4.0 DROUGHT FREQUENCY ANALYSIS FROM RUNOFF TIME SERIES

4.1 Definition of Hydrological Droughts

Drought analysis considers annual minima of daily discharges as expressed by Gumbel E J (1958). If drought is the other extreme of floods, then from Cunane C (1988) drought frequency analysis is used to estimate drought quantile magnitude at a given location. In general, different levels of drought severity can be experienced.

According to Stephenson *et al* (1983) from a runoff record of N years, a cumulative runoff deficit 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.

Herbst (1966) proposes the use of a weighted drought index defined as the product of P and rainfall deficit to denote the severity of a rainfall drought. It follows that a simplified expression of severity of cumulative runoff deficits integrates the product of runoff deficit and drought period. Of even more importance to planners and engineers is the rarity of a drought of a given severity. The rarity of the drought being estimated can be expressed in terms of its recurrence interval RI.

Droughts of different severity and RI produce different effects on life forms and national economies. P, D_p and RI are important parameters in drought risk analysis.

4.2 Generation of Point Runoff for Drought Frequency Analysis

In chapter 3 monthly runoff time series was generated on micro-catchment and sub-zone levels. This data was converted to annual runoff time-series for drought analysis. On the Microsoft Excel Spreadsheet the estimated annual runoff was converted to annual point runoff by dividing it by the total catchment area. This was done at both the micro-catchment and sub-zone levels.

By comparison of point runoff from micro catchments and that from their respective sub-zones the concept of RDFA was tested. This was done through analysis of distribution of runoff for each micro catchment and its respective sub-zone. It entailed frequency analysis on the data. First the unit runoff was ranked in ascending order. Then taking the years of record as n the recurrence interval RI years for point runoff of rank m a recurrence interval was calculated using the Weilbull equation:

$$RI = \left[\frac{n+1}{m} \right] \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \; 4.1$$

Frequency of exceedence important in assessing degree of agreement in low values of runoff estimates. From equation 4.1 the frequency of exceeding an annual point runoff of rank m taken from n years of record was derived as follows:

$$\%Frequency(F) = \left[1 - \frac{1}{RI} \right] x100 \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \; 4.2$$

$$\%Frequency(F) = \left[1 - \frac{m}{n+1} \right] x100 \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \; 4.3$$

4.3 Micro Catchment and Sub-zone Point Runoff Comparison

The computed micro catchment and sub-zone point runoff is shown in Tables 4.1, 4.2 and 4.3. From these tables it was observed that except for sub-zone BNC there was good agreement between micro-catchment and sub-zone point runoff estimates especially in the range of F from 50% to 90% which is the area of focus for this study. However, closer analysis reveals the following:

(a) although AS1 and AS2 used the same rainfall station AS1 produced better agreement between sub-zone and micro catchment low flow estimates although the runoff station used for AS2 was closer to the rainfall station (see Table 3.3). AS2 was about 7.9 times larger than its micro catchment area while AS1 was only about 2.3 times its micro catchment area. This indicated that RAFLER was more sensitive to the relative size of sub-zone to micro catchment areas than to the relative distance between rainfall and runoff stations.

(b) estimates of low flows for AS3 with an area of about 3 times its micro catchment, were within 10% of the micro catchment point runoff. The rainfall station used was within sub-zone AS3.

(c) AS5 used two different rainfall stations almost equidistant from the runoff station. Only small differences were observed between micro catchment runoff estimates in the 50% and 60% exceedence range while in the 70% to 90% there was very good agreement. Sub-zone AS5 was about the same size as its micro catchment. This probably accounted for this rather small difference. There was very good agreement between micro catchment and sub-zone runoff estimates. One rainfall station namely Somabula was in the same sub-zone as the runoff station while the other rainfall station was in another sub-zone of the same major river catchment. This indicates that to get good estimates of point runoff for the micro catchment, extend to the sub-zone and still get good estimates the rainfall station need not be in the same sub-zone as the runoff station.

Table 4.1 Point Runoff of Selected Exceedence for Sub-zones AS1, AS2 and AS3

Percentage Exceedence	Estimated Runoff (mm)					
	Sub-zone AS1		Sub-zone AS2		Sub-zone AS3	
	Lupane Rainfall Station		Lupane Rainfall Station		Lower Gweru Rainfall Station	
	Micro catchment	Sub-zone	Micro catchment	Sub-zone	Micro-catchment	Sub-zone
10	37	27	39	17	109	92
20	24	22	26	12	90	75
30	22	18	21	11	80	68
40	18	16	17	8	70	60
50	16	14	13	8	58	52
60	14	10	11	6	53	48
70	13	9	10	6	45	41
80	12	8	9	5	30	29
90	10	7	7	4	27	26

4.2 Point Runoff of Selected Frequencies for Sub-zones AS5 and AS6

Percentage Exceedence	Estimated Runoff (mm)							
	Sub-zone AS5				Sub-zone AS6			
	Gweru Thornhill		Somabula		Shangani Rail		Shangani Ranch	
	Micro-catchment	Sub-zone	Micro-catchment	Sub-zone	Micro-catchment	Sub-zone	Micro-catchment	Sub-zone
10	43	43	46	46	70	42	79	46
20	33	33	39	39	56	37	56	36
30	29	29	31	31	46	30	59	28
40	26	26	28	28	36	27	36	26
50	23	23	26	26	27	22	29	24
60	21	21	23	23	24	20	24	22
70	19	19	19	19	21	19	20	18
80	16	16	16	16	17	16	17	15
90	13	13	14	14	13	13	12	12

Table 4.3 **Point Runoff of Selected Frequencies for Sub-zones BNC and BS6**

Percentage Exceedence	Estimated Runoff (mm)			
	Sub-zone BNC		Sub-zone BS6	
	Filabusi		Kezi	
	Micro-catchment	Sub-zone	Micro-catchment	Sub-zone
10	131	59	33	48
20	96	39	25	26
30	81	30	16	17
40	62	22	13	11
50	45	15	11	9
60	29	11	9	8
70	22	7	6	6
80	13	5	5	5
90	7	3	4	4

(d) AS6 used two rainfall stations in the same sub-zone as the runoff station. Very good agreement between micro catchment point runoff was achieved using the two stations. Sub-zone AS6 was about 22 times the size of its micro catchment. Very small differences were observed in results of sub-zone point runoff estimates using the two rainfall stations.

(e) BNC low flows were up to 67% less than those of its micro catchment. BNC was about 35 times its micro catchment. The rainfall station used was in a sub-zone and major-river catchment different from those of the runoff station. The rainfall station was only about 38km from the runoff station. This supports observations in (a) and (c) on RAFLER's response to relative size of sub-zone to micro catchment, location of rainfall station relative to runoff station and the distance between rainfall and runoff stations.

(f) for low flows for sub-zone BS6 there was good agreement between micro and sub-zone point runoff.

The rainfall station was in a different sub-zone and major river catchment from the runoff station. [illegible] about 6 times its micro catchment area. RAFLER's response to relative size of sub-zone to micro catchment and location of the rainfall station was again highlighted.

These observations painted two important scenarios as follows:

- there was very good agreement in micro catchment low flow estimates using different rainfall stations within the same sub-zone as the runoff stations for sub-zone to micro catchment ratio of up to about 22. For such cases extension to the sub-zone resulted in good agreement between micro catchment and sub-zone runoff.
- there was good agreement between micro catchment and sub-zone low flow estimates using different rainfall stations in the same major river catchment as the runoff station but in different sub-zones for sub-zone to micro catchment areas ratio of up to 6. For such cases extension to the sub-zone resulted in good agreement between micro catchment and sub-zone runoff.

Thus the nearest reliable station in the same climatic zone, hydrological zone and major river catchment as the runoff observation station can be used to model runoff for a sub-zone depending on the ratio of sub-zone to micro catchment area. Use of a rainfall station in the same climatic and hydrological zone but different major river catchment resulted in a significant difference in flow response in moving from the micro to the sub-zone catchment except where the ratio of sub-zone to micro catchment was small.

The majority of gauged micro catchments in Zimbabwe have areas below 1840km^2 (Government of Zimbabwe Hydrological Branch, 1979). From Kabel (1984) the catchment areas of the majority of sub-zones fall below 4800 km^2. It can be concluded from this observation that RAFLER can be used directly in drought analysis for most of the sub-zones of Zimbabwe.

For this assignment the sub-zone annual point runoff generated using RAFLER for sub-zones AS1, AS2 AS3, AS5, AS6 and BS6 was adopted to derive drought sequences. Sub-zone BNC was dropped because of the discrepancy between micro catchment and sub-zone point runoff.

From the results in Tables 4.1, 4.2 and 4.3 the point runoff distribution of each sub-zone is unique. This observation implies that for extension of runoff data using this methodology the sub-zone is the largest unit to be considered in Zimbabwe if a high degree of accuracy is desired.

4.4 Generation of Hydrological Drought Sequences

Using the annual point runoff time series, cumulative drought runoff D_p of 80%, 70% and 50% of mean annual point runoff of partial duration series of period P were computed. Values of P of 1,2, 3 and 4 consecutive years were taken. Hydrological drought sequences were then generated on the annual point runoff data for each drought period P.

The procedure used for generating a drought sequence was as follows [Stephenson *et al* 1983]:

a) from the annual point runoff a partial duration series was created by cumulative addition of flows in each drought period of P years
b) the long range mean R_{pave} of each partial duration series was computed and the value of D_p was worked out
c) the lowest flow was picked out of the partial duration series and assigned rank number one.
d) to avoid overlapping the preceding and subsequent P-1 records were excluded from further consideration.
e) the next lowest flow of the remaining data on the partial duration series was picked out and ranked number two and again the preceding and subsequent P-1 records were excluded from further consideration.

f) the procedure was repeated until all sequences having a value less than D_p had been considered. Sequences with values greater than D_p were ignored.

The procedure was repeated for each sub-zone for all values of P. Tables 4.4 to 4.9 show the drought sequences for droughts resulting in D_p less than 80%, 70% and 50% of the mean of each partial duration series R_{pave}. These are denoted $D_{p.80}$, $D_{p.70}$ and $D_{p.50}$ in this report.

4.5 AS1: Drought Sequences

Table 4.4 shows the drought sequences for sub-zone AS1. From this Table, R_{pave} for P equal to 1, 2, 3 and 4years is 16mm, 32mm, 48mm and 63mm respectively. For any RI the cumulative runoff deficit for drought lasting any integral duration P from 1 to 4 years can be obtained. The data in Table 4.4 was plotted on Figure 20 to allow extrapolation on the frequency scale to integral years, which cannot be easily performed on the table. For ease of application of the table the lower runoff closest to the drought runoff was used to determine *RI*.

To illustrate how the Table 4.4 is used three drought levels are given namely $D_{p.80}$, $D_{p.70}$ and $D_{p.50}$ and the duty is set at $R_{p.ave}$. From the table, a drought of $D_{1.80}$ occurs once every 2.07 years, $D_{1.70}$ occurs once in 2.52 years and $D_{1.50}$ occurs once in 5.8 years. The values of the cumulative deficits for $D_{1.80}$, $D_{1.70}$ and $D_{1.50}$ are 3mm, 5mm and 8mm respectively.

A drought of $D_{2.80}$ occurs once every 3.87 years, $D_{2.70}$ once in 5.27 years and $D_{2.50}$ once in 19.33 years. The values of the cumulative deficits for $D_{2.80}$, $D_{2.70}$ and $D_{2.50}$ are 7mm, 10mm and 16mm respectively.

A drought of $D_{3.80}$ occurs once every 7.25 years, $D_{3.70}$ once in 9.67 years and $D_{3.50}$ once in 29.00 years. The values of the cumulative deficits for $D_{3.80}$, $D_{3.70}$ and $D_{3.50}$ are 10mm, 15mm and 24mm respectively.

A drought of $D_{4,80}$ occurs once every 11.6 years, $D_{4,70}$ once in 19.33 years and $D_{4,50}$ once in 29.00 years. The values of the cumulative deficits for $D_{4,80}$, $D_{4,70}$ and $D_{4,50}$ are 12mm, 19mm and 31mm respectively.

From these results for sub-zone AS1 once in every 2 years annual runoff drops below 80% of average. It was also noted that droughts lasting longer are less frequent but have greater cumulative deficit conversely droughts resulting in greater cumulative deficit are less frequent but last longer.

Table 4.4 AS1: Drought Sequences

Drought Period P (years) →	1	2	3	4	**Drought Period P (years) →**	1
Value of R_{pave} *(mm)* →	**16**	**32**	**48**	**63**	**Value of R_{pave} *(mm)* →**	**16**
$D_{p,80}$ (mm) →	**13**	**25**	**38**	**51**	**$D_{p,80}$ (mm) →**	**13**
$D_{p,70}$ (mm) →	**11**	**22**	**33**	**44**	**$D_{p,70}$(mm) →**	**11**
$D_{p,50}$ (mm →	**8**	**16**	**24**	**32**	**$D_{p,50}$ (mm) →**	**8**
Recurrence Interval RI ↓					**Recurrence Interval RI ↓**	
58.00	5	11	18	25	3.22	9
29.00	5	14	23	31	3.05	9
19.33	6	14	24	34	2.90	10
14.50	6	16	25	44	2.76	10
11.60	7	17	27	48	2.64	10
9.67	7	17	29	59	2.52	10
8.29	7	18	34	60	2.42	11
7.25	7	18	37		2.32	11
6.44	7	20	38		2.23	11
5.80	7	20	42		2.15	12
5.27	8	20	45		2.07	12
4.83	8	23			2.00	14
4.46	8	23			1.93	14
4.14	8	23			1.87	15
3.87	8	24			1.81	15
3.63	8					
3.41	9					

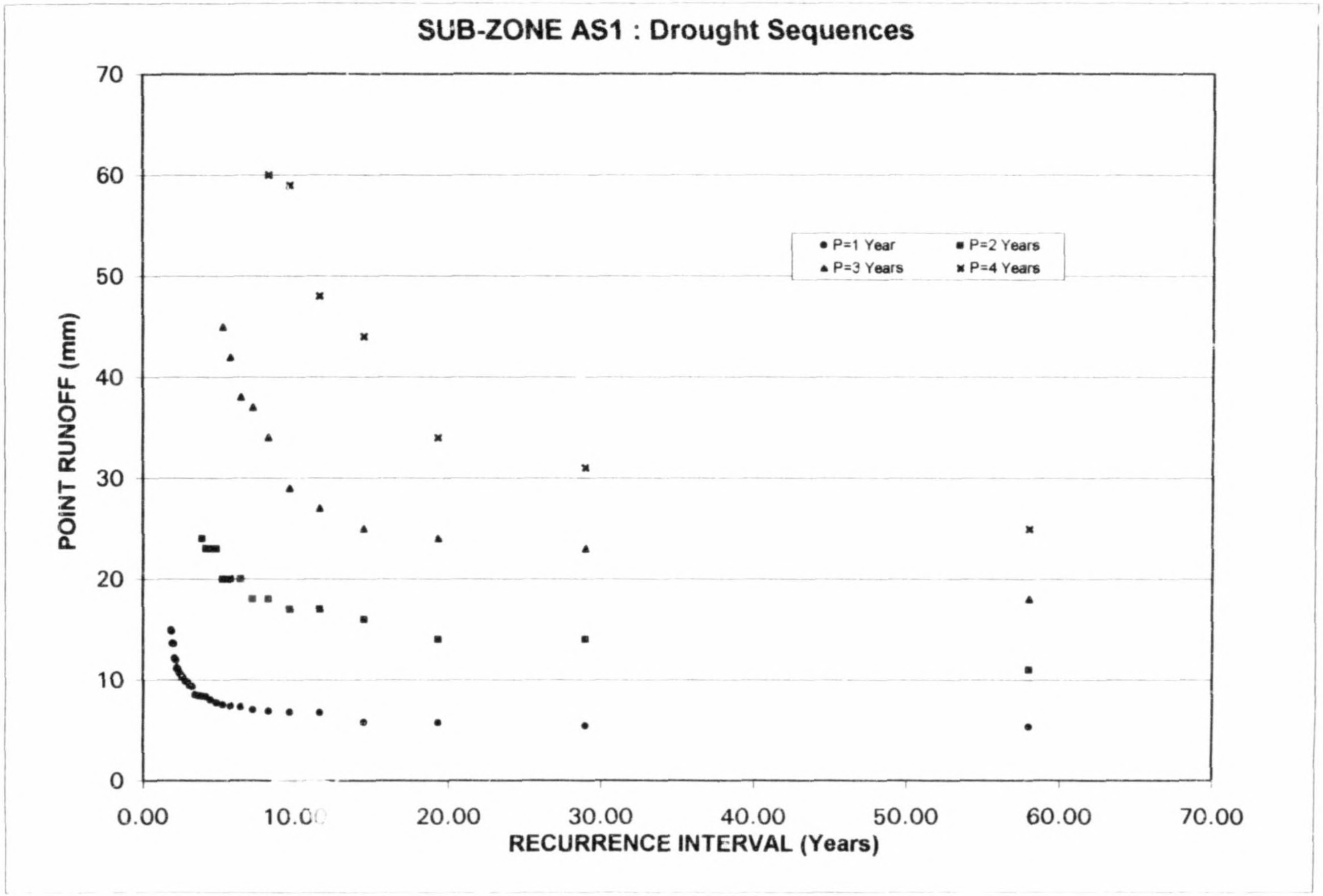

SUB-ZONE AS1 : Drought Sequences
POINT RUNOFF (mm)
RECURRENCE INTERVAL (Years)
P=1 Year
P=2 Years
P=3 Years
P=4 Years
0
10
20
30
40
50
60
70
0.00
10.00
20.00
30.00
40.00
50.00
60.00
70.00

Figure 20

4.6 AS2: Drought Sequences

Table 4.5 shows the drought sequences for sub-zone AS2. From this Table, R_{pave} for P equal to 1, 2,3 and 4years is 9mm, 19mm, 28mm and 38mm respectively. For any RI the cumulative runoff deficit for drought lasting any integral duration P from 1 to 4 years can be obtained.

The data in Table 4.5 was plotted on Figure 21 to allow extrapolation on the frequency scale to integral years, which cannot be easily performed on the table. For ease of application of the table the lower runoff closest to the drought runoff was used to determine *RI*.

To illustrate how the Table 4.5 is used three drought levels are given namely $D_{p,80}$, $D_{p,70}$ and $D_{p,50}$ and the duty is set at R_{pave}. From the table, a drought of $D_{1,80}$ occurs once every 2.42 years, $D_{1,70}$ occurs once in 2.42 years and $D_{1,50}$ occurs once in 9.67 years. The values of the cumulative deficits for $D_{1,80}$, $D_{1,70}$ and $D_{1,50}$ are 2mm, 2mm and 4mm respectively.

A drought of $D_{2,80}$ occurs once every 4.48 years, $D_{2,70}$ once in 5.80 years and $D_{2,50}$ once in 14.5 years. The values of the cumulative deficits for $D_{2,80}$, $D_{2,70}$ and $D_{2,50}$ are 4mm, 6mm and 9mm respectively.

A drought of $D_{3,80}$ occurs once every 6.44 years, $D_{3,70}$ once in 9.67 years and $D_{3,50}$ once in 58.00 years. The values of the cumulative deficits for $D_{3,80}$, $D_{3,70}$ and $D_{3,50}$ are 5mm, 8mm and 14mm respectively.

A drought of $D_{4,80}$ occurs once every 9.67 years, $D_{4,70}$ once in 11.60 years and $D_{4,50}$ once in 29.00 years. The values of the cumulative deficits for $D_{4,80}$, $D_{4,70}$ and $D_{4,50}$ are 8mm, 12mm and 38mm respectively.

From sub-zone AS2 $D_{1.80}$, $D_{1.70}$ show the same RI of 2.42 years and approximately the same cumulative deficit mainly because of rounding off errors. $D_{3.50}$ which is least frequent does not have the greatest cumulative deficit. In fact $D_{4.50}$ is more frequent than $D_{3.50}$ and has a greater cumulative deficit. Therefore the drought behavior of AS2 is markedly different from that of AS1.

Table 4.5 AS2: Drought Sequences

Drought Period P (years) →	1	2	3	4	Drought Period P (years) →	1
Value of R_{pave} (mm) →	9	19	28	38	Value of R_{pave} (mm) →	9
$D_{p.80}$ (mm) →	7	15	23	30	$D_{p.80}$ (mm) →	7
$D_{p.70}$ (mm) →	7	13	20	26	$D_{p.70}$(mm) →	7
$D_{p.50}$(mm) →	5	10	14	19	$D_{p.50}$(mm) →	5
Recurrence Interval RI ↓					Recurrence Interval RI ↓	
58.00	3	8	12	17	2.64	6
29.00	4	8	14	18	2.52	6
19.33	4	9	14	20	2.42	6
14.50	4	9	17	25	2.32	7
11.60	4	10	18	25	2.23	7
9.67	4	11	19	28	2.15	7
8.29	5	11	20	34	2.07	7
7.25	5	11	20	35	2.00	8
6.44	5	12	22		1.93	8
5.80	5	12	23		1.81	8
5.27	5	13			1.76	8
4.83	5	14			1.71	8
4.46	5	14			1.66	8
4.14	6	15				
3.87	6	18				
3.63	6	18				
3.41	6					
3.22	6					
3.05	6					
90	6					
2.76	6					

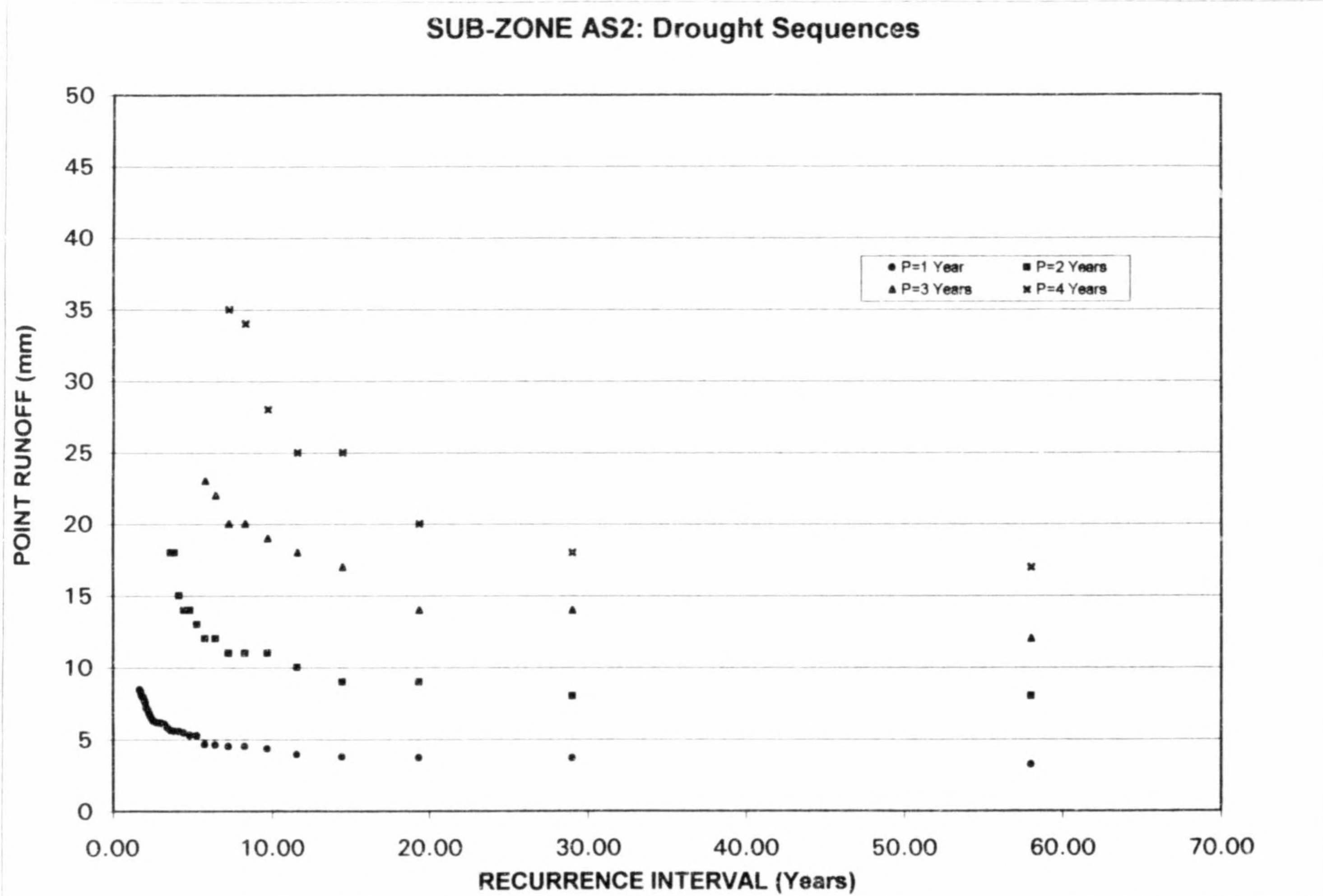

SUB-ZONE AS2: Drought Sequences
POINT RUNOFF (mm)
RECURRENCE INTERVAL (Years)
P=1 Year
P=2 Years
P=3 Years
P=4 Years
0
5
10
15
20
25
30
35
40
45
50
0.00
10.00
20.00
30.00
40.00
50.00
60.00
70.00

Figure 21

4.7 AS3: Drought Sequences

Table 4.6 shows the drought sequences for sub-zone AS3. From this Table, R_{pave} for P equal to1, 2,3 and 4years is 54mm, 109mm, 162mm and 215mm respectively. For any RI the cumulative runoff deficit for drought lasting any integral duration P from 1 to 4 years can be obtained. The data in Table 4.6 was plotted on Figure 22 to allow extrapolation on the frequency scale to integral years, which cannot be easily performed on the table. For ease of application of the table the lower runoff closest to the drought runoff was used to determine RI.

To illustrate how the Table 4.6 is used three drought levels are given namely $D_{p,80}$, $D_{p,70}$ and $D_{p,50}$ and the duty is set at R_{pave}. From the table, a drought of $D_{1,80}$ occurs once every 2.93 years, $D_{1,70}$ occurs once in 2.73 years and $D_{1,50}$ occurs once in 10.25 years. The values of the cumulative deficits for $D_{1,80}$, $D_{1,70}$ and $D_{1,50}$ are 10mm, 16mm and 27mm respectively.

A drought of $D_{2,80}$ occurs once every 5.86 years, $D_{2,70}$ once in 8.20 years and $D_{2,50}$ once in 20.50 years. The values of the cumulative deficits for $D_{2,80}$, $D_{2,70}$ and $D_{2,50}$ are 22mm, 33mm and 54mm respectively.

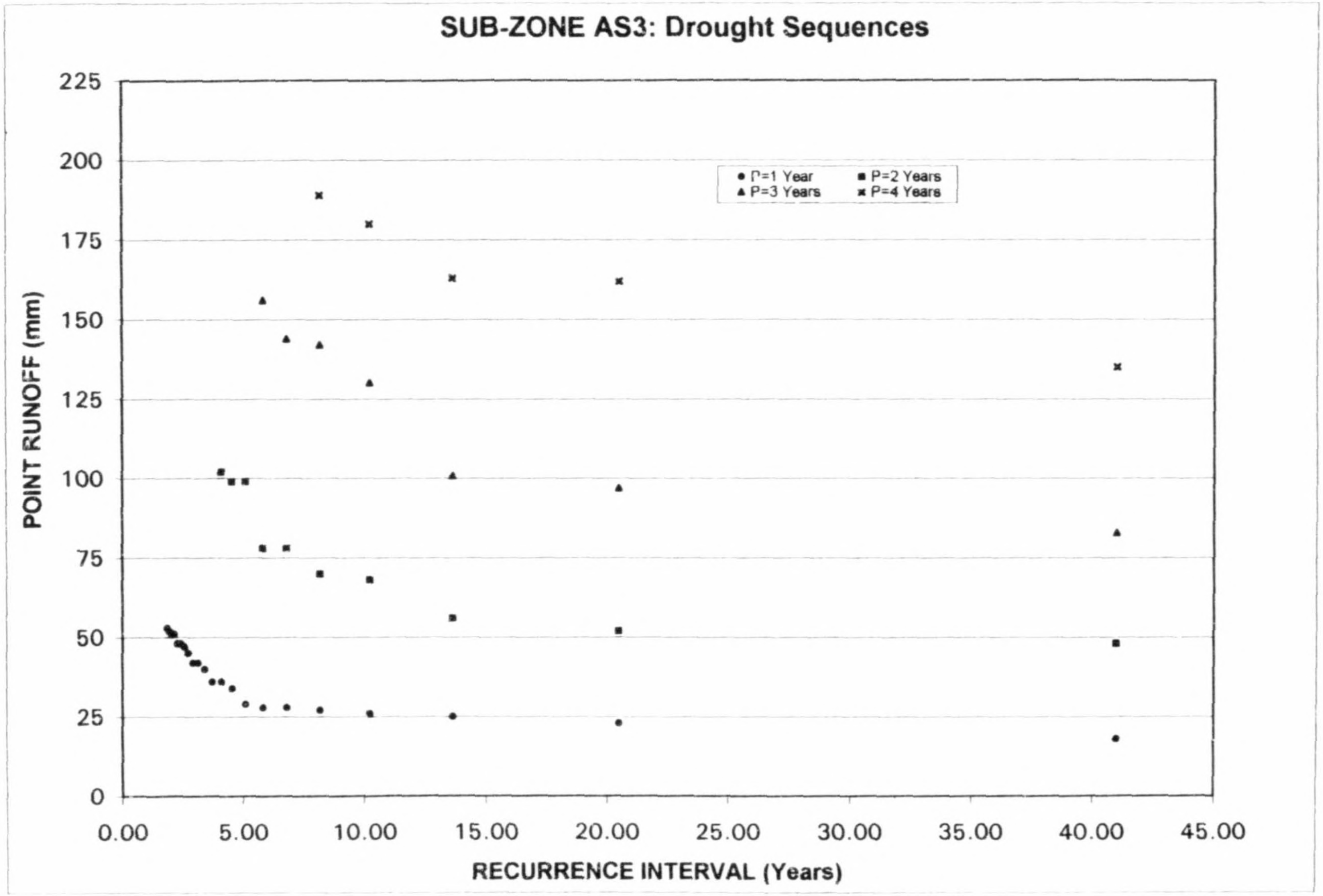
A drought of $D_{3,80}$ occurs once every 13.67 years and $D_{3,70}$ once in 13.67 years. The data is not adequate to estimate the RI of the $D_{3,50}$ drought. The values of the cumulative deficits for $D_{3,80}$ and $D_{3,70}$ are 32mm and 48mm respectively.

A drought of $D_{4,80}$ occurs once every 13.67 years and $D_{4,70}$ once in 41years. The data is not adequate to estimate the RI of the $D_{4,50}$ drought. The values of the cumulative deficits for $D_{4,80}$, and $D_{4,70}$ are 43mm and 64mm respectively.

From sub-zone AS3 $D_{3,80}$, $D_{3,70}$ show the same RI of 13.67 years and approximately the same cumulative deficit mainly because of rounding off errors. $D_{1,80}$ has a deficit of 10mm but is less frequent than $D_{1,70}$ which has a cumulative deficit of 16mm.

Table 4.6 AS3: Drought Sequences

Drought Period P (years) →	1	2	3	4
Value of R_{pave} *(mm)* →	54	109	162	215
$D_{p,80}$(mm) →	44	87	130	172
$D_{p,70}$(mm) →	38	76	114	151
$D_{p,50}$(mm) →	27	55	81	108
Recurrence Interval RI ↓				
41.00	18	48	83	135
20.50	23	52	97	162
13.67	25	56	101	163
10.25	26	68	130	189
8.20	27	70	142	
6.83	28	78	144	
5.86	28	78	156	
5.13	29	99		
4.56	34	99		
4.10	36	102		
3.73	36			
3.42	40			
3.15	42			
2.93	42			
2.73	45			
2.56	47			
2.41	48			
2.28	48			
2.16	51			
2.05	51			
1.95	52			
1.86	53			



SUB-ZONE AS3: Drought Sequences
P=1 Year
P=2 Years
P=3 Years
P=4 Years
POINT RUNOFF (mm)
0
25
50
75
100
125
150
175
200
225
0.00
5.00
10.00
15.00
20.00
25.00
30.00
35.00
40.00
45.00
RECURRENCE INTERVAL (Years)

Figure 22

4.8 AS5: Drought Sequences

Table 4.7 shows the drought sequences for sub-zone AS5. From this Table, R_{pave} for P equal to1, 2,3 and 4years is 27mm, 54mm, 80mm and 107mm respectively. For any RI the cumulative runoff deficit for drought lasting any integral duration P from 1 to 4 years can be obtained. The data in Table 4.7 was plotted on Figure 23 to allow extrapolation on the frequency scale to integral years, which cannot be easily performed on the table. For ease of application of the table the lower runoff closest to the drought runoff was used to determine *RI*.

To illustrate how the Table 4.7 is used three drought levels are given namely $D_{p,80}$, $D_{p,70}$ and $D_{p,50}$ and the duty is set at R_{pave}. From the table, a drought of $D_{1,80}$ occurs once every 2.88years, $D_{1,70}$ occurs once in 3.63 years and $D_{1,50}$ occurs once in 9.8 years. The values of the cumulative deficits for $D_{1,80}$, $D_{1,70}$ and $D_{1,50}$ are 6mm, 8mm and 13mm respectively.

A drought of $D_{2,80}$ occurs once every 5.44 years, $D_{2,70}$ once in 8.91 years and $D_{2,50}$ once in 98.00 years. The values of the cumulative deficits for $D_{2,80}$, $D_{2,70}$ and $D_{2,50}$ are 11mm, 17mm and 27mm respectively.

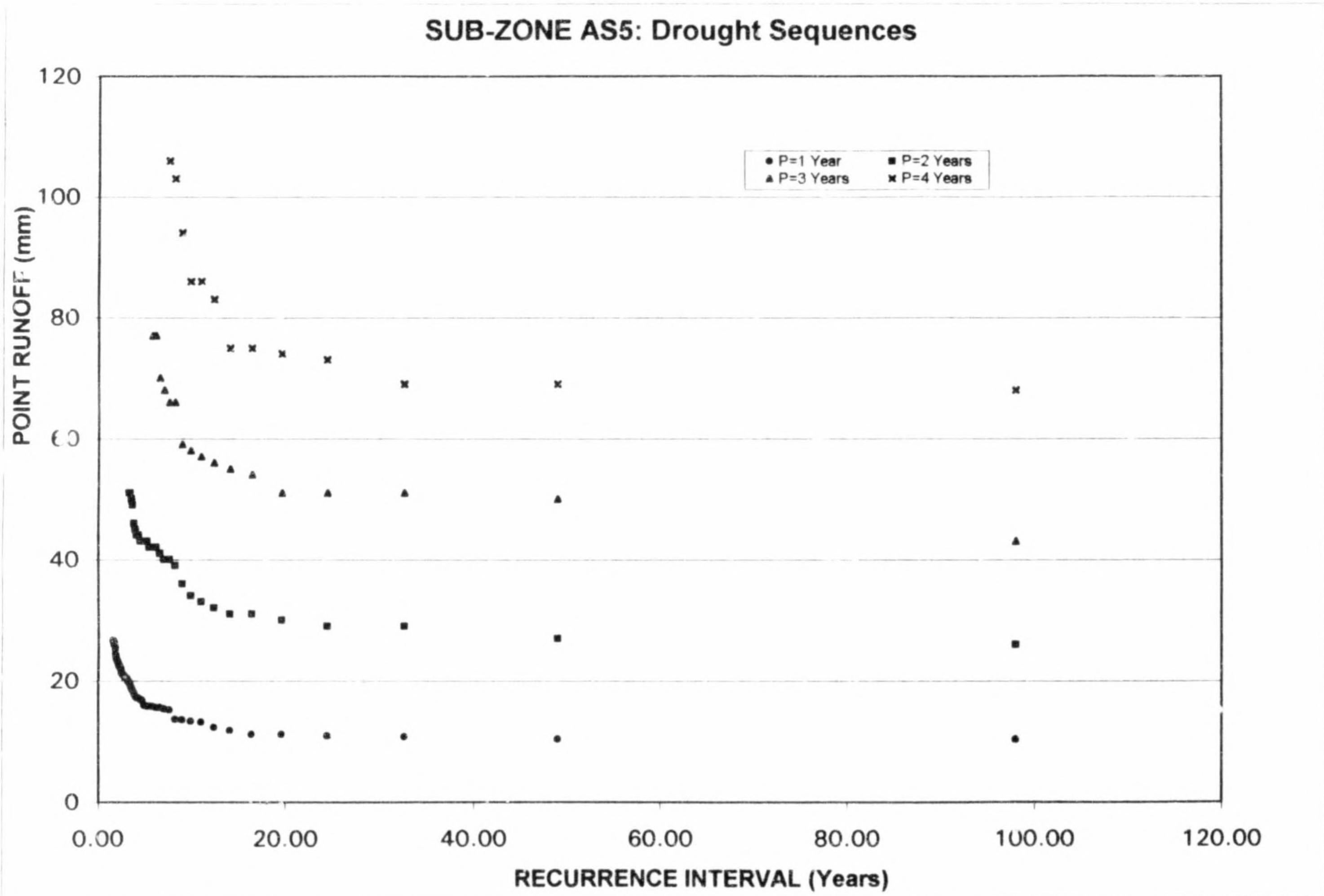
A drought of $D_{3,80}$ occurs once every 8.91 years and $D_{3,70}$ once in 14.00 years. The data is not adequate to estimate the *RI* of the $D_{3,50}$ drought. The values of the cumulative deficits for $D_{3,80}$ and $D_{3,70}$ are 16mm and 24mm respectively.

A drought of $D_{4,80}$ occurs once every 12.25 years and a deficit of 6mm occurs. $D_{4,70}$ once in 19.6years. The data is not adequate to estimate the *RI* of the $D_{4,50}$ drought. The values of the cumulative deficits for $D_{4,80}$, and $D_{4,70}$ are 21mm and 32mm respectively.

Sub-zone AS5 experiences a drought of $D_{1,80}$ once very three years and the deficit is 6mm, sub-zone AS3 also experiences a drought of $D_{1,80}$ once every 3 years but the deficit is about 10mm. It is observed that this level of drought is more severe in AS3 than in AS5.

Table 4.7 AS5: Drought Sequences

Drought Period P (years) →	1	2	3	4	Drought Period P (years) →	1	2	Drought Period P (years) →	1
Value of R_{pave} (mm) →	**27**	**54**	**80**	**107**	**Value of R_{pave} (mm) →**	**27**	**54**	**Value of R_{pave} (mm) →**	**27**
$D_{p,80}$(mm) →	**21**	**43**	**64**	**86**	**$D_{p,80}$(mm) →**	**21**	**43**	**$D_{p,80}$(mm) →**	**21**
$D_{p,70}$(mm) →	**19**	**37**	**56**	**75**	**$D_{p,70}$(mm) →**	**19**	**37**	**$D_{p,70}$(mm) →**	**19**
$D_{p,50}$(mm) →	**14**	**27**	**40**	**54**	**$D_{p,50}$(mm) →**	**14**	**27**	**$D_{p,50}$(mm) →**	**14**
Recurrence Interval RI ↓					**Recurrence Interval RI ↓**			**Recurrence Interval RI ↓**	
98.00	10	26	43	68	4.45	17	43	2.28	22
49.00	10	27	50	69	4.26	17	44	2.23	22
32.67	11	29	51	69	4.08	17	44	2.18	23
24.50	11	29	51	73	3.92	18	45	2.09	23
19.60	11	30	51	74	3.77	18	46	2.04	23
16.33	11	31	54	75	3.63	18	49	2.00	23
14.00	12	31	55	75	3.50	19	50	1.96	23
12.25	12	32	56	83	3.38	19	51	1.92	23
10.89	13	33	57	86	3.27	20	51	1.88	24
9.80	13	34	58	86	3.16	20		1.85	24
8.91	14	36	59	94	3.06	20		1.81	24
8.17	14	39	66	103	2.97	20		1.78	25
7.54	15	40	66	106	2.88	20		1.75	25
7.00	15	40	68		2.80	21		1.72	26
6.53	16	41	70		2.72	21		1.69	26
6.13	16	42	77		2.65	21		1.66	26
5.76	16	42	77		2.58	21		1.63	26
5.44	16	42			2.51	21		1.61	26
5.16	16	43			2.45	21		1.58	26
4.90	16	43			2.39	22		1.56	27
4.67	17	43			2.33	22			



SUB-ZONE AS5: Drought Sequences
POINT RUNOFF (mm)
RECURRENCE INTERVAL (Years)
P=1 Year
P=2 Years
P=3 Years
P=4 Years
0
20
40
60
80
100
120
0.00
20.00
40.00
60.00
80.00
100.00
120.00

Figure 23

4.9 AS6: Drought Sequences

Table 4.8 shows the drought sequences for sub-zone AS6. From this Table, R_{pave} for P equal to1, 2,3 and 4years is 26mm, 52mm, 79mm and 105mm respectively. For any RI the cumulative runoff deficit for drought lasting any integral duration P from 1 to 4 years can be obtained. The data in Table 4.8 was plotted on Figure 24 to allow extrapolation on the frequency scale to integral years, which cannot be easily performed on the table. For ease of application of the table the lower runoff closest to the drought runoff was used to determine *RI*.

To illustrate how the Table 4.8 is used three drought levels are given namely $D_{p,80}$, $D_{p,70}$ and $D_{p,50}$ and the duty is set at R_{pave}. From the table, a drought of $D_{1,80}$ occurs once every 3.00years, $D_{1,70}$ occurs once in 5.09 years and $D_{1,50}$ occurs once in 9.00years. The values of the cumulative deficits for $D_{1,80}$, $D_{1,70}$ and $D_{1,50}$ are 5mm, 8mm and 13mm respectively.

A drought of $D_{2,80}$ occurs once every 7.50 years, $D_{2,70}$ once in 11.25 years and $D_{2,50}$ once in 45.00 years. The values of the cumulative deficits for $D_{2,80}$, $D_{2,70}$ and $D_{2,50}$ are 10mm, 15mm and 26mm respectively.

A drought of $D_{3,80}$ occurs once every 9.00 years, $D_{3,70}$ once in 15.00 years and $D_{3,50}$ once in 45.00 years. The values of the cumulative deficits for $D_{3,80}$, $D_{3,70}$ and $D_{3,50}$ are 13mm 24mm and 39mm respectively.

A drought of $D_{4,80}$ occurs once every 15.00 years and $D_{4,70}$ once in 45.00years. The data is not adequate to estimate the *RI* of the $D_{4,50}$ drought. The values of the cumulative deficits for $D_{4,80}$, and $D_{4,70}$ are 21mm and 32mm respectively.

Sub-zone AS6 experiences cumulative deficits close to those experienced by sub-zone AS5 but the recurrence intervals are generally different. In the majority of cases for the same cumulative deficit and drought period P AS5 experiences more frequent drought than AS6.

Table 4.8 AS6: Drought Sequences

Drought Period P (years) →	1	2	3	4	**Drought Period P (years) →**	1
Value of R_{pave} *(mm)* →	26	52	79	**105**	**Value of R_{ave} *(mm)* →**	**26**
$D_{p,80}$(mm) →	**21**	**42**	**83**	**84**	**$D_{p,80}$(mm) →**	**21**
$D_{p,70}$(mm) →	**18**	**37**	**55**	**73**	**$D_{p,70}$(mm) →**	**18**
$D_{p,50}$(mm) →	**13**	**26**	**40**	**53**	**$D_{p,50}$(mm) →**	**13**
Recurrence Interval RI ↓					**Recurrence Interval RI ↓**	
45.00	10	22	36	65	2.50	22
22.50	11	28	40	79	2.37	22
15.00	11	35	51	81	2.25	23
11.25	12	35	58	91	2.14	23
9.00	12	37	60	92	2.05	24
7.50	14	39	68	102	1.96	24
6.43	14	43	73		1.88	24
5.63	15	44	77		1.80	25
5.00	15	44				
4.50	15	45				
5.09	17	46				
3.75	18	46				
3.46	18	50				
3.21	18	51				
3.00	19					
2.81	21					
2.65	21					

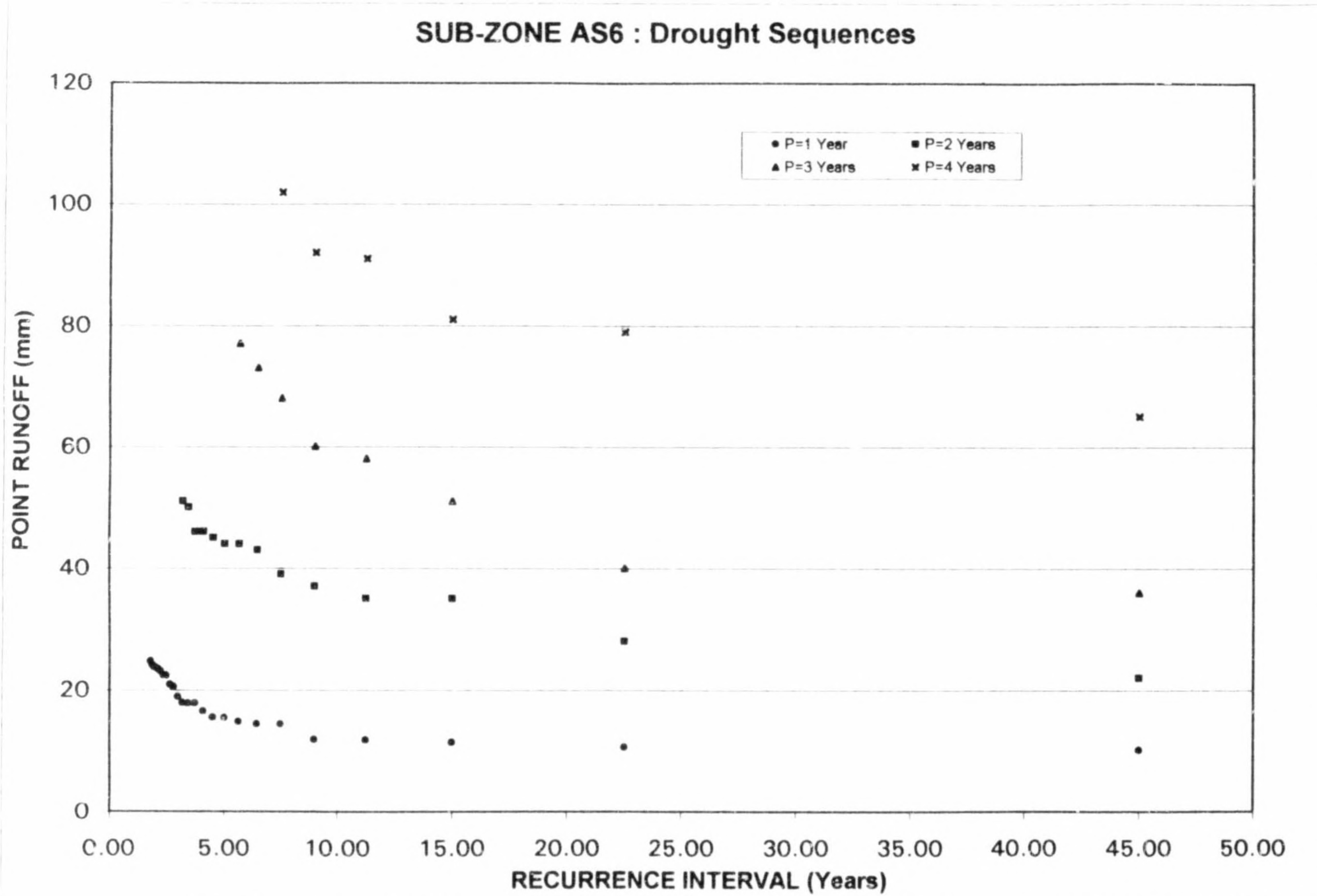

SUB-ZONE AS6 : Drought Sequences
P=1 Year
P=2 Years
P=3 Years
P=4 Years
POINT RUNOFF (mm)
RECURRENCE INTERVAL (Years)
0
20
40
60
80
100
120
0.00
5.00
10.00
15.00
20.00
25.00
30.00
35.00
40.00
45.00
50.00

Figure 24

4.10 BS6: Drought Sequences

Table 4.9 shows the drought sequences for sub-zone BS6. From this Table, R_{pave} for P equal to1, 2,3 and 4years is 11mm, 19mm, 32mm and 43mm respectively. For any RI the cumulative runoff deficit for drought lasting any integral duration P from 1 to 4 years can be obtained. The data in Table 4.9 was plotted on Figure 25 to allow extrapolation on the frequency scale to integral years, which cannot be easily performed on the table. For ease of application of the table the lower runoff closest to the drought runoff was used to determine RI.

To illustrate how the Table 4.9 is used three drought levels are given namely $D_{p.80}$, $D_{p.70}$ and $D_{p.50}$ and the duty is set at R_{pave}. From the table, a drought of $D_{1.80}$ occurs once every 1.91years, $D_{1.70}$ occurs once in 2.34 years and $D_{1.50}$ occurs once in 3.15years. The values of the cumulative deficits for $D_{1.80}$, $D_{1.70}$ and $D_{1.50}$ are 2mm, 3mm and 5mm respectively.

A drought of $D_{2.80}$ occurs once every 3.42 years, $D_{2.70}$ once in 3.90 years and $D_{2.50}$ once in 7.45 years. The values of the cumulative deficits for $D_{2.80}$, $D_{2.70}$ and $D_{2.50}$ are 3mm, 5mm and 9mm respectively.

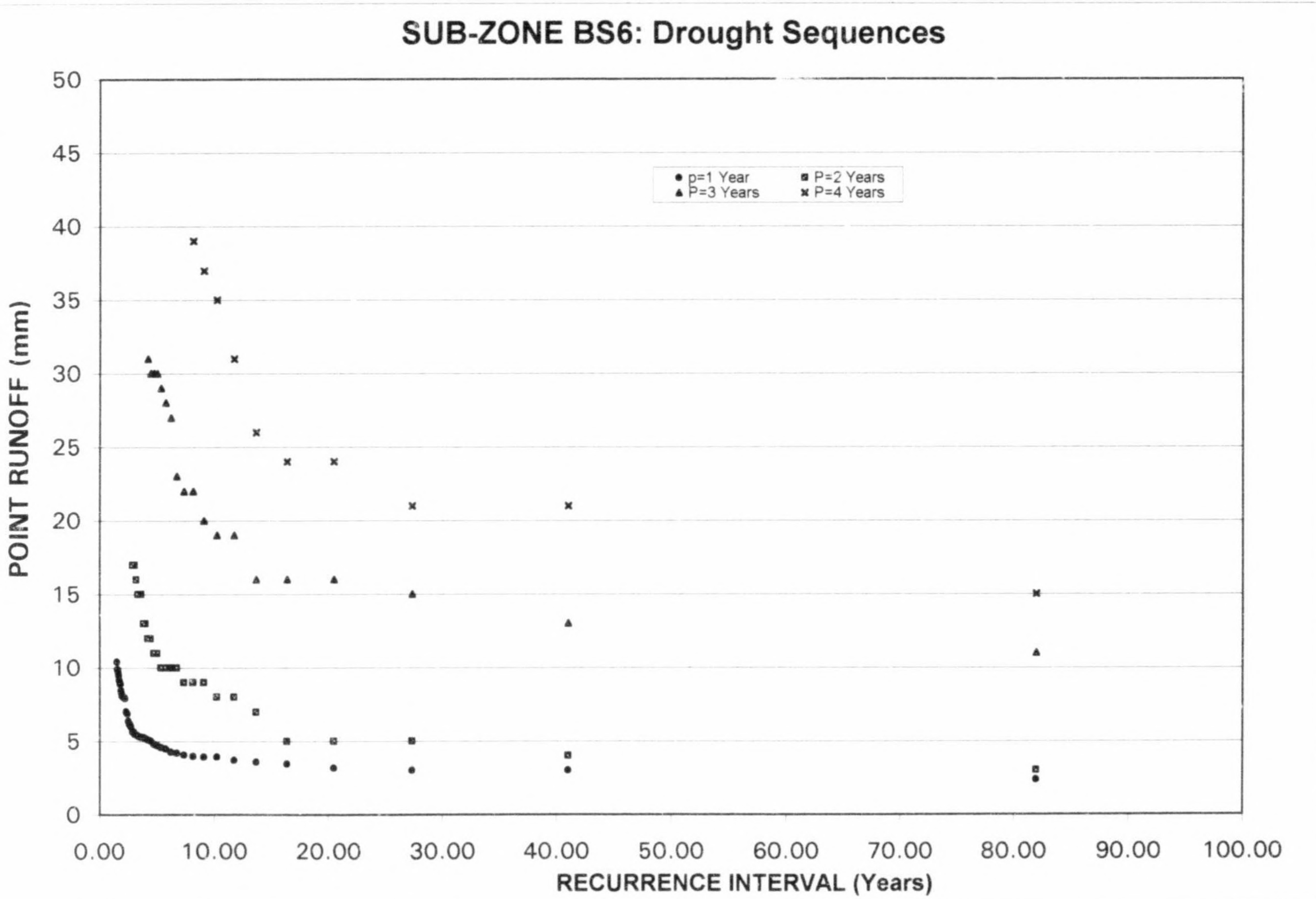
A drought of $D_{3.80}$ occurs once every 6.83 years, $D_{3.70}$ once in 7.45 years and $D_{3.50}$ once in 27.33 years. The values of the cumulative deficits for $D_{3.80}$, $D_{3.70}$ and $D_{3.50}$ are 6mm, 9mm and 16mm respectively.

A drought of $D_{4.80}$ occurs once every 11.71 years, $D_{4.70}$ once in 13.67years and $D_{4.50}$ once in 27.33 years.. The values of the cumulative deficits for $D_{4.80}$, $D_{4.70}$ and $D_{4.50}$ are 8mm, 13mm and 21mm respectively.

From these results for sub-zone BS6 once in every 2 years annual runoff drops below 80% of average. Drought behavior of BS6 is closer to that of AS1 than the other sub-zones but generally for the same cumulative deficit and drought period P BS6 experiences more frequent drought than AS1.

Table 4.10 BS6: Drought Sequences

Drought Period P (years) →	1	2	3	4	Drought Period P (years) →	1	2	Drought Period P (years) →	1
Value of R_{pave} (mm) →	11	19	32	43	Value of R_{pave} (mm) →	11	19	Value of R_{pave} (mm) →	11
$D_{p,80}$ (mm) →	9	16	26	35	$D_{p,80}$ (mm) →	9	16	$D_{p,80}$ (mm) →	9
$D_{p,70}$ (mm) →	8	14	23	30	$D_{p,70}$ (mm) →	8	14	$D_{p,70}$ (mm) →	8
$D_{p,50}$ (mm) →	6	10	16	22	$D_{p,50}$ (mm) →	6	10	$D_{p,50}$ (mm) →	6
Recurrence Interval RI ↓					Recurrence Interval RI ↓			Recurrence Interval RI ↓	
82.00	2	3	11	15	3.73	5	15	1.91	8
41.00	3	4	13	21	3.57	5	15	1.86	9
27.33	3	5	15	21	3.42	5	15	1.82	9
20.50	3	5	16	24	3.28	5	16	1.78	9
16.40	3	5	16	24	3.15	5	17	1.74	9
13.67	4	7	16	26	3.04	6	17	1.71	9
11.71	4	8	19	31	2.93	6	17	1.67	10
10.25	4	8	19	35	2.83	6		1.64	10
9.11	4	9	20	37	2.73	6		1.61	10
8.20	4	9	22	39	2.65	6		1.58	10
7.45	4	9	22		2.56	6		1.55	10
6.83	4	10	23		2.48	7			
6.31	4	10	27		2.41	7			
5.86	4	10	28		2.34	7			
5.47	5	10	29		2.28	8			
5.13	5	11	30		2.22	8			
4.82	5	11	30		2.16	8			
4.56	5	12	30		2.10	8			
4.32	5	12	31		2.05	8			
4.10	5	13			2.00	8			
3.90	5	13			1.95	8			



SUB-ZONE BS6: Drought Sequences
p=1 Year
P=2 Years
P=3 Years
P=4 Years
POINT RUNOFF (mm)
0
5
10
15
20
25
30
35
40
45
50
0.00
10.00
20.00
30.00
40.00
50.00
60.00
70.00
80.00
90.00
100.00
RECURRENCE INTERVAL (Years)

Figure 25

5.0 DISCUSSION

5.1 Extension of Observed Runoff Records

This assignment proved that a computer model RAFLER can be used together with a spreadsheet to extend runoff records using measured rainfall and geo-physical data. The model gives consistently good results of micro catchment runoff if the rainfall records are taken from a station in the same climatic zone, hydrological sub-zone and major river catchment as the runoff observation station for sub-zone to micro catchment ratios of up to 22. The micro catchment can then be used to model runoff for a sub-zone with consistently good results. Use of a rainfall station in the same climatic and hydrological zones but different major river catchment was shown to result in good results for sub-zone to micro catchment ratios of up to 6. Beyond this a significant difference in flow response in moving from the micro to the sub-zone catchment is experienced.

Values of the coefficients in lines 98 and 100 of RAFLER of 6 and 16 respectively were found to be applicable to hydrological zones A and B of Zimbabwe. Sensitivity tests on the parameters on RAFLER showed that precise estimation of rill ratio, saturated permeability, slope and soils suction parameters is important.

In practice within each hydrological sub-zone, a specific river has an area from which it derives its surface runoff. Although groundwater moves much more slowly it also contributes to stream flows and it is perfectly possible, because of underlying geology for areas beyond the boundary of a zone to contribute to the run-off in that zone [Wilson 1983]. The rainfall-runoff transformation process can yield different results where subsurface flow is significant.

The model's sensitivity can be used to model the effects on runoff of man's activities in a catchment. These include land use practices, damming, diversion and abstraction. For example land use changes over years. Activities resulting in silt accumulating in rivers affect low flows. Runoff disappears into the bed of the river.

Diversion and abstraction may reduce low flows while damming may reduce or increase low flows depending on the reservoir management objectives. In this study the model was not sensitive to 50% reduction in vegetation cover mainly because of the well drained sandy soils encountered. However, these effects of man's activities on runoff cannot be precisely assessed.

5.2 Sub-zone and Micro Catchment Point Runoff Analysis

The assignment proved that estimates of point runoff from micro catchment analysis can be used in place of sub-zone figures without significant loss of accuracy for flows less than or equal to the long-term average within the limits pointed out in section 5.1. This was the range of focus for hydrological drought analysis.

5.3 The Regional Drought Frequency Analysis for Zimbabwe

This study proved that RAFLER can be used directly in hydrological drought analysis for most of the sub-zones of Zimbabwe by applying the concept of RDFA. The frequency of different levels of drought of six sub-zones were determined and presented in sections 4.5 to 4.10 of this report.

To cover the whole of Zimbabwe further work is required. On this assignment the BASIC programme RAFLER required about 15kilo bytes of computer memory per station while the spreadsheet took about 400kilo bytes. Thus for the eighteen computations on micro catchments and sub-zones about 7.5Mega bytes were used. But this was only for seven sub-zones. To cover the whole country at two computations per sub-zone about 120Mega bytes would be required. This is achievable using a personal computer. However the data entry and spreadsheet computational time is significant. This could be reduced if the rainfall and runoff data was available a compatible computer software from MET and DWRD respectively. However, the experience of this study showed that Zimbabwe catchment water accounting is not yet sufficiently developed to a stage where rainfall and runoff information systems are synchronized.

This should be a priority area for these two government departments. It has been demonstrated that the cost of mapping and geophysical data would not be excessive.

5.4 Limitations to the Drought Frequency Methodology

As pointed out in 2.3 over 70% of runoff stations in Zimbabwe do not have the required number of years of continuous records for drought studies. However, this assignment has shown that of the remaining 30% significant effort would be required to extend their data to at least 30 years. The screening process on this study eliminated about 63% of the sub-zones in Zone A and 93% in zone B mainly because the stations did not have sufficient years of data to make statistical comparisons with estimates. A computer model such as RAFLER could be used for this task but it requires rainfall records and an accurate estimation of geo-physical parameters. It is necessary that the rainfall station should be located within the same climatic zone, hydrological sub-zone and major river catchment being modeled. At present such rainfall records are not readily available.

Table 3.7 shows that in 75% of the monthly rainfall-runoff and 54% on the annual figures the observed peaks were greater than the estimates. These could have been caused by changes in physical catchment conditions not captured in the model. Limited sensitivity analysis on one sub-zone attempted to model effects of possible changes in physical conditions with time. These include changes in vegetation cover, land use and hydro-geology as pointed out in section 5.1. As catchment geophysical conditions are different catchment responses to rainfall under changes in geophysical conditions are expected to differ also therefore it essential to carry out such sensitivity tests on each sub-zone.

It has been demonstrated that rainfall stations within the same climatic zone as the sub-zone but in other major river catchments can be used to model low flows with reasonable accuracy provided the sub-zone to micro catchment area ratio is below 6. The observed departures are insignificant compared to the advantages and observed data is scant.

5.5 Possible Applications of the Methodology

5.5.1 Dam Design and Storage Management

The probability of a particular flow requirement being violated during droughts of a given severity can now be worked out for sub-zones AS1,AS2,AS3, AS5,AS6 and BS6 less precisely by use of the tables or more precisely by use of graphs. If required duty during the *P* years of drought cannot be met then storage or flow augmentation is required. This is important in reservoir design. The duty can arise from requirements for water such as irrigation, human and animal consumption, industrial and mining use, electricity generation and losses such as evaporation and leakage in transportation.

In reservoir design an underlying assumption is then made that climatic conditions similar to the period of record will prevail in future. However, as pointed out by Kabel (1997) apart from climatic changes there are many factors, which may cause alteration in the flow regime such as, changed land use or deforestation.

The general approach followed in Zimbabwe is to calculate the potential annual yield of a catchment based on the provision of storage capacity equal to the total runoff in a poor year that has a 10% chance of occurrence without draw off during filling. A Gamma distribution has been found to give the best fit for runoff observations in Zimbabwe [Kabel 1984].

Table 5.1 Estimation of Annual Yield Potential of Sub-zones

Sub-zone	Catchment Area (km^2)	MAR (mm)	10% Risk runoff for drought lasting one year from methodology (mm)	10% Risk runoff for drought lasting one year estimated by Kabel (1984) (mm)
AS1	3129	14	7	2.10
AS2	3966	8	5	0.40
AS5	1704	25	13	1.00
AS6	3036	23	15	0.46
BS6	1045	12	4	0.12

From Table 5.1 it appears that there are major differences in the estimation of the drought runoff from the two methodologies. It is possible that there is under estimation of low flows in the methodology generally followed in Zimbabwe due to measurement errors at gauging stations as elaborated in Section 3.7.

Results of the methodology developed on this study can be applied in management of storage for drought conditions. The storage required to meet a given draft U during a critical flow sequence may be determined using the equation [Stephenson *et al* 1983]:

$$S_b = S_e + I_m - U_m - E_m \qquad \text{..................5.1}$$

where S_b = storage at beginning

S_e = storage at end

U_m = average draft

E_m = average evaporation

I_m = average inflow

This methodology can be used to generate various scenarios storage states at different times using probable drought inflows. Probability of a given inflow during a drought of a given duration can be worked out from the tables of graphs in Chapter 4. Thus the draft which can be sustained at different risk levels can be worked out.

According to Durham *et al* (1993) reservoir management in Zimbabwe is aimed at satisfying the requirement for 21 months starting on the 31st of March of any year taking into account the 10% low flow year. If storage volume cannot meet the requirement, rationing starts. This strategy is aimed at bridging two seasons. This methodology can greatly improve on this thumb rule by providing alternatives and their risks. These alternatives can be appropriately valued for informed action [Stephens *et al* 1998].

5.5.2 Environmental Management

Hughes (1998) points out the increasing importance of estimation of reserve water for environmental purposes and to maintain riverine resources to reflect natural occurrences. By adjusting the time step this methodology can be used in deriving instream flow requirements for such purposes. This can be allowed for at the planning stage of reservoirs. Thus reservoir drought rules can be worked out. During reservoir operation in drought conditions once inflows are determined the instream flow releases required can be worked out [D A Hues *et al* 1998].

5.5.3 Catchment Potential Yield Estimation

The assessment of maximum potential catchment yields in Zimbabwe assumes a 10% risk factor and applies the transitional probability matrix a methodology developed by Mitchel [Kabel 1984]. Table 5.2 compares potential yield estimates from 1 in 10 year low flows derived from this methodology and maximum potential yield estimates from the methodology by Mitchel [Kabel 1984]. The same order of magnitude of results is obtained. Estimates from this methodology are within ±30% of those by Mitchel. This shows that this methodology is a realistic more physically based alternative for yield estimation. The 1 in 10 year low flows lasting one year for sub-zones AS1, AS2, AS5, AS6 and BS6 were 7mm, 5mm, 13mm, 15mm and 4mm respectively. These were obtained from tables in chapter 4.

Table 5.2 Estimation of Total Yield Potential of Sub-zones

Sub-zone	Catchment Area (km^2)	MAR (mm)	10% Yield Estimated Methodology, P=1year (x 10^3 m^3)	10%Yield Estimated by Kabel (1984) P=1year (x 10^3 m^3)	Difference %
AS1	3129	14	21903	25960	-16
AS2	3966	8	19830	15680	26
AS5	170	25	23856	20425	17
AS6	3036	23	39468	30800	28
BS6	1045	12	4180	5460	-23

6.0 CONCLUSIONS

A methodology for drought frequency analysis has been developed for the specific conditions of catchments in Zimbabwe. The methodology involves extending runoff records using RAFLER and statistical analysis of the results on a spreadsheet. The results are presented as sub-zone point drought sequences on graphs and tables.

Both the tables and graphs are easy to use. For a given sub-zone a recurrence interval can now be assigned to a drought condition of a given duration and resulting in a deficit. Furthermore the probability of the drought flows can now be worked out. Both the frequency and severity of droughts can be evaluated with a high degree of confidence.

This study considered seven sub-zones and it proved that it is feasible to extend runoff records using rainfall and geophysical data. This task needs to be taken up further to develop a set of drought severity and frequency tables and curves for the whole country. The importance of this information to understanding and managing hydrological droughts has been demonstrated. Its potential for application in catchment yield estimation, environment management, reservoir design and management and in modeling effects of changes in the geophysical environment has been highlighted.

However, both MET and DWRD should synchronize their information systems so that rainfall and runoff are readily available in compatible computer software. Further work may be required on RAFLER if it is to be used for this purpose. This would involve linking its output to a spreadsheet in a matrix of year by record in month. Once the software is in place and as more observed rainfall and runoff data becomes available more runoff estimates can be made which will better inform the drought frequency analysis.

For accurate modeling of the rainfall-runoff transformation process information on geophysical conditions of a catchment is essential. Ground truthing cannot be avoided but techniques such as remote sensing could enhance this model.

This would require more powerful tools than used on this assignment and unless the need justifies the means, it can be expensive and time consuming. The methodology and tools presented in this report offer a more cost-effective option yielding results in a short time.

For extension of runoff data using this methodology the largest unit of area to be considered in Zimbabwe is the sub-zone. However, micro catchments can be used to model estimation of sub-zone runoff from rainfall.

Catchment management in Zimbabwe is changing from the sub-zone to the sub-catchment model as pointed out in section 2.1. Existing databases on sub-zones will change accordingly. Since most of the runoff gauges measure runoff from well-defined micro-catchments, the methodology developed on this assignment can be used to derive drought scenarios for the new sub-catchments with the same reliability as for sub-zones.

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APPENDIX I

Analysis of Observed and Estimated Runoff

Figures 10 to 19	Estimated and Observed Runoff - Overlays
Figures 10.1 to 19.1	Estimated and Observed Runoff -- Scatter Diagrams

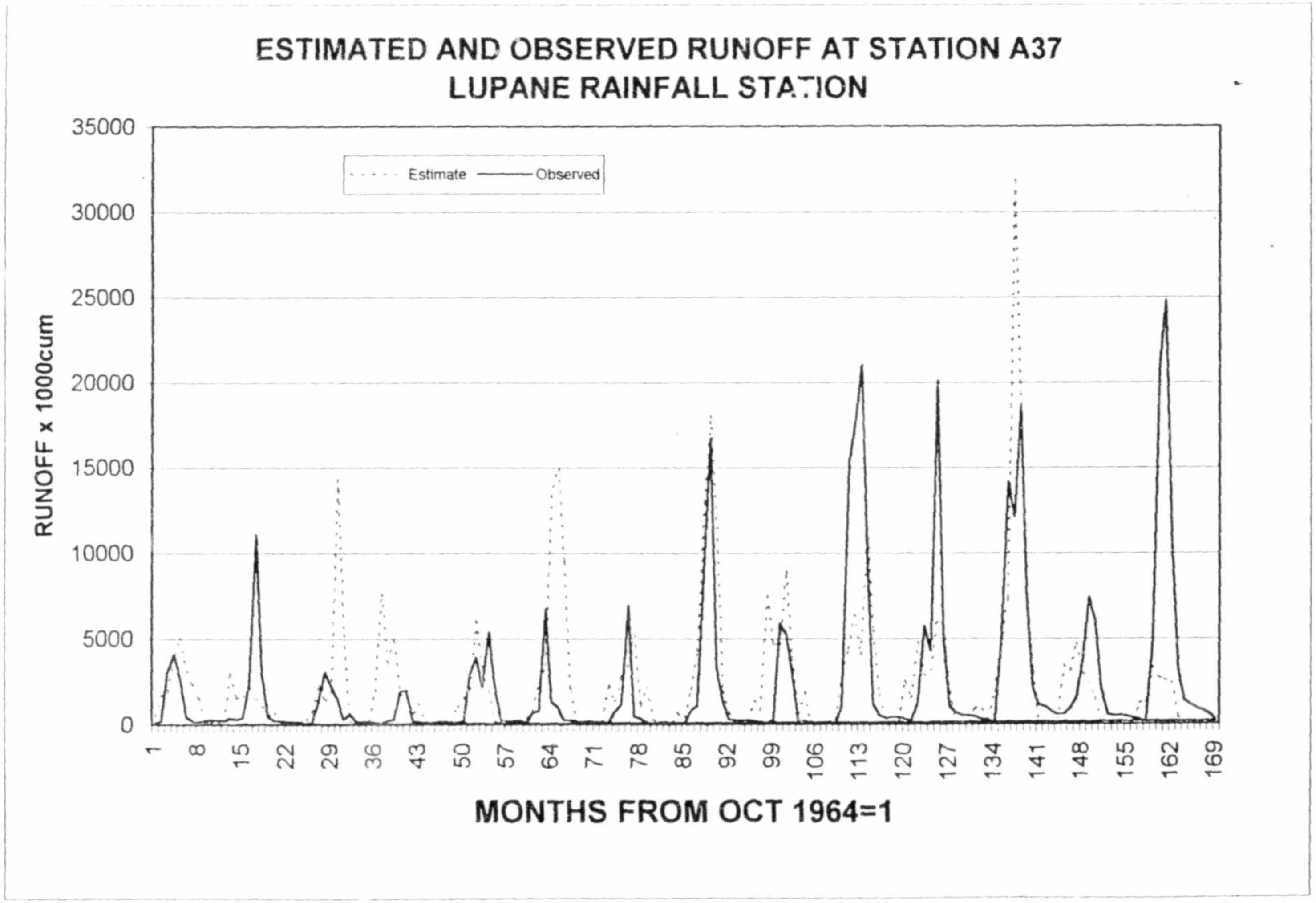
ESTIMATED AND OBSERVED RUNOFF AT STATION A37
LUPANE RAINFALL STATION
Estimate
Observed
RUNOFF x 1000cum
35000
30000
25000
20000
15000
10000
5000
0
1
8
15
22
29
36
43
50
57
64
71
78
85
92
99
106
113
120
127
134
141
148
155
162
169
MONTHS FROM OCT 1964=1

Figure 10