number: PB-222 941
Report Number: DI-14-31-0001-3719; OWRR-C-3353(3719); 13715,; C-3353(3719)(1)

Accession Number: 64881
Main Title: Policy for water allocation in the Lake Tahoe Basin.
Corporate Author: California. State Water Resources Control Board.
Publisher: The Board
Year Published: 1984

Accession Number: 211831
Main Title: Environmental Management Program for the Hampton Roads Virginia Portion of the Albemarle-Pamlico Estuarine Watershed.
Corporate Author: Hampton Roads Planning District Commission, VA.; North Carolina Dept. of Environment, Health, and Natural Resources, Raleigh. Albemarle-Pamlico Estuarine Study.; Environmental Protection Agency, Research Triangle Park, NC. National Estuary Program.
Year Published: 1993
Call Number: PB95-106811
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Section 3 : Strategies for Watershed Management

Accession Number:	182945
Main Title:	Otter Creek Watershed Conservation Tillage Demonstration Project (October 1987).
Personal Author:	Smith, M.; Pielsticker, K.F.
Corporate Author:	Monroe County Soil and Water Conservation District, MI.;Environmental Protection Agency, Chicago, IL. Great Lakes National Program Office.
Year Published:	1987
Call Number:	PB93-128114
Report Number:	GLNPO-08/91; EPA/905/9-91/007

Accession Number:	183950
Main Title:	Compendium of watershed-scale models for TMDL development.
Publisher:	U.S. Environmental Protection Agency
Year Published:	1992
Report Number:	EPA 841-R-92-002 Contract no. 68-C9-0013

Accession Number:	183953
Main Title:	Environmental indicators for surface water quality programs pilot study.
Publisher:	USEPA Region 5 ; USEPA Office of Policy, Planning and Evaluation; USEPA Office of Water
Year Published:	1992
Report Number:	EPA 905/R-92/001

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Main Title:	Baybook a guide to reducing water pollution at home.
Publisher:	U.S. Environmental Protection Agency
Year Published:	1987

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Main Title:	Wildland watershed management
Personal Author:	Satterlund, Donald R.
Publisher:	Wiley
Year Published:	1992

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Main Title:	Role and Function of Forest Buffers in the Chesapeake Bay Basin for Nonpoint Source Management.
Corporate Author:	Environmental Protection Agency, Annapolis, MD. Chesapeake Bay Program.
Year Published:	1993
Call Number:	PB93-207405
Report Number:	CBP/TRS-91/93

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Main Title:	Lake and Reservoir Restoration Guidance Manual: Second Edition.
Personal Author:	Olem, H. ; Flock, G.
Corporate Author:	North American Lake Management Society, Merrifield, VA.; Environmental Protection Agency, Washington, DC. Nonpoint Sources Branch.
Year Published:	1990
Call Number:	PB93-207926
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Corporate Author:	Washington (State). Dept. of Ecology.
Publisher:	The Department
Year Published:	1992

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Main Title: Standard methodology for conducting watershed analysis under chapter 222-22 WAC.
Corporate Author: Washington (State). Forest Practices Board.
Publisher: The Board
Year Published: 1993

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Main Title: Clean water in your watershed a citizen guide to watershed protection.
Personal Author: Alexander, Susan V.
Publisher: Terrene Institute
Year Published: 1993

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Main Title: Watershed Planning in the Albemarle-Pamlico Estuarine System. Report 3. Toxics Analysis.
Personal Author: Cunningham, P.A.; Williams, R.E.; Chessin, R.L.; McCarthy, J.M.; Curry, R.J.
Corporate Author: Research Triangle Inst., Research Triangle Park, NC.; North Carolina Dept. of Environment, Health, and Natural Resources, Raleigh. Albemarle-Pamlico Estuarine Study.
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Call Number: PB94-196573
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Personal Author: Shoemaker, L.L.; Lahlou, M.; Thoms, S.; Xue, R.; Wright, J.
Corporate Author: Tetra Tech, Inc., Fairfax, VA.; Environmental Protection Agency, Washington, DC. Office of Wetlands, Oceans and Watersheds.
Year Published: 1992
Call Number: PB94-218955
Report Number: EPA-68-C9-0013; EPA/841/R-94/002

Accession Number: 216478
Main Title: Mitigation Technical Guidance for Chesapeake Bay Wetlands.
Personal Author: Eckles, S.D.; Barnard, T.; Dawson, F.; Goodger, T.; Kimidy, K.
Corporate Author: Environmental Protection Agency, Annapolis, MD. Chesapeake Bay Program.
Year Published: 1994
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Main Title: Lake Water Quality Assessment Program, 1993. Northeastern Illinois Lakes.
Personal Author: Hudson, H.L.; Soulliere, K.F.
Corporate Author: Northeastern Illinois Planning Commission, Chicago.; Illinois State Environmental Protection Agency, Springfield. Div. of Water Pollution Control.; Environmental Protection Agency, Washington, DC.
Year Published: 1995
Call Number: PB95-200903
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Personal Author: Shulyer, L.R.
Corporate Author: Environmental Protection Agency, Annapolis, MD. Chesapeake Bay Program.
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Corporate Author:	Environmental Protection Agency, Washington, DC. Science Advisory Board.
Year Published:	1991
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Corporate Author:	Environmental Protection Agency, Washington, DC. Office of Water.
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Main Title:	Information resources management tools for making water program decisions.
Publisher:	U.S. Environmental Protection Agency
Year Published:	1990
Report Number:	EPA/500/9-90/005 68-W9-0039

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Main Title:	Selecting Priority Nonpoint Source Projects: You Better Shop Around.
Personal Author:	Adler, K.J.; Smolen, M.D.
Corporate Author:	Environmental Protection Agency, Washington, DC. Office of the Assistant Administrator for Water; North Carolina State Univ. at Raleigh.
Year Published:	1989
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Main Title:	Protecting Coastal and Wetlands Resources: A Guide for Local Governments.
Corporate Author:	Industrial Economics, Inc., Cambridge, MA.; Environmental Protection Agency, Washington, DC. Office of the Assistant Administrator for Water.
Year Published:	1992
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Main Title:	Saving Bays and Estuaries: A Primer for Establishing and Managing Estuary Programs. Appendices G, H, and I.
Corporate Author:	Environmental Protection Agency, Washington, DC. Office of the Assistant Administrator for Water.
Year Published:	1990
Call Number:	PB93-116077
Report Number:	EPA/503/8-90/005

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Main Title:	Office of Water administrative systems compendium information resources management : tools for making water program decisions.
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Year Published:	1990
Report Number:	EPA/500/9-90/005 68-W9-0039

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Main Title:	Organizing lake users a practical guide.
Personal Author:	Flock, Gretchen H.

Publisher:	Terrene Institute
Year Published:	1991

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Main Title:	Watershed Handbook. A Management Technique for Choosing Among Point and Nonpoint Control Strategies.
Personal Author:	Monteith, T.J.; Sullivan, R.A.C.; Heidtke, T.M.; Sonzogni, W.C.
Corporate Author:	Great Lakes Basin Commission, Ann Arbor, MI.; National Oceanic and Atmospheric Administration, Ann Arbor, MI. Great Lakes Environmental Research Lab.
Year Published:	1981
Call Number:	PB84-231240
Report Number:	EPA-905/9-84/002

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Main Title:	Review of a framework for improving surface water monitoring support for decision-making.
Publisher:	U.S. Environmental Protection Agency
Year Published:	1987

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Main Title:	Decision support techniques for lakes and reservoirs.
Publisher:	CRC Press
Year Published:	1991

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Main Title:	Chesapeake Bay Toxics Reduction Strategy Stakeholder Roundtables: Pennsylvania, Maryland and the District of Columbia Summaries.
Personal Author:	Flanigan, F.; Barth, C.A.; Dunn, C.
Corporate Author:	Alliance for the Chesapeake Bay, Baltimore, MD.; Environmental Protection Agency, Annapolis, MD. Chesapeake Bay Program.
Year Published:	1994
Call Number:	PB94-209558

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Accession Number: 77237
Main Title: 1987 Chesapeake Bay Agreement final draft.
Corporate Author: Chesapeake Executive Council.
Publisher: Chesapeake Executive Council,
Year Published: 1987

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Main Title: 1987 Chesapeake Bay agreement draft proposals.
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Year Published: 1988

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Main Title: Potomac River basin compact. April 1970.
Corporate Author: Potomac River Basin Advisory Committee.
Publisher: Potomac River Basin Advisory Committee
Year Published: 1970

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Main Title: Susquehanna River Basin compact.
Corporate Author: Interstate Advisory Committee on the Susquehanna River Basin.; New York (State)
Publisher: Interstate Advisory Committee on the Susquehanna River Basin
Year Published: 1967

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Main Title: Water and the West : the Colorado River Compact and the politics of water in the American West
Personal Author: Hundley, Norris.
Corporate Author: Colorado River Commission. Colorado River Compact. 1975.
Publisher: University of California Press
Year Published: 1975

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Main Title: Chesapeake Bay Research Coordination Act : hearing before the Subcommittee on Governmental Efficiency and the District of Columbia of the Committee on Governmental Affairs, United States Senate, Ninety-sixth Congress, second session, on S. 1316 and H.R. 4417, July 31, 1980.
Corporate Author: United States. Congress. Senate. Committee on Governmental Affairs. Subcommittee on Governmental Efficiency and the District of Columbia.
Publisher: U.S. G.P.O.
Year Published: 1980

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Main Title: Water Resources Policy Act of 1981 : hearing before the Subcommittee on Conservation, Credit, and Rural Development of the Committee on Agriculture, House of Representatives, Ninety-seventh Congress, first session, on H.R. 3432, June 16, 1981.
Corporate Author: United States. Congress. House. Committee on Agriculture. Subcommittee on Conservation, Credit, and Rural Development.
Publisher: U.S. G.P.O.
Year Published: 1981

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Main Title: State laws mandating water conservation
Personal Author: Sawyer, Stephen W.; Eney, Allen B.

Corporate Author:	United States. Office of Water Policy.; University of Maryland, College Park. Water Resources Research Center.
Publisher:	Maryland Water Resources Research Center, University of Maryland,
Year Published:	1983

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Main Title:	Growth of water-resources law under the American federal system
Personal Author:	Laurent, Francis W.
Corporate Author:	University of Wisconsin--Madison. Water Resources Center.
Publisher:	Water Resources Center, University of Wisconsin,
Year Published:	1977

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Main Title:	Legal Aspects of Water Use and Control in South Carolina. Part A. Legal Considerations Relating to a New Water Resources Law for South Carolina.
Personal Author:	Randall, J, Charles H.
Corporate Author:	Clemson Univ., S. C. Water Resources Research Inst.
Year Published:	1900
Call Number:	PB-200 654
Report Number:	WRRI-20; OWRR-B-003-SC; 09363; B-003-SC(2)

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Main Title:	Symposium on Water Law and Its Relationship to the Economic Development of Montana's Water Resources.
Personal Author:	Holj, Helmer
Corporate Author:	Montana State Univ., Bozeman. Water Resources Research Center.
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Personal Author:	Sherida, Richard G.
Corporate Author:	Montana State Univ., Bozeman. Water Resources Research Center.
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Main Title:	Water Resources Laws for Virginia.
Personal Author:	Walke, William R.; Co, William E.
Corporate Author:	Virginia Polytechnic Inst., Blacksburg. Water Resources Research Center.
Year Published:	1900
Call Number:	PB-206 986
Report Number:	VPI-WRRC-Bull-9; OWRR-A-088-VA; A-088-VA(1); 05533

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Main Title:	Interstate Ground-Water Aquifers of the State of Washington, Physical and Legal Problems. A Preliminary Assessment. Part A. The Physical Situation. Part B. Legal Aspects.
Personal Author:	Agne, Allen F.; Busc, Russel W.
Corporate Author:	Washington State Water Research Center, Pullman.
Year Published:	1900
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Report Number:	DI-14-31-0001-3048; OWRR-A-038-WASH; 06608; A-038-WASH(1)

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Main Title: Columbia River Interstate Compact, Politics of Negotiation.
Personal Author: Doerkse, Harvey R.
Corporate Author: Washington State Water Research Center, Pullman.
Year Published: 1900
Call Number: PB-213 456
Report Number: DI-14-31-0001-3548; OWRR-A-046-WASH; 02614; A-046-WASH(1)

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Main Title: Economic, Political, and Legal Aspects of Colorado Water Law.
Personal Author: Radosevic, G. E.; Nob, K. C.; Mee, R. L.; Flac, J. E.
Corporate Author: Colorado State Univ., Fort Collins. Environmental Resources Center.
Year Published: 1900
Call Number: PB-217 868
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Main Title: Bibliography on Legal and Regulatory Aspects of Water Pollution Control and Abatement. I. Abstracts. II. Center of Competence for Eastern U.S. Water Laws.
Corporate Author: Florida Univ., Gainesville. Coll. of Law.
Year Published: 1900
Call Number: PB-222 228-SET

Accession Number: 130315
Main Title: Compilation of selected water resources and water pollution control laws Federal Water Pollution Control Act ; sections 9 to 20 of the Act of March 3, 1899 ; selected provisions of the Water Resources Development Act of 1986.
Corporate Author: United States.
Publisher: U.S. G.P.O.
Year Published: 1989
Report Number: 100-83 (United States. Congress. House. Committee on Public Works and Transportation).

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Main Title: Law of water rights and resources
Personal Author: Tarlock, A. Dan
Publisher: C. Boardman
Year Published: 1988

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Main Title: Water resources legislation and administration in selected Caribbean countries
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Main Title: Water law in historical perspective
Personal Author: Teclaff, Ludwik A.
Publisher: W.S. Hein
Year Published: 1985

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Main Title: Down by the river the impact of federal water projects and policies on biological diversity.
Personal Author: Hunt, Constance Elizabeth.
Publisher: Island Press
Year Published: 1988

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Main Title:	Colorado water laws a compilation of statutes, regulations, compacts and selected cases.
Personal Author:	Radosevich, George
Publisher:	County Information Service, Agricultural and Natural Resource Economics & Colorado Water Resources Research Institute, Colorado State University,
Year Published:	1987

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Main Title:	Law of international water resources some general conventions, declarations, and resolutions adopted by governments, international legal institutions, and international organizations, on the management of international water resources.
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Personal Author:	Bell, D. Craig.
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Main Title: Water resources Delaware River Basin Commission's management of certain water activities : report to the Honorable Peter H. Kostmayer, House of Representatives.
Personal Author: Kostmayer, Peter H.
Corporate Author: United States. General Accounting Office.
Publisher: The Office
Year Published: 1986

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Main Title: Proceedings of the California Watershed Management Conference, November 18-20, 1986, West Sacramento, California
Personal Author: Callaham, Robert Z.; DeVries, Johannes J.
Corporate Author: University of California, Berkeley. Wildland Resources Center.
Publisher: Wildland Resources Center, Division of Agriculture and Natural Resources, University of California
Year Published: 1987

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Main Title: Recharge as augmentation in the South Platte River Basin
Personal Author: Warner, James W.; Sunada, D.; Hartwell, Anne.
Corporate Author: Colorado Water Resources Research Institute.
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Year Published: 1986

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Main Title: State of the Chesapeake Bay ... biennial monitoring report
Corporate Author: United States. Environmental Protection Agency. Chesapeake Bay Program. Monitoring Subcommittee.
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Corporate Author: Environmental Protection Agency, Annapolis, MD. Chesapeake Bay Program.
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Main Title: New Alsea watershed study.
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Main Title: California watersheds at the urban interface proceedings of the Third Biennial Watershed Conference, Ontario Hilton, Ontario, California, October 30-31, 1990.
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Main Title: Evaluation of the Watershed Protection and Flood Prevention Program
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Personal Author:	Horton, Tom
Publisher:	Island Press
Year Published:	1991

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Main Title:	Republic of Haiti agroforestry and watershed management project Artibonite river pre-feasibility study.
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Year Published:	1991

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Main Title:	Watershed management balancing sustainability and environmental change.
Publisher:	Springer-Verlag
Year Published:	1992

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Main Title:	Some Emerging Issues in Watershed Management-Landscape Patterns, Species Conservation, and Climate Change.
Personal Author:	Swanson, F.J.; Neilson, R.P.; Grant, G.E.
Corporate Author:	Pacific Northwest Forest and Range Experiment Station, Corvallis, OR. Forestry Sciences Lab.; Corvallis Environmental Research Lab., OR.
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Main Title:	Irrigation planning with environmental considerations a case study of Pakistan's Indus Basin.
Personal Author:	Ahmad, Masood.
Publisher:	World Bank
Year Published:	1992

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Main Title:	Protecting drinking water quality at the source proceedings of a conference, Sacramento, California, April 3-4, 1991.
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Year Published:	1991

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Main Title:	President Clinton's Clean Water Initiative: Analysis of Benefits and Costs.
Corporate Author:	Environmental Protection Agency, Washington, DC. Office of Water.
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Main Title: Geographic targeting selected state examples.
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Main Title: Overcoming obstacles proceedings of the Fourth Biennial Watershed Management Conference, Embassy Suites Hotel, South Lake Tahoe, California, November 18-20, 1992.
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Year Published: 1994

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Main Title: Runoff report.
Publisher: National NonPoint Source Federation,
Year Published: 1993

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Main Title: WATERSHED '93: A National Conference on Watershed Management. Held in Alexandria, Virginia on March 21-24, 1993.
Corporate Author: Environmental Protection Agency, Washington, DC. Office of Wetlands, Oceans and Watersheds.
Year Published: 1993
Call Number: PB94-181609
Report Number: EPA/840/R-94/002

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Main Title: Annotated bibliography of publications on watershed management and ecological studies at Coweeta Hydrologic Laboratory, 1934-1994.
Personal Author: Stickney, Patricia L.
Publisher: U.S.Department of Agriculture, Forest Service, Southeastern Forest Experiment Station
Year Published: 1994

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Main Title: Watershed restoration sourcebook collected papers presented at the Conference "Restoring Our Home River - Water Quality and Habitat in the Anacostia" held November 6th and 7th, 1991, in College Park, Md.
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Year Published: 1992

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Main Title: Investing in natural capital the ecological economics approach to sustainability.
Publisher: Island Press
Year Published: 1994

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Year Published: 1994
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Year Published: 1993

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Year Published: 1993

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Main Title: Proceedings of a Workshop on Risk Assessment, Communication and Management in the Great Lakes Basin February 1-2, 1993, St. Catherines, Ontario.
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Main Title: Integrated economic hydrologic model for groundwater basin management.
Personal Author: Faisal, Islam M.
Publisher: Colorado Water Resources Research Institute, Colorado State University,
Year Published: 1994

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Main Title: Mill Creek an unnatural history of an urban stream.
Personal Author: Hedeen, Stanley E.
Publisher: Rivers Unlimited Mill Creek Restoration Project : Blue Heron Press
Year Published: 1994

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Personal Author: Magnien, R.; Boward, D.; Bieber, S.
Corporate Author: Environmental Protection Agency, Annapolis, MD. Chesapeake Bay Program.
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Corporate Author: Environmental Protection Agency, Washington, DC. Office of Wetlands, Oceans and Watersheds.
Year Published: 1995

Call Number:	PB95-199345
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Main Title:	Proceedings of the 1990 Clark Fork River Symposium, April 20, 1990, University of Montana, Missoula, Montana.
Publisher:	s.n.
Year Published:	1992

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Main Title:	Agriculture and the environment information on and characteristics of selected watershed projects : report to the Committee on Agriculture, Nutrition, and Forestry, U.S. Senate.
Corporate Author:	United States. General Accounting Office.
Publisher:	The Office
Year Published:	1995
Report Number:	GAO/RCED-95-218 B-261576

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Main Title:	Watersheds '94 respect, rethink, restore : proceedings of the Fifth Biennial Watershed Management Conference, Ashland Hills Inn, Ashland, Oregon, November 16-18, 1994.
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Year Published:	1995

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Main Title:	Rehabilitating damaged ecosystems
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Year Published:	1995

Accession Number:	230504
Main Title:	Mobilizing the Watershed Community: Linking Land, Water, and People.
Corporate Author:	Illinois State Environmental Protection Agency, Springfield. Bureau of Water.
Year Published:	1995
Call Number:	PB96-139589
Report Number:	IEPA/WPC/95-023

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Main Title:	Nisqually watershed Glacier to Delta : a river's legacy.
Personal Author:	Gordon, David G.
Publisher:	Mountaineers
Year Published:	1995

Accession Number:	237108
Main Title:	Seminar publication National Conference on Urban Runoff Management : enhancing urban watershed management at the local, county, and state levels.
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Year Published:	1995
Report Number:	EPA/625/R-95/003

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Main Title:	Ecology, diversity, and sustainability of the Middle Rio Grande Basin
Publisher:	U.S. Dept. of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station
Year Published:	1995