DEVELOPMENT OF A METHODOLOGY FOR DROUGHT FREQUENCY ANALYSIS USING SUB-CATCHMENTS IN ZIMBABWE

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DECLARATION

I declare that this project is my own unaided, work. It is being submitted for the degree of Master of Science in Engineering in the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination at any other university.

Signed..............................

.....6th.......day of March 1999

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ABSTRACT

The state of runoff and rainfall data in Zimbabwe is reviewed to determine the extent to which it can be used for drought analysis. The need to augment the available observed records was established. A brief review of literature on rainfall-runoff computer programs was undertaken. RALFER was selected for use in this methodology mainly because it was available and matched the requirements to model different hydrological regions of Zimbabwe.

The selected program was used to model micro catchment runoff using rainfall measurements and a priori knowledge of the catchments. The output was compared with observed figures. By application of the same computer program on the same data and with only a few modifications to the parameters runoff was generated for the sub-zones.

Statistical analysis derived drought frequency graphs and tables This was done on six micro catchments and sub-zones. The consistency of the program was checked by use of different rainfall stations for two of the catchments.

The results showed that micro catchment runoff can be easily transformed to sub-zone runoff for hydrological drought analysis. These drought frequency graphs and tables are important for informed water resource planning and management. They can also be used in environmental management. There is scope to apply the methodology to the whole of Zimbabwe but it may be necessary to improve computer software compatibility between the different sources of data and the point of analysis.

ACKNOWLEDGEMENTS

I would like to thank the staff at the Meteorological Department and the Department of Water Resources and Development for providing me access to their records. Special gratitude goes to my family for standing by me during this study.

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NOMENCLATURE

ANSWERS	Areal Non-point Source Watershed Environment Response Simulation
D_p	Cumulative drought runoff for a drought period P expressed as a percentage of average runoff of for a period of drought
$D_{p,80}$	Cumulative runoff drought for a drought period P of magnitude 80% of average runoff
DWRD	Department of Water Resources and Development
E_m	Average evaporation
F	Frequency of exceeding a stated flow
I_m	Average inflow
m	Number of years
MAR	Mean Annual Runoff
MET	Department of Meteorological Services
n	Manning's Coefficient
n	Number
q	Discharge
P	Duration of drought in years
R	Runoff
R_{ave}	Mean annual runoff
RAM	Random Access Memory
RDFA	Regional Drought Frequency Analysis
RI	Recurrence interval in years
R_{pave}	Average runoff for a sequence of period P
s	Ground slope
S_b	Storage state of reservoir at beginning of period
S_e	Storage state of reservoir at end of period
SHE	Systeme Hydrologique Europeen
SHIFT	*Sistema Hydrologico de Facetas Triangulares*
t	Time

U_m	Average draft
VTI	Variable time interval
x	Aerial precipitation in mm
y	Discharge

1.0 INTRODUCTION

1.1 Problem Definition

This project attempts to introduce a method for predicting various levels of hydrological droughts based on analysis of runoff time series.

1.2 The Hypothesis

Using computer models adequate runoff can be generated from available data and this can be used to determine frequency of various levels of hydrological droughts.

1.3 Importance of Study

Knowledge of stream flow conditions is essential to make well-founded water management decisions. This is of particular importance in design and efficient operation of storage reservoirs, which provide water for various uses among them hydro-electric power generation, irrigation and domestic water [Kachroo,1991]. Water management in Southern Africa is complicated by the frequent occurrence of droughts [Roland,1994]. According to Donkor *et al* (1992) there is no singular definition of drought. The most common definition of drought considers the occurrence of precipitation. According to Brewer (1989) and Laing (1990), in South Africa drought occurs when less than 70% of annual average precipitation is received and it is severe if it extends over two consecutive seasons. Periodic drought occurs when precipitation is between 70% and 85% of annual mean precipitation and long term drought occurs when precipitation is less than 70% of annual mean precipitation [Rowland,1994]. In hydrological terms periods of rainfall shortfall are linked to surface or subsurface water supply deficit [A Booth *et al* 1994]. According to Stephenson *et al* (1983) from a runoff record of N years, a cumulative runoff deficit (drought) would occur if the cumulative runoff R_p of any duration P years is less than the average R_{pave} of the cumulative flows of that duration. For a given location the recurrence interval RI of different magnitudes of cumulative runoff less than R_{pave} lasting P years can be estimated from a frequency analysis on an independent sequence of R_p taken from N years of runoff record.

During a drought period of P years the resulting cumulative runoff R_p expressed as a percentage of the average R_{pave} of the cumulative flows of that duration reflects the cumulative drought runoff D_p.

Droughts of different duration P years and recurrence interval RI produce different effects on life forms and national economies. About 90% of Zimbabwe's water supply is met by surface water resources [Thornton *et al* 1982]. The country is periodically affected by severe and prolonged droughts. Drought is associated with suffering, large-scale crop failure, loss of grass cover, livestock, wildlife, in extreme cases human life is also lost and economies perform poorly [Booth *et al* 1994]. Campbell (1986) shows that in Southern Africa droughts of duration P between one and five years may occur at local or regional scale and in Tyson (1987) Southern Africa which includes Zimbabwe has experienced at least three centuries of recurring drought of varying severity. The following years were drought periods: years 1820-30, 1844-49, 1921-1930, 1946-47, 1967-73, 1982-83,1986-87 (Tyson 1987, Booth *et al* 1994). In the following decade, 1991-92 and 1994-95 were also drought years. The financial cost and losses of the 1982-83 drought to Zimbabwe was estimated at about US$479.6 million [Norman, 1984]. According to Benson and Clay (1994) during 1991-92, compared to the pre-drought levels manufacturing sector production dropped by 9.3%, actual volume of manufacturing output dropped by 25% and foreign currency receipts dropped by 6%. During the same drought Zimbabwe's stock market was identified by the International Finance Corporation as the worst performer of 54 stock markets with a decline of 62%. Companies were forced to pull out from Bulawayo and relocate elsewhere because of lack of water. Those left behind cut back on production and retrenched workers. Half of the city's small businesses crumbled. Reduced use of water resulted in increased sewer blockages. Inadequate irrigation water almost halted sugar cane industries. About 1.5 million head of cattle was lost [Booth *et al* 1994].

Reservoir sedimentation is a serious problem in Zimbabwe leading to diminished draft or even total loss of live storage capacity. According to Booth *et al* (1994), soil loss from water erosion slows down during drought periods but when rain returns erosion rates can go up to three times higher during dry years. This is attributed to loss of plant cover and loosening up of soil during drought. Thus the continued loss of soil following a drought magnifies the impact of drought through further rapid loss of the soil's productive capacity. In Zimbabwe dry communal lands are the most vulnerable. According to Kelly (1973) during high rainfall years in the southern part of Zimbabwe's dry communal range lands grass cover is only 9% below commercial range lands but during drought years the cover is 80% lower.

Despite the long experience with recurring drought of devastating impact limited hydrological modeling of low flows has been undertaken for Zimbabwe. Hence the derivation of D_p, P and RI can significantly enhance understanding the risk of drought, enable long term planning and improve resource management in different catchments in Zimbabwe. A methodology for evaluation of these parameters is set to become more important as the scale of human interference with nature increases.

1.4 Research Methodology

The first step involved the specification of the problem to be solved namely the lack of a methodology for hydrological drought frequency analysis for application to conditions prevailing in Zimbabwe. Then the observed runoff time series were reviewed for suitability for direct application on the assignment. This exposed the limitations of the available data in terms of density of stations, length and quality of records and established the need to limit the study to specific catchments and augment existing data using a rainfall-runoff model.

A review of rainfall-runoff estimation models is presented. This followed by a brief review of available rainfall-runoff computer models and the selection of one available for the task at hand.

The selected rainfall-runoff model is applied on specific micro-catchments. First estimates of parameters are taken off geo-physical maps and then available rainfall and runoff data is used to refine them. The sensitivity of the model to the values of selected parameters is tested.

The computer model is then used to generate runoff for sub-catchments.

Statistical analysis is carried out on the annual runoff generated. First this runoff is converted to point runoff time series then droughts resulting in D_p less than 80%, 70% and 50% of the mean of each partial duration series R_{pave} are calculated. The drought duration P was set at values of 1,2, 3 and 4 consecutive years. A discussion of the results is presented to highlight the main observation and the utility of the output. Limitations to prediction of drought severity and frequency using this methodology are analyzed.

2.0 A REVIEW OF AVAILABLE DATA AND MODELS FOR ANALYSIS OF HYDROLOGICAL DROUGHTS

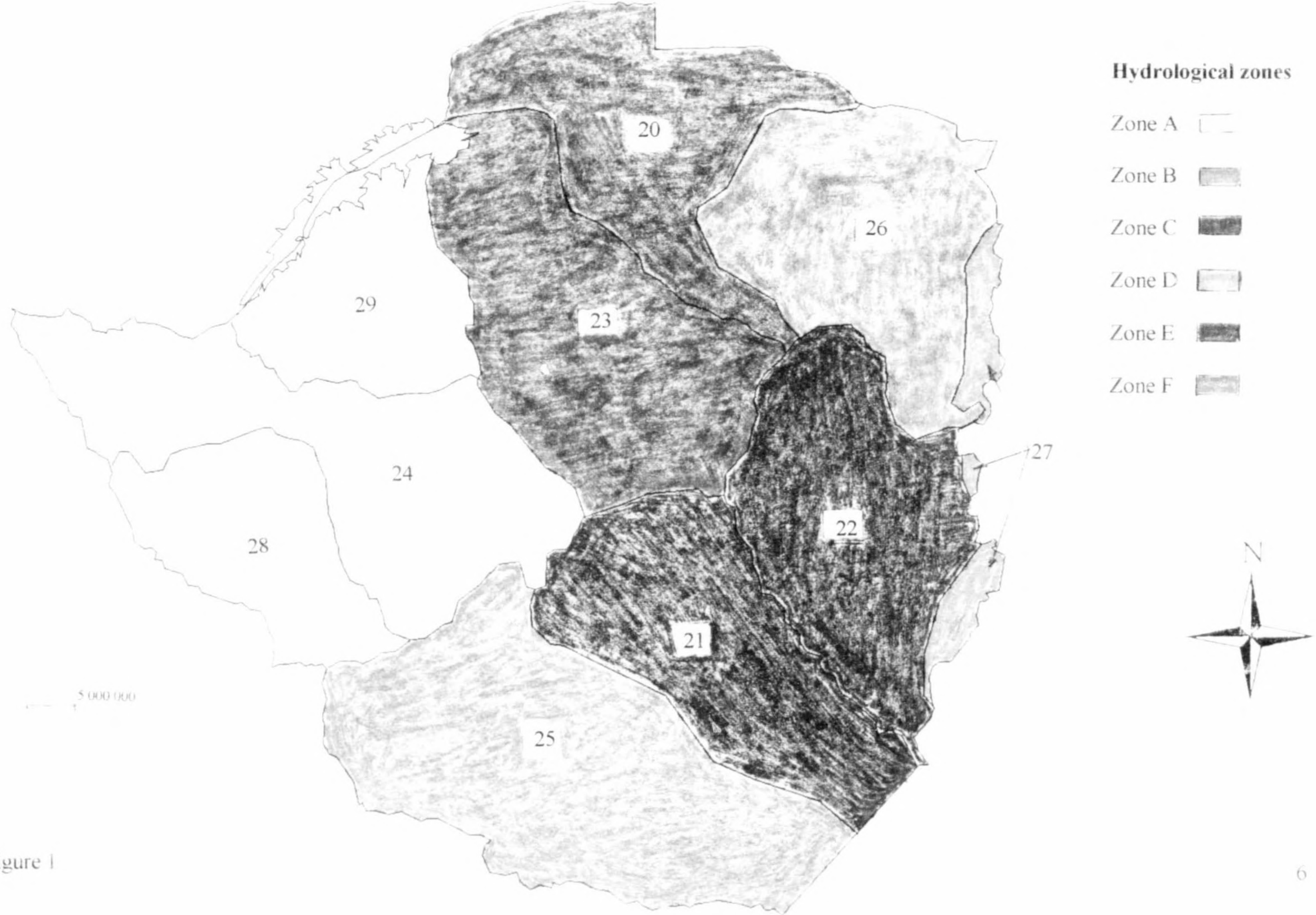
2.1 Catchment Discretization Approaches in Zimbabwe

The Department of Water Resources and Development (DWRD) has divided Zimbabwe into six hydrological zones following the major drainage basins [Kabel 1984]. These zones are assigned the letters A, B, C, D, E and F as in Figure 1 attached.

The Meteorological Services Department (MET) on the other hand uses ten climatic zones, which also run along watersheds. The hydrological and climate zones are superimposed on each other in Figure 1. It is observed that the hydrological zones also subdivide the climate zones and vise versa.

Sub-zones are formed by further discretization of the zones following conservation criteria. These are used as the basic elements of catchment water management in Zimbabwe. As shown in Kabel (1984) there are 151 sub-zones altogether, 27 in Zone A, 30 in Zone B, 23 in Zone C, 22 in zone D, 40 in zone E and 9 in zone F. These are named after the first letters of the major rivers draining the sub-zone. Figure 2 shows the division of zones to sub-zones.

The Zimbabwe Government is in the process of reviewing its water resources management strategy and it intends to come up with a new Water Act to address issues of equity, environment protection, administration and management. The government is proposing to establish catchment councils along the boundaries shown in Figure 3. The term Zone is replaced by Catchment. Seven major rivers namely Gwayi, Sanyati, Manyame, Mazowe, Save, Runde and Mzingwane are used to determine the direction of drainage and demarcate the catchments. At the zone level, the major change is that Zone F disappears. The northern part of Zone F goes in to Mazowe catchment while its southern part goes into Save Catchment. It follows that the term sub-zone will be replaced by sub-catchment. It is proposed to set up new sub-catchments based on hydrological criteria.



CLIMATE AND HYDROLOGICAL ZONES OF ZIMBABWE

Figure 1

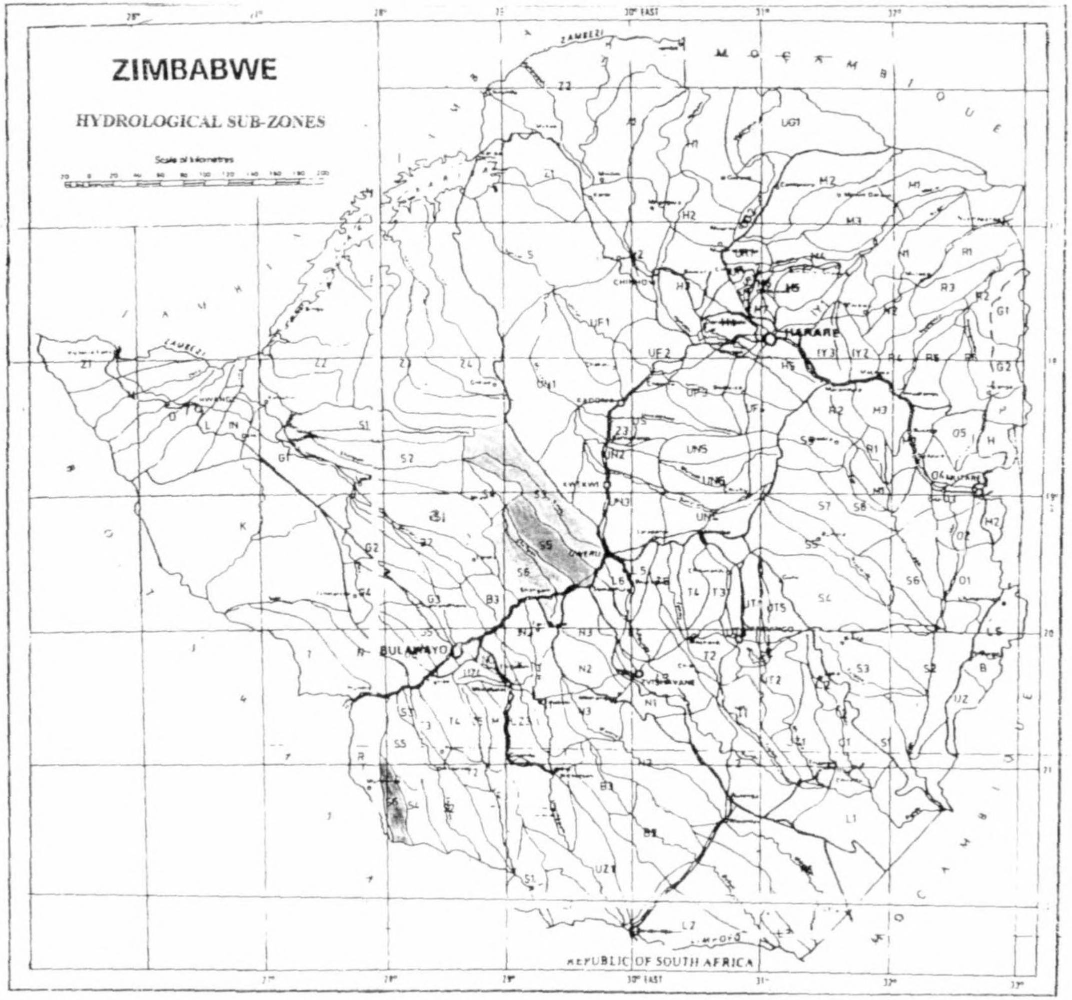


Figure 2

Source: Department of Water Resources and Development, 1997

PROPOSED CATCHMENTS UNDER THE NEW WATER MANAGEMENT STRATEGY

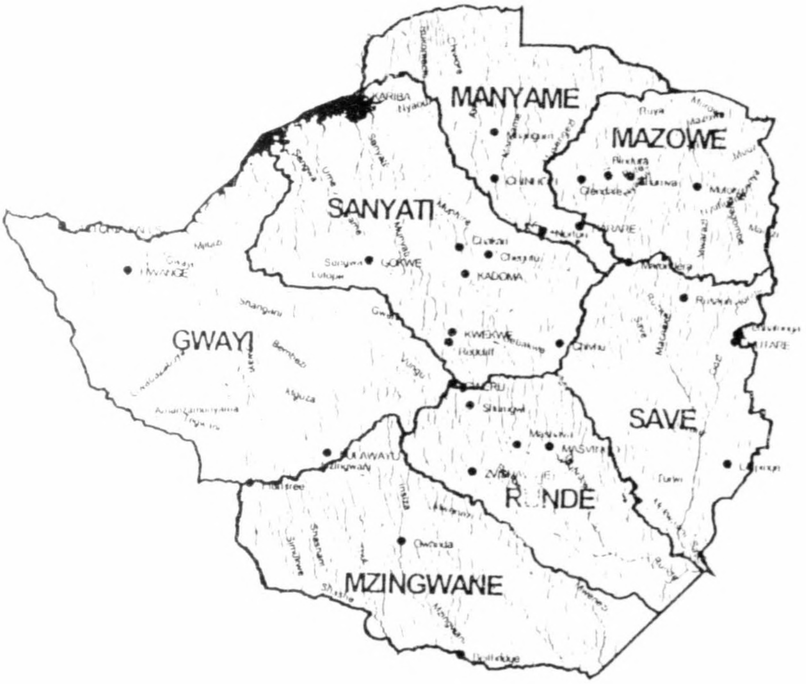


Figure 3

The Zimbabwe National Water Authority (ZNWA), to be established will be charged with the responsibility to manage the country's water resources [Ministry of Rural Resources and Water Development 1998, Williams 1998]. However, the new Water Act has not yet been proclaimed by the President and the ZNWA authority is not in place, in the meantime the zone and sub-zone system is still being applied.

2.2 Screening of Observed Runoff Data

DWRD has selected suitable sites on the major rivers and installed flow measuring stations with automatic recording devices. According to the Ministry of Rural Resources and Water Development, (1998), conservation criteria influenced the selection of these sites. Except for areas along the Zimbabwe border where outflow is not restricted to a single channel or point, such gauging posts mark the lower point of sub-zones. Watersheds describe the boundaries of the area contributing runoff to the gauging post. Thus the watersheds mark the boundaries of the sub-zones. DWRD maintains these hydrological stations to build a database on flows which is a prerequisite for informed water development plans for each river system, a responsibility bestowed to the DWRD in the [Zimbabwe Water Act 1996]. In line with the provisions of this Act, other recorder stations were subsequently installed within the sub-zones to account for abstraction and damming. With the proposed changes in water management the sub-catchment boundaries are likely to differ from the current sub-zone boundaries. Where this takes place new recorder stations may be required to measure inflow and outflow for each sub-catchment. In the short to medium term while data from actual measurements is inadequate synthetic data generated using suitable models and records from existing stations may be applied. The methodology being developed on this assignment could be used for this purpose.

Kabel (1984) shows mean annual point runoff estimates for zones A, B C, D, E and F of 17mm, 19mm, 62mm, 113mm, 70mm and 172 respectively with coefficient of variation of 130% for Zones A and B, 100%, 90%, 90% and 60% for zones C, D, E and F respectively.

According to Kabel (1984) the large variation in runoff in zones A and B necessitates the provision of large storage capacities in order to balance out several years of poor flow. Calculation of hydrologic drought conditions for a hydrological zone with high runoff variability requires several years of continuous runoff observations taken at a sufficient number of stations that are spaced to adequately describe that zone.

Existing runoff data was reviewed to determine its suitability for use on this assignment. Although Zimbabwe has computerized data for about 320 runoff stations over 70% of them do not have continuous observations. Recording of runoff measurements virtually stopped during the period of civil war that ended in 1980 for most of the country but for the Midlands, Matabeleland North and South Provinces the stoppage continued until the civil strife ended in 1985. These provinces fall mainly in hydrological zones A and B. The overall effect of these activities is that available observations cannot be easily naturalized which means for zones A and B most of the observed data cannot be directly applied in simulation of long term runoff time series. This is compounded by man's activities such as land use and unregistered damming, diversion and abstraction. Unfortunately the stations most affected are those at the sub-zone boundaries which would otherwise have longer and more useful records.

The experience in developing a model for drought frequency analysis for hydrological zones with limited observed data, the least potential for runoff production and a high coefficient of variation presented the author with an interesting challenge. Although drought also occurs in areas normally classified as wet, its occurrence in drier areas is often more frequent and has more significant economic effects [Booth *et al* 1994]. The need for mitigation measures is likely to demand the use of a methodology for modeling different drought conditions. The 1992-93 drought showed that management of transport of water to Bulawayo from sources such as the Nyamandlovu Aquifer, the surrounding dams and the Matabeleland Zambezi Pipeline Project could be done against more broad based planning for drought [Mpande 1995].

A methodology for drought analysis could significantly improve water management in Zones A and B. Thus these two zones were selected for the study. Tables 2.1 and 2.2 show the major rivers, hydrological sub-zones and climatic zones of hydrological zones A and B [Kabel 1984]. The hydrological zone letter prefixes the letters for each sub-zone in the nomenclature in common use in Zimbabwe. This nomenclature is used in this document.

Discussions with staff at the Hydrological Branch of the Department of Water Resources Development (DWRD) helped identify the following shortcomings:

- there is a large number of small dams which do not have flow measurement devices, this is only revealed by analysis of each sub-zone
- in general government owned and operated gauges have more reliable flow measurements
- in practice most users of water measure inflow and outflow at designated points they do not directly measure abstraction

A review was undertaken of the runoff data from all the observation stations within the 27 and 30 sub-zones in zones A and B respectively. Of the 57 sub-zones only 12 had gauging posts with at least 10 years of continuous data. These are shown in Table 2.3. In extending runoff data at least ten years of continuous observed runoff data is essential to make statistical comparisons between observations and estimates. The number of years of continuous record is also shown in this table. Thus only 9 and 3 sub-zones were selected from zones A and B respectively. This means that only 33% and 10% of the sub zones in zones A and B respectively could be easily naturalized. However on closer analysis of each station it was observed that in some cases there were years when one or several months had no records.

Table 2.1: Zone A – Hydrological and Climatic Divisions

Description	Major River In Zone	Hydrological Sub-Zone(s)	Climatic Zone
Draining North West into the Zambezi River and Lake Kariba and to the West into Botswana	Gwaai	AG1, AG2, AG3, AG4, AG5, AG6	24
	Lukozi	AL	24
	Bembezi	AB1, AB2, AB3	24
	Shangani	AS1, AS2, AS3, AS4, AS5, AS6	24
	Matetsi	AM	24
	Deka	AD	24
	Inyantue	AN	28
	Gwabazabuya	AK	28
	Manzamnyama	AN	28
	Tengwani	AT	28
	Ruziruhuru	AR	29
	Zambezi	AZ1, AZ2, AZ3, AZ4	29

Source: Zimbabwe Hydrological Zones Map, 1: 1 000 000, Department of the Surveyor General, 1984

Table 2.2: Zone B – Hydrological and Climatic Divisions

Description	Major River In Zone	Hydrological Sub-Zone(s)	Climatic Zone
Draining South West into the Limpopo River	Bubye	BB1, BB2, BB3	25
	Ingwezi	BR	25
	Sansukwe	BS6	25
	Simukwe	BS4, BS5	25
	Shashani	BS2, BS3	25
	Tuli	BT1, BT2, BT3, BT4, BT5	25
	Shashe	BS1	25
	Limpopo	BL1, BL2, BL3	25
	Msthabezi	BM	25
	Umzingwane	BUZ1, BUZ2, BUZ3, BUZ4	25
	Insiza	BIN1, BIN2	25
	Ncema	BNC	25
	Inyankuni	BIK	25
	Mwenezi	BN1, BN2, BN3	25

Source: Zimbabwe Hydrological Zones Map, 1: 1 000 000, Department of the Surveyor General, 1984

According to Gumbel E J (1958) the return period of a drought can be determined with small sampling errors if the number of years of drought records is large enough. Considering that the drought duration *P* of 1,2, 3 and 4 consecutive years no less than 30 years of continuous data would be required for drought analysis. The need to augment the data was recognized.

Table 2.3 List of Runoff Observation Stations

Hydrological Sub-zone	**Runoff Observation Station**	**Latitude**	**Longitude**	**Date Opened**	**Years of Continuous Records**
AM	A27	18° 15' S	25° 57'E	12/04/58	10
AS3	A28	19° 03' S	29° 21'E	11/02/58	17
AS5	A29	19° 06' S	29° 03'E	18/11/58	15
AB3	A33	19° 54' S	29° 01'E	07/02/59	12
AS1	A37	18° 34' S	27° 33'E	29/10/64	17
AS2	A41	18° 40' S	27° 34'E	16/03/65	28
AL	A52	18° 24' S	26° 36'E	20/02/69	24
AS6	A60	19° 37' S	29° 24'E	01/08/72	17
AD	A65	18° 23' S	26° 19'E	01/05/73	14
BS6	B26	21° 06' S	28° 00'E	29/07/55	17
BNC	B36	20° 19' S	29° 00'E	15/09/59	10
BT4	B39	20° 32' S	28° 21'E	21/06/60	14

2.3 Rainfall-Runoff Modeling Approaches

The existence of a wide variety of rainfall-runoff models implies that careful selection is essential for any assignment [Takasao *et al* 1987, Dunn *et al* 1999]. As a start, the rainfall-runoff model should input observed historical records of rainfall and transform them into the corresponding function of discharge. The model should be able to represent differences in physical states through changes in parameter values [Kachroo *et al* 1991]. In this regard a model that captures the physical description of the hydrological process occurring in a region has significant advantages over purely empirical ones [Gan *et al* 1997]. This is weighed against data limitations, computational time as a result of the large number of parameters, spatial and time variability of the input data and model parameters [Chiew *et al* 1993].

Nevertheless it was recognized that models which simulate the relationship between rainfall and runoff with no internal representation of the system would not be suitable for this assignment. Such models are referred to as black-box models [Crabtree *et al* 1987, Chiew *et al* 1993]. A simplification of the transformation of input to output could take a series of interconnected conceptual steps or elements to represent the known physical processes [Chiew *et al* 1993]. Such conceptual models would then be tuned or calibrated for a particular catchment by searching for parameter values in a space of reasonable values based on the extend of diversion between observed outputs and the corresponding computed outputs of the model [Kachroo *et al* 1992, Gan *et al* 1997].

An additional requirement for this assignment was that the selected model should not only accurately model the rainfall runoff transformation processes for a region, it should be consistent when applied to different regions. Differences in behavior of different regions are expressed as differences in their conversion of rainfall to discharge. The model consistency would be shown in the level of accuracy with which the estimates of parameter values persistently give accurate output through different sub-zones and zones.

In order to select one among several different rainfall-runoff models it is essential to look at two basic components. The first one the expression of the *a priori* knowledge on the phenomenon, which is the physical component and the second, the stochastic component which expresses in statistical terms what cannot be explained by the degree of *a priori* knowledge. Total *a priori* ignorance in a model reduces it to a purely stochastic process where not even the cause and effect postulate is advocated. A purely physical model fully describing the dynamics of the model results in a deterministic model with a fixed relationship between input and output [Crabtree *at al* 1987, Todini 1988].

According to Todini (1988) the value of *a priori* knowledge is in retaining the physical meaning of the model parameters, which eliminates uncertainty associated with statistically derived parameters hence purely stochastic models are to be avoided in rainfall-runoff modeling.

In Todini (1988) the input and output variables of a physical model M with a set of parameters is assumed, and model behavior is presented as;

$$y = f(M, \alpha, x) + g(\varepsilon)$$

where y is the observed output variable in terms of the model structure M, parameters α and input variable x.

The physical parameters α are adjusted within a physically meaningful range and following basic physical justifications. Their actual values being determined from field or laboratory investigations. This will result in a residual whose structure is $g(\varepsilon)$, a stochastic component which is then minimized as the physical parameters are adjusted. The parameters M, α, x and the residual change in time and space [Takasao et al 1998].

The system dynamics can be represented in integral form as in lumped integral models mainly for computational tractability. The lumped integral model relates to a catchment or sub-catchment as a whole by considering its overall behavior. Parameters are then estimated using statistical techniques because the complex internal relationships are difficult to interpret on the basis of physical catchment characteristics [Todini 1988, Takasao *et al* 1988].

In distributed integral models an attempt is made to derive physically meaningful parameters by representing all the phenomena at sub-catchment scale using either empirical formulae or the impulse response of its sub-units in integral form and combining all the components by matching their "boundary conditions". Boundary conditions are assumed a priori which means that the sub-units and the time interval have to be sufficiently small not to hide the system dynamics, but as the number of sub-units increases the number of parameters to be handled increases hence the computational effort also increases [Todini 1988].

Distributed differential models represent the catchment behavior in terms of all the differential equations discretised in time and space expressing mass and momentum balance for each sub-system and linking together the subsystems by matching at each step their mutual boundary conditions. They require large amounts of data and computational effort but allow the study of internal phenomena at the sub-catchment scale [Todini 1988].

2.4 Selection of a Computer Program for Rainfall-Runoff Estimation

Hughes *et al* (1994) and Gan *et al* (1997) point out that over-parameterization may increase model complexity beyond what available data can support. Thus it is desirable to assess the availability of model calibration data in selecting a model. In the case of Zimbabwe hydrological zone and sub-zone maps are available from the Department of the Surveyor General on a scale of 1: 1 000 000 but this scale of mapping does not give adequate resolution of physical and geo-physical information. Topographic and vegetation maps are available on a scale of 1:250 000 with an improved resolution to estimate average values of parameters for each sub-zone. At this mapping scale 28 pieces of topographic maps and the same number of vegetation maps are required to describe the country. Resolution beyond this scale would require use of aerial photography or satellite images which were not available for this assignment. The state of runoff data has been described in section 2.2. To generate annual runoff sequences, rainfall on a monthly time-scale is required. The spatial variation of the rainfall data needs to match the spatial resolution of the model [Hughes 1994]. The objective function on this assignment was to generate low flow sequences in semi-arid rural catchments of Zimbabwe. A secondary objective was to consider how land use impacts on low flows.

Three stages are essential before application of a model namely calibration, validation and testing [Crabtree et al 1987]. Measurement errors, spatial variability of rainfall and catchment properties can contribute to the dilemma of model calibration validation and testing [Gan *et al* 1997]. Model calibration, validation and testing require computational time. Computational effort is also reflected in the amount of input data required and also the output data generated. A desktop computer with a Pentium 160Mega Hertz processor, 16Mega Bytes RAM and 2.0Giga Bytes of hard disk memory was available for the assignment. It was imperative that any model selected should perform well on this computer.

The computer model should be readily available and its cost should be affordable. Crabtree *et al* (1987) recommend that model costs should include cost of obtaining it, cost of the necessary documentation, equipment, data and time to calibrate, validate and test the model. In particular for this assignment the model should be user friendly and at the same time be reliable and consistent. According to Crabtree *et al* (1987) user friendliness should include possibilities of sensitivity analysis and generation of a complete and clear output data set.

Holden (1992) lists a total of 24 computer programs for rainfall-runoff modeling. The classification system adopted by Holden (1992) was applied to a total of 27 programs as shown in Table 2.4. Out of these programs four capture the physical description of the hydrological process in a sub-zone through infiltration, conduit routing, subsurface flow, interception, evapo-transpiration and reservoir routing and apply to continuous events. These are SWM, HYDROCOMP, HSPF and RAFLER. VTI also captures the physical description of the hydrological process and non-linear storage routing [Hughes 1994].

Of these five programs RAFLER was available for the assignment. Krohn (1989) and Mzila (1995) obtained satisfactory monthly stream flows when they appled this program on some catchments in Zimbabwe. Gan *et al* (1997) on a statement of caution points out that the majority of rainfall runoff models have been built for temperate or wet catchments. RAFLER is a BASIC program compiled by Stephenson *et al* (1992). Close proximity to the compiler facilitated easier consultation especially during calibration, validation and testing of the model. It is acknowledged that under similar conditions the other programs namely SWM, HYDROCOMP, HSPF and VTI could have been used for the assignment.

Table 2.4: Computer Models Reviewed

Model Title	Modeling Approach	Process Modeled	Catchment Dicritisation	Reference
SWM	A conceptual model	Surface runoff, conduit routing, infiltration, subsurface flows, interception, evapo-transpiration, reservoir routing	Yes	Crawford and Linsey (1966)
TR-20	SCS curve number and Unit hydrographs	Surface runoff, conduit routing, infiltration, subsurface flows, reservoir routing	Yes	Soil and Conservation Services (1972)
USGS	Time area routing	Surface runoff, conduit routing, infiltration, subsurface flows, evapo-transpiration	No	Carrigan (1973)
HYMO	SCS curve number and Unit hydrographs	Surface runoff, conduit routing, infiltration, subsurface flows, reservoir routing	Yes	Williams and Hann (1973)
HEC-1	Time-area theory and unit hydrographs	Surface runoff, conduit routing, infiltration, subsurface flows, reservoir routing	Yes	US Army Corps (1973)
ILLUDAS	Time-area routing	Surface runoff, conduit routing, infiltration, subsurface flows, reservoir routing	Yes	Tersriep and Stall (1974)
USDAHL	Empirical relationships with fitted measurable parameters	Surface runoff, conduit routing, infiltration, subsurface flows	Yes	Holtan et al (1975)
SSARR	Empirical relationships with fitted measurable parameters	Surface runoff, conduit routing, infiltration, subsurface flows, evapo-transpiration, reservoir routing	Yes	Rockwood(1975)
HYDROCOMP	Based on Stanford Watershed Model	Surface runoff, conduit routing, infiltration, subsurface flows, interception, evapo-transpiration, reservoir routing	Yes	Crawford et al (1976)
PITMAN	Conceptual	Surface runoff, conduit routing, infiltration. subsurface flows, interception, evapo-transpiration, reservoir routing	No	Pitman (1977)
IHCM	Conceptual	Surface runoff, conduit routing, infiltration, subsurface flows, interception, evapo-transpiration	No	Eeles (1978)
RUNOFF	Finite element solutions of flow equations	Surface runoff, infiltration, subsurface flows, interception	No	Jayawardena and White (1979)

Table 2.4: continued

SHE	Diffusion wave surface routing. A distributed differential model	Surface runoff, conduit routing, infiltration, subsurface flows, interception, evapo-transpiration	No	Abbott, M.B, et al [8,9]
SHIFT	A physically based 'event model'. A distributed parameter model.	Surface runoff, conduit routing, infiltration, subsurface flows, interception, reservoir routing	No	Oscar Luis Palacios-Velez and Baltasar Cuevas-Renaud [1992]
ANSWERS	A Physically based model using kinematic wave surface routing.	Surface runoff, conduit routing, infiltration, subsurface flows, interception, evapo-transpiration		Beasely, D. B. and Huggins, L.F. [1980, 1981]
CREAMS	SCS method with Physically based soil functions	Surface runoff, conduit routing, infiltration, subsurface flows, evapo-transpiration	No	Knisel (1980)
SWMM	Numerical solutions of flow equations	Surface runoff, conduit routing, infiltration, reservoir routing	Yes	Huber et al (1982)
KINE 2	Kinematic model.	Surface runoff, conduit routing, infiltration	No	Constantinides (1983)
HSPF	Derivative of Stanford Watershed Model	Surface runoff, conduit routing, infiltration, subsurface flows, interception, evapo-transpiration, reservoir routing	Yes	Johanson et al (1984)
ACRU	SCS curve number and unit hydrographs	Surface runoff, conduit routing, infiltration, subsurface flows, interception, evapo-transpiration	Yes	Schulze (1984)
IHDM	Numerical solutions of surface and subsurface flows	Surface runoff, conduit routing, infiltration, subsurface flows, interception, evapo-transpiration	Yes	Institute of Hydrology (1984)
WITWAT	Kinematic wave approximation ot surface flows	Surface runoff, conduit routing, infiltration, reservoir routing	Yes	Green (1984)
MDOR	Automatic self-calibrating model	Surface runoff, conduit routing, infiltration, subsurface flows, interception, reservoir routing	No	Villeneuve et al (1986)
WITSKM	Kinematic wave approximation to flow equations	Surface runoff, conduit routing, infiltration, subsurface flows, reservoir routing	Yes	Stephenson D. (1989)
P -EXPORT	Surface runoff generated using SCS equation	Surface runoff	Yes	Hughes (1994)
VTI	Non-linear storage routing after loss to depressions and small dam storage	Surface runoff, channel routing, infiltration, subsurface flows, reservoir routing	Yes	Hughes (1994)
RAFLER	Diffusion and kinematic wave approximation to flow equations	Surface runoff, conduit routing, infiltration, subsurface flows, interception, evapo-transpiration, reservoir routing	Yes	Stephenson D., Paling W.A.J. (1992).

3.0 APPLICATION OF RAINFALL RUNOFF MODEL ON SPECIFIC MICRO CATCHMENTS AND SUB-ZONES

3.1 Specification of Input Parameters for RAFLER

RAFLER is a conceptual deterministic model based on the simplified hydrodynamic equations of overland flow and the simplified Green Apt infiltration model for vertical flow into the soil and underlying aquifers [Stephenson *et al* 1992]. The following input parameters were specified to generate runoff estimates to extend the observed runoff data for micro catchments in each sub-zone:

i) constant for calculation of rain hours per month
ii) annual evaporation
iii) average rain-days per year for catchment
iv) catchment length
v) catchment width
vi) average ground slope
vii) Mannings 'n'
viii) rill ratio
ix) cover factor
x) saturated permeability
xi) soil suction
xii) sediment diameter and
xiii) direct runoff fraction
xiv) mean annual rainfall
xv) monthly rainfall time series

Parameters (vi) and (vii) were not input directly, they were used to calculate the ratio $\mathbf{s^{0.5}/n}$. In order to reduce the scope of the work each sub-zone was treated as homogeneous with respect to all the above factors except rainfall (parameters (xiv), and (xv)).

This meant that average sub-zone values of the following factors could be applied at the micro-catchment level:

- i) ground slope,
- ii) land use
- iii) soil characteristics
- iv) precipitation
- v) infiltration,
- vi) evaporation and
- vii) evapo-transpiration

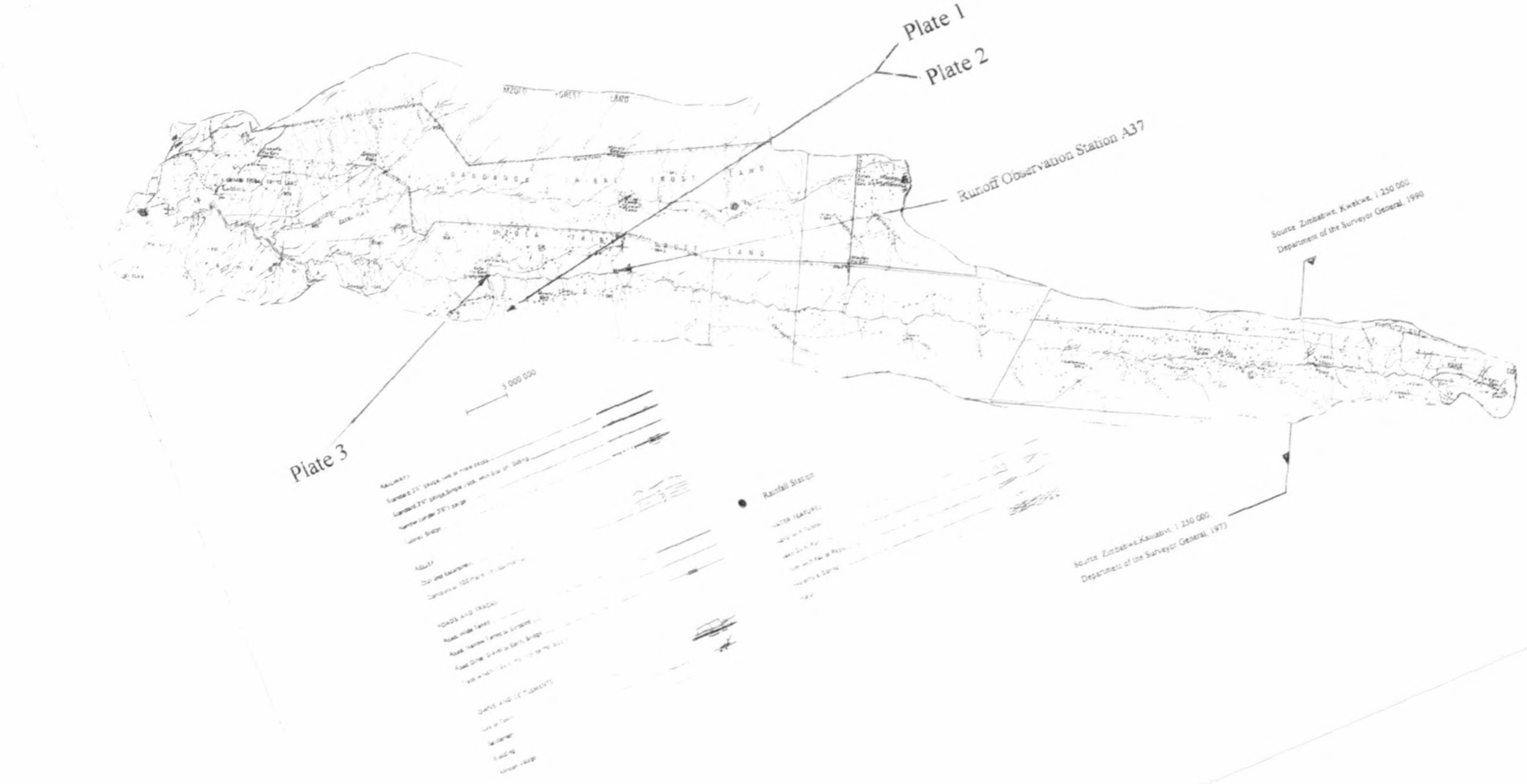
Average sub-zone topographic parameters were taken off 1:250 000 scale maps.

The use of average sub-zone parameters is built on the concept of regional drought frequency analysis (RDFA). This concept allows drought quantiles for any region to be expressed in terms of the run-off data for a site in that region. It is assumed that for a given region there is a system of runoff stations whose drought-frequency is homogenous in some quantifiable manner. This means that input parameters need not be estimated for individual sites, only their regional average values need to be estimated. Homogeneity can be judged on statistical tests of hypothesis. For example, to test if all stations in a given geographic region could be considered homogeneous an index drought could be defined. It could assume an extreme value distribution such as type one, however, if small departures from perfect homogeneity are observed they can be weighed against the advantages of RDFA [Singh 1987, Cunane 1988].

3.2 General Description of Selected Sub-zones

As presented in Table 3.3 sub-zones AS1, AS2, AS3, AS5, AS6, BNC and BS6 were selected for the study. These are the ones shaded on the hydrological sub-zone map, Figure 2. A brief description of the topographic and land use patterns of the first six sub-zones is given here. Estimates of the parameters were derived from this geo-physical information and a ground truthing visit. On all the map extracts the grid lines show the direction of North.

Figure 4 Sub-zone AS1 Topographic Features



Source: Zimbabwe, Kwekwe, 1:250 000,
Department of the Surveyor General, 1990

Source: Zimbabwe, Kadoma, 1:250 000,
Department of the Surveyor General, 1973

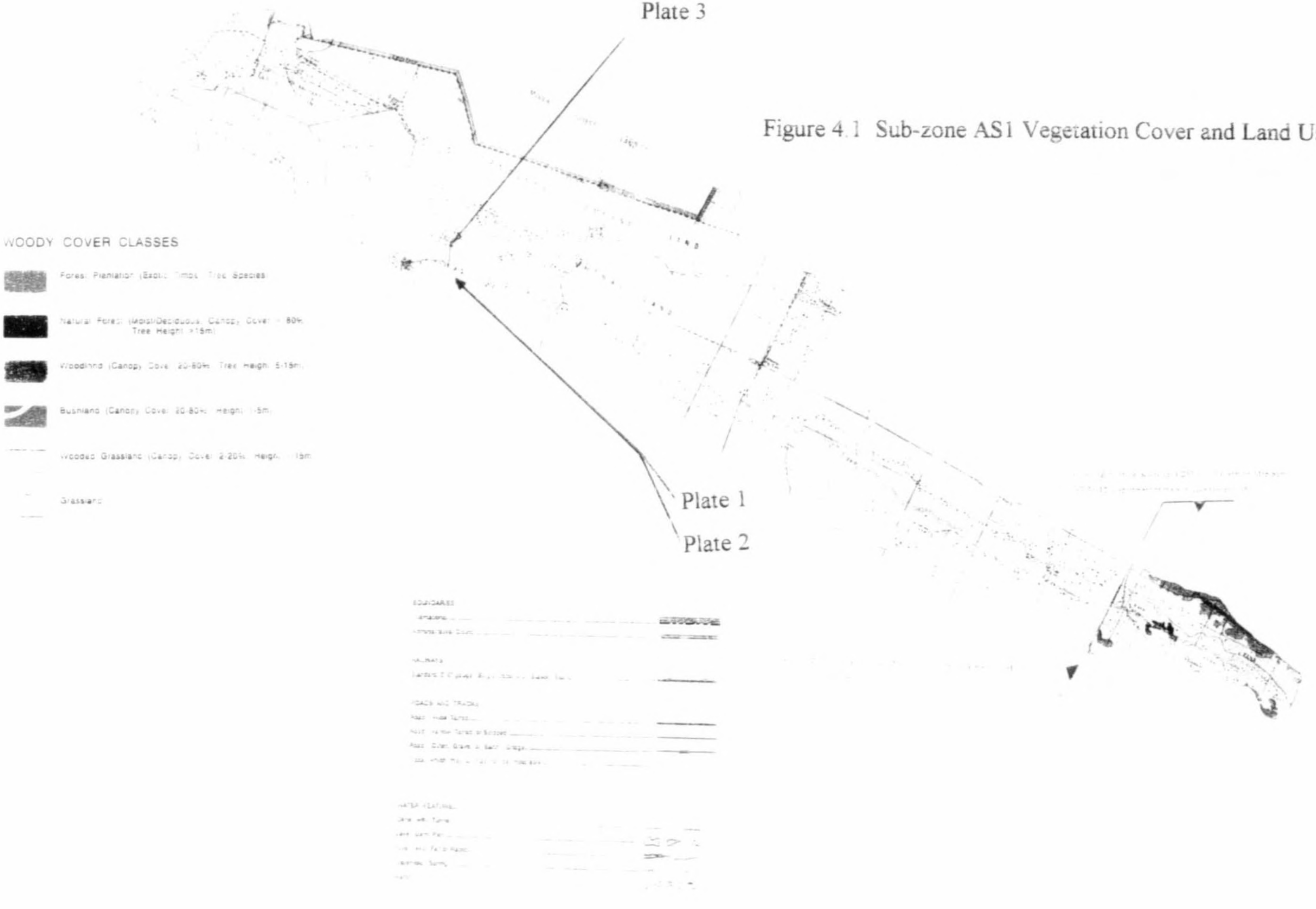


Figure 4.1 Sub-zone AS1 Vegetation Cover and Land Use

Plate [illegible] Sub-zone AS1 Vegetation Cover

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