The incremental cost for the incremental demand of $42 \times 10^6 m^3$ is computed as:

$$\text{cost} = RC(400).42.10^{-3}$$
$$= \underline{R0,42 \text{ million}}$$

The total capital investment during 1981 is then given by:

$$8,74+0,42 = \underline{R9,16 \text{ million}}$$

Incremental cost during 1982

Plant now exists to cope with water with an average TDS of 400 mg/l. The additional capital investment is now given by:

$$\{RC(450) - RC(400)\}.916.10^{-3} + RC(450).\{959-874\}.10^{-3}$$
$$= (15 - 10).916.10^{-3} + \text{[illegible]}0^{-3}$$
$$= \underline{R3,86 \text{ million}}$$

Incremental cost during 1983

In this year the average TDS level has been reduced to 350 mg/l (perhaps due to the commissioning of a demineralisation plant or some other ameliorative measure). There is no capital saving on the first $959.10^6 m^3$ of water supplied, as the investment in plant to utilise this water at 450 mg/l has already been made in 1982. The marginal cost on the incremental demand of $46 \times 10^6 m^3$ will, however, be lower than would have been the case if the TDS concentration had not been reduced. The total incremental cost is thus:

$$RC(350).46.10^{-3} = 5.46.10^{-3} = \underline{R0,23 \text{ million}}$$

Incremental cost during 1984

In the final year the TDS has again increased to 400 mg/l. There is still no capital investment required for the first $959.10^6 m^3$, as plant exists to cope with 450 mg/l. The incremental cost on the next $46.10^6 m^3$ is then calculated as:

$$\{RC(400) - RC(350)\}.46.10^{-3} = (10-5).46.10^{-3} = \underline{R0,23\ \text{million}}$$

while the incremental cost on the final $47.10^6 m^3$ is given by:

$$RC(400).47.10^{-3} = 10.47.10^{-3}$$
$$= \underline{R0,47\ \text{million}}$$

The total cost during 1984 is thus R0,70 million

The costs incurred in the years 1981 to 1984 can now be converted to equivalent 1980 (present value) annual costs in a manner similar to that described for annual running costs.

The above example clearly illustrates the complex nature of the calculations involved in estimating the capital costs. It should be noted that neither Heynike's cost curves (Heynike, 1980) nor the above method take any account of the benefits of scale which can be realised by increasing treatment plant capacities in larger steps, instead of in small annual increments.

It is beyond the scope of this report to compare capital investment costs (due to TDS in the water supply) for various options. The procedure outlined in this section has been presented merely as an approach which could be adopted when detailed feasibility studies of pollution abatement strategies are performed.

3.2 Examples demonstrating the model capability

In this section several options for improving the quality of water in the system are compared. Each option has been run for projected demand conditions for the period 1980/81 to 1999/2000, using the hydrology for the period 1914/15 - 1933/34.

3.2.1 Model input data

Annual demands are shown in Table 3.4. Except where otherwise stated the demands are based on White Paper R'77 (Secretary for Water Affairs, 1977). The split between water supplied to the

Table 3.4 : Projected annual water demands for the period 1980 - 2000

Year	Annual water demand ($m^3 \times 10^6$)							
	Grootdraai Dam to Vaal Dam[1]	southern PWV region[2]	northern PWV region	Welkom Dam catchment[3]	Welkom Dam to Bloemhof Dam		downstream of Bloemhof Dam	
					urban	other[4]	urban	other[4]
1980	34	485	348	41	180	134	33	615
1981	63	512	363	41	184	134	35	615
1982	105	539	378	42	188	134	37	615
1983	129	569	394	42	192	134	39	615
1984	148	599	410	43	196	134	41	615
1985	160	635	431	44	201	134	43	615
1986	172	676	453	44	205	134	45	615
1987	186	724	480	45	209	134	47	615
1988	196	769	503	46	213	134	48	615
1989	200	814	530	46	218	134	50	615
1990	207	857	552	47	222	134	52	615
1991	213	903	576	48	226	134	54	615
1992	219	952	600	49	230	134	56	615
1993	226	1003	626	50	234	134	58	615
1994	228	1057	653	51	238	134	61	615
1995	229	1113	682	52	243	134	63	615
1996	237	1174	71[illegible]	53	247	134	66	615
1997	246	1239	743	54	252	134	69	615
1998	255	1274	758	56	256	134	72	615
1999	264	1378	811	57	261	134	75	615
2000	274	1453	847	58	265	134	78	615

1 Revised estimates (Perkins, 1981)

2 After 1985 the demands have been adjusted to account for the Lethabo power station, the first stage of which is due to be commissioned in September, 1985.

3 Users in the southern PWV region whose effluent is discharged downstream of Vaal Barrage (i.e. SASOL and Vanderbijl Park Municipality)

4 Irrigation and river losses.

southern and northern PWV region catchments was based on the estimates made by Hall (April 1980). (He estimated the supply to the northern catchment during the year 1978/79 at 40,2 percent of the total PWV region demand, declining to 35,9 percent by the year 2000). Pumping rates for water delivered from the Tugela basin to Sterkfontein Dam have been assumed to be as given in White Paper R'77 (i.e. $130x10^6m^3$ p.a. until the end of 1981 when the transmission rate is to be increased to $346x10^6m^3$ p.a.). From 1985 onwards it is anticipated that water will be pumped into the upper reaches of the Vaal (upstream of Grootdraai Dam) at the rate of $99,7x10^6m^3$ p.a. In consultation with the mining houses, Hall (February 1980) made estimates of future mine pumpage rates (de-watering of mine workings) and TDS concentrations for the period 1980 to 2000. Hall notes that roughly 60 percent of the pumpage from the S.A. Lands mine is delivered to the ERGO reduction plant. It has been assumed that half of this is eventually discharged to stream. Since Hall's estimates were made, however, the gold price has risen dramatically and it has therefore been assumed that the trends estimated by Hall will be delayed a further ten years. Table 3.5 gives the projected mine pumpage values used in this study.

Details of the hydrological input data, reservoir characteristics, rainfall and evaporation data and other model parameters are given in Appendix A.

Table 3.5: Projections of future mine pumpage discharges and TDS concentrations

Year	1980	1990	2000
Discharge (m^3x10^6 p.a.)	46	46	21
TDS (mg/l)	3200	3200	4100

3.2.2 Testing of options

It must again be stressed that the following results are presented purely by way of example. A much more thorough analysis along the lines suggested in section 3.2.1 will have to be made before any option is rejected as worthless. The comparisons are drawn on the basis of only one hydrological sequence. The period used (1914/15 -1933/34) embraces a fairly normal period followed by a long severe drought broken by a flood; in fact, it contains the most severe recorded drought sequence (terminating in November 1933, corresponding to the demand year 1998). Part of this 20-year hydrological sequence is therefore exceptional. It may not be the most satisfactory period to adopt in comparing the system behaviour for various options (as dry conditions may favour certain of the options).

a) Option 1

The first option simulated is the status quo. In this option it is assumed that the pattern of abstractions in future years will remain essentially the same as at present. In particular, the proportionate abstractions required to meet PWV region demands from the Vaal Barrage upstream and downstream of the Klip river confluence and from Vaal Dam are assumed to remain unaltered (i.e. 39,8, 25,1 and 35,1) percent respectively). This so-called 'status quo' option does not in fact represent the most likely future operating rule because a canal to deliver increased volumes of Vaal Dam water to the Zuikerbosch pump station is already under construction. It is conceivable, however, that a policy could be adopted requiring the Rand Water Board to restrict the use of the canal in such a way that the status quo will be preserved.

This option is therefore a useful benchmark against which other options may be compared.

Fig. 3.3 is a plot of simulated monthly reservoir storage states, average monthly TDS concentrations of water supplied and end-of-month reservoir TDS concentrations. In this option there is no dam at Schoemansdrift (i.e. no Welkom Dam). The 'Welkom Dam' monthly salt concentrations are in fact salt concentrations in the Vaal river at the potential dam site

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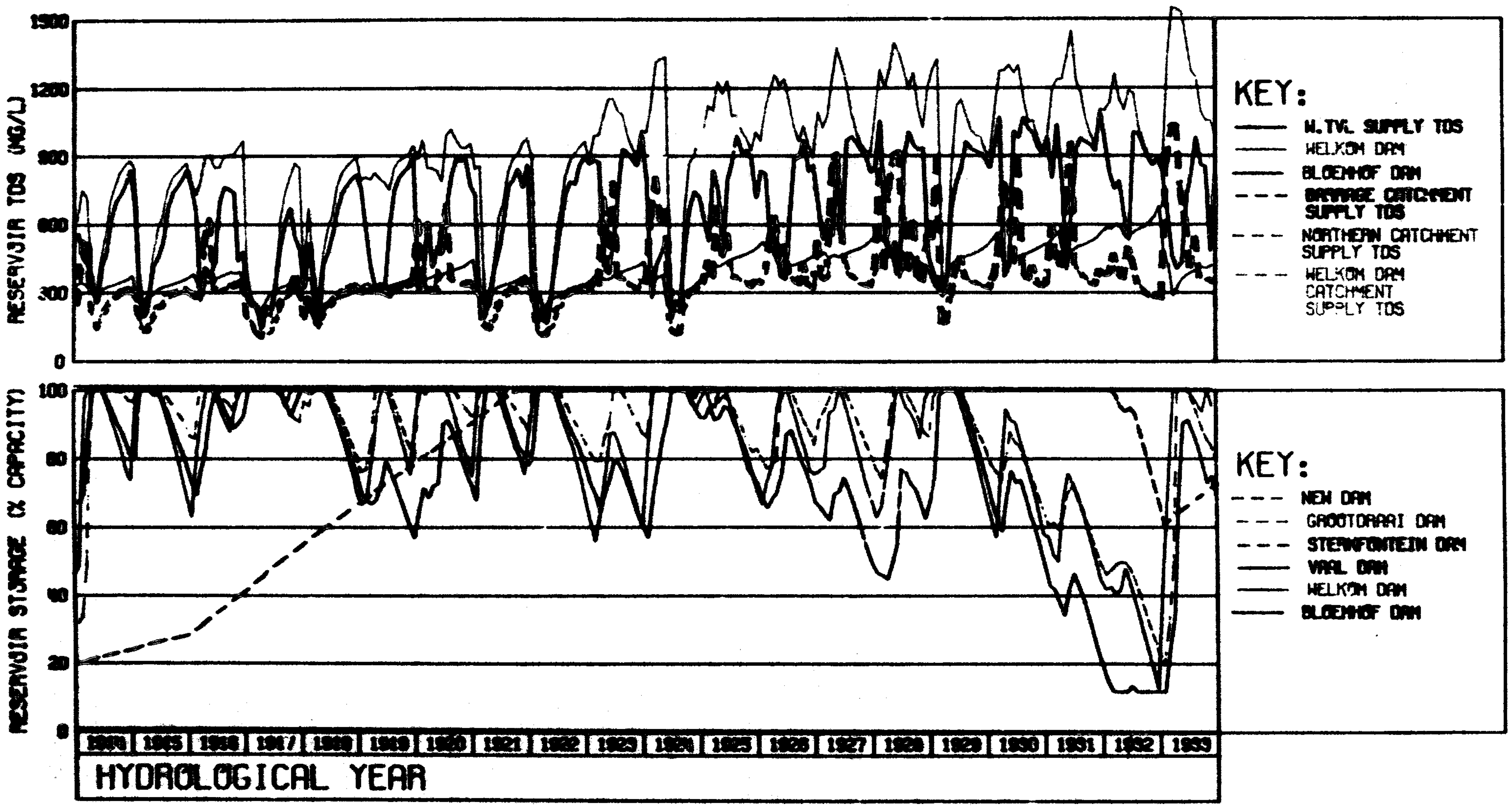

FIGURE 3.3 MONTHLY STORAGE STATES AND AVERAGE MONTHLY TDS CONCENTRATIONS FOR OPTION 1 (TIME HORIZON: 1980-1999)

(on the farm Welkom). In this option it is assumed that all users in the PWV region receive the same blend of water. The black, green and red dashed lines representing the TDS concentrations of water supplied to the Barrage, northern and Welkom Dam catchments therefore plot on top of one another, giving the appearance of a heavy black dashed line.

It can be seen that this option gives rise to occasional sharp rises in the water supply TDS concentrations, which become more frequent towards the end of the simulation. These peaks are attributable to the washoff of diffuse source salts during the wetter months. The mean TDS concentration can also be seen to rise gradually throughout the simulation. This is attributable partly to increased generation of diffuse source salts and partly to increased water demands in the Barrage catchment, with consequent increased effluent return flows.

The water passing down the Vaal river steadily deteriorates with time (as evidenced by salt concentrations at Welkom Dam and at the western Transvaal Vaal river intakes). Bloemhof Dam salinities remain reasonably low throughout the simulation, while Vaal Dam salt concentrations (which are not plotted) vary between 90 and 150 mg/l . (The Vaal Dam catchment has been assumed to remain in a virgin state throughout the simulation. This assumption may not remain valid, however, because of the extensive petro-chemical industries now being developed at Secunda, giving rise possibly to increased fall-out on catchments tributary to the Vaal.)

The Sterkfontein Dam storage rises steadily until 1982, when the second phase of the Tugela-Vaal scheme comes into operation with an ensuing increased pumping rate. After Sterkfontein Dam fills in 1987, pumping is assumed to continue, the excess water spilling to Vaal Dam. The remaining reservoirs spill frequently and do not really come under stress until 1995 when, after all the dams have spilled, a critical drought sequence begins, culminating in October 1999 with Vaal Dam drawn down to reserve and Sterkfontein Dam is called upon to make up the system shortfall. Grootdraai Dam is drawn down to within 20 percent of its capacity, but does not fail. Bloemhof Dam is also drawn down nearly to reserve, but this is not critical as Bloemhof calls upon upstream reservoirs to meet shortfalls. In October of 1999 Sterkfontein Dam is left with 60% capacity in reserve.

The following points should be borne in mind:

(i) Although the system is placed under stress only during the period 1995 to 1999 in this simulation, the critical drought sequence is just as likely to occur earlier than that date. This consideration is particularly important for options 4A, 4C, 6 and 7 which result in failure to meet demands in 1999. The large supply deficits associated with some of the options under 1999 demand conditions suggest that the system could fail prior ' '999 if the 1929 - 1932 critical drought sequence were to occur earlier.

(ii) Although the 1929 to 1932 drought sequence was the most severe observed in some 75 years of hydrology, a drier sequence than this could conceivably occur, and this would lead to a much more serious situation.

(iii) When all the reservoir storages begin falling dramatically water restrictions would almost certainly be imposed. No provision for such restrictions was made in this or any of the other simulations.

It is not the intention of this study to establish storage requirements in the system to meet various demand levels. The Directorate of Water Affairs has its tried and trusted techniques for analysing reservoir yields. The model can however give some indication of varying water requirements associated with different pollution control strategies.

It is interesting to note that the assumed policy of continuing to pump water from the Tugela after Sterkfontein Dam fills would have as a consequence (if the 1914-1933 hydrology were to be duplicated exactly from 1980 to 1999) wastage of all the water pumped between 1987 and 1994 because all the dams spill in 1995. On the other hand, the policy has the advantage that continued pumping between 1995 and 1997 helps to alleviate the drought and increases the margin of safety. It would thus appear that increased benefit could be derived from the relatively expensive imported water by providing additional storage after 1987. It is possible, however, that the cost of additional storage might outweigh the advantages to be derived. (It would obviously be unwise to keep on extending the storage of Sterkfontein Dam indefinitely because as demands increase calls on Sterkfontein will become more frequent, with the consequence that beyond a certain demand level the dam may never again fill).

The monthly TDS concentrations of Fig. 3.3 have been expressed in the form of cumulative frequency curves in Fig. 3.4. From Fig. 3.4 it can be seen that during the 20-year simulation the average monthly TDS of water supplied in the PWV region exceeds 500 mg/l for 18% of the time, with peak months averaging 1000 mg/l. The situation immediately downstream of Vaal Barrage can be seen to be much worse. Further downstream, however, the concentrations decrease due to the diluting effect of runoff from the surrounding catchment.

The TDS concentrations in Bloemhof Dam remain at acceptable levels. Fig. 3.2 suffers from the drawback that it is compiled from the combined monthly salinities of twenty different demand years. Similar curves for each of the demand years from 1980 to 1999 compiled from the results of the simulation of several different hydrological sequences would be much more significant, but such a detailed study is beyond the scope of this report.

The analysis of the running costs was performed in a manner similar to that discussed in section 3.1 for the 20-year sequence. Annual running costs for each option assuming

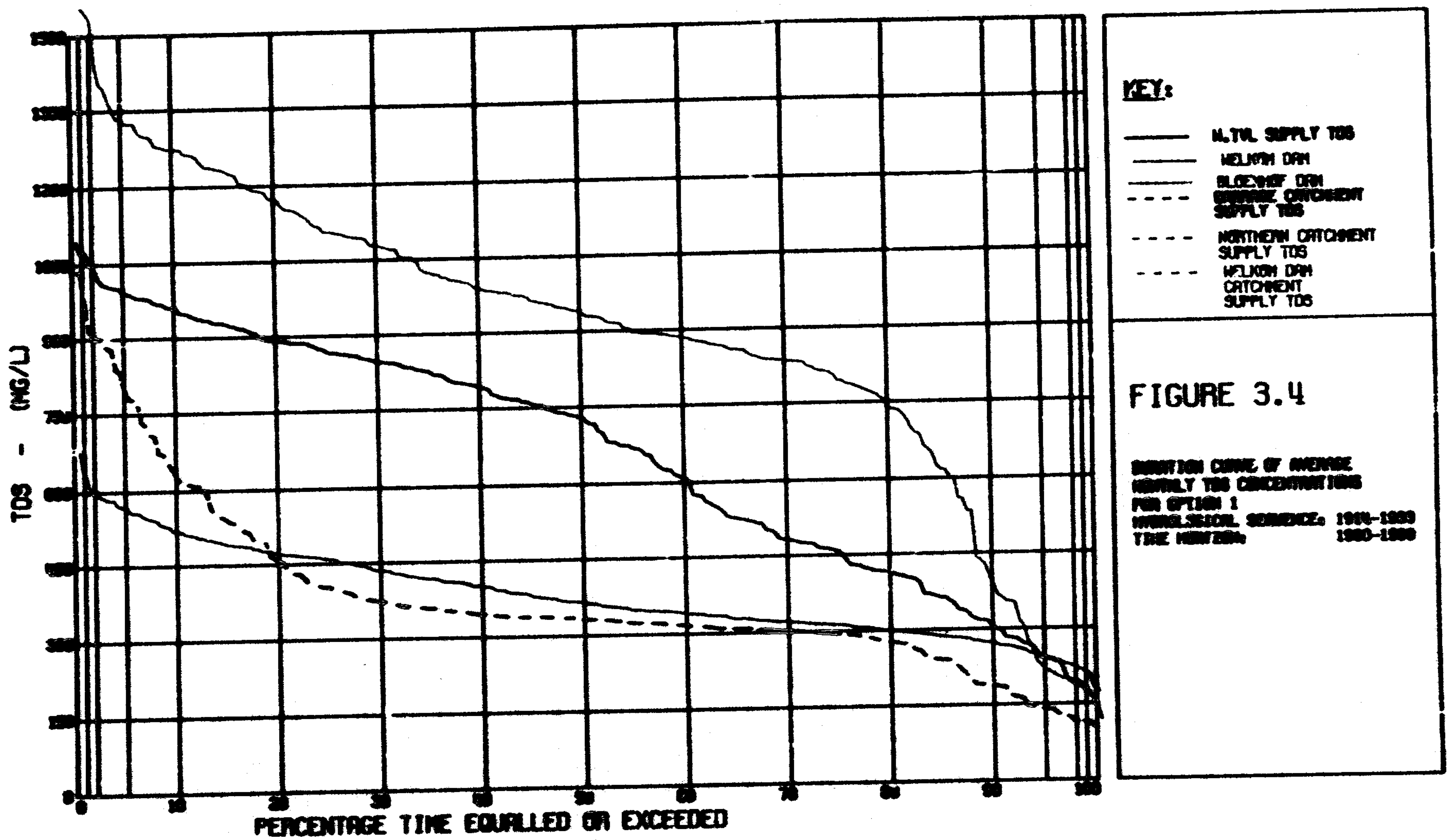
TDS - (MG/L)
PERCENTAGE TIME EQUALLED OR EXCEEDED
0
10
20
30
40
50
60
70
80
90
100
KEY:
N.TVL SUPPLY TDS
WELKOM DAM
NORTHERN CATCHMENT
SUPPLY TDS
WELKOM DAM
CATCHMENT
SUPPLY TDS

FIGURE 3.4

effective interest rates of -3, 0, 5 and 10 per cent are given in Tables 3.6 to 3.9. The running costs for different TDS levels derived by Heynike for the PWV region were assumed to hold true also for domestic and industrial users downstream of Vaal Barrage.

From Tables 3.6 to 3.9 it can be seen that the total running cost for the status quo option, assuming that the 1914 to 1933 hydrology is duplicated over the next 20 years, would vary between R31,6 million and R61,7 million, depending upon the prevailing effective interest rate. With the present high rate of inflation the most applicable effective interest rate available to the general public (i.e. to those who will have to bear the brunt of the running costs) would be in the -3 to 0% range. How interest rates and the rate of inflation will vary in the future is, of course, debatable.

It is of interest to note that for the hydrological sequence simulated in this example urban users downstream of Vaal Barrage suffer a disproportionately higher economic loss per unit of water supplied than do users in the PWV region. The reason lies in the much higher salt concentrations in the lower reaches of the Vaal river (see Fig. 3.4).

In order to facilitate comparison of annual running costs for the remaining options, the total costs given in Tables 3.6 to 3.9 have been expressed in the form of annual cost savings relative to the status quo option. These cost savings, or annual benefits, are summarised in Table 3.10.

Table 3.11 shows simulated reservoir storages in November 1999 (corresponding to the hydrological year 1933). This is in fact the critical month, when reservoir storages reach their lowest levels. Total supply deficits for the entire simulation are also indicated in Table 3.11. It should be noted that the probability of failure for any of the listed options cannot be deduced from Table 3.11. The tabulated values do, however, give an indication of the relative impact of the different options on reservoir storage states.

Table 3.6 : Annual running cost for the period 1980-1999 assuming an effective interest rate of -3% (rands x 10^6)

Option number	Demand centre				
	southern PWV region	northern PWV region	PWV users discharging downstream of Barrage	urban users downstream of Vaal Barrage	All domestic & industrial users
1	24,3	14,7	1,1	21,6	61,7
2A	128,3	-9,2	-0,8	7,8	126,2
2B	129,8	81,1	-0,7	8,9	219,1
2C	-32,1	-20,8	-0,8	8,1	-45,0
3A	12,5	7,3	0,5	17,5	37,8
3B	13,6	7,9	0,5	17,7	39,7
4A	-52,0	-32,7	-2,7	24,9	-62,5
4B	-3,9	-2,5	-0,2	23,7	17,1
4C	-4,7	-3,0	-0,3	-1,5	-9,4
5A	64,4	39,8	3,2	9,8	117,2
5B	-4,1	-2,6	-0,2	-1,3	-8,2

Table 3.7 : Annual running cost for the period 1980-1999 assuming an effective interest rate of 0% (rands x 10^6)

Option number	Demand centre				
	southern PWV region	northern PWV region	PWV users discharging downstream of Barrage	urban users downstream of Vaal Barrage	All domestic & industrial users
1	20,3	12,3	0,9	20,3	53,8
2A	117,8	-9,2	-0,8	7,6	115,2
2B	119,0	74,8	-0,8	8,5	201,5
2C	30,5	-19,4	-0,8	7,6	-42,8
3A	8,9	5,0	0,3	16,1	30,3
3B	9,9	5,6	0,3	16,3	32,2
4A	-48,9	-31,1	-2,7	23,5	-59,1
4B	-3,9	-2,5	-0,2	22,1	15,5
4C	-4,5	-2,9	-0,3	-1,5	-9,2
5A	57,4	35,8	2,9	8,9	105,0
5B	-4,1	-2,6	-0,2	-1,3	-8,3

Table 3.8: Annual running cost for the period 1980-1999 assuming an effective interest rate of 5% (rands x 10^6)

Option number	Demand centre				
	southern PWV region	northern PWV region	PWV users discharging downstream of Barrage	urban users downstream of Vaal Barrage	All domestic & industrial users
1	14,2	8,6	0,6	18,2	41,6
2A	100,5	-9,2	0,9	7,2	97,7
2B	101,4	64,4	-0,8	8,0	173,0
2C	-27,6	-17,8	-0,8	7,5	-38,7
3A	3,5	1,6	0,0	13,9	18,9
3B	4,4	2,[illegible]	0,0	14,1	20,7
4A	-44,2	-28,5	-2,6	21,4	-53,9
4B	-3,8	-2,5	-0,2	19,5	13,0
4C	-4,3	2,8	-0,3	-1,4	-8,8
5A	47,0	29,7	2,5	7,6	86,8
5B	-4,1	-2,6	-0,2	-1,4	-8,3

Table 3.9 : Annual running cost for the period 1980-1999 assuming an effective interest rate of 10% (rands x 10^6)

Option number	Demand centre				
	southern PWV region	northern PWV region	PWV users discharging downstream of Barrage	urban users downstream of Vaal Barrage	All domestic & industrial users
1	9,3	5,6	0,4	16,4	31,6
2A	84,9	-9,0	-0,9	7,1	82,2
2B	85,4	54,9	-0,8	7,7	147,1
2C	-24,7	-16,1	-0,8	7,3	-34,3
3A	-0,9	-1,2	-0,3	12,0	9,7
3B	-0,1	-0,6	-0,2	12,3	11,3
4A	-40,3	-26,4	-2,5	19,5	-49,6
4B	-3,7	-2,4	-0,2	17,3	11,0
4C	-4,0	-2,7	-0,3	-1,4	-8,4
5A	38,7	24,9	2,2	6,6	72,4
5B	-3,9	-2,6	-0,3	-1,4	-8,2

Table 3.10 : Annual saving in running costs compared with the status quo option (rands x 10^6)

Option number	Effective interest rate (%)			
	-3	0	5	10
1	0	0	0	0
2A	-64,5	-61,4	-56,1	-50,6
2B	-157,4	-147,7	-131,4	-115,5
2C	106,7	96,6	80,3	65,9
3A	23,9	23,5	22,7	21,9
3B	22,0	21,6	20,9	20,3
4A	124,2	112,9	95,5	81,2
4B	44,6	38,3	28,6	20,6
4C	71,1	63,0	50,4	40,0
5A	-55,5	-51,2	-45,2	-40,1
5B	69,9	62,1	49,9	39,8

Table 3.11 : Reservoir storage states in October 1999 and total supply shortfall during the 20-year simulation (m^3 x 10^6)

Reservoir	Option number												
	1	2A	2B	2C	3A	3B	4A	4B	4C	5A	5B	6	7
Balmoral	0	0	0	0	0	0	0	0	0	0	0	0	0
Grootdraai	70	70	70	70	70	70	70	70	70	70	70	70	70
Sterkfontein	1583	1660	2600	1942	1491	1560	10*	1033	10*	2600	159	10*	26
Vaal	300*	300*	691	300*	300*	300*	300*	300*	300*	304	300*	300*	300*
Barrage	44*	44*	44*	44*	44*	44*	48	44*	48	44*	48	48	48
Welkom	0	0	0	0	0	0	0	0	0	82*	1532	0	0
Bloemhof	158	154	160	154	157	158	994	490	810	154	734	994	994
Total	2155	2228	3565	2510	2062	2132	1422	1937	1238	3254	2843	1422	1393
Deficit	0	0	0	0	0	0	743	0	800	0	0	511	403

* reserve storage

b) Option 2A: In this simulation it was assumed that a reclamation plant is commissioned in October, 1983, capable of treating the entire effluent return flow from the southern PWV (Barrage catchment) region. It is further assumed that plant capacity is increased in step with growing effluent returns between 1983 and 1999. The reclaimed water is blended, without demineralisation, with the water supply to the southern PWV region.

The consequences of this option are shown in Figs. 3.5 and 3.6 and Tables 3.10 and 3.11.

By comparing Figs. 3.3 and 3.4 with Figs. 3.5 and 3.6 it can be seen that a reclamation plant operated in this manner would result in sharply increased TDS levels in the southern PWV region, while users in the northern and Welkom Dam catchments, as well as those downstream of Vaal Barrage, would enjoy an improvement in water quality. Table 3.10 shows that this re-distribution of salt in the system could increase annual running costs in the entire system by between R51 million and R64 million, depending upon the interest rate assumed. (Tables 3.6 to 3.9 show that the savings to users in other parts of the system are more than outweighed by the large increase in costs in the southern PWV region).

The effect upon water resources can best be gauged by referring to the storage remaining in the reservoirs upstream of, and including, Vaal Dam. (Downstream reservoirs are not relevant because most of the demands arise in the PWV region and excess water stored downstream of Vaal Barrage is effectively lost to users in this area). Contrary to what might be expected, exercise of this option has only a marginal effect upon water reserves at the end of the critical drought sequence. Table 3.11 shows an improvement in residual storage upstream of Vaal Barrage of only 77 x $10^6 m^3$. This meagre improvement can be traced to two causes:

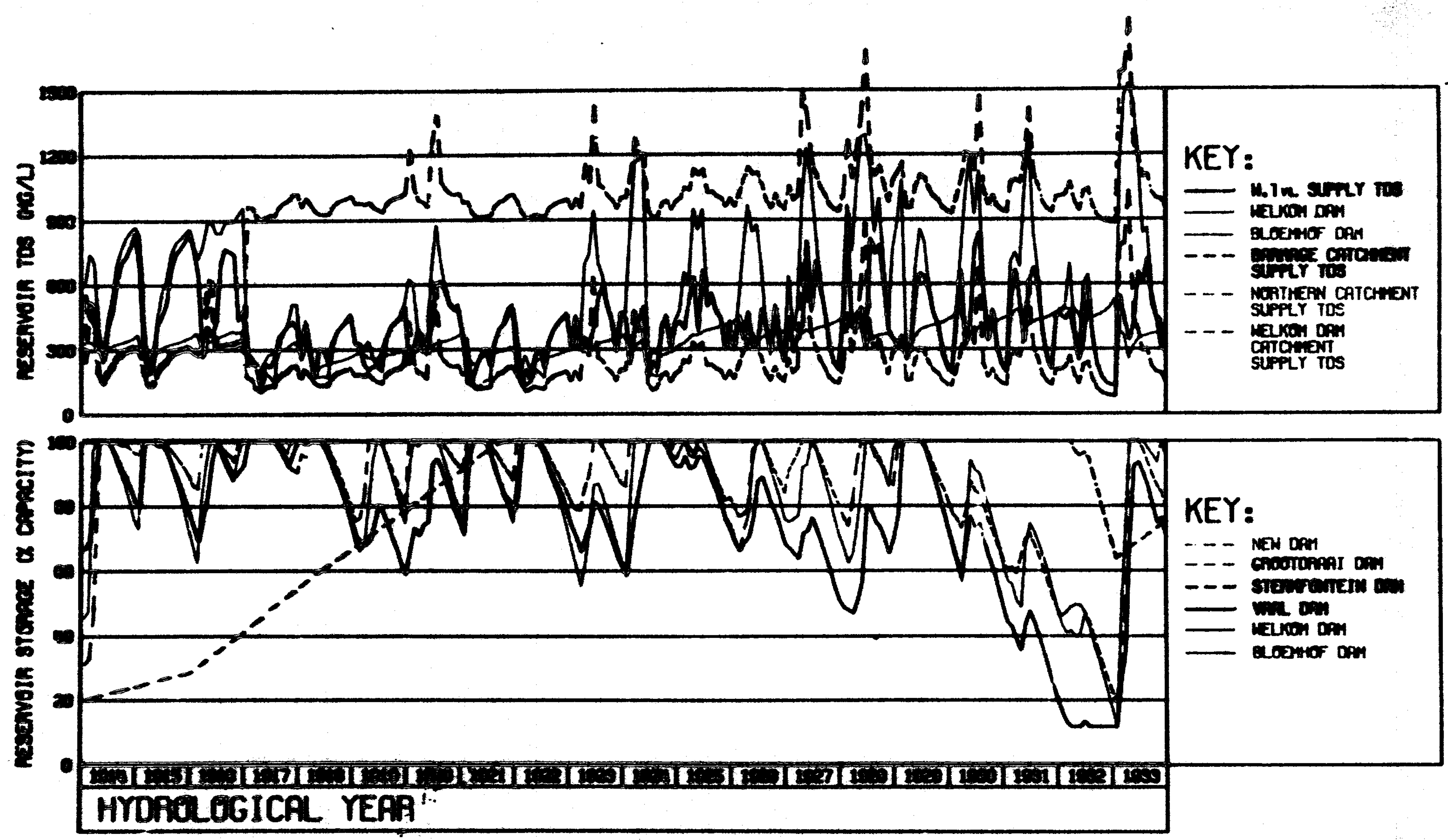

FIGURE 3.5 MONTHLY STORAGE STATES AND AVERAGE MONTHLY TDS CONCENTRATIONS FOR OPTION 2A (TIME HORIZON: 1980-1999)

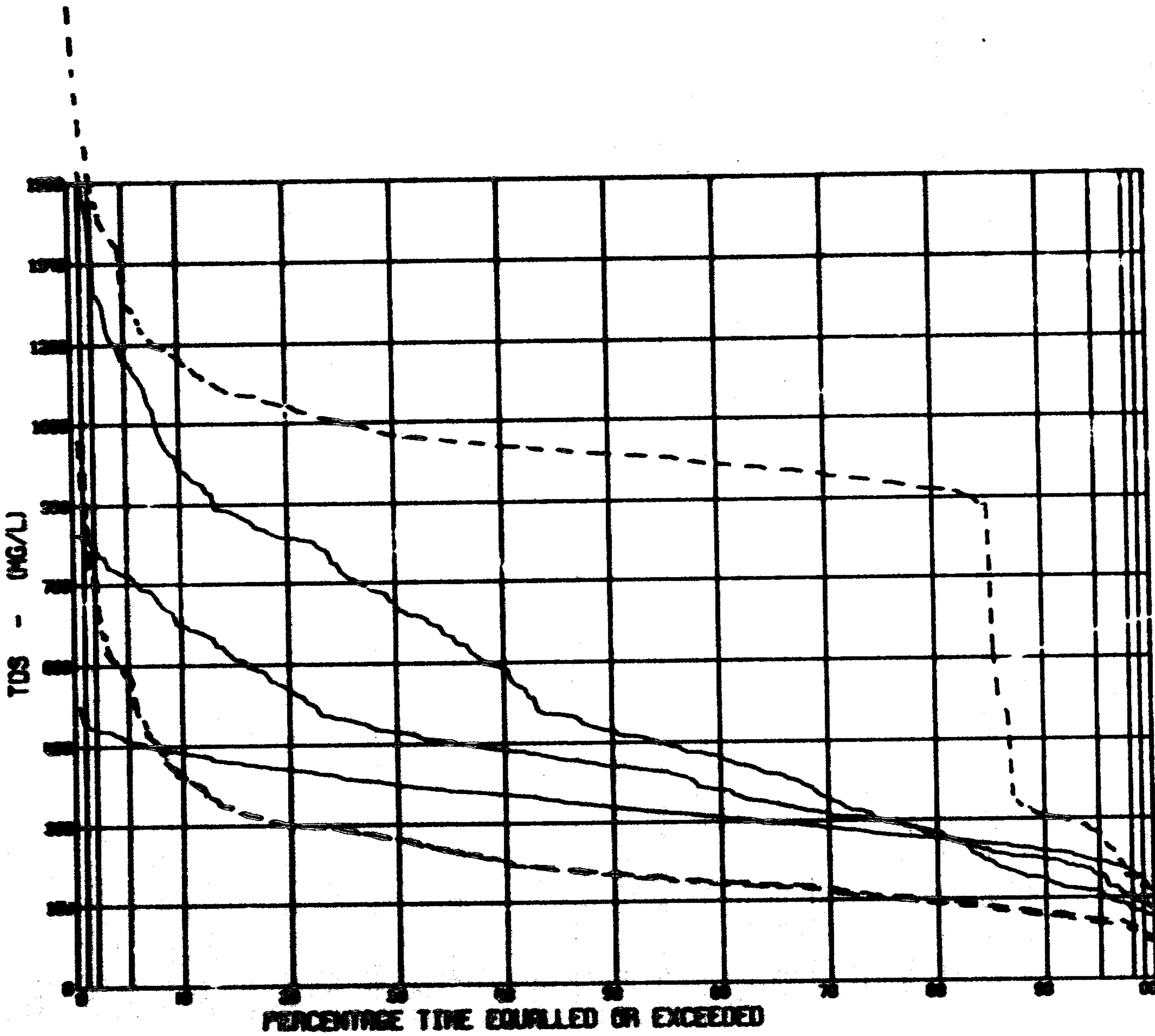

FIGURE 3.6

DURATION CURVE OF AVERAGE MONTHLY TDS CONCENTRATIONS FOR OPTION 2A
HYDROLOGICAL SEQUENCE: [illegible]
TIME HORIZON: [illegible]

(i) In the status quo option a substantial proportion of the southern PWV region effluent return flow is already being indirectly recycled via the RWB Vaal Barrage river intakes;

(ii) Of the remaining saving associated with reduced Vaal Dam abstractions (amounting to 3403 x $10^6 m^3$ during the twenty-year simulation) most is lost to increased releases from Vaal Dam to meet downstream water requirements that would otherwise have been met from return flows from the Barrage catchment. The main effect of option 2A is therefore to redistribute the salt in the system, to the detriment of the southern PWV region users.

With a different hydrological sequence there could perhaps be a more substantial saving in water. What emerges, however, is the disastrous effect on water quality that would be brought about by the implementation of option 2A.

c) Option 2B: This option is similar to 2A except that now another reclamation works has been introduced in the northern PWV catchment (both plants being commissioned in October 1983). As a result the water qualities in the northern and southern catchments become identical again, users in both regions now being supplied with poor quality water. Users downstream of Vaal Barrage, however, do not gain any improvement in water quality as a result of the second reclamation plant. On the contrary, their water quality deteriorates slightly (relative to option 2A) due to the decreased abstractions from Vaal Barrage. (This means that more of the mine pumpage and southern PWV region diffuse-source catchment washoff passes downstream). Table 3.10 indicates for users throughout the entire system an increased annual running cost of well in excess of R100 million. Fig. 3.7 and Table 3.11 do, however, show a substantial saving in water. This is because water reclaimed in the northern catchment would otherwise have been lost to the system (unlike the case of the southern catchment where most of the reclaimed water would in any event have been recycled via the Barrage intakes). This saving of water

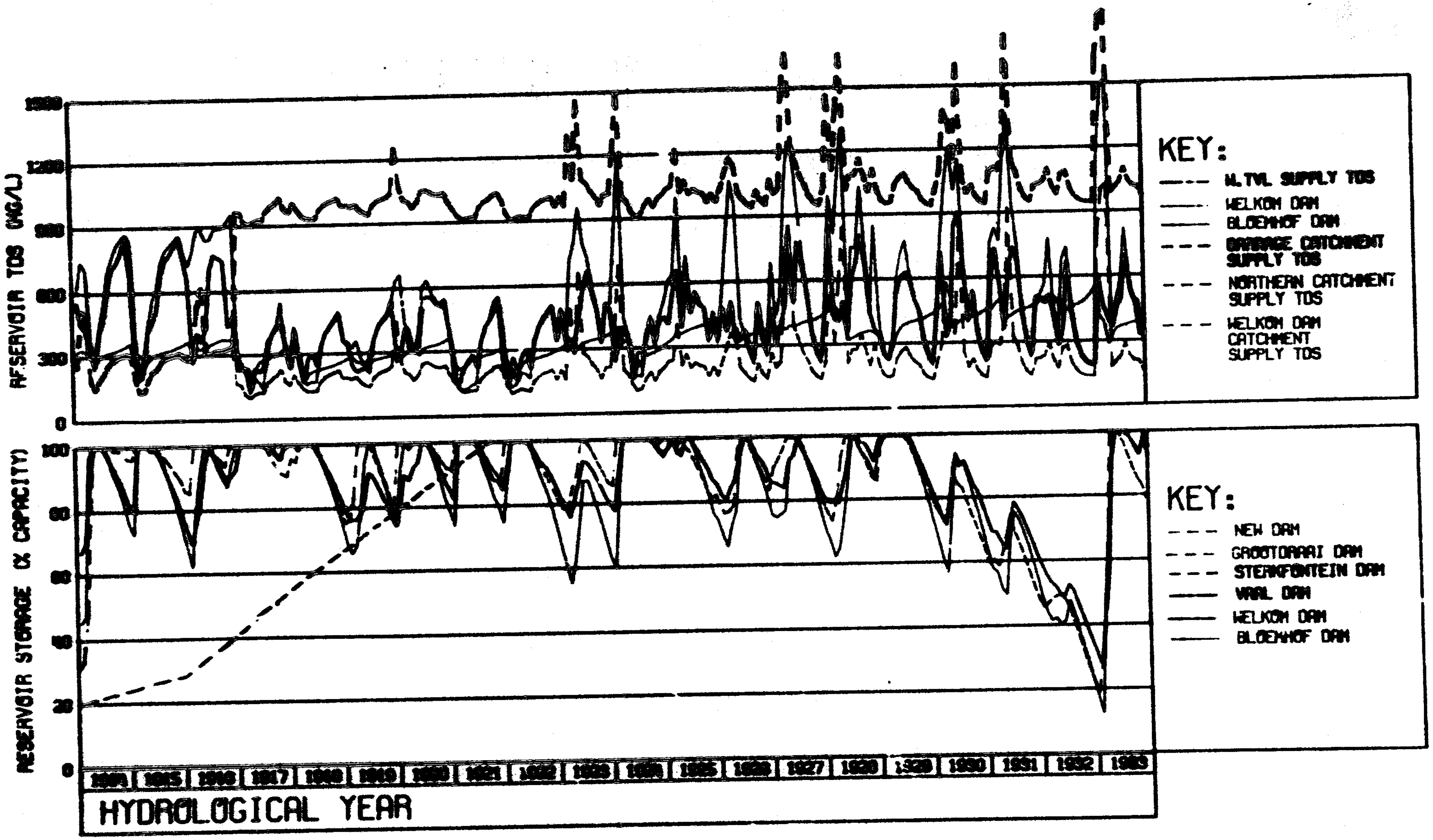

FIGURE 3.7 MONTHLY STORAGE STATES AND AVERAGE MONTHLY TDS CONCENTRATIONS FOR OPTION 2B (TIME HORIZON: 1980-1999)

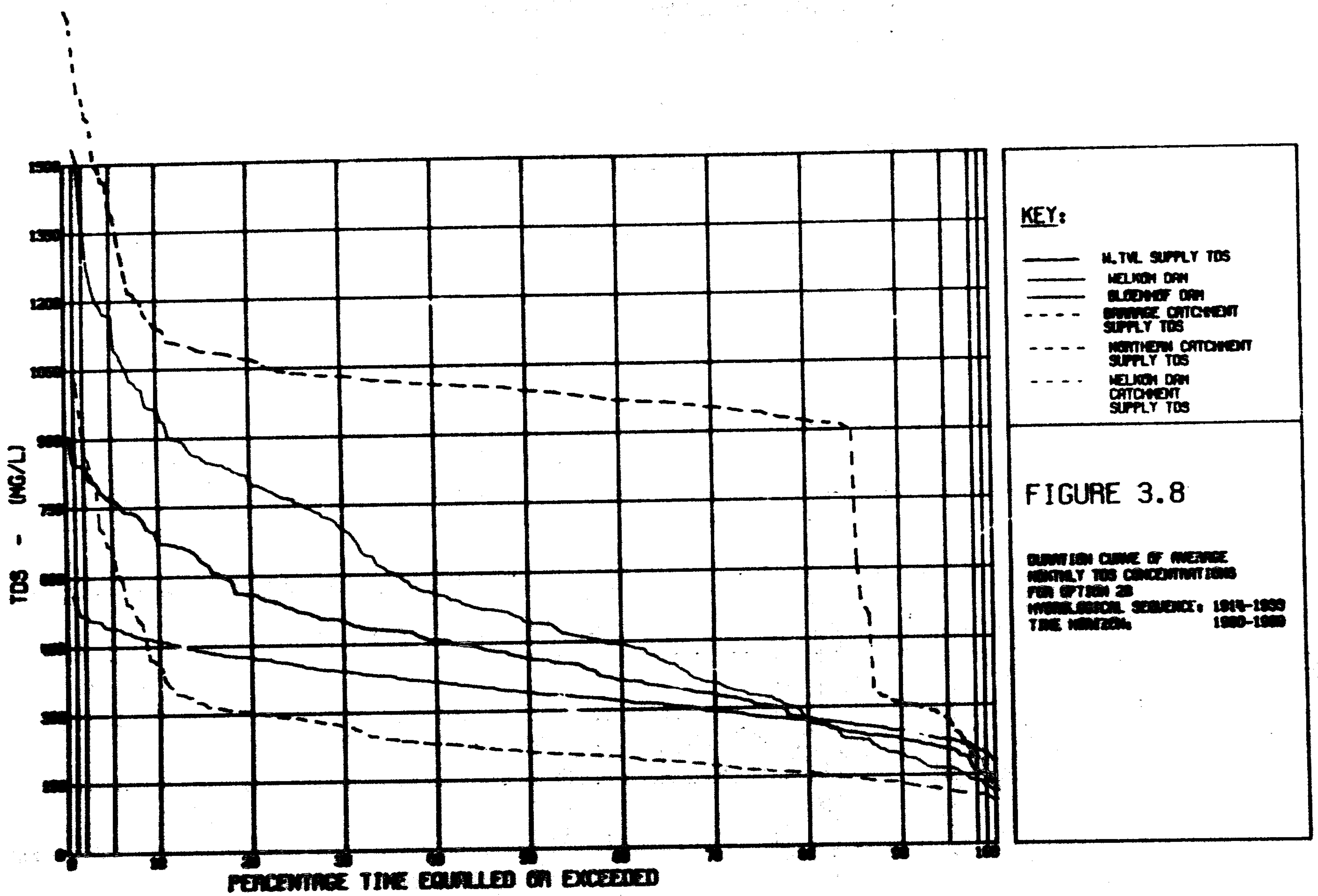

FIGURE 3.8

DURATION CURVE OF AVERAGE MONTHLY TDS CONCENTRATIONS FOR OPTION 2B
HYDROLOGICAL SEQUENCE: 1914-1933
TIME HORIZON: 1980-1989

($1408 \times 10^6 m^3$), together with the reduced pumping costs (water has to be lifted 300 m over a distance of about 50 km to supply most PWV region users) would have to be weighed against the cost of the advanced waste water treatment works, high TDS concentrations, health risks and adverse public opinion.

d) Option 2C: In option 2C it was assumed that the two reclamation plants of option 2B would be linked to demineralisation plants (of the reverse osmosis type) capable of reducing the TDS concentration by 90%, with a 30% brine bleed-off.

Figs. 3.9 and 3.10 show a dramatic improvement in the quality of water supplied to users in the PWV region. Table 3.10 shows an annual saving in running costs (compared with the status quo) in the range R66 million to R107 million. The quality of water supplied to downstream users is virtually the same as in option 2B, but users in the PWV region would now also enjoy a substantial improvement in water quality. It is of importance to note, however, that all users would continue to experience occasional high peak average monthly TDS concentrations (and the peak daily values can be expected to be considerably higher). A high capital cost is likely to be associated with these peak values. (Industrial demineralisation plants and storage reservoirs will have to be designed to deal with the peak salinities).

Table 3.11 shows that the saving in water is not as pronounced as in option 4B. This is because of the 30% brine bleed-off which has to be replaced with water from Vaal Dam. The saving in water compared with the status quo option is $359 \times 10^6 m^3$ (compared with $1408 \times 10^6 m^3$ for option 2B).

A thorough analysis of all economic costs involved, based on a large number of simulations, would have to be made to determine whether or not option 2C is viable. A major consideration will be the disposal of the large quantities

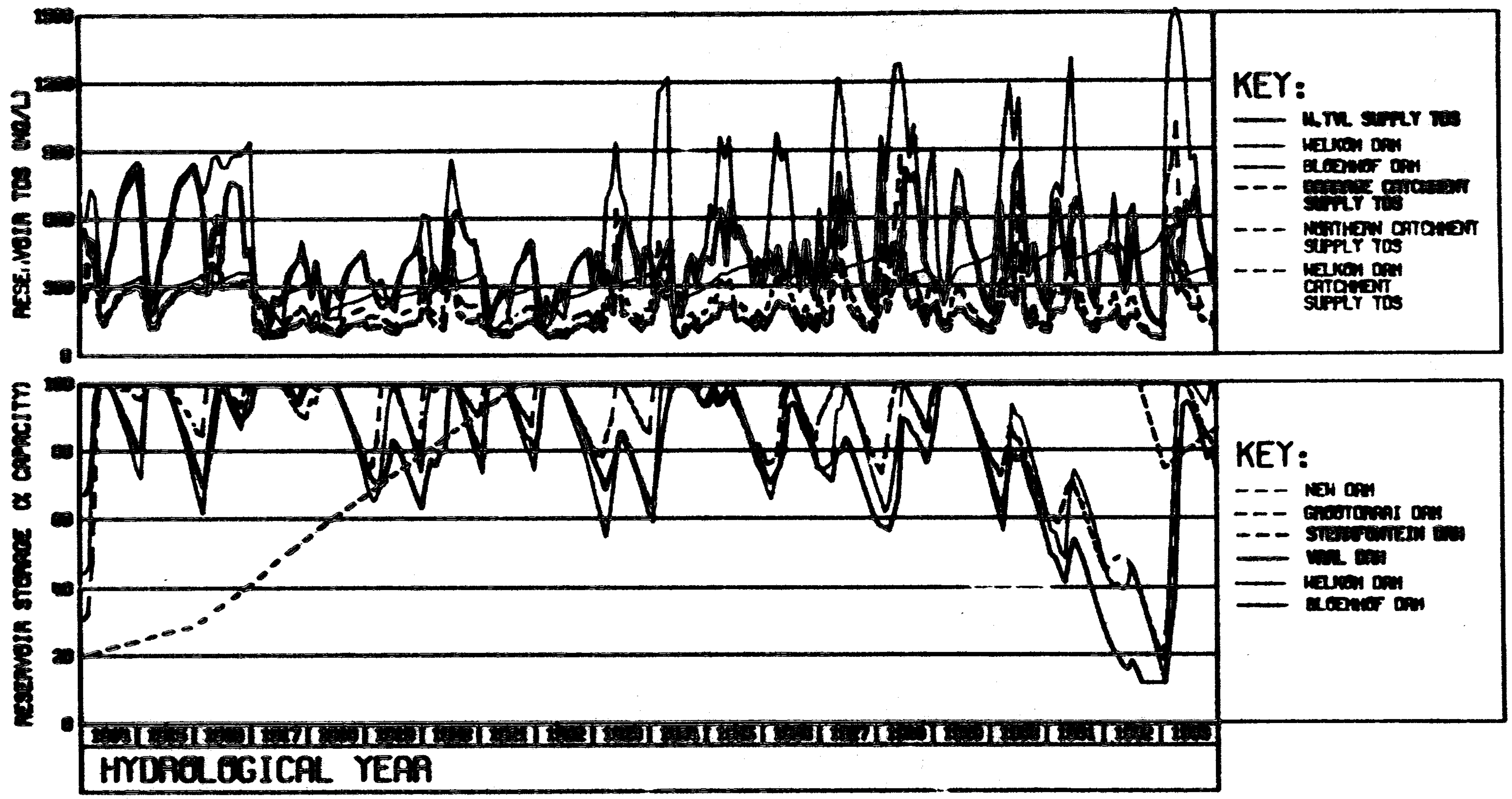

FIGURE 3.9 MONTHLY STORAGE STATES AND AVERAGE MONTHLY TDS CONCENTRATIONS FOR OPTION 2C (TIME HORIZON: 1980-1999)

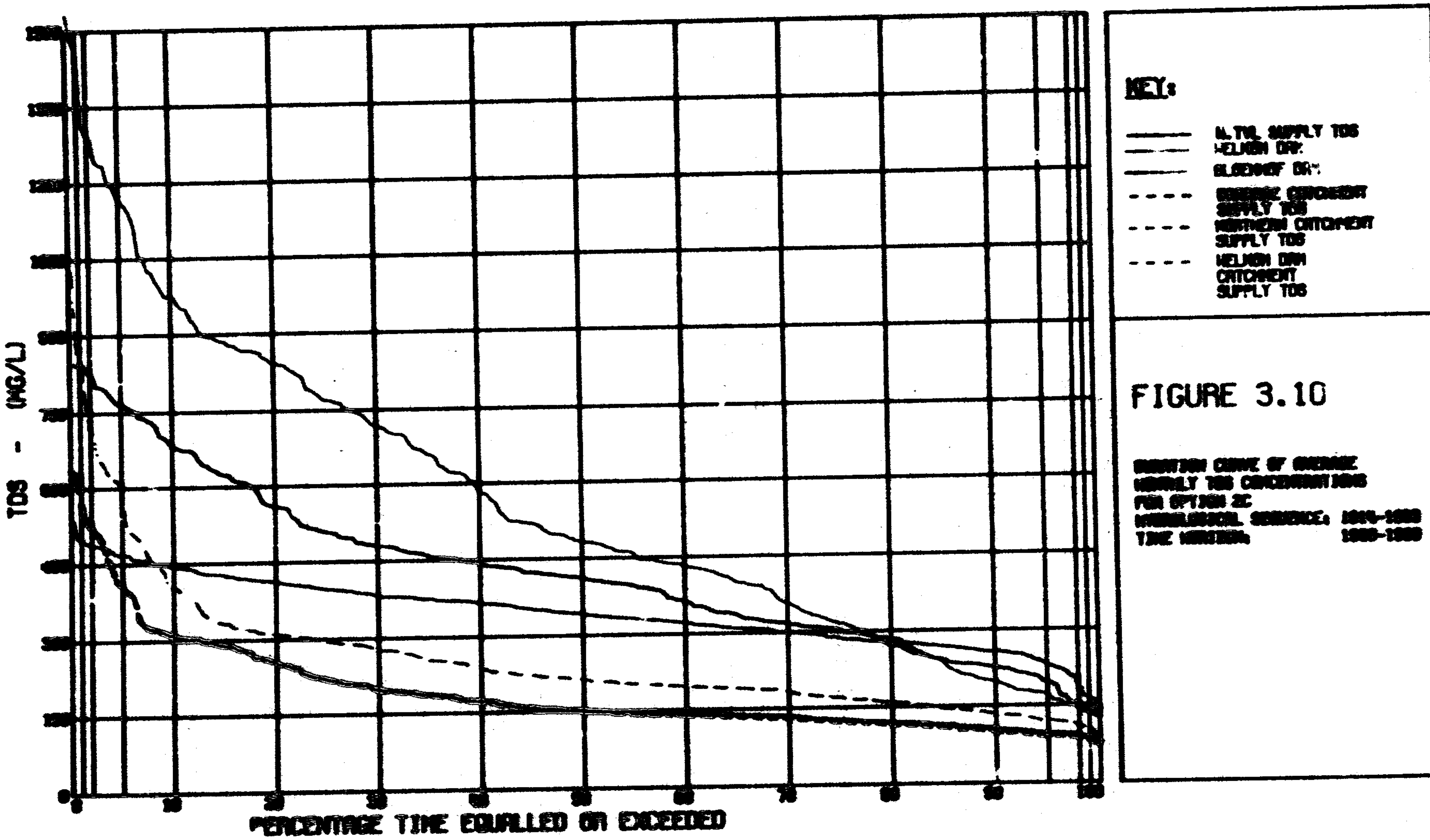

FIGURE 3.10

FOR OPTION 2C

of brine, viz.289 x $10^6 m^3$ p.a. in 1983, rising to 657 x $10^6 m^3$ p.a. in 1999.

e) <u>Option 3A</u>: This option involves collecting together and disposing of the saline waters pumped from the mine workings; these are normally discharged into the tributaries draining the southern PWV region. As can be seen by comparing Figs. 3.3 and 3.4 with Figs. 3.11 and 3.12, the consequences of removing the mine pumpage would be a lowering of the mean TDS concentration in the water supplied to all users in the system. Peak months, however, are barely affected. Table 3.10 indicates an annual saving in running costs of the order of R23 million. The capital costs to users associated with the peaks, however, are likely to be unaltered. From Table 3.11 it can be seen that removing the mine pumpage slightly decreases the residual storage in the reservoirs upstream of Vaal Barrage at the end of the simulation.

f) <u>Option 3B</u> : This option differs from 3A in that the mine pumpage is demineralised and discharged to the rivers. It was assumed that a reverse osmosis plant would be installed, capable of lowering salt concentrations by 90% with a 25% brine bleed-off.

It is difficult to distinguish the difference between simulated monthly TDS concentrations arising from options 3A and 3B (compare Figs. 3.11 and 3.12 with Figs. 3.13 and 3.14). Table 3.10, however, indicates that option 3A results in a greater saving in running costs than does option 3B. This is because mine water starting at a TDS concentration of 3200 mg/l is reduced to about 320 mg/l by a demineralisation plant of the type assumed. The water which is saved replaces water which would otherwise have had to be made good from Vaal Dam, at a TDS averaging about 120 mg/l.

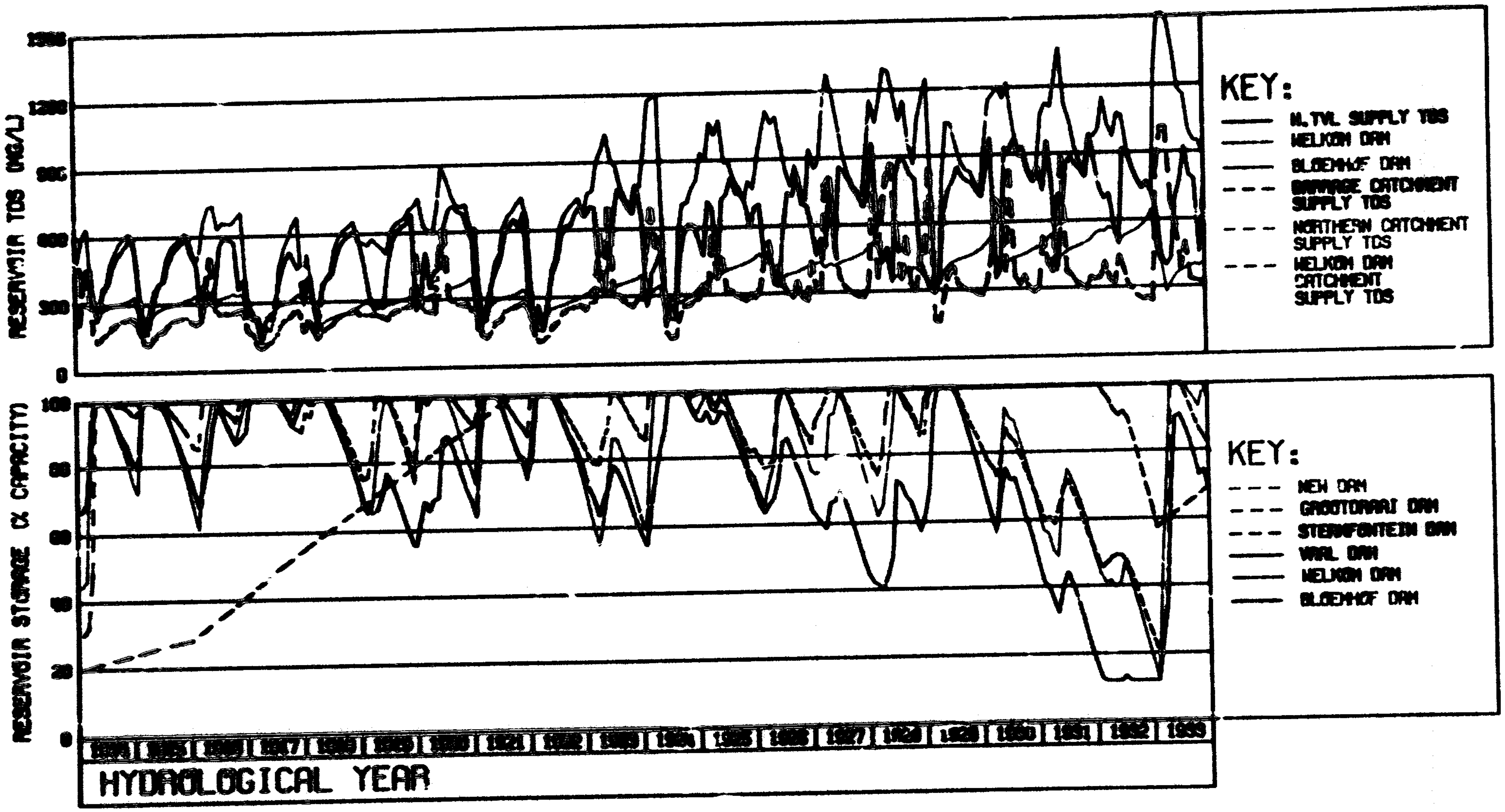

FIGURE 3.11 MONTHLY STORAGE STATES AND AVERAGE MONTHLY TDS CONCENTRATIONS FOR OPTION 3A (TIME HORIZON: 1980-1990)

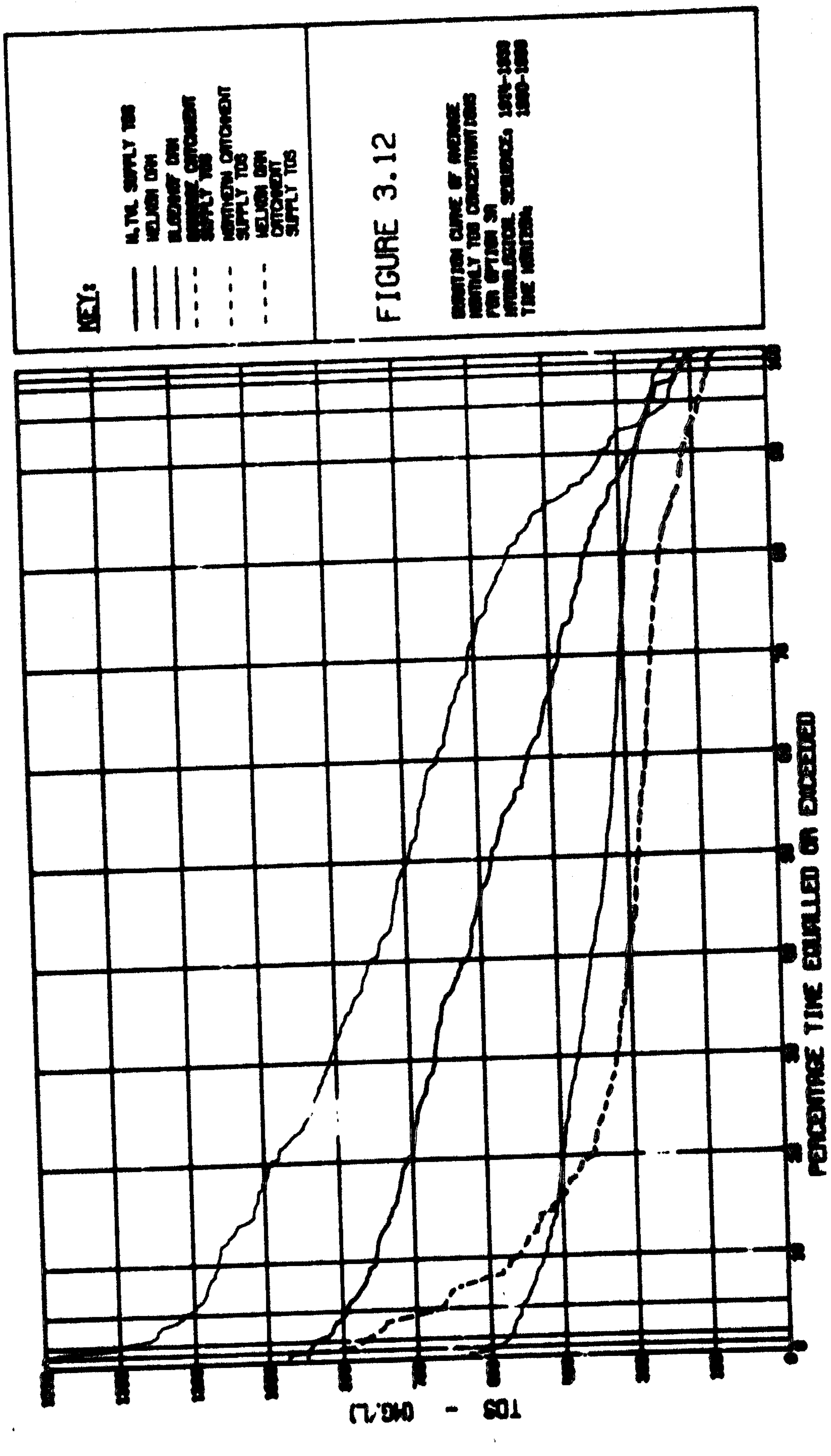

FIGURE 3.12

DURATION CURVE OF AVERAGE MONTHLY TDS CONCENTRATIONS FOR OPTION 3A HYDROLOGICAL SEQUENCE, TIME HORIZON

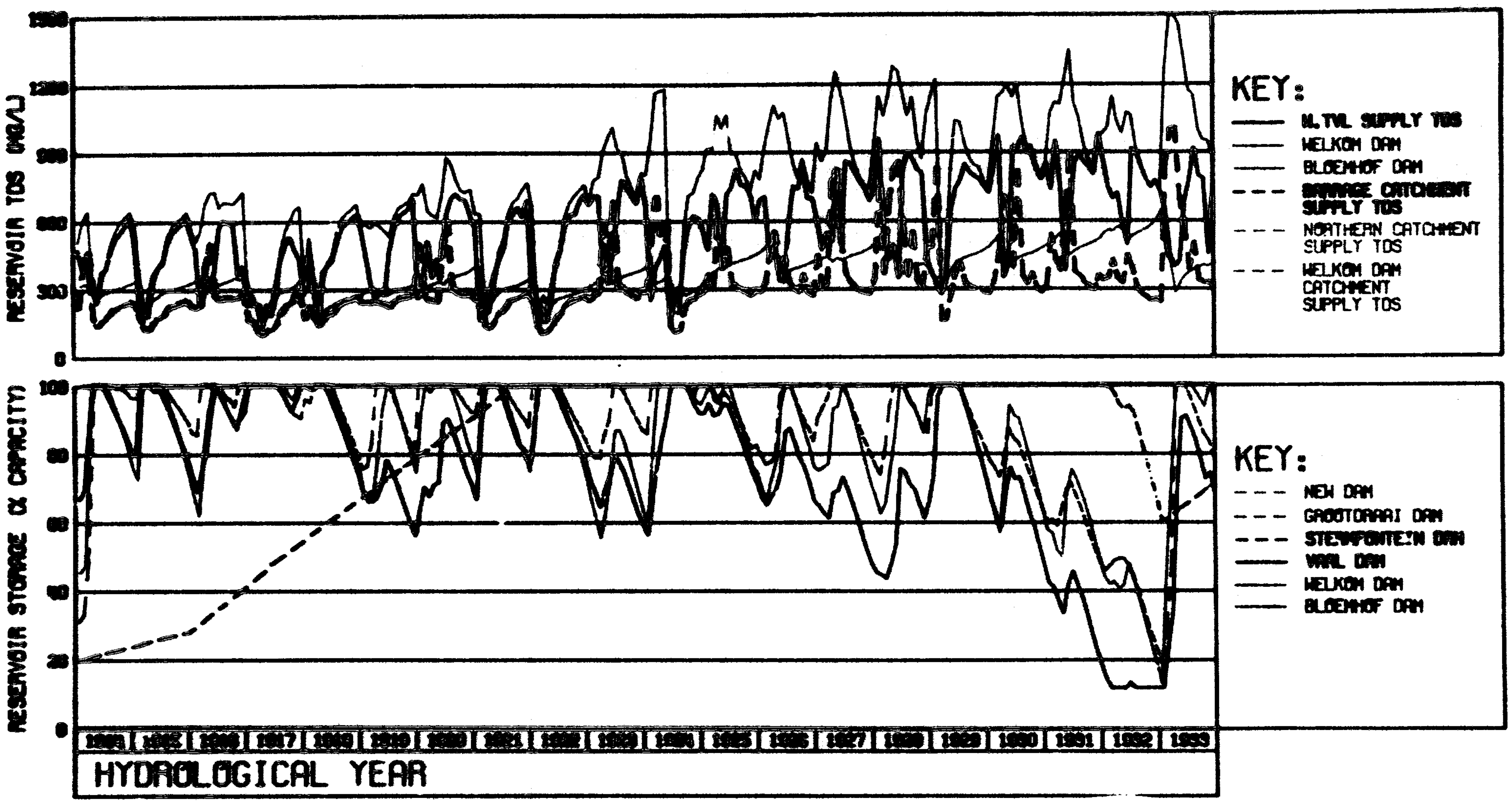

FIGURE 3.13 MONTHLY STORAGE STATES AND AVERAGE MONTHLY TDS CONCENTRATIONS FOR OPTION 3B (TIME HORIZON: 1980-1999)

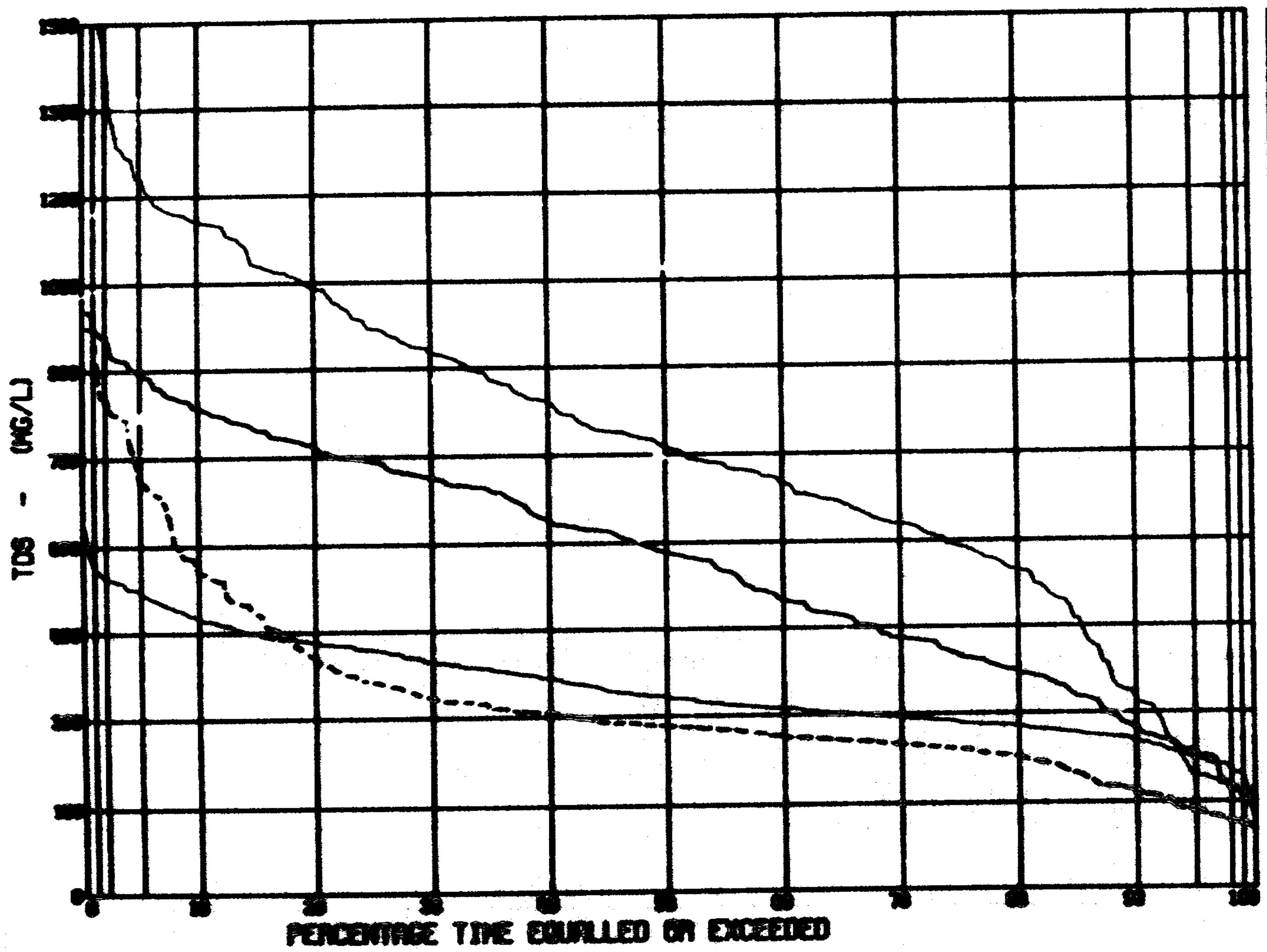

FIGURE 3.14

DURATION CURVE OF AVERAGE
MONTHLY TDS CONCENTRATIONS
FOR OPTION 3B
HYDROLOGICAL SEQUENCE: 1914-19[illegible]
TIME HORIZON: 1980-19[illegible]

It is highly unlikely that the economic value of the small quantity of water saved ($92 \times 10^6 m^3$ in the critical month) could justify the costs associated with demineralising the mine pumpage. On face value option 3A therefore appears to be more attractive than 3B. A thorough economic analysis would have to be made, however, before option 3B could be discarded.

In both options 3A and 3B most of the benefit to users of the water is accrued in the earlier years. As the volumes of effluent return flows increase, along with inevitable increases in diffuse-source salt loads, the relative importance of the mine pumpage declines.

g) Option 4A : For this simulation it was assumed that all users in the PWV region would be supplied directly from Vaal Dam. Figs. 3.15 and 3.16 show a dramatic improvement in the quality of water supplied to consumers in this region, resulting in a large saving in annual running costs (see Tables 3.6 to 3.9).

Increased quantities of salt passed downstream of Vaal Barrage are accompanied by an increased flow volume and as a result the quality of water in the Vaal river upstream of Bloemhof Dam deteriorates only slightly. Salt concentrations in the water stored in Bloemhof Dam rise significantly with resultant higher running costs incurred by downstream domestic and industrial consumers. These, however, represent less than 3% of all urban users in the Vaal system. The saving to users in the PWV region far outweighs the loss to downstream users and, compared with the status quo, the result is a large net decrease in running costs, of between R81 million and R124 million per annum. Capital costs associated with incremental increases in the quantity of water supplied to the PWV region in future years would also be much lower in view of the absence of any sharp peaks in TDS concentrations.

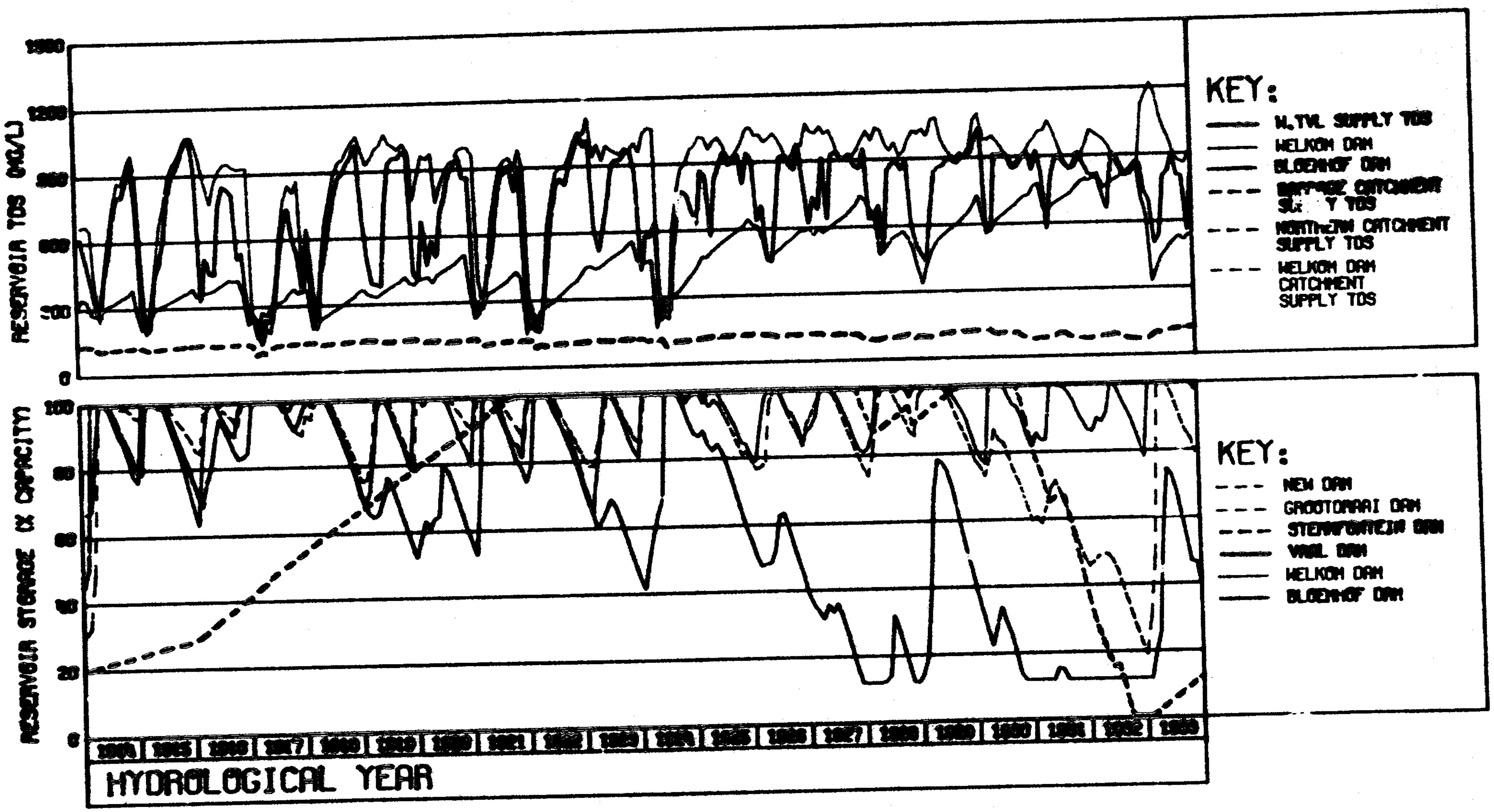

FIGURE 3.15 MONTHLY STORAGE STATES AND AVERAGE MONTHLY TDS CONCENTRATIONS FOR OPTION WA (TIME HORIZON: 1980-1999)

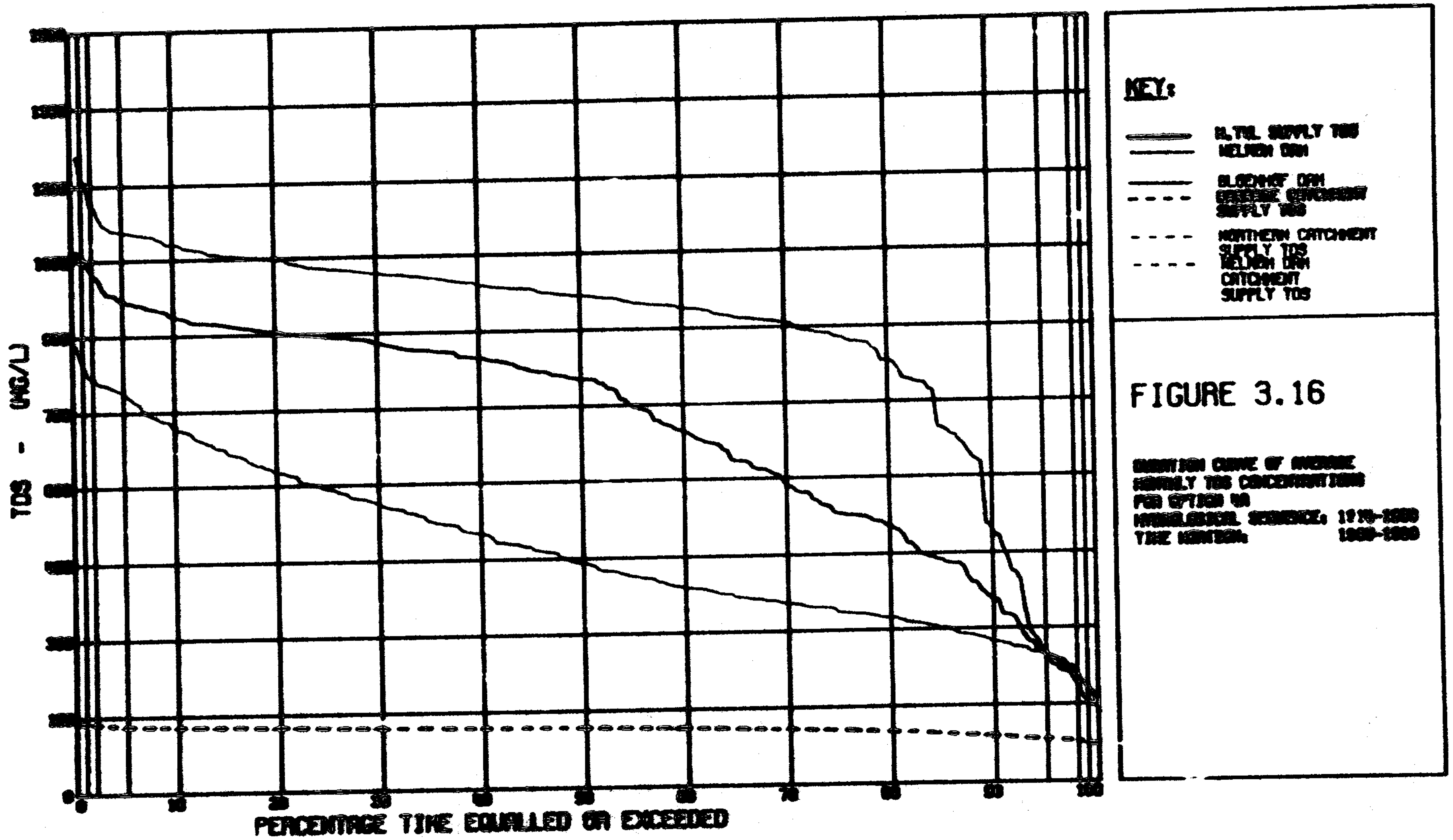

FIGURE 3.16

DURATION CURVE OF AVERAGE MONTHLY TDS CONCENTRATIONS FOR OPTION 4A [illegible]

No attempt has yet been made to ascertain what the effects of the increased salt concentrations in Bloemhof Dam would have on agricultural users. Option 4A also results in a supply shortfall of 743 x $10^6 m^3$. (The high residual storage in Bloemhof Dam at the end of the simulation period, as indicated in Table 3.11, would be of no benefit to users in the PWV and western Transvaal regions). The total decrease (relative to option 1) in storage in the reservoirs upstream of Vaal Barrage in the worst month, including the deficit, amounts to 2316 x $10^6 m^3$. As may have been expected, option 4A can therefore be seen to be costly in terms of water. It should be borne in mind, however, that water held in reserve at the end of the drought sequence would have no economic value (other than perhaps recreational) and that only the deficit (743 x $10^6 m^3$) would have to be made good.

Clearly this option, if it were to be retained right through to the end of the century, would necessitate importation of additional water. In the near term, however, with total system demand levels about half of those projected for 1999, it is evident that option 4A could well be adopted (at virtually no additional cost because the new canal to transmit water from Vaal Dam to the RWB Zuikerbosch pump station , by-passing the Barrage, is already under construction).

Much more detailed analysis would have to be carried out, however, to determine the risk involved in terms of the water resources and to decide at what demand level the risks would become unacceptable. The Directorate of Water Affairs would be in the best position to make such an analysis.

h) <u>Option 4B</u> : It was assumed that all users in the PWV region would be supplied with water from Vaal Barrage and Vaal Dam blended in such a way that the proportion abstracted from Vaal Barrage was maximised but not allowing the supply TDS concentration to exceed 300 mg/l. Figs. 3.17 and 3.18 reflect the consequences of such a policy. In this option there is an improvement in the quality of the water passing downstream of the Vaal Barrage relative to that for

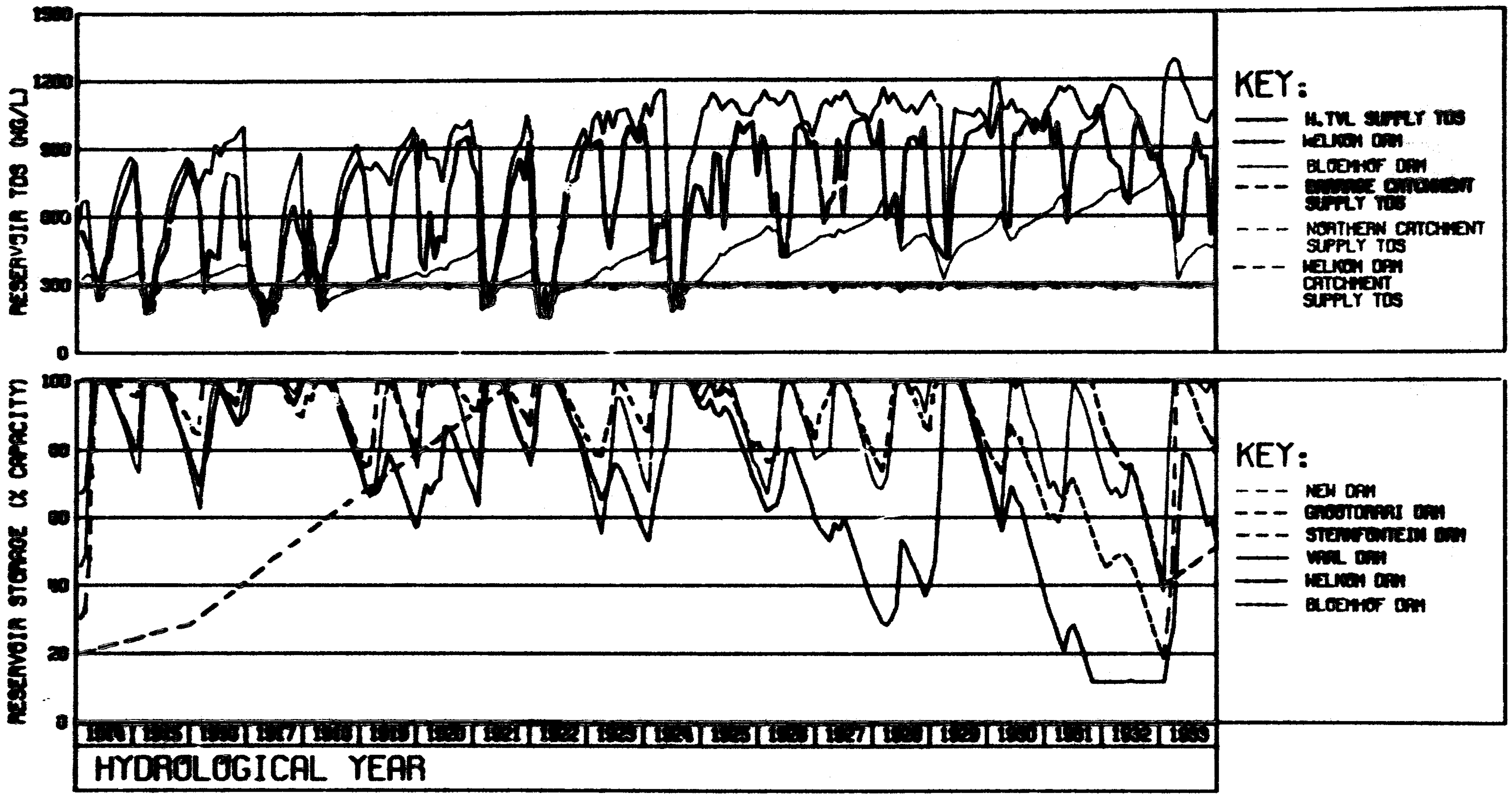

FIGURE 3.17 MONTHLY STORAGE STATES AND AVERAGE MONTHLY TDS CONCENTRATIONS FOR OPTION 4B (TIME HORIZON: 1980-1999)

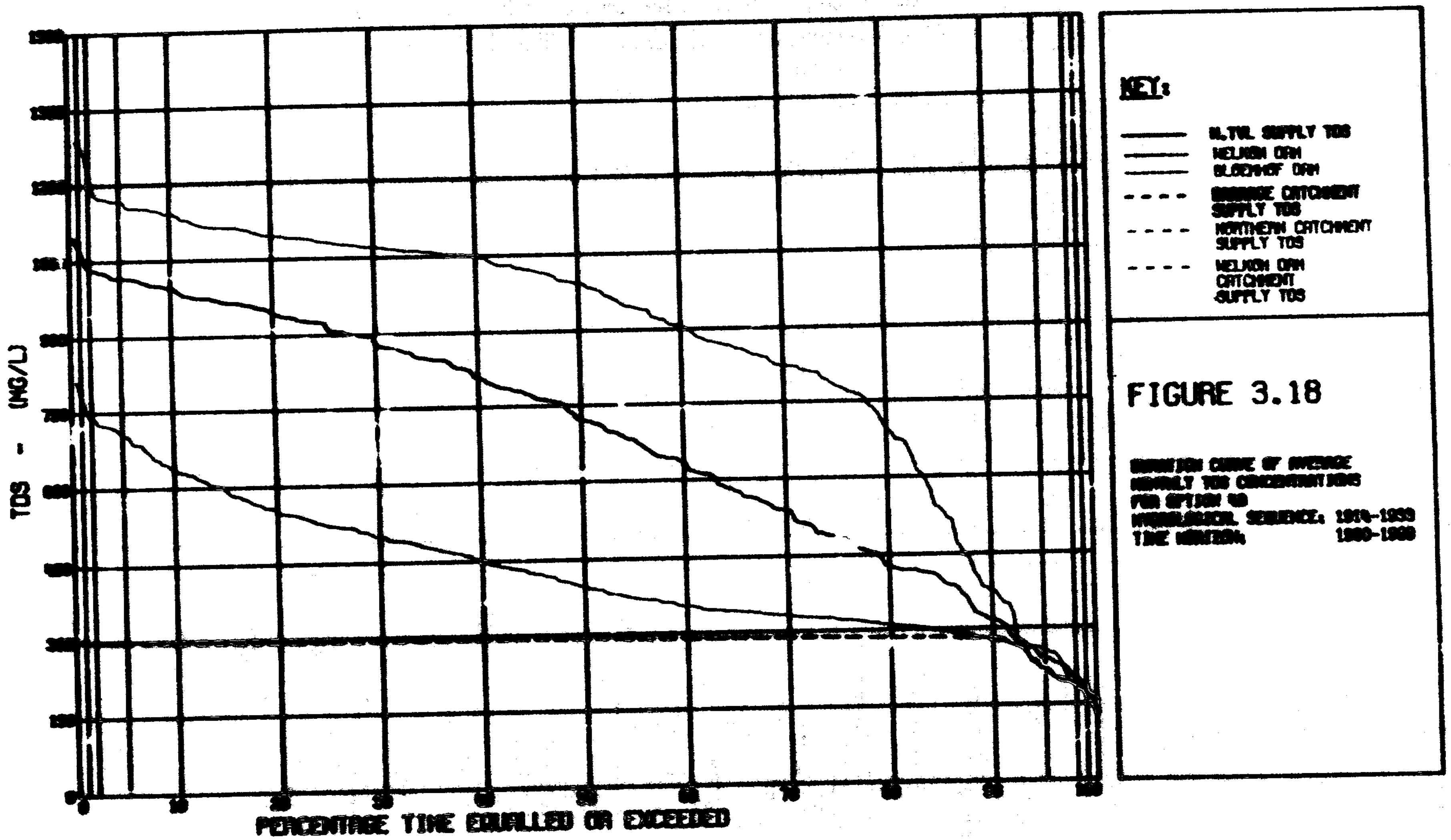

FIGURE 3.18

DURATION CURVE OF AVERAGE MONTHLY TDS CONCENTRATIONS FOR OPTION [illegible]
HYDROLOGICAL SEQUENCE: [illegible]
TIME HORIZON: [illegible]

option 4A, although the downstream quality is still poorer than for the status quo option. The benefit to users in the PWV region is not nearly as pronounced as was the case for option 4A (see Tables 3.6 to 3.9) and the reduction in running costs for users in the entire system is between R21 million and R45 million per annum. The savings in capital costs should be substantial in view of the absence of any TDS peaks in the PWV water supply.

Table 3.11 shows a marked improvement in the residual storage at the end of the drought sequence (as compared with option 4A). There is no supply shortfall, but the residual storage in reservoirs upstream of Vaal Barrage is 550 x $10^6 m^3$ less than in the case of the status quo option.

As with option 4A users downstream of Vaal Barrage receive water of a much poorer quality than that delivered to the PWV region (although the costs to western Transvaal users are only marginally higher than in the case of the status quo option). The option which follows is an attempt to arrive at a more equitable solution.

i) Option 4C : This is similar to option 4B except that now all domestic and industrial users downstream of Vaal Barrage are also supplied with water from Vaal Dam and Vaal Barrage, blended so as to prevent the TDS concentration from exceeding 300 mg/l.

Under this option all urban users enjoy appreciable savings in running costs and will presumably derive further economic benefit from the absence of TDS peaks in excess of 300 mg/l (resulting in savings in capital costs). The savings in running costs for the total system would now be between R40 million and R71 million per annum (see Table 3.10). Water quality in Bloemhof Dam would deteriorate somewhat during the drier years due to the fact that users between Vaal Barrage and Bloemhof Dam would no longer be withdrawing water between Vaal Barrage and Bloemhof Dam. No attempt

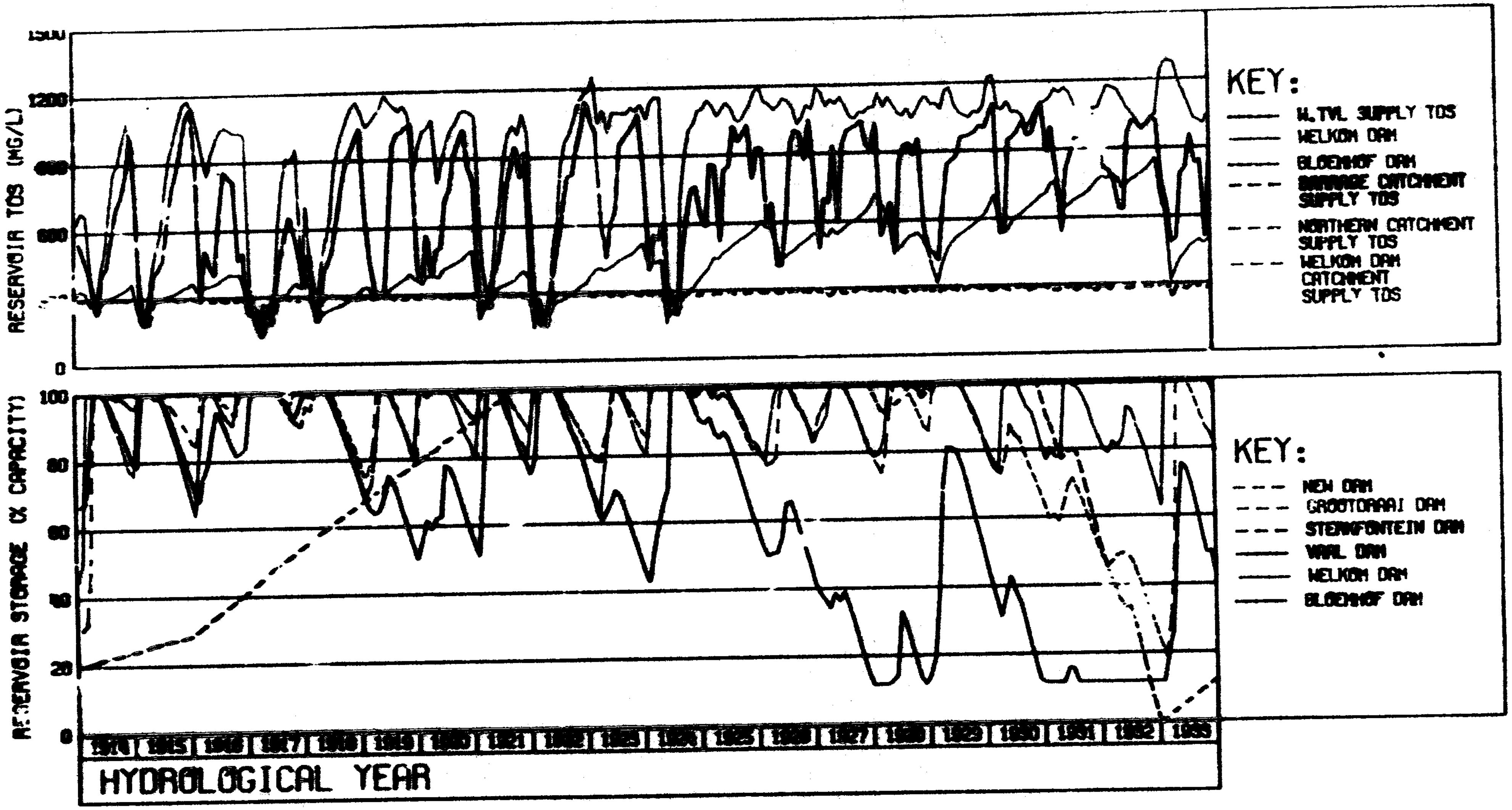

FIGURE 3.19 MONTHLY STORAGE STATES AND AVERAGE MONTHLY TDS CONCENTRATIONS FOR OPTION 4C (TIME HORIZON: 1980-1999)

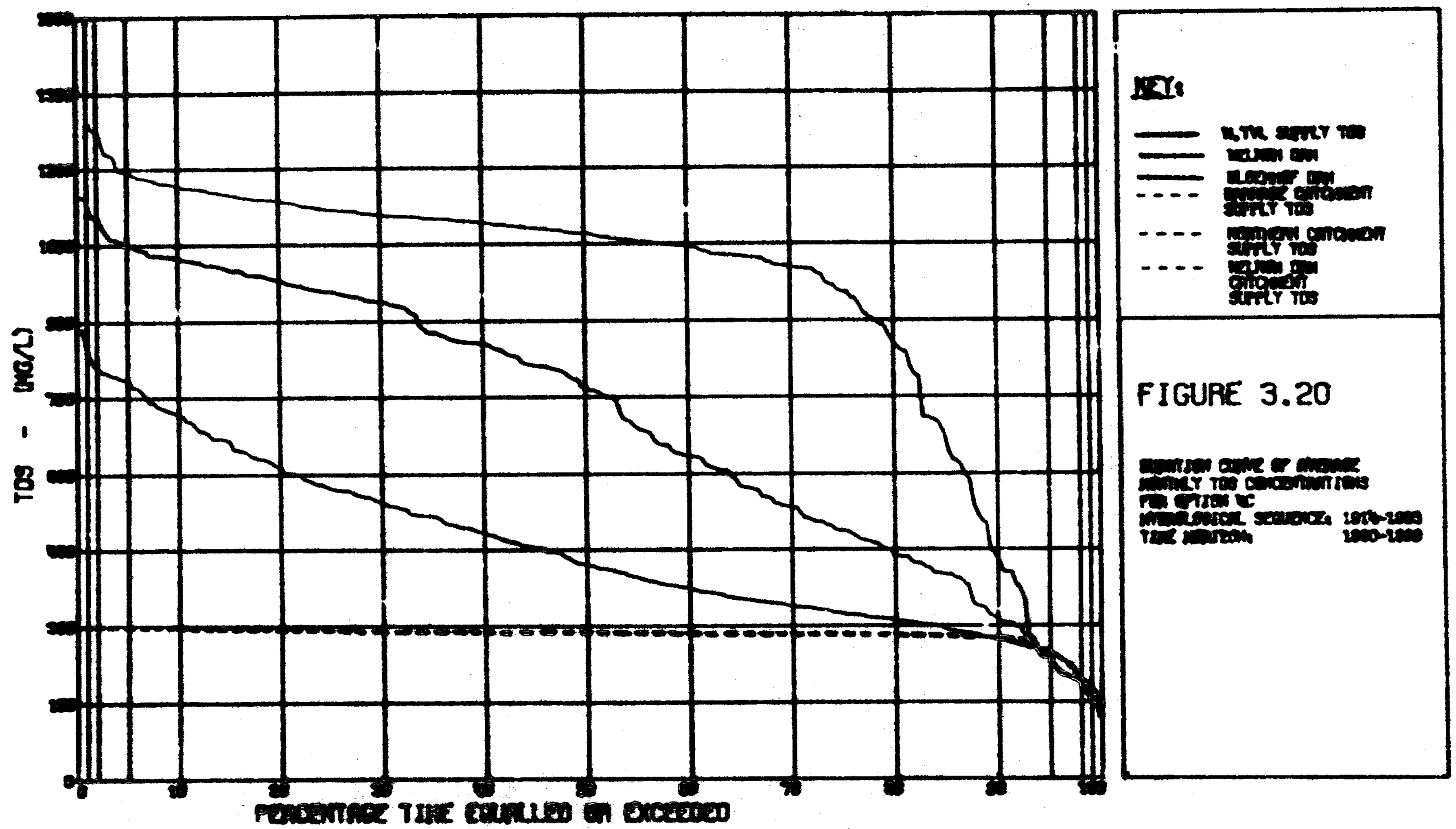
TDS - (MG/L)
PERCENTAGE TIME EQUALLED OR EXCEEDED
KEY:
SUPPLY TDS
NORTHERN CATCHMENT
SUPPLY TDS
SUPPLY TDS

FIGURE 3.20

has been made to estimate the economic loss to irrigators as a consequence of the elevated TDS concentrations. It is likely that higher salt concentrations will force irrigators to leach more frequently to remove excess salts, with a consequent rise in water demand. If this is the only consequence, the problem should not be too serious in view of the surplus that accumulates in Bloemhof Dam (see Table 3.11).

This policy would result in the need to provide at least an additional 800 x $10^6 m^3$ by 1999 to meet supply shortfalls arising in the reservoirs upstream of Vaal Barrage. As with option 4A, this option could probably be employed in the near term, until water demands force either the acceptance of a higher target TDS (higher than 300 mg/l), or the importation of more water.

It should be noted that options 4B and 4C could be tried with different target water supply TDS concentrations, which could be varied with time, depending upon demand levels relative to available water reserves. A full study to optimise the water quality management strategies associated with these two options would involve a great deal of further analysis, which is beyond the scope of this report.

j) Option 5A : In this option it is assumed that storage capacity of 1538 x $10^6 m^3$ is provided at Schoemansdrift on the farm Welkom. This reservoir is referred to as Welkom Dam. It is assumed that Welkom Dam is commissioned in October 1984, and that all the water requirements of the PWV region are abstracted from it. The result should be maximum utilisation of the water resources of the upper Vaal basin. It was hoped that storage at Welkom Dam would attenuate peak salt concentrations, but Figs. 3.21 and 3.22 show that this is not the case.

Welkom Dam is flushed out whenever Vaal Dam spills large quantities of fresh water, but the benefits are short-lived for the fresh water is rapidly replaced by sewage effluents with resulting rise in TDS concentration.

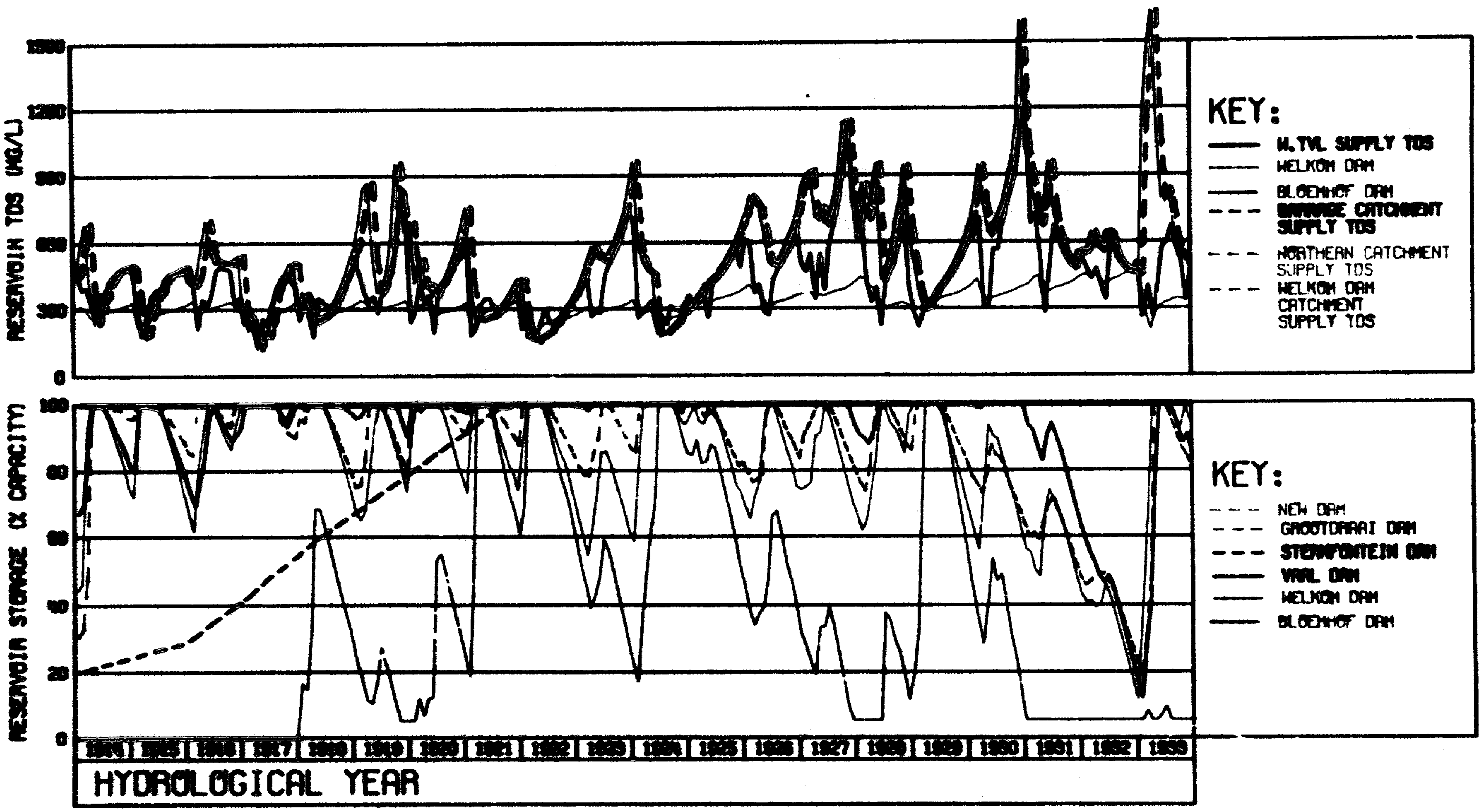

FIGURE 3.21 MONTHLY STORAGE STATES AND AVERAGE MONTHLY TDS CONCENTRATIONS FOR OPTION 5A (TIME HORIZON: 1980-1989)

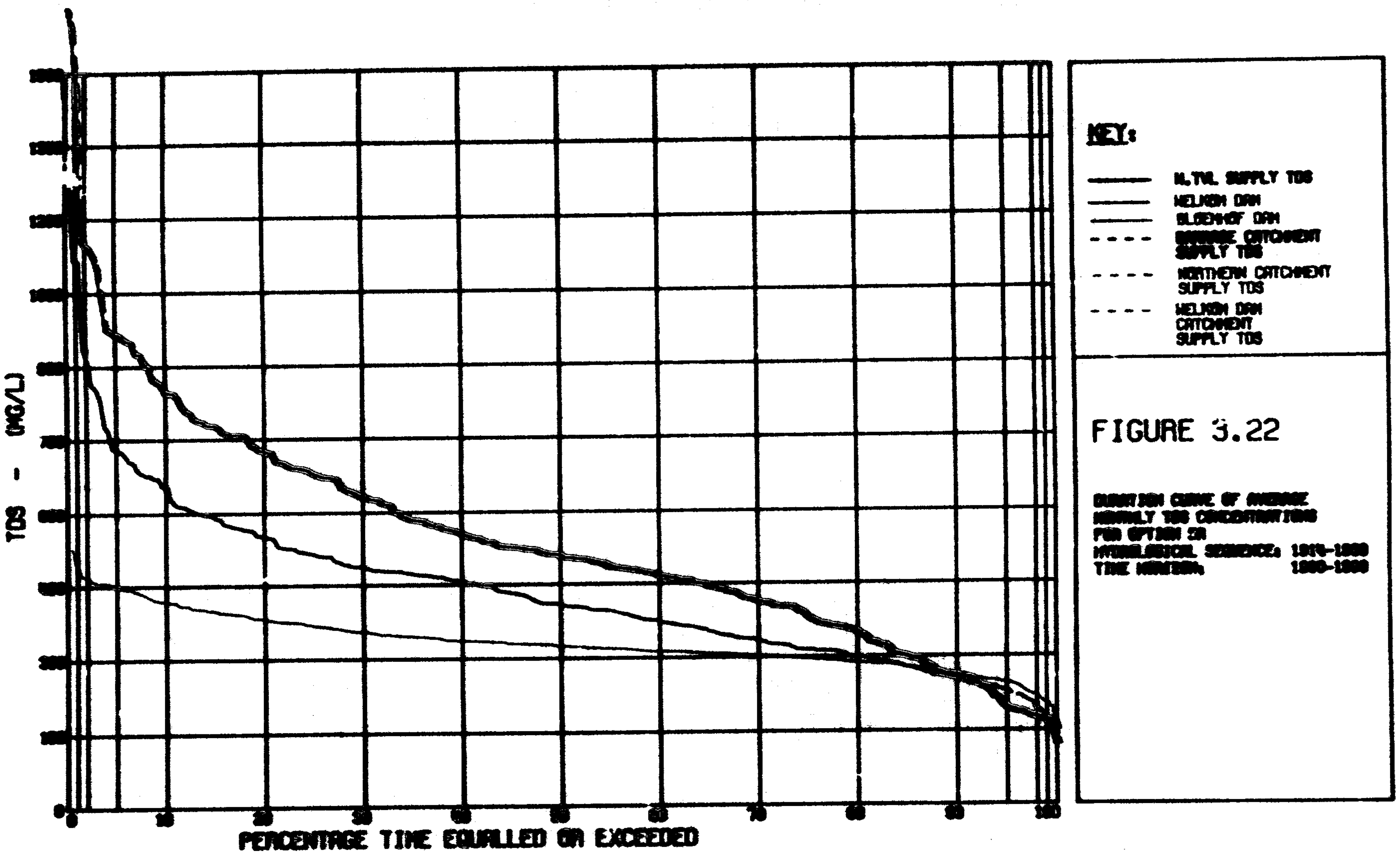

FIGURE 3.22

DURATION CURVE OF AVERAGE MONTHLY TDS CONCENTRATIONS FOR OPTION 2A
HYDROLOGICAL SEQUENCE: [illegible]
TIME HORIZON: [illegible]

Water qualities further downstream in Bloemhof Dam are good on account of the fact that most of the mineralised water is recycled in the PWV region with most of the bleed-off of salts from the system diverted into the northern PWV catchment.

Table 3.10 shows that this option is costly in terms of running costs to consumers (an additional cost relative to the status quo of between R40 million and R56 million per annum). In addition, the capital investment required to deal with peak average monthly supply TDS concentrations in excess of 1500 mg/l is likely to be very high.

This option naturally results in a considerable saving in water, as reflected by the increased residual storage in October 1999 - an increase of 1103 x $10^6 m^3$ relative to the status quo option. This figure includes storage in Welkom Dam which can now be supplied to PWV region users because of the installed pumping capacity which must exist for this option to operate. It might be argued, however, that this additional residual storage has no real economic value in view of the fact that it is never used.

Apart from the poor quality of water resulting from this option, the wastage of energy associated with allowing water to gravitate all the way to Welkom Dam and then pumping it back again must also be taken into consideration. (There would even be a waste of water because of transmission losses and the additional water consumption of power stations upstream of Vaal Dam generating electricity to meet the energy demands of the pumps). The costs of pipe-lines and pumps, too, must not be overlooked.

k) Option 5B : As with option 5A it is assumed that Welkom Dam is commissioned in 1984, but the water supply is assumed to be blended in a manner similar to that for option 4C. All users in the PWV region, together with domestic and industrial users downstream of Vaal Barrage receive a blend of Vaal Dam and Welkom Dam water, such that utilisation of Welkom Dam water is maximised with the constraint that the supply TDS concentration may not exceed 300 mg/l.

In order to simulate this option a slight alteration to the coding of program RESØØ1 became necessary. In this variation of option 4C the values of PV, PA and PB are initially set equal to zero at the start of each month (see section 2.4.11) and are subsequently adjusted by means of modified versions of equations 2.64 and 2.65:

$$PW' = 100.\frac{(CTARGX-COUTV)}{CWØ - COUTV} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2.64a)$$

$$PV' = 100 - PW \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2.64b)$$

Figs. 3.23 and 3.24 show the effects of this option. The differences between options 4C and 5B are:

(i) Peak salt concentrations downstream of Welkom Dam are attenuated by the new reservoir

(ii) Bloemhof Dam salt concentrations begin to rise only towards the end of the simulation (i.e. during the driest years)

(iii) There is no supply shortfall. Reserve storage upstream of Vaal Barrage becomes critically low but does not fail. Furthermore there is stored a large quantity of rather saline water that could presumably be used (at high cost) in an emergency.

Table 3.10 shows a saving in running costs of between R40 million and R70 million per annum. As with option 4C, the savings in capital costs associated with elimination of TDS peaks in the water supply should also be appreciable. However, as with option 5A, the installed pumping capacity would have to be very large, although energy costs should be lower as the overall quantity of water pumped from Welkom Dam would be less than in option 5A.

In practice, if an option such as 5B were to be adopted, it is likely that as much water as possible would be

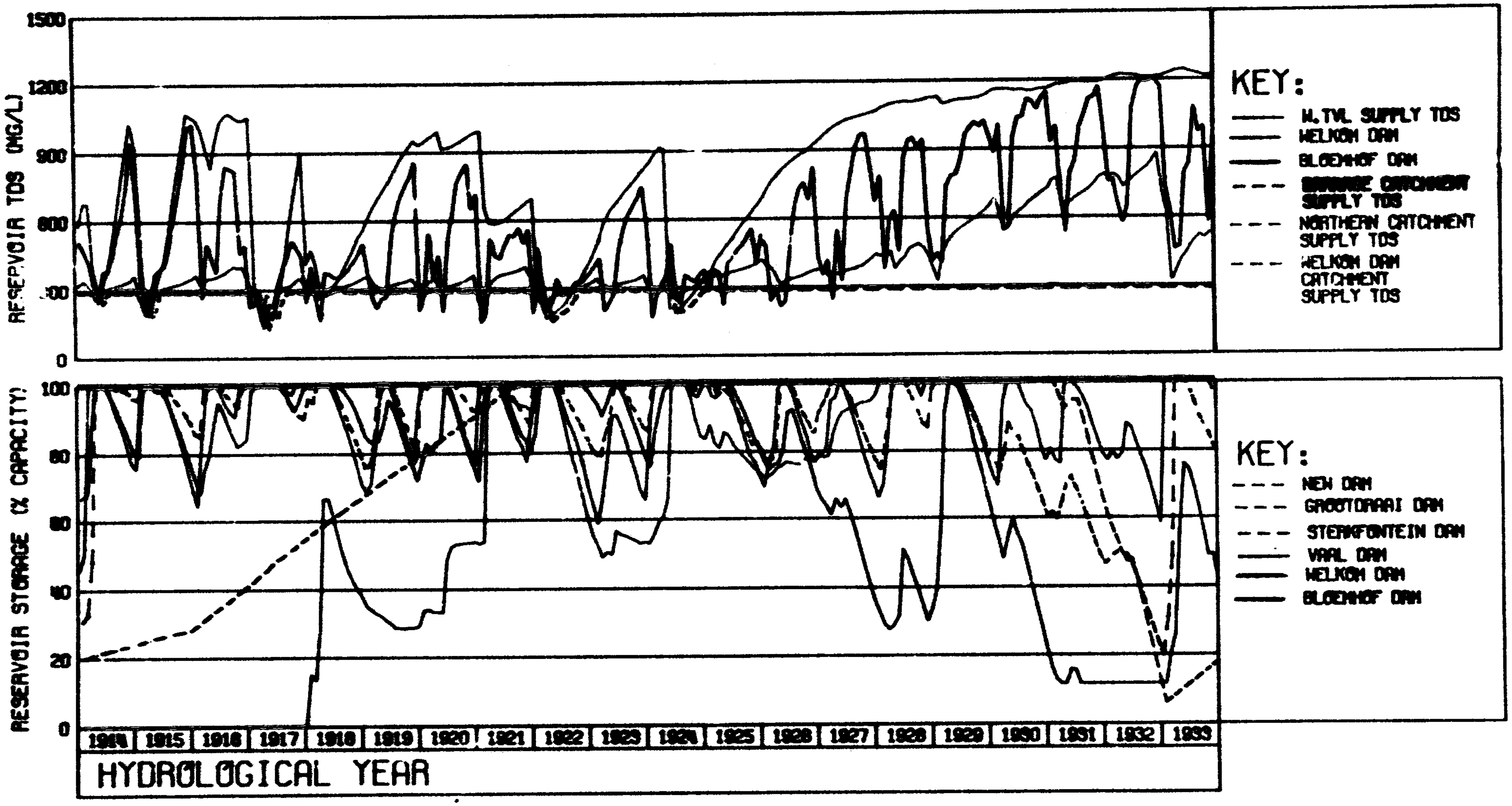

FIGURE 3.23 MONTHLY STORAGE STATES AND AVERAGE MONTHLY TDS CONCENTRATIONS FOR OPTION 5B (TIME HORIZON: 1980-1999)

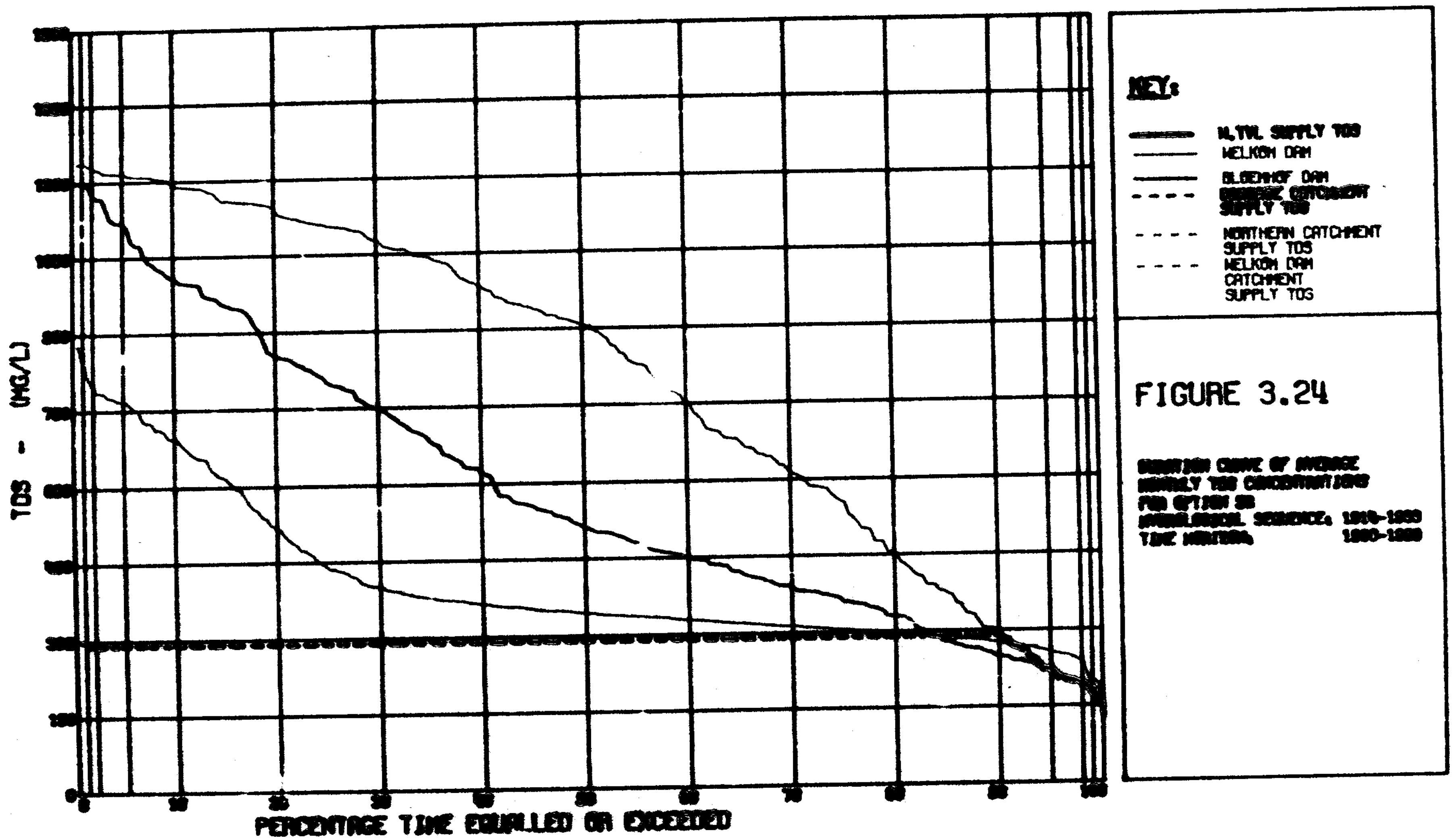
TDS - (MG/L)
PERCENTAGE TIME EQUALLED OR EXCEEDED
KEY:
WELKOM DAM
NORTHERN CATCHMENT
SUPPLY TDS
WELKOM DAM
CATCHMENT
SUPPLY TDS

FIGURE 3.24

abstracted from Vaal Barrage, and only a relatively small quantity would be pumped back from Welkom Dam to keep the TDS at 300 mg/l. Careful analyses would have to be made in order to optimise the capacity of pumps and pipelines.

As with previous options involving the blending of water, it might prove necessary to increase the target TDS level gradually if supplementary water supplies are not available or are too expensive.

A management rule, whereby the accepted TDS level is varied according to the season and the current storage state of key reservoirs, might also be examined. In such circumstances, however, the benefits to industry associated with a predictable average TDS (with no peaks, and hence low capital investment for treatment plants and storage reservoirs) might be lost.

Options 1 to 5B are all related to management of water quality in the system. The following limitations should, however, be taken into consideration:

(i) It was assumed that the salt generation rates for the Vaal Dam catchment remain stationary with time. Increasing industrial development, particularly the petro-chemical industries at Secunda, could change this situation

(ii) It was assumed that diffuse-source salt generation rates in the southern PWV region grow in proportion to the industrial water supply (a measure of human pollution-generating activity in the catchment). This assumption is based on the results obtained by Herold (1981a) which in turn are based on limited data. The actual salt generation rates could be higher or lower than those assumed. It may be advisable to test all options assuming salt generation growth rates both higher and lower than those assumed for this study, so as not to bias the results in favour of certain options

(iii) The assumption that diffuse-source salt generation rates in the catchment between Vaal Barrage and Welkom Dam remain constant is highly questionable. Already several smaller tributaries of the Vaal in this catchment are showing signs of increasing mineral loads associated with human activity. Furthermore, owing to lack of adequate data, no account was taken of point source effluent discharges in this region. (Table 3.4 shows that by 1999 the domestic and industrial demand in this region is expected to be of the order of 261 x $10^6 m^3$ per annum, i.e. more than half of the present demand in the heavily polluted southern PWV region).

A much more exhaustive study of the Bloemhof Dam catchment, similar to that undertaken for the southern PWV region, may therefore prove necessary in order to obtain more reliable estimates of pollutant loads.

Despite these limitations it is believed that the model discussed in this report provides a valuable tool (indeed, the only method at present available) for objectively comparing various pollution control strategies.

The list of options which have so far been discussed is by no means exhaustive. Many other options have been suggested (Hall et al., 1979), and any number of options can be combined to arrive at the best overall strategy. (For example option 3A, the diversion of mine pumpage, can be implemented in tandem with any of the other options.).

Although this is primarily a pollution control study, two options which are related more to water resources have also been simulated for the same hydrological sequence to demonstrate the potential of the model in this capacity. These are options 6 and 7, dealt with in what follows.

1) Option 6 : It is an unfortunate fact that the Vaal Dam reservoir has the disadvantage of an unfavourable storage-surface area relationship which results in high evaporation losses. A novel solution (van Robbroeck, 1979) involves the building of isolating barriers to divide the reservoir into three portions, the idea being that as much water as possible is pumped out of the two outside (western) portions into the central portion, where the storage-area relationship is more favourable. The partitioning of the Vaal Dam reservoir is shown in Fig. 3.25. Fig. 3.26 shows the effective storage-area curve for Vaal Dam with the isolating barriers. These curves were provided by van Robbroeck (1979). It should be pointed out, however, that the effective storage-area curve of Fig. 3.26 will hold true only if excess water in cells B and C can be transferred quickly enough into cell A. In a more rigorous approach Vaal Dam would have to be modelled as three cells and the pump capacities would have to be prescribed.

For options 6 and 7 the assumptions regarding the distribution of demands are the same as those used in option 4A, i.e. 100 percent of PWV region abstractions taken from Vaal Dam. This assumption was used because in option 4A the system failed to meet demands during the critical drought (with a deficit of 743 x $10^6 m^3$). Option 4A therefore serves as a benchmark against which options 6 and 7 can be compared. Water qualities are virtually unchanged for these three options. For this reason duration curves of average monthly TDS concentration have not been plotted for options 6 and 7, nor are running costs given in Table 3.10.

Comparison of Fig. 3.15 with Fig. 3.27 reveals little difference except that the length of time during which Sterkfontein Dam remains empty is now a little shorter. This is confirmed by Table 3.11 which shows that the deficit is reduced from 743 x $10^6 m^3$ in the case of option 4A to 511 x $10^6 m^3$ for option 6, a saving of 232 x $10^6 m^3$. The cost of building the isolating barriers and maintaining and running the balancing pumps would have to be compared

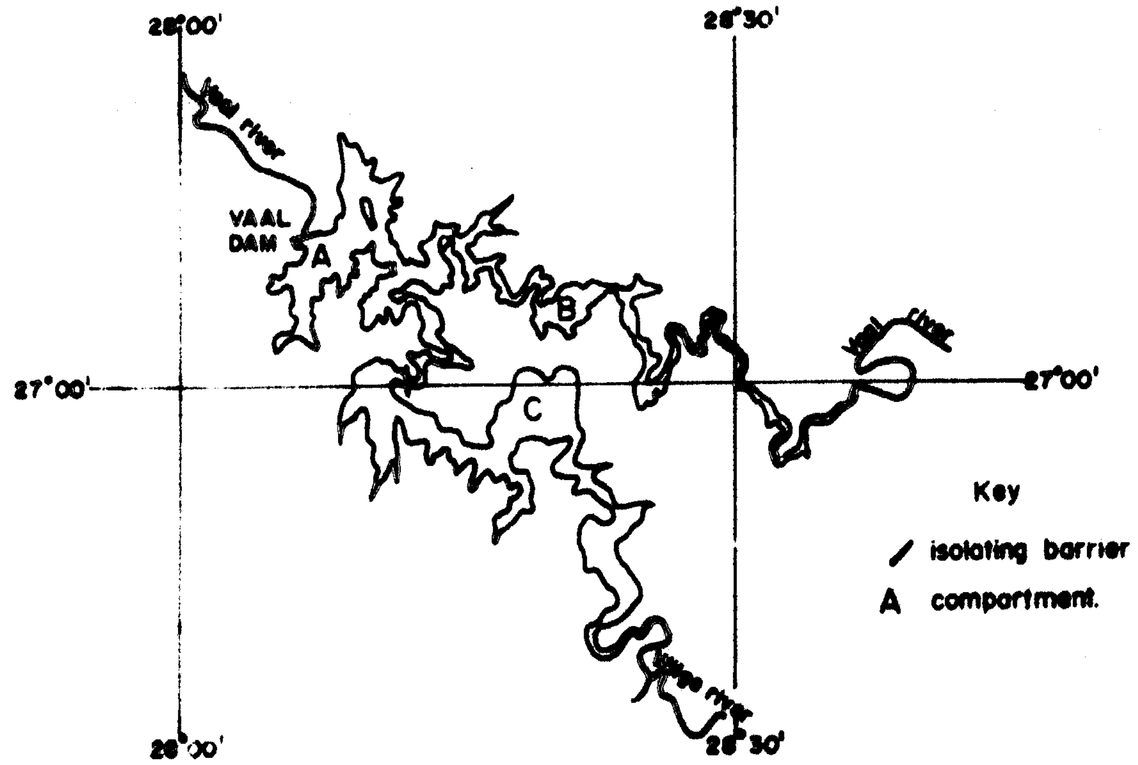

Fig.3.25 : Map showing the proposed compartmentalisation of the Vaal Dam reservoir.

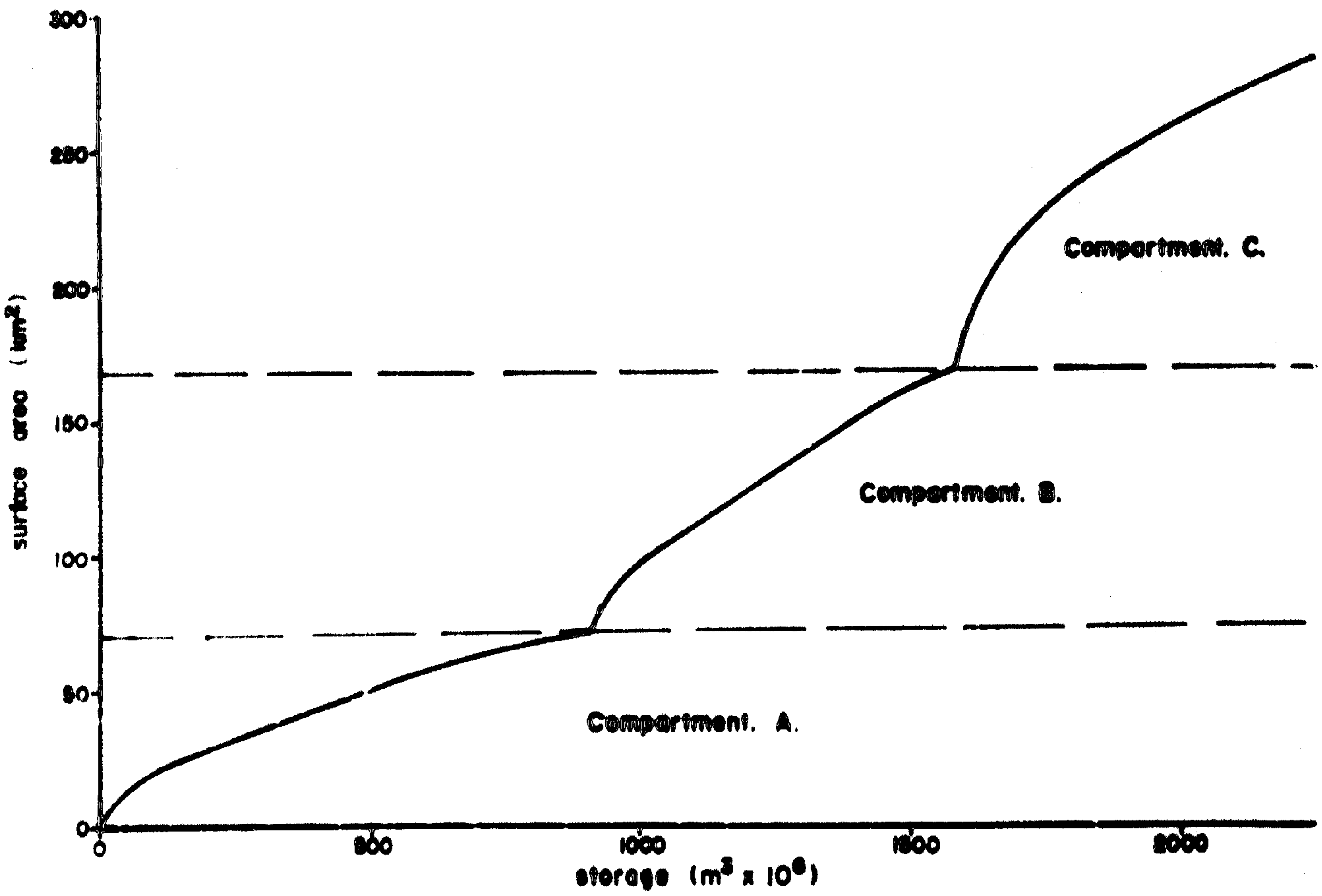

Fig.3.26 : Effective storage-area relationship for option 6.

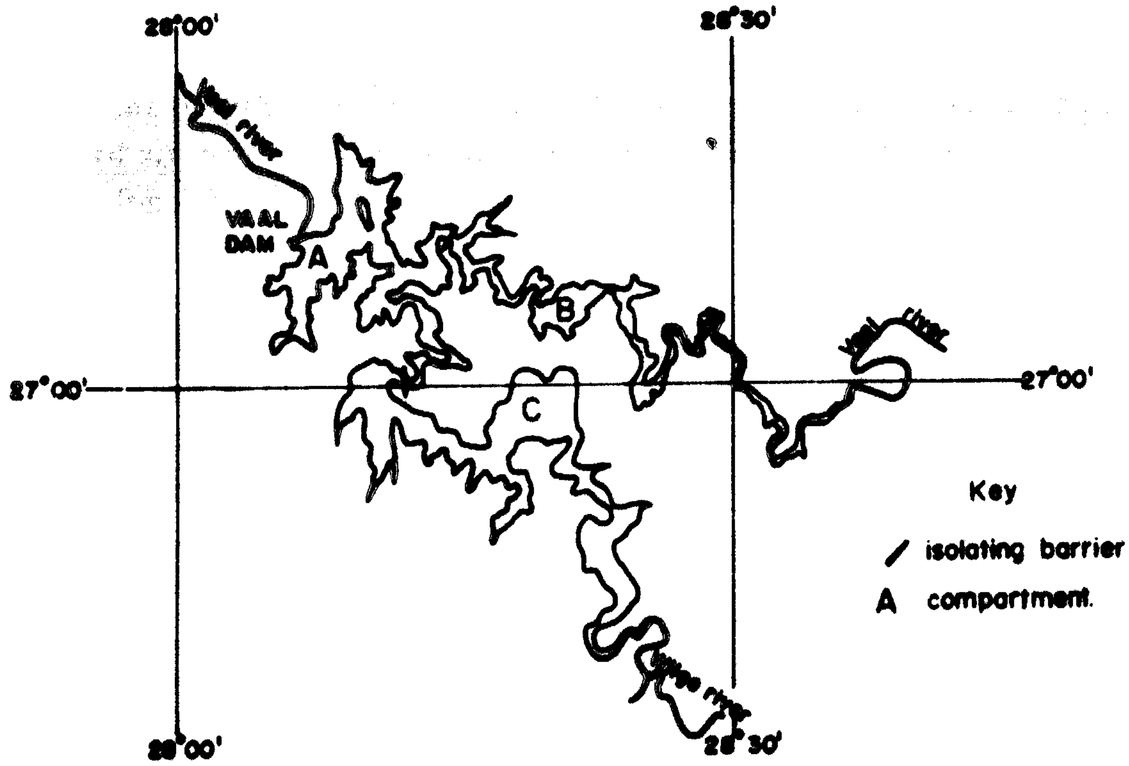

Fig.3.25: Map showing the proposed compartmentalisation of the Vaal Dam reservoir.

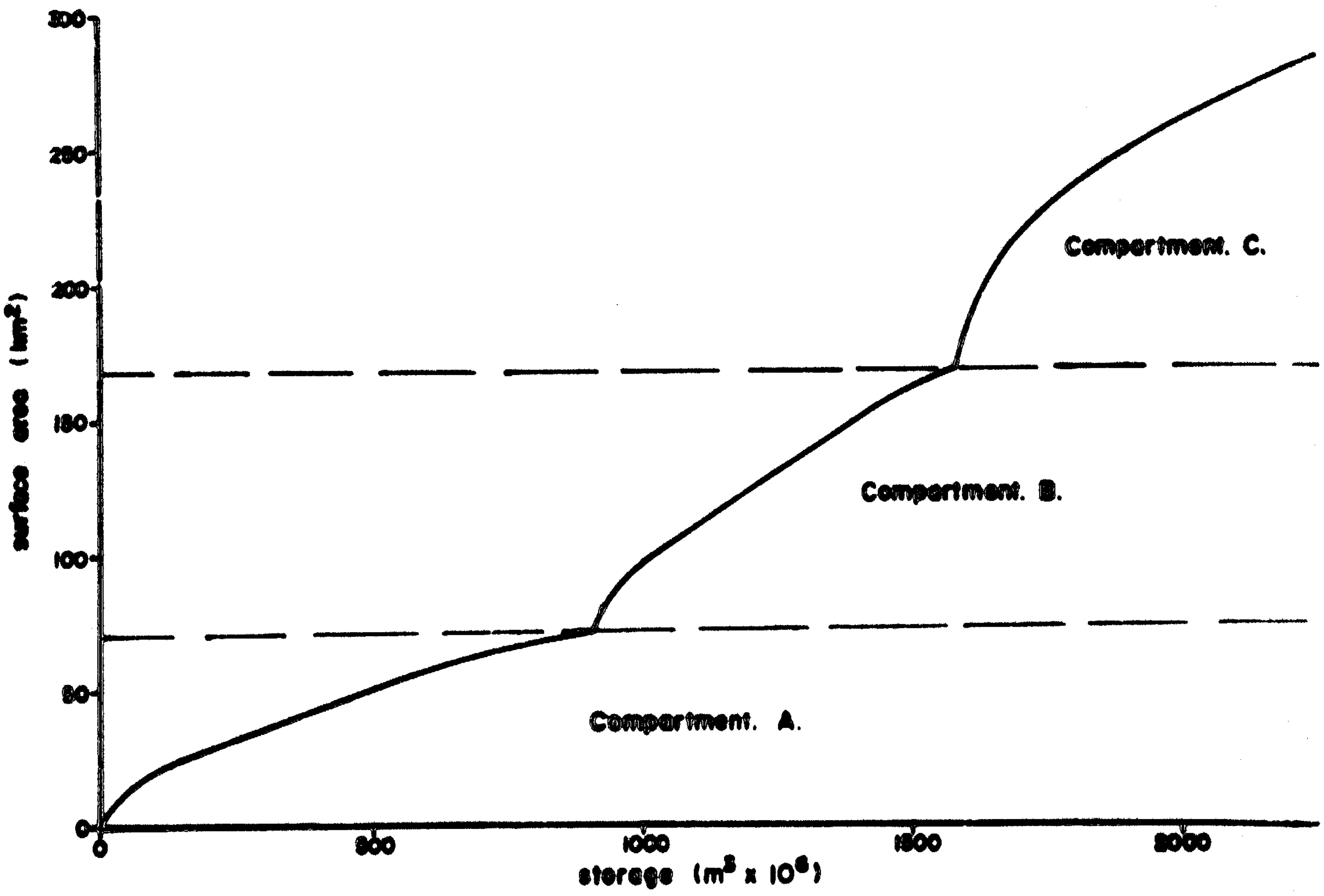

Fig.3.26: Effective storage-area relationship for option 6.

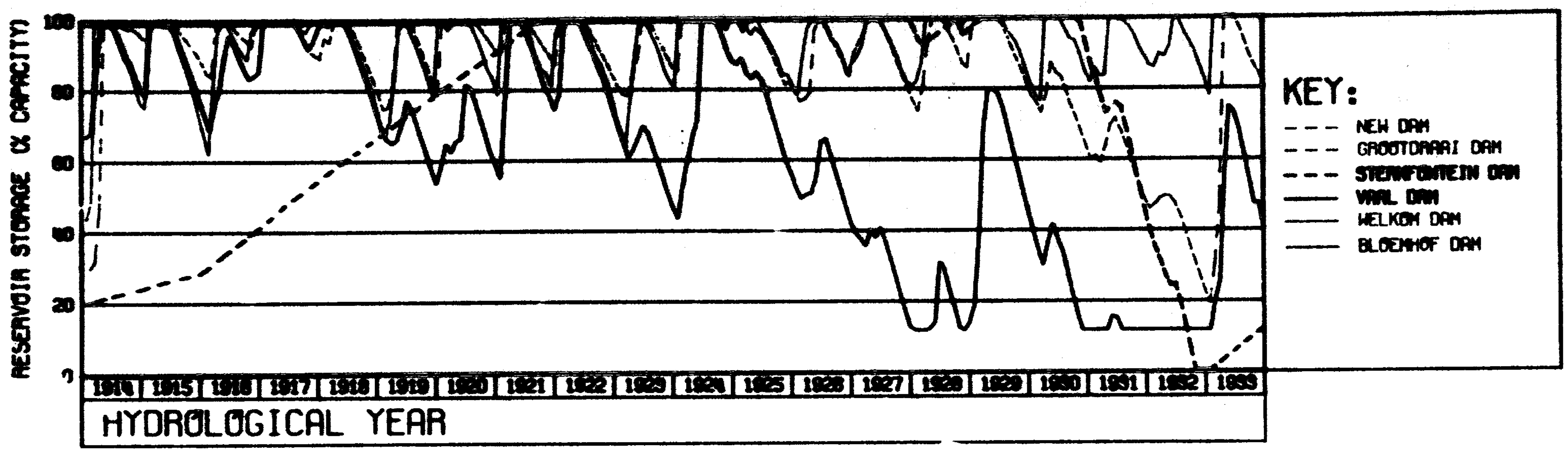

FIGURE 3.27 MONTHLY STORAGE STATES AND AVERAGE MONTHLY TDS CONCENTRATIONS FOR OPTION 6 (TIME HORIZON: 1980-1999)

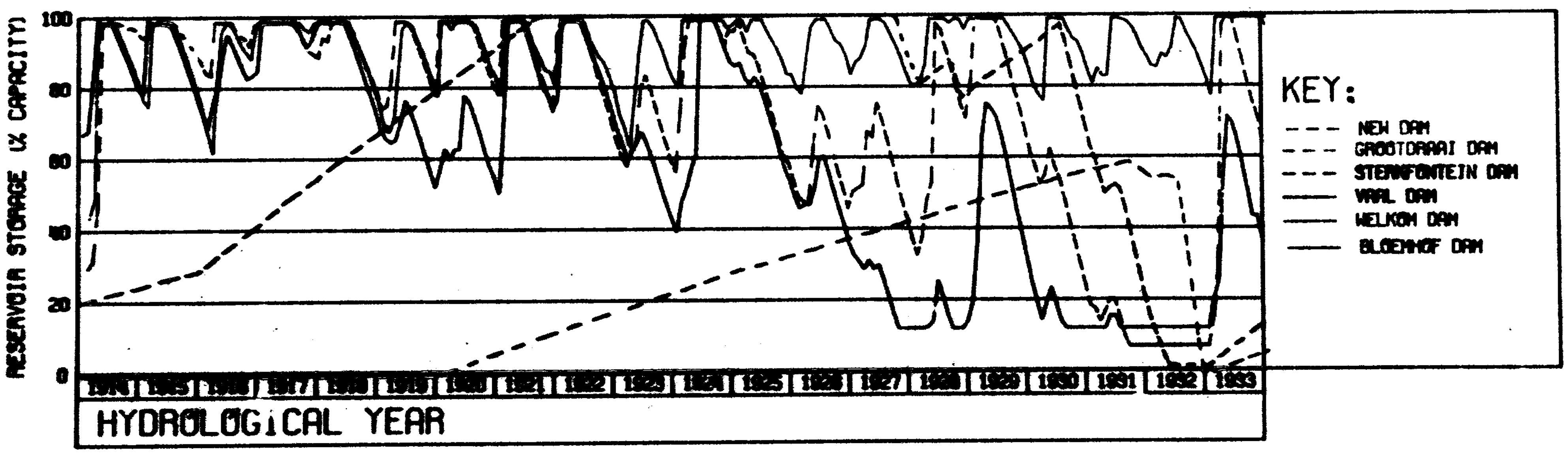

FIGURE 3.28 MONTHLY STORAGE STATES AND AVERAGE MONTHLY TDS CONCENTRATIONS FOR OPTION 7 (TIME HORIZON: 1980-1999)

with the cost of increasing the assured yield of Vaal Dam by an equivalent amount by some other means. Obviously a much more detailed analysis involving the simulation of several hydrological sequences would be required to establish the probability of failure at various demand levels with and without the isolating barriers.

m) Option 7 : This option differs from option 4A in that it is assumed that by 1986, when pumping of water from the Usutu into the upper reaches of the Vaal river commences, a new dam (referred to in Fig. 3.28 as 'New Dam') will have been commissioned, with a storage capacity of 1500 x $10^6 m^3$. (A site for such a dam has been investigated by the Directorate of Water Affairs (1979) and the storage-area relationship for this site, near Balmoral, has been assumed.) The pumping rate for water imported from the Usutu has been assumed to be identical to that used in options 1 to 6. An operating rule was introduced whereby, when Sterkfontein Dam fails, shortfalls in Vaal Dam are met by releases from the new dam via Grootdraai Dam.

To simulate this option a slightly modified version of program RESØØ1 was necessary so as to incorporate the operating rule which calls on Grootdraai Dam to supplement Vaal Dam shortfalls when Sterkfontein Dam is emptied. In special cases such as options 5B and 7 it is more efficient to make minor ad hoc alterations to the standard version of the model rather than attempt to incorporate every conceivable option into one program. The remaining options discussed in this chapter were all simulated with the standard version of RESØØ1, all the changes being incorporated in the input data.

Fig. 3.28 shows that for the hydrological sequence simulated the storage state of the new dam never rises above 60%. It follows that a higher pumping rate might well be justified if the new dam is to be used as a reserve storage reservoir to supplement reservoirs downstream of Grootdraai Dam. On the other hand, a higher pumping rate would be pointless if the purpose is merely to supplement Grootdraai Dam.

Table 3.11 shows that option 7 decreases the deficit resulting from option 4A to only 403 x $10^6 m^3$. It should be noted, however, that in this option Grootdraai Dam has been drawn down to reserve storage (25 x $10^6 m^3$) while in option 4A the 70 x $10^6 m^3$ storage in Grootdraai Dam was not called upon at all to supplement Vaal Dam. The net saving is thus given by:

$$743 - 403 - (70 - 25) = 295 \times 10^6 m^3.$$

It is clear from this option that the effectiveness of water imported at a constant pumping rate can be dramatically improved by the provision of additional storage capacity. The rate of pumping of water from the Usutu was assumed to be 99,7 x $10^6 m^3$ per annum. The 295 x $10^6 m^3$ which would otherwise have been wasted is 21 percent of the total quantity of water pumped from the Usutu between 1986 and 1989. During wetter hydrological sequences than that simulated the proportion of this expensive imported water wasted as the result of more frequent spillage of Grootdraai Dam would be even higher than 21 percent.

CHAPTER 4 : CONCLUSION AND RECOMMENDATIONS

A numerical model of the Vaal system has been developed capable of simulating monthly reservoir storages and salt concentrations at key points for any given sequence of hydrology. Used in conjunction with the daily and monthly washoff models (Herold, 1980 and Herold, 1981a), this model can provide results with which to compare the effects on water quality of a wide variety of planning and management alternatives. Economic factors have been incorporated in the model to facilitate comparison of the costs to users resulting from different levels of TDS in the water supply associated with each proposed strategy.

The models constitute a powerful tool in the hands of the planner faced with the task of selecting the most attractive strategy.

The following conclusions and recommendations emerge:

a) Some of the more promising options demonstrated in Chapter 3, along with any others which present themselves, should be examined in perhaps greater depth than has been feasible here. For instance, (see section 3.1) each option should be tested against a large number of different hydrological sequences to establish the most probable TDS levels and the most probable costs.

b) Capital costs to users (associated with TDS in the water supply) should be estimated in a manner similar to that described in Chapter 3. It may prove necessary, however, to refine the cost functions associated with capital costs developed by Heynike (1980). Heynike's costs were based on estimates made by individual industries. Each industry was asked to estimate its additional capital expenditure arising from an increase in <u>average</u> TDS concentration from the present 300 mg/l to 500-600 mg/l and then to 800 mg/l. It must be surmised that those industrialists canvassed in this manner made their own assumptions (based on present-day conditions) as to what <u>peak</u> daily TDS levels would be associated with <u>average</u> values of 550 and 800 mg/l respectively. Some options (e.g. options 4a, 4B, 4c and 5b), however, eliminate the peaks entirely, presumably with a large saving in capital costs, while others (such as options 3a and 3b) reduce the mean but have little effect on the peaks. Revised estimates of capital costs associated with peak TDS concentrations (possibly maximum expected 2-day peak value or 5 percent exceedance level) would probably lead to improved estimates.

c) While monthly average TDS values are adequate for estimating running costs associated with mineralised water, they are of little value for estimating probable peak daily values. It will be necessary, therefore, to test each option against several hydrological sequences using the daily version of this model (Herold, 1981c). The more sophisticated daily model also makes allowance for differences in the blend of water supplied to various users. (This factor is important in view of the soon-to-be-implemented delivery of water direct from Vaal Dam to the SASOL complex.)

It is recommended that the monthly model (which is much less costly to run) be used initially to sift out the less attractive options. For each of the retained options the daily model can be run to establish probable daily TDS levels for two or three specific demand horizons (for example, year 1980, 1990 and 2000 conditions). For several hydrological sequences the monthly model could be run up to the start of the year of interest (say 1990) in order to establish starting conditions (vis. reservoir storage state and salt concentration) for the daily model. Table 4.1 serves to illustrate this process.

Table 4.1 : Illustration of how the monthly model can be used to provide starting conditions for the daily model

Hydrological sequence no.	Demand year										
	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990
1	1913	1914	1915	1916	1917	1918	1919	1920	1921	1922	1923
2	1914	1915	1916	1917	1918	1919	1920	1921	1922	1923	1924
3	1915	1916	1917	1918	1919	1920	1921	1922	1923	1924	1925
.	.	.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.	.	.
56	1968	1969	1970	1971	1972	1973	1974	1975	1976	1977	1978
57	1969	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979
	+	+	+	+	+	+	+	+	+	+	≠

+ these years simulated by means of the monthly model

≠ these years simulated by means of the daily model.

In the first sequence the monthly model is run for the hydrological years 1913 to 1922. Storage states and salt concentrations simulated for the end of September 1923 (corresponding to assumed demand and catchment conditions for September 1990) are then fed as input to the daily model which is run for the year October 1923 to September 1924. This process can then be repeated for the 57 available 10-year hydrological sequences. Output from the daily model for the 57 historical hydrological years 1923, 1924,... 1979 corresponding to expected 1990 conditions can then be used to compile 57 duration curves for TDS at points of interest in the system. The most probable exceedance levels (as well as confidence limits, if necessary) could then be computed. The most probable 5 percent exceedance level could, for example, be computed by taking the mean of the 57 TDS levels which are exceeded 5 percent of the time for each of the years simulated.

The entire process could be repeated for other demand conditions (say 1990 and 2000). From the results a series of curves similar to those shown in Fig. 4.1 could be derived.

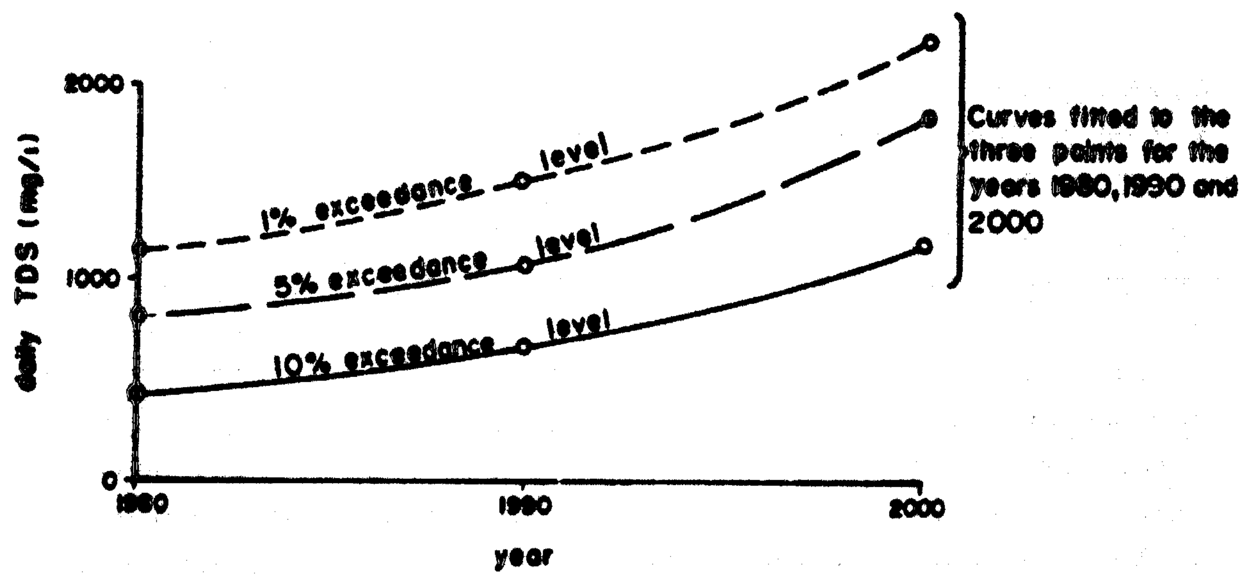

Fig. 4.1: Example showing the variation of daily TDS of exceedance levels with time.

The capital costs associated with peak TDS levels could then be calculated using the method given in Chapter 3, provided the cost functions are revised as suggested in (b) above.

It is not anticipated that it will be necessary to run every option for 57 hydrological sequences. An equally valid comparison of options can probably be made by simulating only five or six carefully selected sequences.

This complex procedure is necessary for two reasons. In the first place, water demands are growing at a rapid rate. (The RWB demand, for instance, has increased at an average rate of more than 6% per annum since 1903). It would be wrong, therefore, to simulate several hydrological years consecutively with 1990 demands, as this would presuppose antecedent conditions that are much more severe than the real situation (i.e. the reservoir storages at the start of each year simulated would be unrealistically low). Secondly, diffuse-source salt generation rates, as well as effluent point discharges, are also increasing in pace with the demands. It would be completely unrealistic, therefore, to simulate several hydrological years consecutively using assumed 1990 diffuse-source salt generation rates and effluent discharges, as this would lead to meaningless water quality values. (The salt content of a major impoundment, for example, is a product of the accumulated inflows over several years.)

d) Further research to establish the relationship between water demands and effluent return flows in terms of both quantity and water quality is recommended. Table A.2, for example, shows that the percentage of water supplied that is discharged as effluent varies considerably from year to year. It should be possible to relate these variations to climatological or other factors. Seasonal variations could also be investigated.

The change in TDS through usage also needs to be investigated in some detail (Table A.3 of Appendix A is based on the analysis of data for only one year).

It must be stressed that an ongoing water quality monitoring programme is imperative in order to identify any changes that may occur in the system. A re-evaluation of the relationships between demands and effluent return flows will also have to be made at regular intervals.

e) Adequate data are not available either in the northern PWV catchment or in the Bloemhof Dam catchment. To fill in the gaps in our knowledge of these systems a comprehensive study is recommended. The recent establishment of petro-chemical industries within the Vaal Dam catchment and coal-fired power stations close enough to affect the waters of the Vaal river give cause for concern. It is likely that these industries will begin to have a detrimental effect upon the highly strategic good quality water resources of the upper Vaal basin. It is recommended that a comprehensive monitoring program be implemented at an early date, together with a detailed study of the region with a view to establishing background pollutant loadings. These new developments provide an excellent opportunity for the study of changes brought about by these types of industrial activity. This is especially important in view of the almost inevitable expansion of SASOL-type industries.

f) There are uncertainties about adopting a relationship between diffuse-source salt generation and industrial water supply. Factors, such as the nature of the industries, population densities, standards of living and pollution control legislation must also affect the rate of generation of diffuse pollution runoff. The present programme for monitoring the Barrage catchment should be continued, preferably indefinitely, to permit periodic re-evaluation of the system to be made. Calibration of the daily washoff model (Herold, 1981a) can then be improved and adjusted as catchment conditions change.

g) Although a correlation has been established between diffuse-source salt generati and catchment characteristics, the available data did not permit a causal relationship to be established. For the purposes of this study diffuse-source pollution loads were assumed to be given by the difference between observed loads leaving the catchment and known point inputs. Part of this 'diffuse' load presumably consists of illegal discharge to the stream of industrial effluents during flood, and is therefore not 'diffuse' but 'point'. The source of the remaining diffuse-source salt load is also open to speculation. If the major sources can be identified, appropriate measures can be taken to alleviate the situation. For instance, if atmospheric fall-out is a major cause, air pollution control legislation could be strictly applied, or if spillage from saline impoundments during storms or washoff from waste dumps are significant contributors, appropriate measures could be introduced.

It is therefore recommended that detailed research be conducted in the more heavily polluted sub-catchments to determine actual sources of pollutants. It may even prove necessary to compute chemical mass balances of individual factories or portions of catchments, taking into account all known inputs and outputs, including raw materials and solid, liquid or gaseous wastes.

An investigation such as this would no doubt be very costly and time-consuming and could consequently be applied only to a limited number of small catchments. Nevertheless, the possibility of greatly extending knowledge of the mechanisms of diffuse-source water pollution may lead to identification of effective controls.

h) The models will have to be updated from time to time to incorporate new developments and management policies. If this is done, the model will grow with the system and continue to provide an effective planning and management tool in the years to come. As a great deal of money has been spent in developing the models it would be a pity to allow them to become redundant. There can be little doubt that in the long term it will be cheaper to maintain and continuously update the models on a regular basis than to use them this once and then at some later date have to develop new models.

i) The scope of the study may have to be extended to incorporate other water quality parameters. At the inception of the PWV project mineralisation was recognised as the most serious water quality hazard. Problems associated with other water quality parameters may, however, emerge in the future. (Eutrophication has already become a problem in Hartbeespoort Dam in the northern PWV catchment). The model in its present form can be used to model any conservative pollutants, but extensive modification would be needed if non-conservative pollutants had to be modelled.

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APPENDIX A : INPUT DATA USED IN MODEL SIMULATIONS

This chapter has details of the data input to program RESØØ1 used to simulate the options described in Chapter 3.

Fig. A.1 shows the locations of the major impoundments in the system.

A.1 Model parameter values

Table A.1 shows the model parameter values used for each option simulated. The assumptions behind each parameter value are discussed below.

a) PI and PS: Based on estimates provided by the Department of Water Affairs, the transmission losses between Sterkfontein and Vaal Dam are 9% for the first month of release, declining to 5% for subsequent months. If releases cease and subsequently resume, the loss reverts to 9% for the first month.

b) PRETB, PRETN and PRETW: ..er contract to the Water Research Commission, consulting engineers, Stewart, Sviridov and Oliver, have for the past 5 years or more been collecting data pertaining to water supplied to users in the southern PWV region, as well as details of effluent return flows. From these data it was possible to deduce the proportions of water supplied to users in the catchments of the Barrage and of Welkom Dam[≠] for the years 1976/77, 1977/78 and 1978/79. The averages for the three years are given in Table A.1. As no data were available for the northern catchment it had to be assumed that the percentage return flow for this region was the same as that for the Barrage catchment.

≠ Welkom Dam catchment users are defined as those situated in the southern PWV region whose effluent is discharged downstream of Vaal Barrage (e.g. SASOL and Vanderbijl Park Municipality).

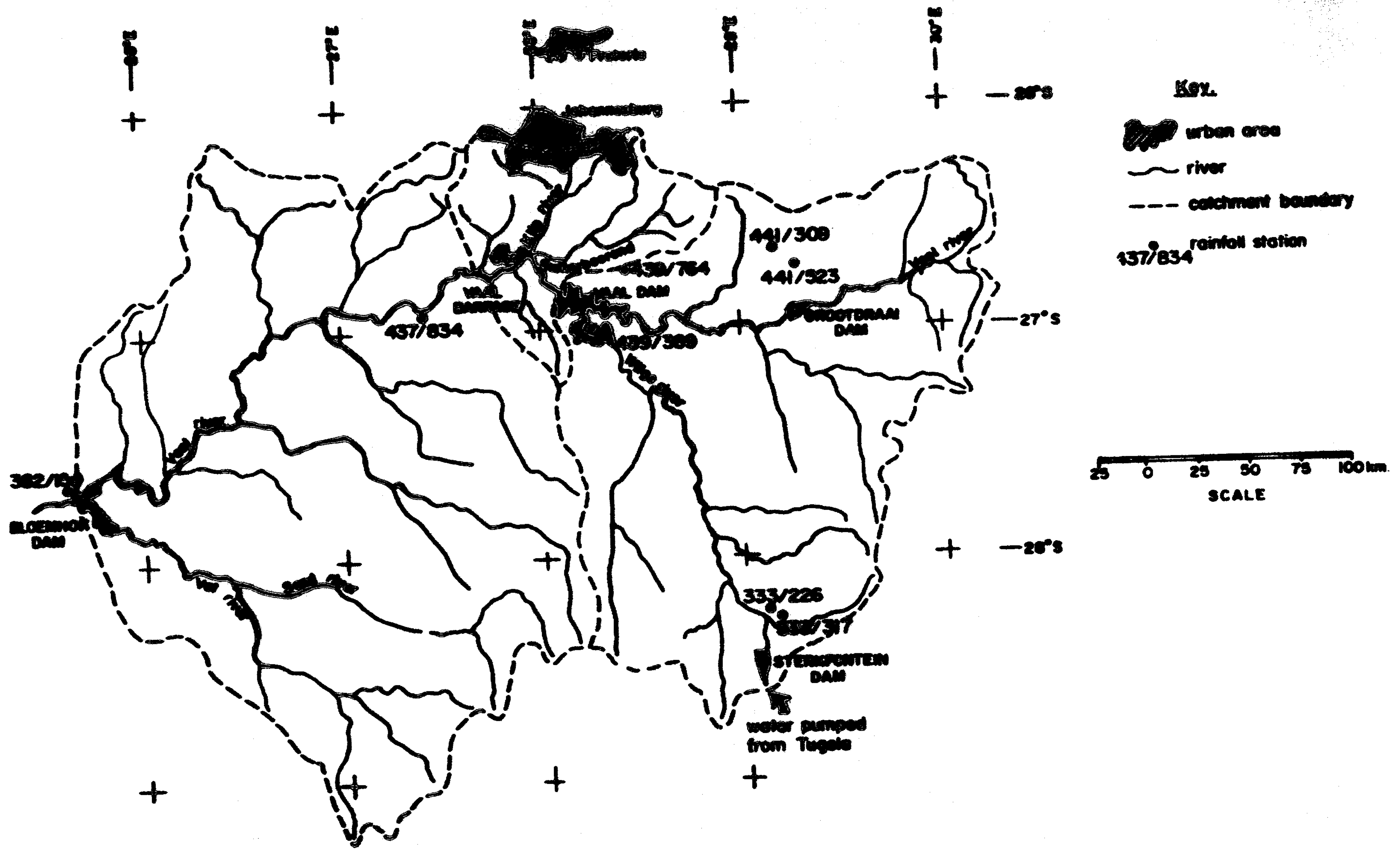

Fig.A1 : Map of study area showing drainage system and location of major impoundments and nearby rainfall stations

Table A.1 : Model parameter values used in simulations

Parameter	Units	Option number												
		1	2A	2B	2C	3A	3B	4A	4B	4C	5A	5B	6	7
PI	-	9	9	9	9	9	9	9	9	9	9	9	9	9
PS	-	5	5	5	5	5	5	5	5	5	5	5	5	5
PRETB	-	61,6	61,6	61,6	61,6	61,6	61,6	61,6	61,6	61,6	61,6	61,6	61,6	61,6
PRETN	-	61,6	61,6	61,6	61,6	61,6	61,6	61,6	61,6	61,6	61,6	61,6	61,6	61,6
PRETW	-	56,6	56,6	56,6	56,6	56,6	56,6	56,6	56,6	56,6	56,6	56,6	56,6	56,6
BLOSS	$m^3 x 10^6$	1,83	1,83	1,83	1,83	1,83	1,83	1,83	1,83	1,83	1,83	1,83	1,83	1,83
A1V	km^2	135	135	135	135	135	135	135	135	135	135	135	135	135
A2V	-	0	0	0	0	0	0	0	0	0	0	0	0	0
AIRRIG	km^2	78	78	78	78	78	78	78	78	78	78	78	78	78
FEVAP	-	0,6	0,6	0,6	0,6	0,6	0,6	0,6	0,6	0,6	0,6	0,6	0,6	0,6
FIRRIG	-	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0
PIQRET	-	20	20	20	20	20	20	20	20	20	20	20	20	20
PLOSB	-	0	0	0	30	0	0	0	0	0	0	0	0	0
PLOSN	-	0	0	0	30	0	0	0	0	0	0	0	0	0
CADDB	mg/l	500	500	500	500	500	500	500	500	500	500	500	500	500
CADDN	mg/l	500	500	500	500	500	500	500	500	500	500	500	500	500
CADDW	mg/l	500	500	500	500	500	500	500	500	500	500	500	500	500
CTARG	mg/l	999[+]	999	999	999	999	999	999	300	300	999	300	999	999
PSUBB	-	0	0	0	90	0	0	0	0	0	0	0	0	0
PSUBN	-	0	0	0	90	0	0	0	0	0	0	0	0	0
PILLOS	-	70	70	70	70	70	70	70	70	70	70	70	70	70
PCWTVL	-	0,40	0,40	0,40	0,40	0,40	0,40	0,40	0,40	0,40	0,40	0,40	0,40	0,40
PV[♯]	-	35,1	35,1	35,1	35,1	35,1	35,1	100	0	0	0	0	100	100
PA[♯]	-	39,8	39,8	39,8	39,8	39,8	39,8	0	0	0	0	0	0	0
PB[♯]	-	25,1	25,1	25,1	25,1	25,1	25,1	0	100	100	0	0	0	0
PW[♯]	-	0	0	0	0	0	0	0	0	0	100	100	0	0
RCAPB	$m^3 x 10^6$	0	200[f]	200[f]	200[f]	0	0	0	0	0	0	0	0	0
RCAPN	$m^3 x 10^6$	0	0	200[f]	200[f]	0	0	0	0	0	0	0	0	0

♯ For all options these values were assumed to remain unaltered for each year simulated.

\+ When the value of CTARG is set equal to 999, no attempt is made to blend the PWV supply water and the target TDS is ignored.

f Prior to October 1983 the capacity of the reclamation plant was set equal to zero. The values shown apply to all subsequent years. A very large plant capacity of 200 x $10^6 m^3$ per month was deliberately chosen so as to ensure that all effluent return flows would be modelled as being reclaimed (i.e. case II of section 2.4.3 applies). If options 2A, 2B or 2C are implemented, the plant capacity would be adjusted in step with the annual demand levels.

It should be noted, however, that the percentage return flows tend to vary according to climatic conditions and may not be stationary with time. (The ratio of effluent return flow to water supply is dependent upon such factors as population densities, proportion of industrial demand and price of water. Changes in any of these could alter the ratio). Table A.2 gives details of the ratio of effluent return flows to water supplied for both municipal and industrial users in the Barrage and Welkom Dam catchments.

Table A.2 : Relationship between water supply and effluent return flow for the southern PWV region

Parameter	Water supply ($m^3 x 10^6$/year)			Effluent return flow ($m^3 x 10^6$/year)			Effluent return flow: percentage of supply		
Year	1976/77	1977/78	1978/79	1976/77	1977/78	1978/79	1976/77	1977/78	1978/79
Barrage catchment									
municipalities	288,4	299,8	311,6	185,4	209,1	189,4	64,3	69,7	60,8
industries	61,7	62,0	73,3	29,4	30,7	31,1	47,8	49,5	42,4
total	350,1	361,8	384,9	214,8	239,8	220,5	61,4	66,3	57,3
Welkom Dam catchment									
municipalities	8,8	8,9	9,5	6,9	7,5	6,5	78,1	84,3	68,2
industries	35,1	42,4	46,5	21,0	21,2	21,6	60,0	50,0	46,6
total	43,9	51,3	56,0	27,9	28,7	28,1	63,6	56,0	50,3

Table A.2 shows that the percentage return flow differs from catchment to catchment and also according to the use to which the water is put. Changes in the nature of the industries and the usage habits of domestic users obviously play a part in the differences indicated by Table A.2. Of considerable importance is the change from year to year in the proportion of effluent returned to stream. The steady decline shown for the Welkom Dam catchment is attributable to changes in the usage patterns within a single industry, namely SASOL. The Barrage catchment, however, incorporates a multiplicity of industries and municipalities and therefore depicts more accurately the overall annual changes.

It would appear that the changes in the percentage effluent return flows in the Barrage catchment are strongly related to the climate (for example, 1977/78 was a relatively wet year whereas 1978/79 was an exceptionally dry year). Closer examination of the data with a view to establishing the inter-relationship of effluent return flows, demands and climatic and other factors would therefore appear to be warranted.

c) BLOSS: The average bed loss from the tributaries of the southern PWV region was obtained by summating the bed loss values for each sub-catchment as calibrated with the daily washoff model (Herold, 1981a).

d) A1V and A2V: It was assumed that the surface areas of the tributaries of the southern PWV region remain constant. They were based on average channel widths and the full plan area of all vleis in the system.

e) AIRRIG: The irrigated area was assumed to remain constant at the 1978 value.

f) FEVAP: The evaporation factor was set equal to 0,6 in view of the net reduction in lake evaporation associated with the shading effect of the extensive reed beds in the southern PWV tributaries. This assumption is in accordance with that made by Herold (1981a).

g) FIRRIG: The irrigation demand factor in equation 2.43 was set equal to 1,0, implying a demand equal to the potential evaporation rate. This factor is a little high for most crops, but should counterbalance the fact that an effective rainfall factor is not included in equation 2.4.3. (Equation 2.43 is identical in form to that used in the daily washoff model. It is not quite valid for a monthly model, however, in view of the fact that the rainfall is unlikely to be evenly distributed over the month).

h) PIQRET and PILLOS: The irrigation return flow factors were set equal to those used in the daily washoff model (Herold, 1981a).

i) PLOSB, PLOSN, PSUBB and PSUBN: The percentage of brine bleed-off from the desalination works (PLOSB and PLOSN) was estimated for a reverse osmosis plant designed to reduce the salt concentration by 90% (i.e. PSUBB and PSUBN are set equal to 90). For such a plant researchers of the National Institute of Water Research (Botha, G.R., 1981) estimate a brine bleed-off of the order of 25 to 50 percent, depending on the nature of the influent water. A value of 30% was adopted in view of the fact that the water would most probably be pre-treated before desalination.

j) CADDB, CADDN and CADDW: The quantity of TDS added to water in one usage cycle was computed by comparing the salt concentrations of influent and effluent water for the major industries and municipalities of the southern PWV region (i.e. Barrage catchment). Stallard (Hydrological Research Unit, 1978) divided the Barrage catchment into twenty sub-catchments and computed for each the difference between influent and effluent TDS. Fig. A.2 shows the twenty sub-catchments while Table A.3 gives details of the average increases in TDS together with the 1977/78 effluent return flows.

Table A.3 : Average increase in TDS through one usage cycle for each sub-catchment

Sub-catchment	Average effluent discharge (Ml/d)	Average increase in TDS (mg/l)
1	409≠	368
2	139≠	430
3	7	450
4	Insufficient data but discharges small	
5	27	914
6,7	Insufficient data but discharges small	
8	4,5	400
9	42	1756
13	4	400
14	2,5	343
10-12,15-20	Discharges insignificant	-
total	635	498

≠ revised values

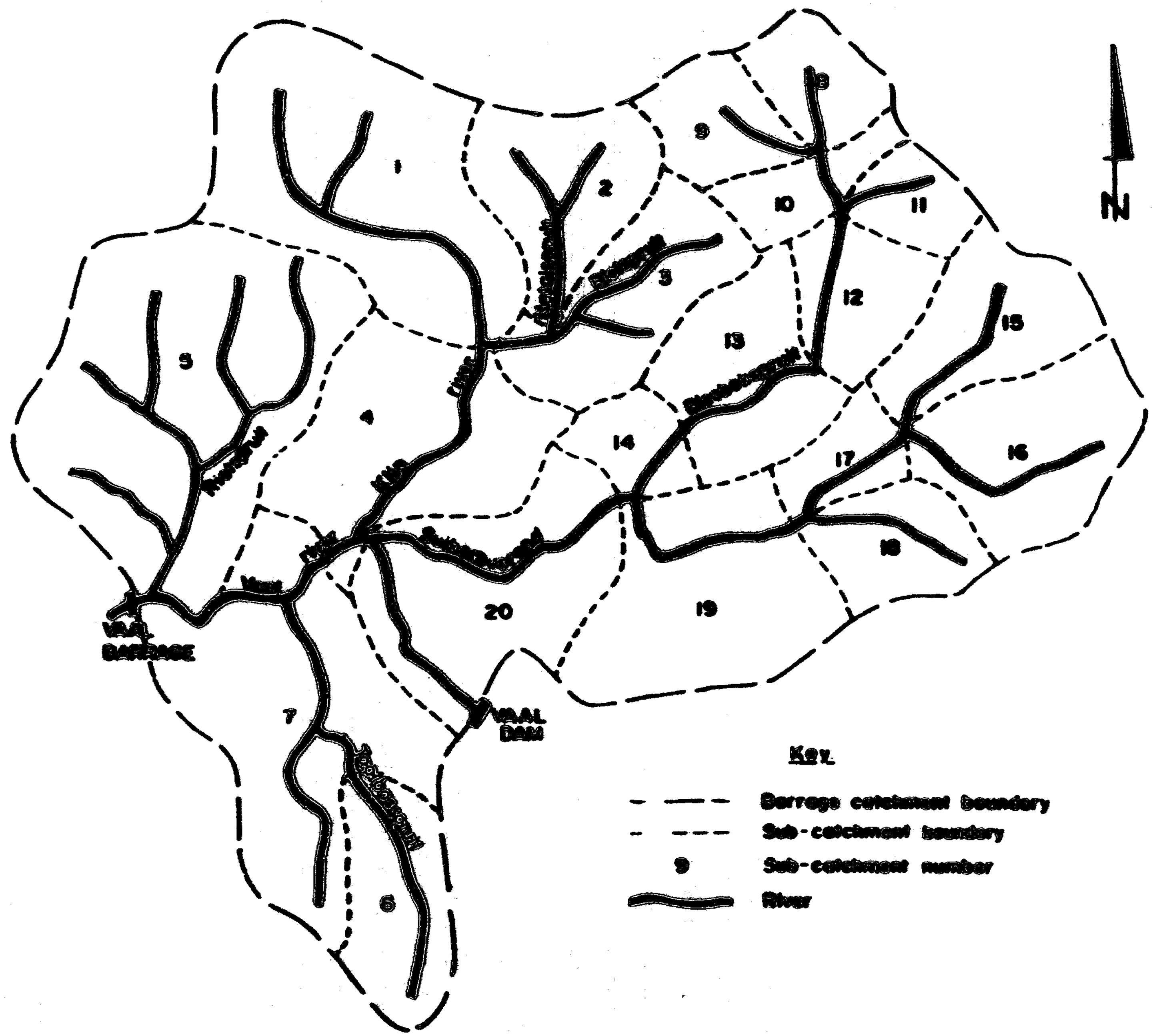

Fig.A.2: Map showing the sub-catchments for which the average addition of TDS through one cycle of usage has been completed.

It should be noted that the point discharges shown in Table A.3 comprise 90,7% of the total effluent discharged to the Barrage catchment (excluding mine pumpages). Mine pumpages were not included as the quality of water in the mine workings is independent of the quality of the supply water.

The weighted average increase in TDS for the sub-catchments shown in Table A.3 (498 mg/l) was rounded to 500 mg/l. It was assumed for the purposes of the simulations in Chapter 3 that the same average addition of TDS would hold in the northern and Welkom Dam catchments.

k) PCWTVL: The proportion of the Bloemhof catchment runoff entering the Vaal river upstream of the western Transvaal Regional Water Company intakes was based on estimates of the MAR for several smaller sub-catchments (Midgley and Pitman, 1969). From these estimates of MAR it was concluded that 40% of the catchment runoff between Vaal Barrage and Bloemhof Dam enters the Vaal upstream of the intakes.

l) PV, PA, PB and PW: The percentages of the PWV region demand met from Vaal Dam, Vaal Barrage cells A and B and from Welkom Dam were assumed to remain the same as the averages during the years 1976/77, 1977/78 and 1978/79 for options 1 to 3B. Table A.4 gives details of the abstractions during these three years.

A.2 Reservoir characteristics

a) Storage-area relationship: Storage-area curves for each reservoir are shown in Figs. A.3 to A.8. In these figures the points used as input data to program RESØØ1 are ringed. (The co-ordinates of these points are the A and V coefficient of equation 2.1).

b) Initial values: All simulations described in Chapter 3 are for the demand time frame October 1980 to September 2000. Initial reservoir storages and salt concentrations were therefore based