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TECHNICAL NOTE 35

RESERVOIR OPERATION DURING DROUGHT PERIODS

by

W. J. R. Alexander

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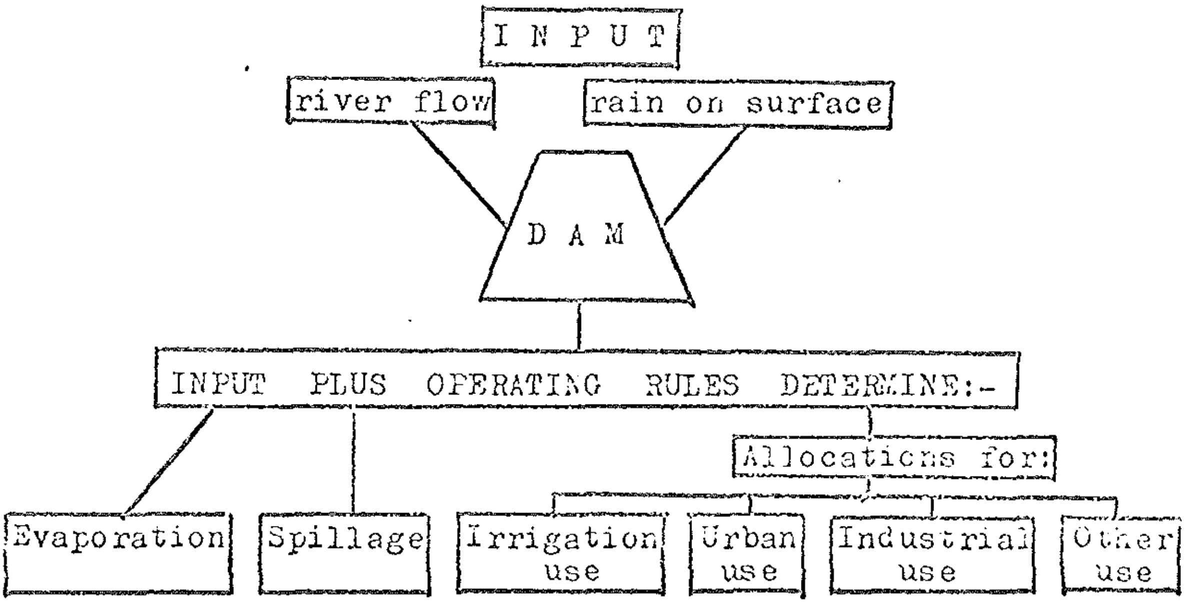
RESERVOIR OPERATION DURING DROUGHT PERIODS

Abstract

This report discusses some of the unresolved problems in reservoir operation and develops a method of operation using sequential analysis of critical drought periods. This method can be applied to both historical and synthetically generated records. Probabilities of occurrence can be determined in both cases.

INTRODUCTION



The above sketch shows the interrelationship between the principal variables that have to to taken into account when determining the yield of a dam under drought conditions.

The assurance of supply for any one usage depends on the hydrological factors of inflow, rainfall on the dam, and evaporation from the dam, which are largely unpredictable, and the operating rules which are predictable. The risk of failure is therefore a direct result of the unpredictability of the hydrological factors, of which river flow is the main component.

Properties of river flow

Most of the major dams in South Africa have carry-over periods of more than one year. The effect of variations of

daily/......

daily or monthly flows is of less consequence than variations in the annual flows.

Many hydrologists have long thought annual flows to be randomly distributed, Gauss or Gauss-Markov processes. This being so, it should be possible to determine the relationship between the parameters of the frequency distribution function which best fits the observed flows in a river, and the reservoir size required to meet various drafts.

A number of methods have been proposed for determining this.

Non-sequential analysis

Hurst (1951) proposed that the total reservoir capacity R required to sustain a constant gross draft equal to the mean inflow during a period of N years could be derived from the relationship

$$R = s.(\frac{N}{2})^H$$

where s is the standard deviation of N successive inflows, and H a constant with a value of 0,5 for independent Gaussian processes. However, Hurst and others have found that the value of H varied from 0,5 to unity for many hydrological and other geophysical phenomena. This has led to a controversy regarding the true nature of the frequency distribution function ("Hurst's Ghost") which is still raging in hydrological circles. (Mandelbrot and Wallis 1968).

Langbein (1965) maintained (erroneously in my view) that sequential analysis of inflows using the classical mass-curve method introduced by Rippl provided unique answers which may be deceiving in accuracy. He proposed the use of queuing theory by which the flow duration curve could be related to

storage/....

storage requirements, and the frequency derived with which a proposed reservoir would contain various amounts of storage.

Stochastic reservoir theory, which uses matrix algebra as its principal tool, has been described by Lloyd (1967). A number of authors have used this method including Steinijans in his recently published paper in the Transactions, of the South African Institution of Civil Engineers (1970).

All non-sequential analyses rely on the acceptance of an assumed frequency distribution function, and their reliability is therefore dependent on the accuracy of this assumption.

Sequential analysis

Sequential analysis is till the traditional method in South Africa, the USA, and probably in most other countries. In the Department of Water Affairs mass flow analysis of the historical record is used exclusively. Where the historical record is deficient, the record is extended, and missing flows are derived by rainfall/run-off correlation or by correlation with the run-off of adjacent catchments.

The main advantage in the use of the historical record is that there can by no doubt that it is a reliable set of data generated by the hydrological processes in the catchment. However, as it is extremely unlikely that the historical flow sequence will repeat itself within the life of the project, caution must be exercised when using past historical records to predict the future assurance of supply of a reservoir.

The future

Reliable answers to the problem of assurance of supply can best be provided by the sequential analysis of a synthetically generated record of at least 500 years long. The

generation/.......

generation and analysis of a record of this length is well within the capacity of presently available computers. The only major difficulties are the determination of the frequency distribution parameters of inflow, rainfall on the dam surface, evaporation from the dam surface, and the correlation between these factors. Regional studies will enable these parameters to be determined with greater condidence.

It is my view that we should begin to wean ourselves from the exclusive use of the historical record, and begin supplementing our analyses with those of synthetically generated flows, despite the many pitfalls (known and unknown) that lie ahead. By following this road we will ge a cleares insight into the degree of assurance of supply from our reservoirs.

Analysis of critical drought sequences

A series of critical drought sequences can be derived from the record (historical or generated), plotted on probability paper, recurrence intervals determined, and then selected sequences corresponding to the required recurrence intervals can be analyses to determine the safe yields for various drafts.

This method of analysis is now used routinely for drought analyses of the Vaal River system, and more recently for Verwoerd Dam.

The attached report by myself dated January, 1971 (Appendic A) describes the method; and the report of February, 1972 by C.S. James is a worked example for Vaal Dam. (Appendix B).

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Appendix 'A'

RESERVOIR OPERATION DURING DROUGHT PERIODS

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1. INTRODUCTION

1.1 When a dam is full, predicting the future safe yield for droughts of varying severity can be accomplished without difficulty by routine methods of analysis. One of these is the use of the past historical flow and the determination of the 'assured yield' based on the assumption that future droughts will not be more severe than the worst drought experienced in the past. Another method is that given in the Wits HRU Report 2/69 (Chapter 3 pps 11-17). The Wits method has the advantage that the relationship between the draft and droughts of varying severity can be determined. When using historical flows in the analysis, it must always be borne in mind that only a single sequence of flows is used which may or may not be typical of the catchment and which will certainly never be repeated again in future.

1.2 Both the above methods are of doubtful value when assessing the safe yield from a dam which is only (say) half full at a particular time. If the flow during the immediately preceding years was well below average and the critical period of the historical record is used for forward projection, then this implies that the whole drought period (immediately preceding sub-normal years plus critical period from the historical record) will be much more severe than the past historical record itself. However, there is no way of telling how much more severe it is.

1.3 The method proposed in HRU 2/69 (Chapter 4, paras 4.6 and 4.7) makes the same assumption i.e. it states the problem as follows: "At what net rate may water be drawn from the reservoir such that a reserve of R units will not be encroached upon should the inflow from this day onward be that associated with a drought sequence having a T-year return period?"

1.4 The implication of both of the above assumptions is that the drought will be far more severe than that originally used to determine the safe yield of the dam. The second implication is that if the future operation of a reservoir is to be determined by its storage level at a given time, then the safe yields of our reservoirs should be re-appraised as they will be significantly less than those derived in the conventional way. If we are to be consistent in our analyses of the safe yields of reservoirs, the problem should be

/restated ......

restated as follows: 'At what net rate may water be drawn from the reservoir such that a reserve of K units will not be encroached upon should the inflow from the time the dam last filled be that associated with a drought sequence having a T-year return period?' (or that of equal severity to the worst experienced during the historical record).

1.5 The difference in approach can best be explained by means of an example:-

Assuming that a safe draft of 100 units has been determined using either the historical record or the HRU method for (say) R.I. = 20 years. The method of analysis is exactly the same in both cases, the only difference being the assumed inflow pattern. In both cases a full dam would be able to sustain the draft and would just reach the reserve level at the end of the critical period i.e. whatever the water level in the dam the calculated draft can be maintained provided the inflows are not less than those assumed in the initial calculation. Clearly the warning signal for the imposition of water restrictions should be the total inflow since the dam was last full i.e. the severity of the present drought, and not some arbitrary water level in the dam.

1.6 In determining reservoir operation procedures, we should first of all determine the reserve storage. This reserve should be based on a severe drought (say 100 year R.I.), and the absolute minimum requirements for the area being served. The reserve required during each month of the year can then be determined. Once this reserve is fixed, the safe yield of the dam can be determined from either the historical flow or assumed inflow patterns for various frequencies. This draft will be maintained in safety regardless of the amount of water in storage at any particular time provided the inflow pattern is not more severe than that assumed in the initial calculations.

1.7 If several years have elapsed since the dam was last full and the water in storage is low, it would naturally be wise to carry out further calculations. The purpose of these calculations would be to determine whether or not the actual inflow pattern was more severe than the assumed inflows and also what draft could be maintained should the drought worsen. The method of analysis is given in the following section of these notes.

/2. THE ANALYSIS

2. THE ANALYSIS

2.1 The basic data required for this analysis are a long record of monthly river flow (historical or synthetic) and a corresponding record of net evaporation (gross evaporation less rainfall).

2.2 Using the standard method of ranking and plotting on probability paper the cumulative annual flow - frequency relationship can be determined for the worst 12 months, 2 consecutive years, 3 consecutive years, etc. for each frequency (see Fig. 1).

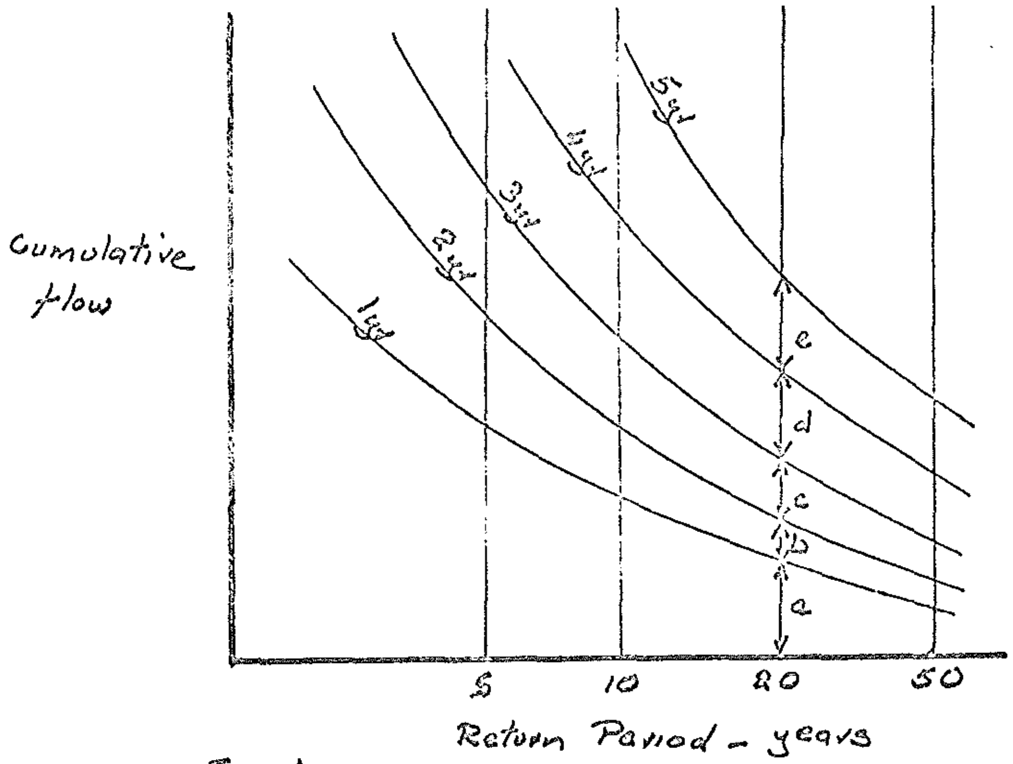

Fig 1

2.3 For any particular R.I. (say 20 year) the worst possible inflow during one year would have a value 'a' in Fig. 1. The worst two year sequence would have a value of (a + b), making 'b' the flow in the second year of the worst two year sequence. The worst five year sequence would be made up of flows a, b, c, d, e.

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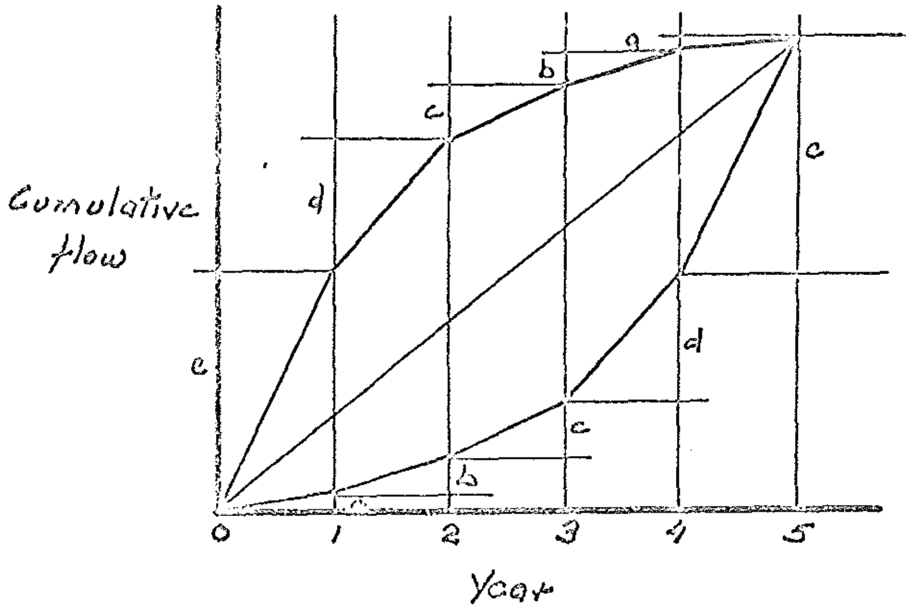
2.4 In a five year drought the actual annual flow would have to be that enclosed in the envelope contained by the sequences a,---,e and e,---,a as shown in Fig. 2.



20 Year Return period

Fig 2

2.5 From the point of view of dam operation, the worst five year sequence would be the one where the annual flow decreases with time i.e. in the order e, d, c, b, a. This exposes the greatest surface area to evaporation. We cannot legitimately assume that this particular sequence has the same R.I. as the data from which it was derived (it will have a higher R.I. i.e. more severe), but it is nevertheless adopted for the present calculation.

2.6 Before proceeding with the calculation it is necessary to derive the monthly flows for each year. The method adopted in HRU 2/69 is to determine the average monthly flow as a percentage of the annual flow for all years when the annual flow was less than the M.A.R. This method makes no allowance for the variance of the flows for each month. A better method is to determine the frequency distribution of flows for each month as well as for the annual flows (this is best done graphically). The flows for each month of the year for a particular R.I. are derived and totalled. These totals will naturally be a lot less than that for a year of the same R.I. Knowing the annual flow for a particular R.I., the monthly distribution is obtained from the sum of the monthly flows whose total equals the annual flow. The process is repeated for each annual flow.

2.7 Net evaporation does not vary greatly and the average of the five highest figures for each month of the year will provide a satisfactory estimate for the whole of the critical period.

/2.8 ......

2.8 For any particular R.I. we now have a series of annual flows with associated monthly flows and monthly evaporation. These are ranked in order of decreasing annual flow.

2.9 Using the standard programme, the maximum draft is determined on the assumption that the dam is just empty (or just reaches the reserve storage) at the end of the period. The analysis is best carried out in reverse chronology. This draft can be sustained for any drought equal to or less severe than the one assumed <u>regardless of the state of the reservoir at any time</u>.

2.10 There is a note of caution. If the analysis shows that the critical storage is developed in the first year of the sequence (last year if the analysis is in reverse chronology) then the length of the sequence should be increased to ensure that the most severe conditions are included in the analysis.

2.11 The whole process is repeated for other R.I's so that a series of say 50, 20, 10 and 5 year R.I's is obtained. For each of these, curves can be drawn on a graph showing minimum flow for successive years as shown in Fig. 3. The cumulative inflow is obtained from the calculation outlined in para 2.5 above and the associated safe draft from the calculation in para 2.9.

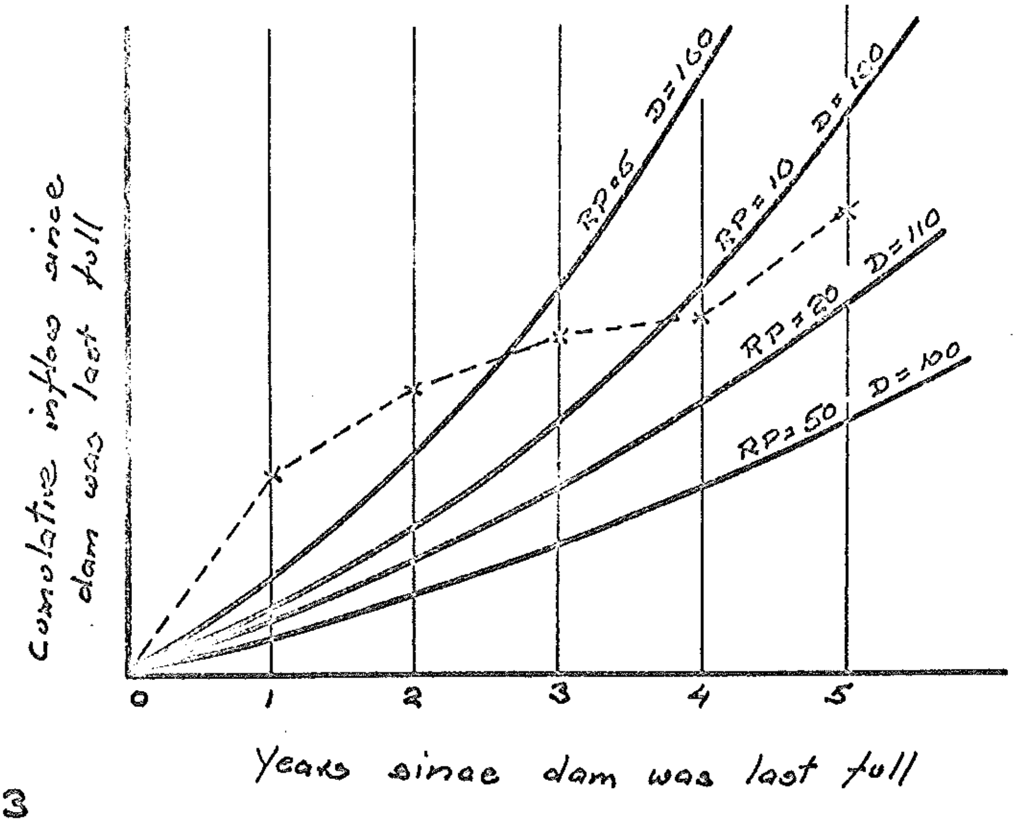


Fig 3

/2.12 ......

2.12 Assuming that the actual draft was say 130 units, the dam would be able to sustain this for any drought equal to or less than that of a 10 year R.I. We can determine the severity of the inflow since the dam was last full by plotting the subsequent inflow against time as in Fig. 3. If this inflow is less than the curve for 10 year R.I. then the dam can no longer sustain the draft should the drought continue. The curves can not be used to determine the new safe draft i.e. it is not 120 in the above case, but some lesser draft which has still to be determined.

2.13 The position now is that the dam is (say) 40% full and that we are experiencing a drought of greater severity than that for which the draft was determined. The question is what drafts can be maintained should the present severity continue or become worse?

2.14 Let us consider what the maximum safe draft would be to see us through a 20 year R.I. drought. We have already determined the minimum annual flows for this drought (a, b, c, etc. in para2.3). Let us assume that the actual flows since the dam was last full were:

year	flow during year
1st	g
2nd	h
3rd	i
4th	j
5th	k

We now have to estimate what the worst successive future inflows could be if we were in a 20 year R.I. drought period.

The succession of flows could be written in order of occurrence since the dam was last full as follows:-

year	1	2	3	4	5	now	6	7	8	9	10
flow	g	h	i	j	k		s?	t?	u?	v?	w?

The minimum flow in year 6 would have to meet two conditions i.e.

$$s \nless a \quad \text{and} \quad s + k \nless a + b$$

as 'a' and (a + b) are respectively the minimum 1 and 2 year inflows for a 20 year R.I. drought.

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We can rewrite this as:-

(i) If $k > b$ then $s = a$
otherwise $s = a + b - k$.

(ii) If $k > b$ and $(j + k) > (a + b)$
then $s = a, \quad t = b$

otherwise $s = (a + b) - k$
$t = (a + b + c) - (j + k)$.

Continue determining the annual flows in this way to make a series of three to five additional terms.

2.15 We now have a series of annual flows which would be associated with a 20 year drought sequence. This time the sequence is one of decreasing severity, but as the reservoir is already at a low level, the difference in evaporation losses between a series of decreasing and increasing severity is unlikely to be significant.

2.16 The calculation explained in paras 2.6 to 2.9 is then carried out but starting with the dam at 40% capacity and ending with an empty dam or at the reserve storage (vice versa if the calculation is in reverse chronology).

2.17 Repeat the calculation for other R.I. droughts and plot the results on a new graph similar to Fig. 3, but with the starting point the reduced storage in the dam as shown in Fig. 4.

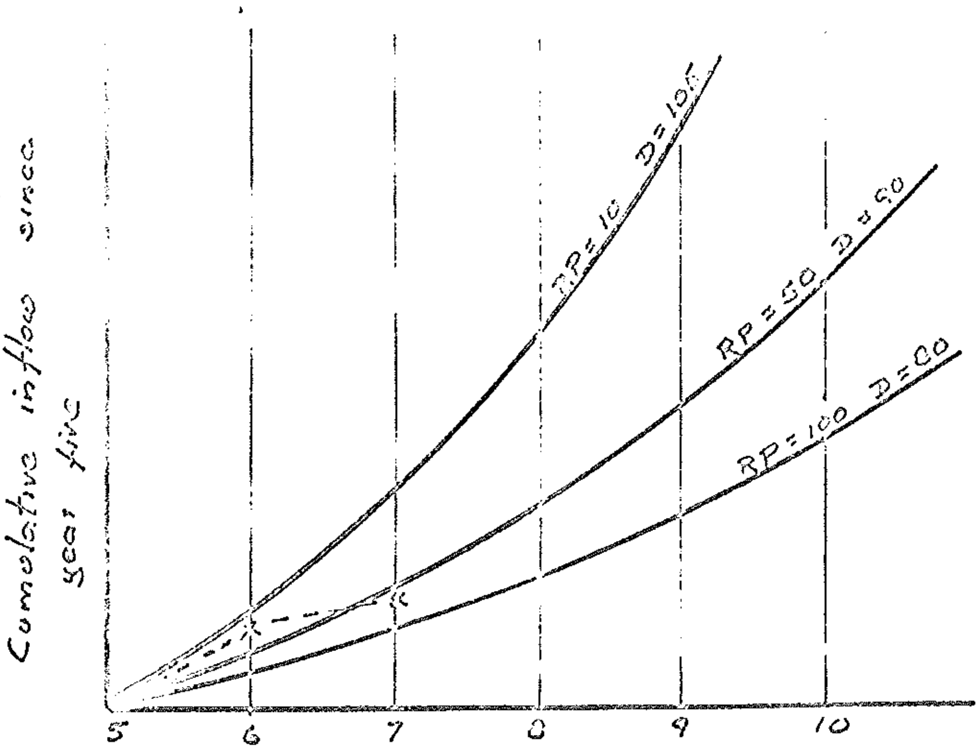

Fig 4 Years since dam was last full

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2.18 Assuming that in view of the prevailing drought the draft is reduced to 90 units (R.I. = 50), but once again the actual inflow falls below the R.I. = 50 curve. The implication is that the drought has now become more severe than a 50 year R.I. drought and even the new draft cannot be sustained if the drought continues at this severity. Under these circumstances, a fresh set of calculations must be made as before, and the draft reduced still further to meet the more severe conditions.

2.19 Should the conditions improve rather than deteriorate, then by continuing to plot inflow on Fig. 3 (extend it if necessary) it can be seen when the original draft can be re-instated. This will be when the cumulative inflow again rises above the R.I. = 10 curve.

3. DRAFT PATTERN

3.1 No mention was made of the draft pattern (i.e. the percentage of the annual draft during each month of the year) in the above analysis. This is a function of the draft itself and must also be determined. In the case of a particular dam for example, the distribution might be as follows:-

	Demand		
Total draft	Urban %	Industrial %	Irrigation %
(a) ≮ 150 units	100	100	100
(b) 140 - 150 "	95	100	90
(c) 130 - 140 "	85	90	75
(d) 120 - 130 "	80	80	25
etc.			

3.2 Knowing the monthly demand pattern for urban, industrial and irrigation usage respectively, the monthly demand pattern expressed as a percentage of the total annual demand, and thus the draft for each month can be determined.

/3.3 ......

3.3 Another point worth bearing in mind is that the irrigation demand pattern (and to a lesser extent the urban pattern) is also a function of the severity of the drought i.e. in dry years the proportionate demand in the months of normally high rainfall will be greater than in wet years. Whether or not this factor should be taken into account will depend on the method of controlling the usage of water when restrictions are imposed.

ASST. CHIEF : DIVISION OF HYDROLOGY

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Appendix 'B'

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VAAL DAM - DETERMINATION OF RESERVE STORAGE

1. AIM

The aim of the analysis is to determine the storage required in Vaal Dam to cater for severe drought conditions. Two cases are considered, viz. four-year drought sequences with recurrence intervals of 100 and 200 years.

2. CALCULATIONS

Monthly run-off values for Vaal Dam from October 1923 to September 1971 were subjected to a drought-flow frequency analysis by computer. From the results sequences of 1, 2, 3, 4, 5 and 6 years were selected and plotted on log-probability paper using the Weibull plotting position (Fig. 1).

A table (Table 1) was drawn up from this plot giving the inflow values for the selected sequences corresponding to recurrence intervals of 5, 10, 20, 50, 100 and 200 years. The values on this table were adjusted with the object of constructing a family of curves having closer relationships than were exhibited in the original plot. This was achieved by idealising existing sequential relationships between values in the same columns and rows. The adjusted values were plotted in Figure 2.

The successive differences between cumulative flow values for recurrence intervals of 100 and 200 years were calculated to give annual flows for consecutive years (Table 2). It will be noted that the annual flow for the fourth year is higher for the 200 year sequence than for the 100 year sequence and consideration could be given to further adjustment of Table 1 to change this.

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The annual flows were distributed into monthly flows according to Table 3 which was derived as follows : The annual flows from historical records were divided into the ranges indicated. In each range the flows for each month of the year as well as the annual flows were totalled and each monthly total then expressed as a percentage of the annual total.

Demand projections were done from October 1971 until September 1977 for Vaal Dam to Bloemhof Dam and for Bloemhof Dam to Maselsfontein at the confluence of the Vaal and Orange Rivers. The values were then added to give the total demand for the whole river. These projections were based on actual no-restriction demand figures and the assumption that municipal and industrial use (including that of the Rand Water Board) will continue to increase at the rate of 6⅓% per annum as is the present trend while irrigation and river losses will remain constant.

Monthly net evaporation was calculated by means of the formula $E_n = K E_g - P$ where E_n = Net evaporation
E_g = Gross evaporation
K = Evaporation coefficient
P = Precipitation.

The evaporation coefficient was obtained from tables in "Korrelasie van Verdamping vanuit Symons Panne en Opgaardamme in Suid-Afrika" by Muller and Alberts. The relevant extract is shown as Table 6.

Calculated and gauged evaporation and precipitation figures from 1923 to 1971 were used and monthly net evaporation calculated using the above formula. By computer the monthly figures for each year were added to give annual net evaporation values and the mean of these values was calculated. Also, the values for each month of the year were added and the means calculated from these results the monthly distribution table for net evaporation (Table 7) was constructed by the same method as described for the monthly distribution table for inflow (Table 3).

The / ...

The monthly net evaporation figures for the entire record were subjected to the same frequency analysis by computer as had been the monthly run-off figures. For each sequence 1 to 6 years the ranking was reversed to descending order and the values plotted on log-probability paper using the Weibull plotting position (Fig. 3.). The curves were not adjusted as in the case of run-off as evaporation has a relatively insignificant effect on the analysis as a whole. From the plot cumulative values were taken for 100 and 200 year recurrence intervals and the annual net evaporations calculated by successive subtraction (Tables 8 and 9). The annual net evaporation figures were distributed into monthly figures according to Table 7 (Tables 10 and 11).

The inflow, net evaporation and demand data were analysed by computer and the results expressed in figures 4 and 5.

3. INTERPRETATIONS

It will be noticed that the curve of required capacity for a drought of recurrence interval 200 years lies below that for a drought of recurrence interval 100 years during the third year (1974). This anomaly has not been investigated but might be due to the adjustment of the curves and the difference in monthly distribution.

The storage requirements indicated in the results of this analysis should be regarded as being more severe than would actually be the case in the event of droughts of the nature considered. Reasons for this are that all demand predictions were made on the basis of unrestricted use throughout the drought period and that it was assumed that Vaal Dam will supply all demands for the whole river downstream, i.e. Bloemhof Dam was excluded and run-off from the whole catchment area below Vaal Dam was ignored for the purpose of this exercise.

4. / ...

4. METRICATION

It will be noted that all the work was done in Imperial units. This is due to the fact that not all of the computer programs used have been converted.

Figures 4 and 5 are given in metric units as these are the portions of the report that will be used in practice.

C.S. James,
Vacation Student

Supervisor:

J.J. Wessels,
Senior Hydrologist,
Department of Water Affairs.

4/2/1972.

TABLE 1: ADJUSTED CUMULATIVE FLOWS (morgen feet x 10^3)

Period (years)	Recurrence Interval (years)					
	5	10	20	50	100	200
1	277	215	176	145	126	112
2	940	670	539	440	385	356
3	2 100	1 130	908	765	698	650
4		1 900	1 500	1 300	1 200	1 170
5		3 000	2 200	2 000	1 900	1 870
6			2 750	2 550	2 500	2 450

TABLE 2: ANNUAL FLOWS (MORGEN FEET x 10^3)

	Recurrence Interval (years)					
	5	10	20	50	100	200
First year					126	112
Second year					259	244
Third year					313	294
Fourth year					502	520
Fifth year					700	700
Sixth year					600	580

Fig. 1

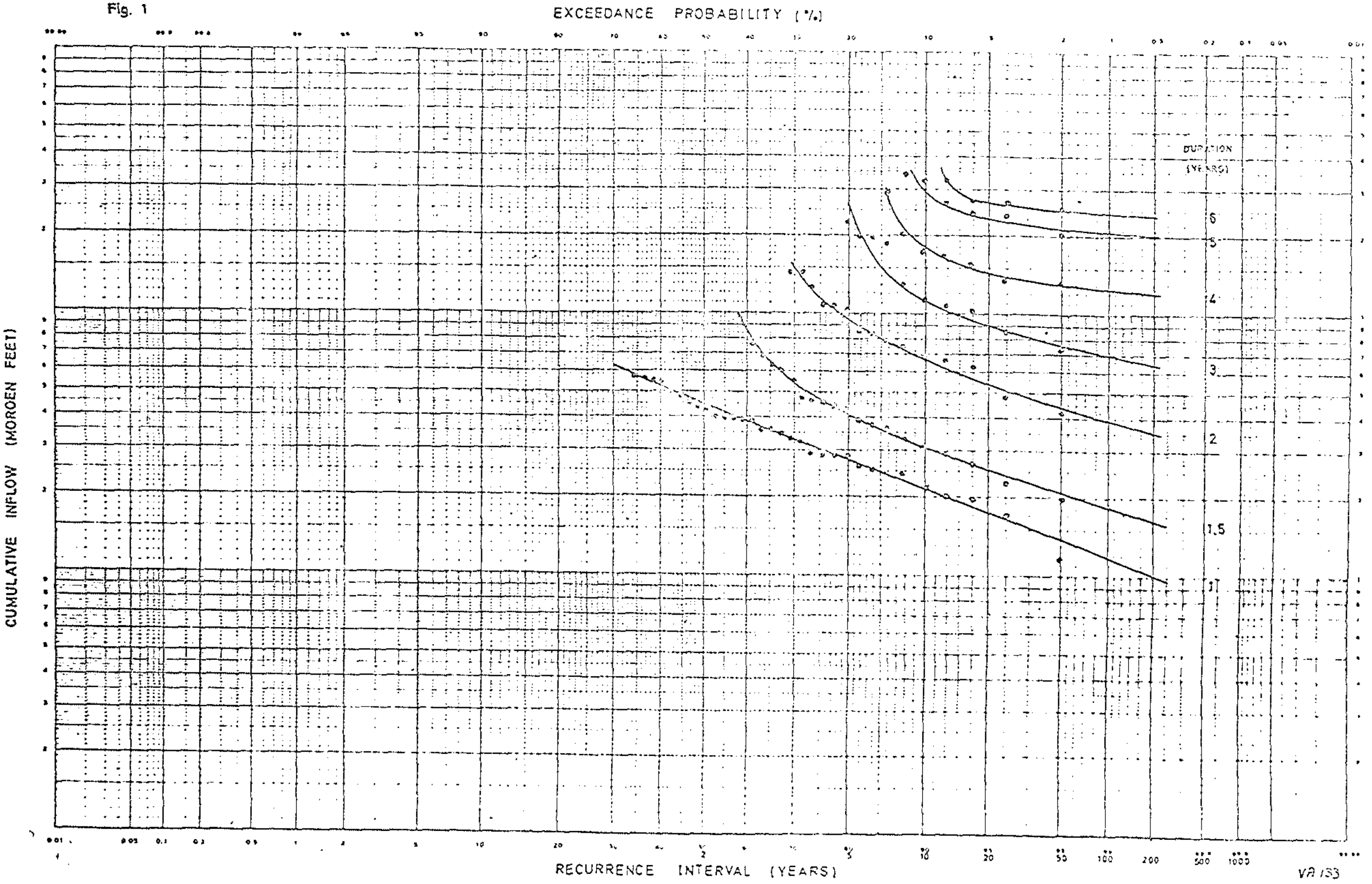
EXCEEDANCE PROBABILITY (%)
CUMULATIVE INFLOW (MORGEN FEET)
RECURRENCE INTERVAL (YEARS)
DURATION (YEARS)
6
5
4
3
2
1.5
1
0.01
0.05
0.1
0.2
0.5
1
2
5
10
20
2
5
10
20
50
100
200
500
1000
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Fig. 2

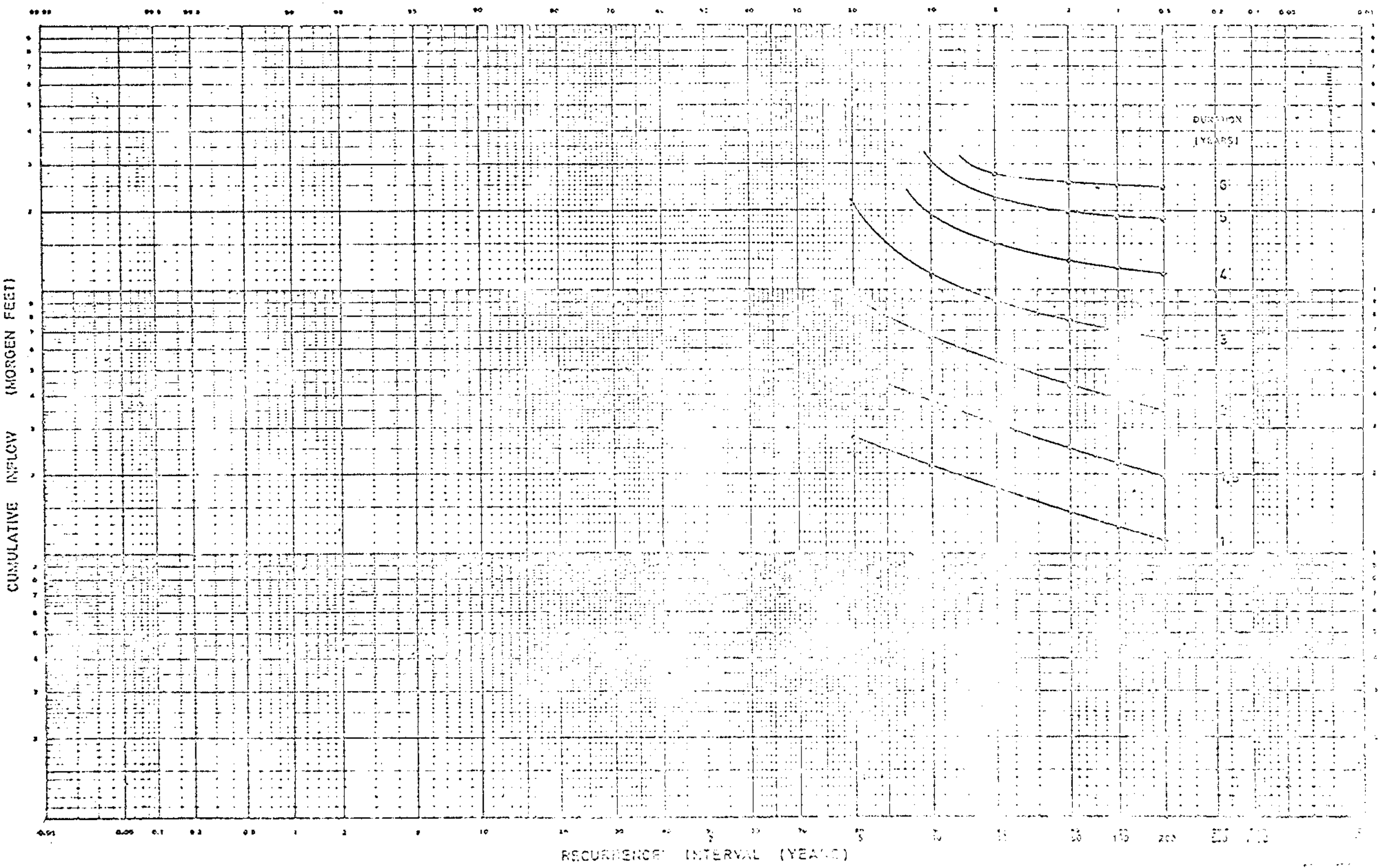
EXCEEDANCE PROBABILITY (%)
99.99
99.9
99.8
99
98
95
90
80
70
60
50
40
30
20
10
5
2
1
0.5
0.2
0.1
0.05
0.01
CUMULATIVE INFLOW (MORGEN FEET)
DURATION
(YEARS)
6
5
4
3
2
1.5
1
0.01
0.05
0.1
0.2
0.5
1
2
5
10
20
30
40
50
60
70
80
5
10
20
50
100
200
RECURRENCE INTERVAL (YEARS)

Fig. 3

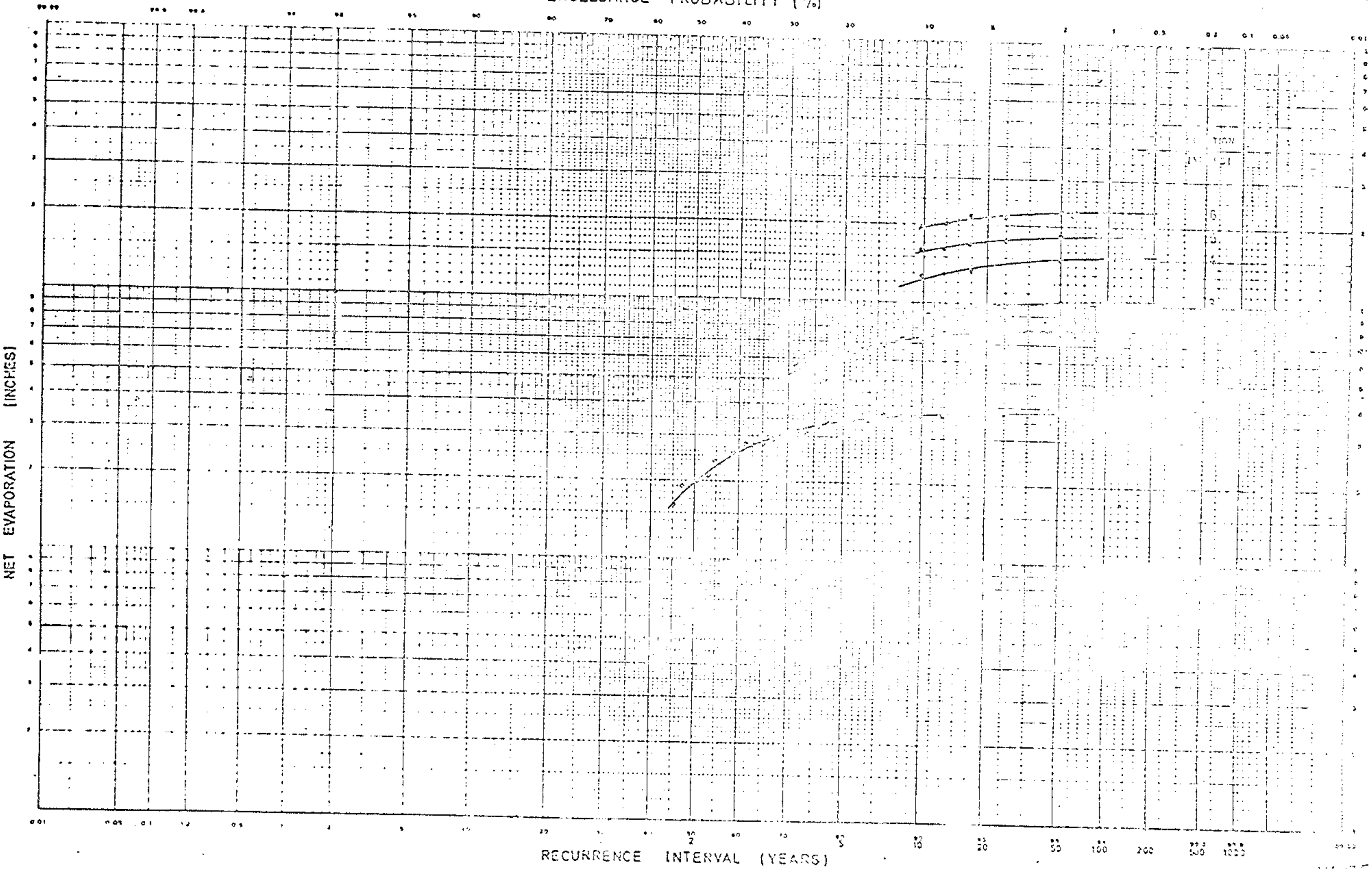
EXCEEDANCE PROBABILITY (%)
NET EVAPORATION (INCHES)
RECURRENCE INTERVAL (YEARS)
2
5
10
20
50
100
200
500
1000

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TABLE 3: MONTHLY FLOW DISTRIBUTION AS PERCENTAGES OF THE ANNUAL FLOW (FLOWS IN MORGEN FEET X 10^3)

Annual Flow	O	N	D	J	F	M	A	M	J	J	A	S
50-150	0,8	6,6	10,6	28,1	26,9	14,3	6,2	2,4	1,6	1,3	0,8	0,4
150-250	2,1	7,8	14,1	25,5	23,0	14,3	6,1	2,5	1,5	1,4	1,0	0,7
250-350	2,7	9,3	17,5	23,6	20,1	13,9	6,0	2,2	1,4	1,4	1,0	0,9
350-450	3,1	10,5	19,5	22,1	18,0	13,6	6,1	2,3	1,4	1,3	1,0	1,1
450-550	3,4	11,7	20,8	21,3	16,6	13,4	6,2	2,5	1,4	1,3	1,0	1,2
550-650	3,6	12,8	20,4	20,6	15,5	13,1	6,4	2,5	1,4	1,3	1,0	1,2
650-750	3,8	14,0	20,6	20,0	14,7	12,9	6,4	2,5	1,5	1,3	1,1	1,3
Whole Record	6,1	13,0	16,7	15,5	19,9	11,6	5,4	3,6	1,3	2,3	1,2	3,4

TABLE 4: MONTHLY FLOWS FOR DROUGHT OF RECURRENCE INTERVAL 100 YEARS (FLOWS IN MORGEN FEET x 10^3)

	O	N	D	J	F	M	A	M	J	J	A	S
First Year	1,008	8,316	13,356	35,406	33,894	18,018	7,812	3,024	2,016	1,638	1,008	0,504
Second Year	6,993	24,087	45,325	61,124	52,059	36,001	15,540	5,698	3,626	3,626	2,590	2,331
Third Year	8,451	29,109	54,775	73,868	62,913	43,507	18,780	6,886	4,382	4,382	3,130	2,817
Fourth Year	17,068	58,734	104,416	106,926	83,332	67,268	31,124	12,550	7,028	6,526	5,020	6,024
Fifth Year	26,600	98,000	144,200	140,000	102,900	90,300	44,800	17,500	10,500	9,100	7,700	9,100
Sixth Year	21,600	75,600	122,400	123,600	93,000	78,600	38,400	15,000	8,400	7,800	6,000	7,200

TABLE 5: MONTHLY FLOWS FOR DROUGHT OF RECURRENCE INTERVAL 200 YEARS (FLOWS IN MORGEN FEET x 10^3)

	O	N	D	J	F	M	A	M	J	J	A	S
First Year	0,896	7,392	11,872	31,472	30,128	16,016	6,944	2,688	1,792	1,456	0,896	0,448
Second Year	5,124	19,032	34,404	62,220	56,120	34,892	14,884	6,100	3,660	3,416	2,440	1,708
Third Year	7,938	27,342	51,450	69,384	52,094	40,866	17,640	6,468	4,116	4,116	2,940	2,646
Fourth Year	17,680	60,840	108,160	110,760	86,320	69,680	32,240	13,000	7,280	6,760	5,200	6,240
Fifth Year	26,600	98,000	144,200	140,000	102,900	90,300	44,800	17,500	10,500	9,100	7,700	9,100
Sixth Year	20,880	74,240	118,320	119,480	89,900	75,980	37,120	14,500	8,120	7,540	5,800	6,960

TABLE 6: EVAPORATION COEFFICIENTS

-	J	F	M	A	M	J	J	A	S	O	N	D
Region C	0,82	0,66	0,88	0,86	0,90	0,94	0,85	0,87	0,83	0,81	0,87	0,83

TABLE 5: MONTHLY FLOWS FOR DROUGHT OF RECURRENCE INTERVAL 200 YEARS (FLOWS IN MORGEN FEET x 10^3)

	O	N	D	J	F	M	A	M	J	J	A	S
First Year	0,896	7,392	11,872	31,472	30,128	16,016	6,944	2,688	1,792	1,456	0,896	0,448
Second Year	5,124	19,032	34,404	62,220	56,120	34,892	14,884	6,100	3,660	3,416	2,440	1,708
Third Year	7,938	27,342	51,450	69,384	52,094	40,866	17,640	6,468	4,116	4,116	2,940	2,646
Fourth Year	17,680	60,840	105,160	110,760	86,320	69,680	32,240	13,000	7,280	6,760	5,200	6,240
Fifth Year	26,600	98,000	144,200	140,000	102,900	90,300	44,800	17,500	10,500	9,100	7,700	9,100
Sixth Year	20,880	74,240	118,320	119,480	89,900	75,980	37,120	14,500	8,120	7,540	5,800	6,960

TABLE 6: EVAPORATION COEFFICIENTS

	J	F	M	A	M	J	J	A	S	O	N	D
Region C	0,82	0,66	0,88	0,86	0,90	0,94	0,85	0,87	0,83	0,81	0,87	0,83

TABLE 7: MONTHLY NET EVAPORATION DISTRIBUTION AS PERCENTAGES OF ANNUAL NET EVAPORATION.

Annual net evaporation (inches)	O	N	D	J	F	M	A	M	J	J	A	S
→ 25	21,97	10,91	28,90	14,35	0,21	-1,38	4,08	-0,90	14,19	-10,80	13,71	4,76
25 - 30	16,18	1,44	13,86	7,64	9,79	-0,53	6,52	3,24	7,24	4,34	14,48	15,84
30 - 35	10,66	7,82	4,87	8,56	5,88	5,80	6,45	5,58	6,90	9,33	13,79	14,36
35 - 40	12,72	7,22	9,94	7,39	5,78	3,00	6,31	6.06	7,22	8,56	11,49	14,33
40 - 45	11,54	10,48	8,71	7,70	5,05	8,55	5,79	6,64	6,45	5,35	10,39	13,39
45 - 50	9,86	10,24	8,92	9,19	7,68	5,02	5,50	7,24	6,58	7,24	9,84	12,71
50 →	9,85	9,75	10,43	8,73	6,61	8,36	7,77	6,35	5,33	5,27	9,39	12,17
Whole Record	11,57	8,53	9,40	8,28	6,39	5,56	6,32	6,07	6,64	6.59	11,19	13,50

TABLE 8: CUMULATIVE NET EVAPORATION (INCHES)

Period (years)	RECURRENCE INTERVAL (YEARS)					
	5	10	20	50	100	200
1					88,9	39,1
2					79,8	80,0
3					104,0	105,0
4					153,0	154,0
5					184,0	185,0
6					227,0	228,0

TABLE 9: ANNUAL NET EVAPORATION (INCHES)

	RECURRENCE INTERVAL (YEARS)					
	5	10	20	50	100	200
First Year					38,9	39,1
Second Year					40,9	40,9
Third Year					24,2	25,0
Fourth Year					49,0	49,0
Fifth Year					31,0	31,0
Sixth Year					43,0	43,0

TABLE 10: MONTHLY NET EVAPORATION (INCHES) RECURRENCE INTERVAL 100 YEARS

	O	N	D	J	F	M	A	M	J	J	A	S
First Year	4,95	2,81	3,87	2,87	2,25	1,17	2,45	2,36	2,81	3;33	4,47	5,57
Second year	4,72	4,29	3,56	3,15	2,07	3,50	2,37	2,72	2,64	2,19	4,25	5,48
Third year	5,32	2,64	6,99	3,47	0,05	-0,33	0,99	0,22	3,43	-2,61	3,32	1,15
Fourth year	4,83	5,02	4,37	4,50	3,76	2,46	2,70	3,55	322	3,55	4,82	6,23
Fifth year	3,30	2,42	1,51	2,65	1,82	1,80	2,00	1,73	2,14	2,89	4,27	4,45
Sixth year	4,96	4,51	3,75	3,31	2,17	3,68	2,49	2,86	2,77	2,30	4,47	5,76

TABLE 11: MONTHLY NET EVAPORATION (INCHES)
RECURRENCE INTERVAL 200 YEARS

	O	N	D	J	F	M	A	M	J	J	A	S
First Year	4,97	2,82	3,89	2,89	2,26	1,17	2,47	2,37	2,82	3,35	4,49	5,60
Second Year	4,72	4,29	3,56	3,15	2,07	3,50	2,37	2,72	2,64	2,19	4,25	5,48
Third Year	5,49	2,73	7,23	3,59	0,05	-0,35	1,02	-0,23	3,55	-2,70	3,43	1,19
Fourth Year	4,83	5,02	4,37	4,50	3,76	2,46	2,70	3,55	3,22	3,55	4,82	6,23
Fifth Year	3,30	2,42	1,51	2,65	1,82	1,80	2,00	1,73	2,14	2,89	4,27	4,45
Sixth Year	4,96	4,51	3,75	3,31	2,17	3,68	2,49	2,86	2,77	2,30	4,47	5,76

5 VAAL DAM

CAPACITY REQUIRED DURING DROUGHT SEQUENCE OF RECURRENCE INTERVAL 200 YEARS

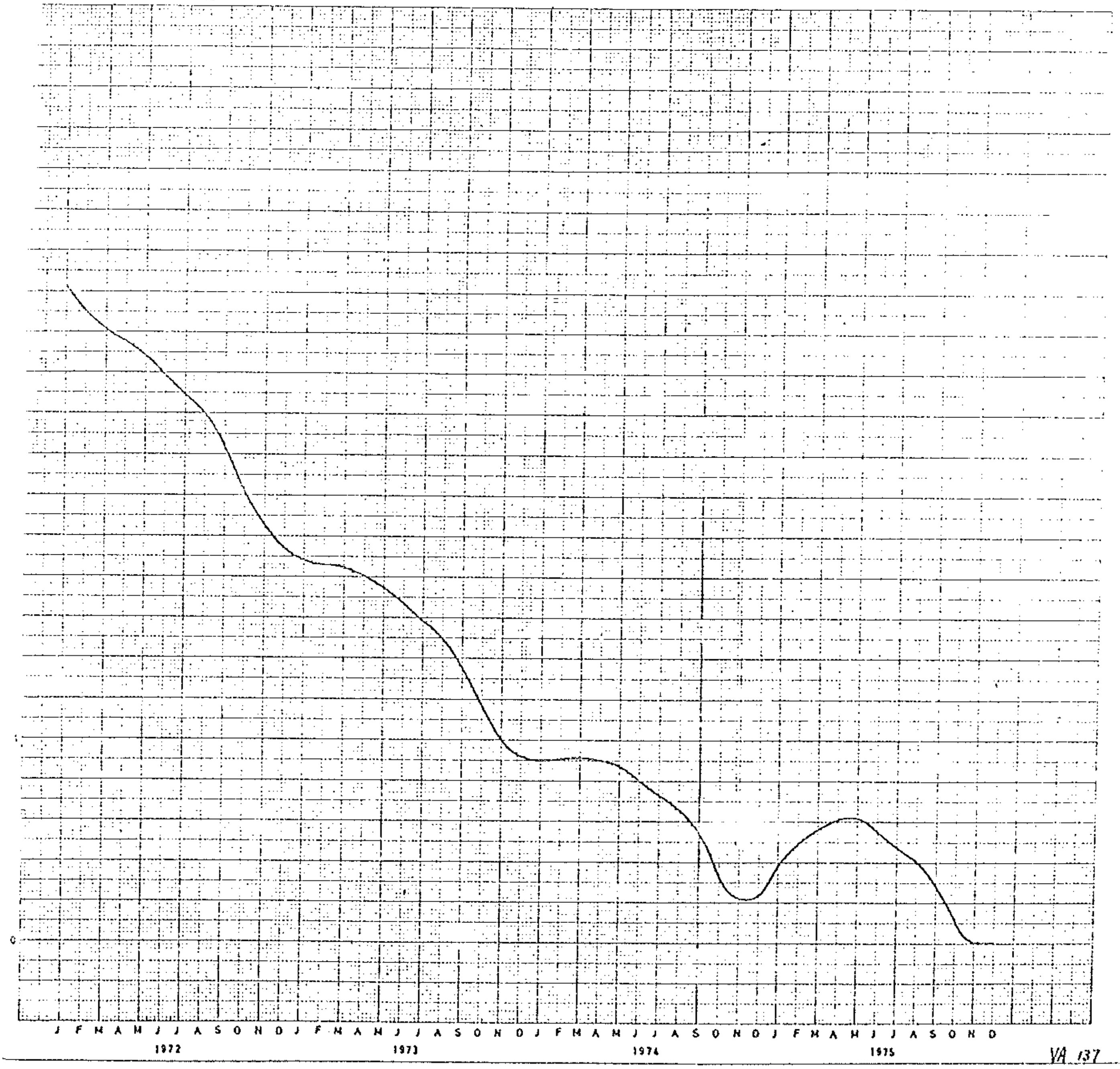

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Fig. 4 **VAAL DAM** CAPACITY REQUIRED DURING DROUGHT SEQUENCE OF RECURRENCE INTERVAL 100 YEARS