Table A.4: Abstractions from Vaal dam and Vaal Barrage to meet PWV region demands during the years 1976/77, 1977/78 and 1978/79

Flow line Code	Description	Abstraction ($m^3 x 10^6$) 1976/77	1977/78	1978/79	Average
Abstractions from Vaal Dam					
A1719	Vaal Dam to RWB Vereeniging pump station	0	16,7	49,4	
A1811	Vaal Dam to RWB Zuikerbosch pump station	238,2	246,0	235,0	
	total:	238,2	262,7	284,4	
	percentage of total PWV region supply:	34,4	35,5	35,4	35,1
Abstractions from Vaal Barrage upstream of Suikerbosrand confluence (Cell A)					
A1111	)ESC Vaal river pump station				
A1512	) to Taaibos and Highveld power				
A1514	) stations and Coalbrook				
A3111	) colliery	16,8	17,3	18,0	
A1416	ESC Vaal pump station to SASOL	12,2	15,9	19,8	
A1611	ESC Vaal pump station to Vaal power station and Cornelia Colliery	9,1	9,2	9,6	
A1817	Vaal river to RWB Zuikerbosch pump station	242,3	244,6	275,0	
	total	280,4	287,0	322,5	
	percentage of total PWV region supply:	40,5	38,8	40,1	39,8
Abstractions from Vaal Barrage downstream of Suikerbosrand confluence (Cell B)					
A1211	ISCOR Vaal river pump station	12,1	12,3	15,1	
A1311	ESC Klip power station Vaal river intakes	7,8	6,2	8,2	
A1412	SASOL Vaal river intakes	12,4	15,4	15,0	
A1711	RWB Vereeniging Vaal river intakes	140,1	155,4	158,0	
A7811	USCO Klip works Vaal river intakes	0,1	0	0,1	
A8111	USCO Vaal works Vaal river intakes	0,1	0,1	0,1	
A8212	Vereeniging Refractories Vaal river intakes	0,4	0,3	0,3	
	total	173,0	189,7	196,8	
	percentage of total PWV region supply	25,0	25,7	24,5	25,1
Total PWV region supply:		691,6	739,4	803,7	

on conditions as at 30 September 1980. Initial values, together with storage capacities and reserve storages, are given in Table A.5.

Table A.5: <u>Reservoir storages and salt concentrations as at 30 September, 1980</u>

Reservoir	Sterkfontein Dam	New Dam	Grootdraai Dam	Vaal Dam	Vaal Barr.	Welkom Dam	Bloemhof Dam
Storage capacity ($m^3 x 10^6$)	2600≠	1500	364	2533+	48	1538	1273
Reserve storage ($m^3 x 10^6$)	10	0‡	25	300	44	82	100
Initial storage ($m^3 x 10^6$)	506	0	108	1782	48	0	631
initial TDS‡ (mg/l)	70	130	100	130	500	500	300

‡ assumed values

≠ after implementation of phase 2 of the Tugela-Vaal scheme in 1985

\+ after completion of the raising of Vaal Dam. Full supply capacity as at November 1979 was 2191 x $10^6 m^3$ (Department of Water Affairs, 1979), while the recent betterments to Vaal Dam should increase the supply storage by a further $342 x 10^6 m^3$ (Secretary for Water Affairs, 1979).

c) <u>TDS concentrations of imported water</u>: The TDS of water pumped from the Tugela river to Sterkfontein Dam was assumed to average 70 mg/l, while that imported from the Usutu to the upper reaches of the Vaal was assumed to be 100 mg/l.

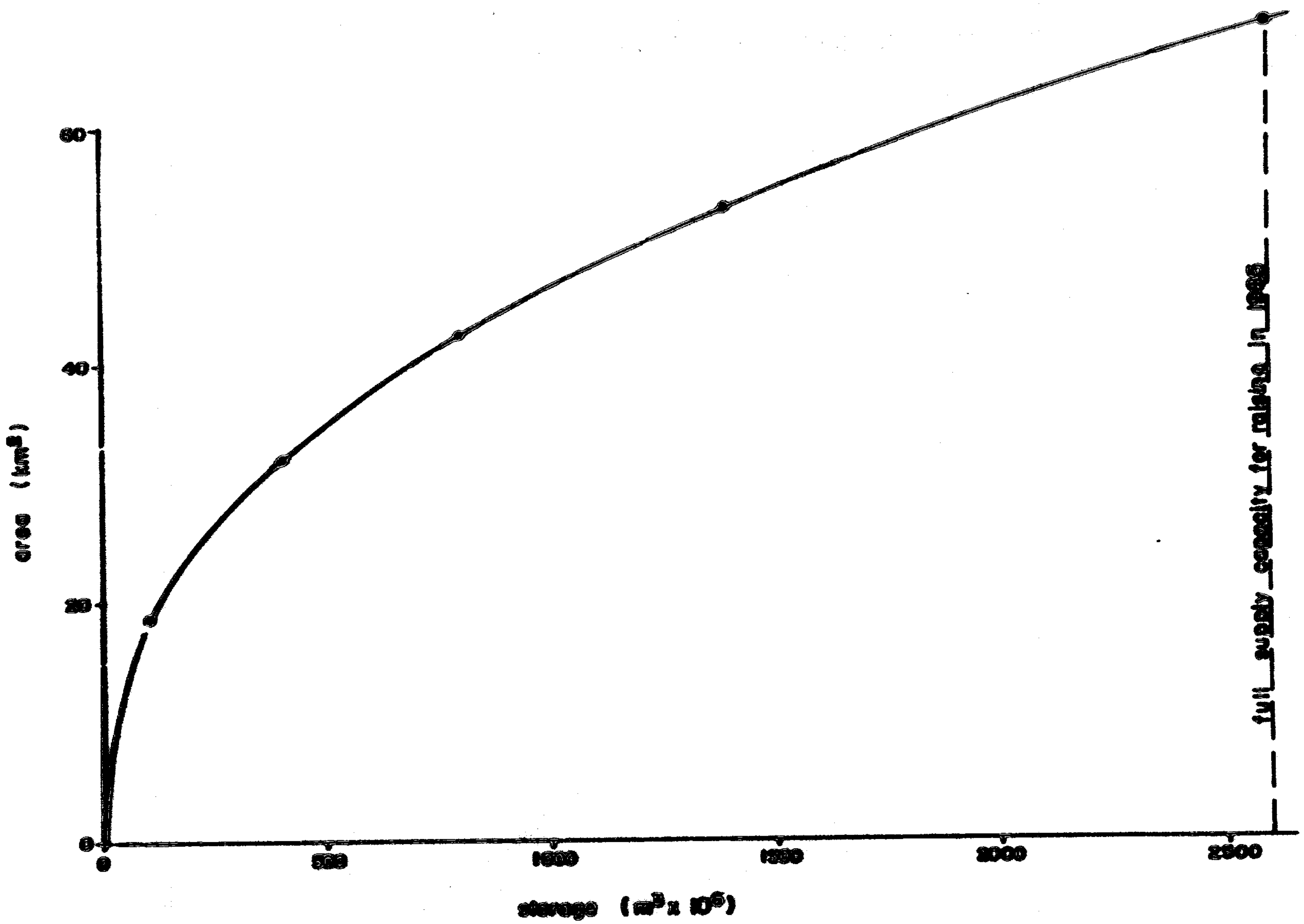

Fig.A.3: Storage-area curve for Sterkfontein Dam.

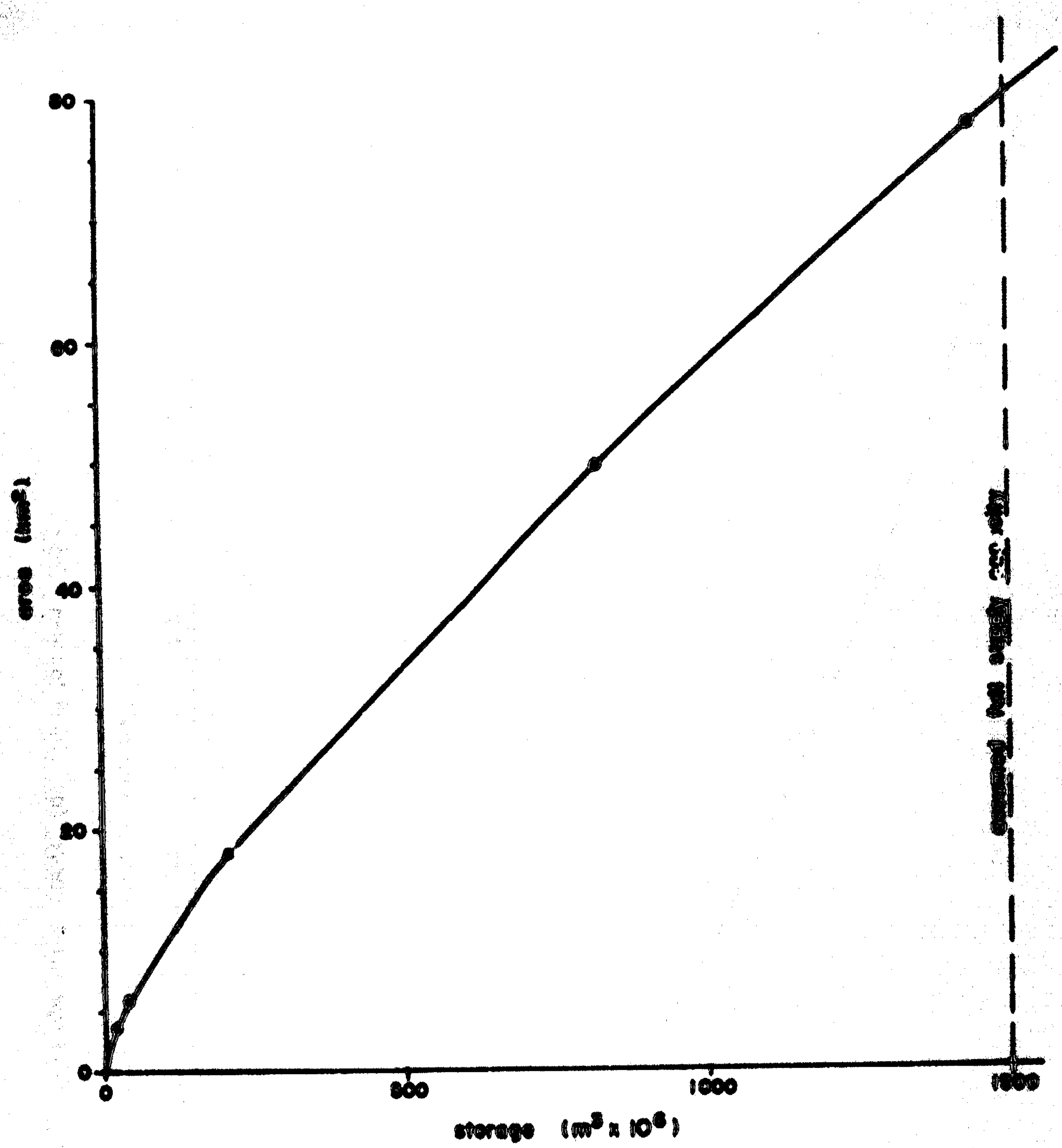

Fig. A.4: Storage-area curve for Balmoral Dam Site as at 1979.

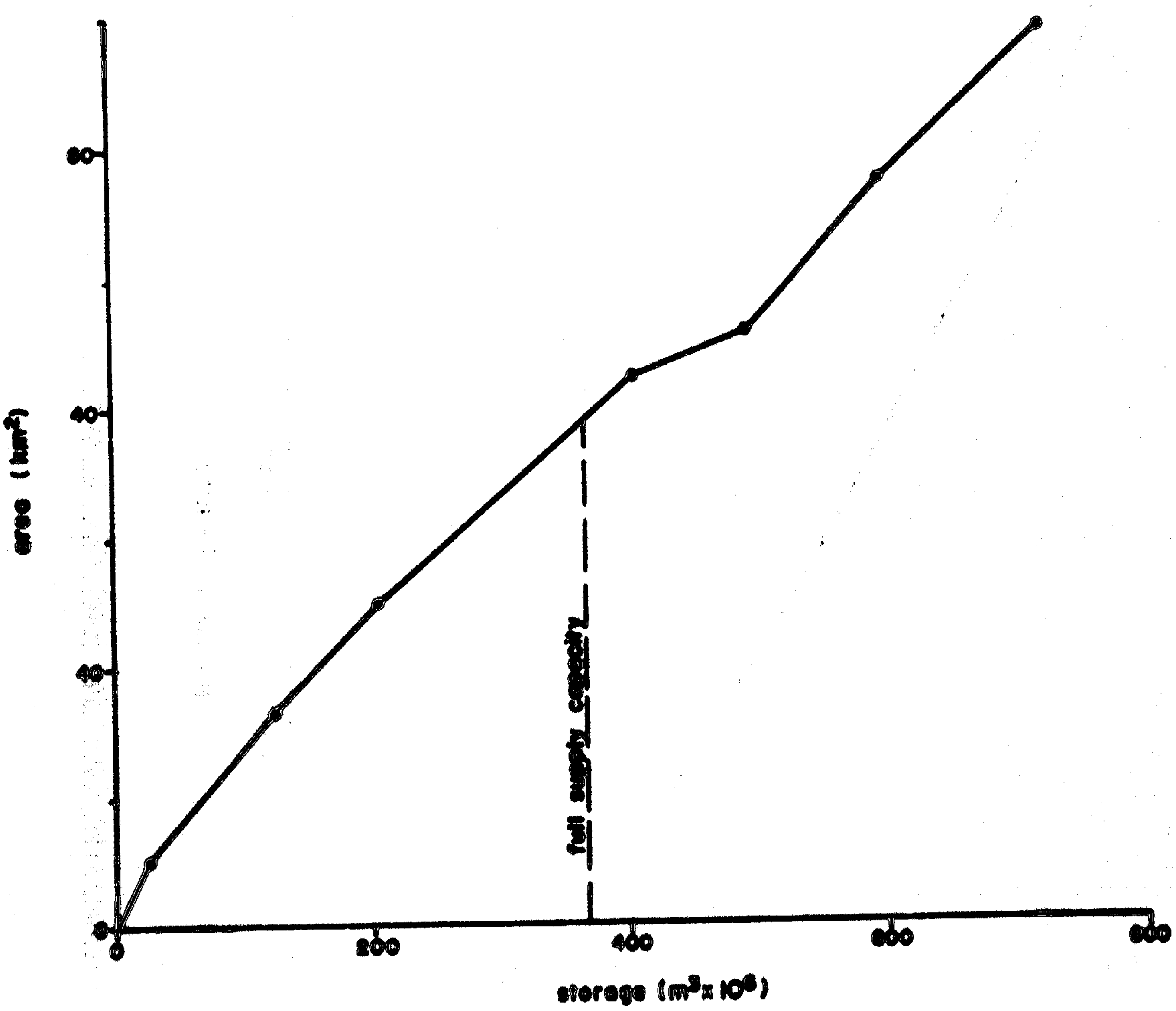

Fig.A.5: Storage-area curve for Grootdraai Dam as at February 1977

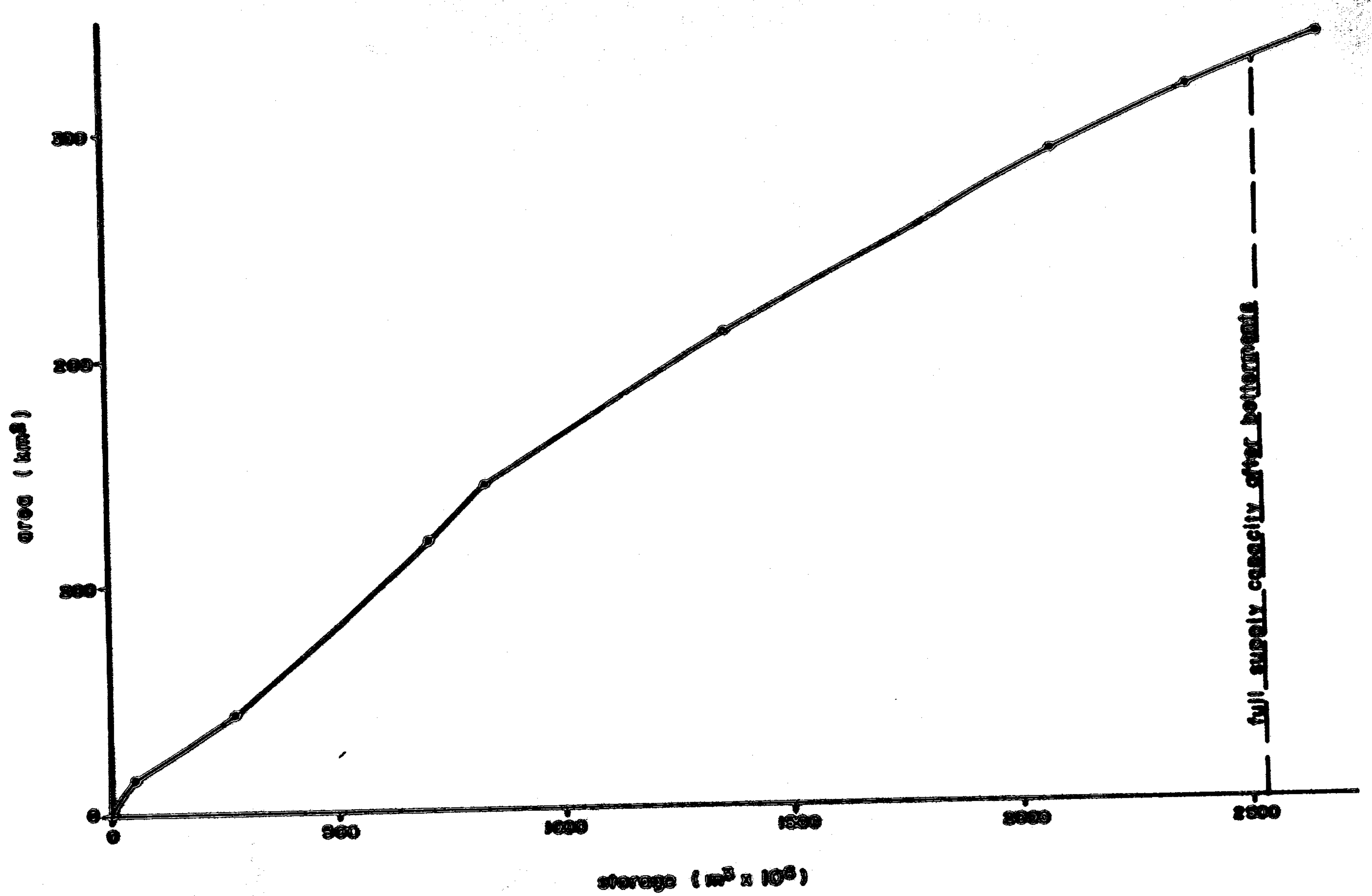

Fig.A.6: Storage-area curve for Vaal Dam as at November 1979

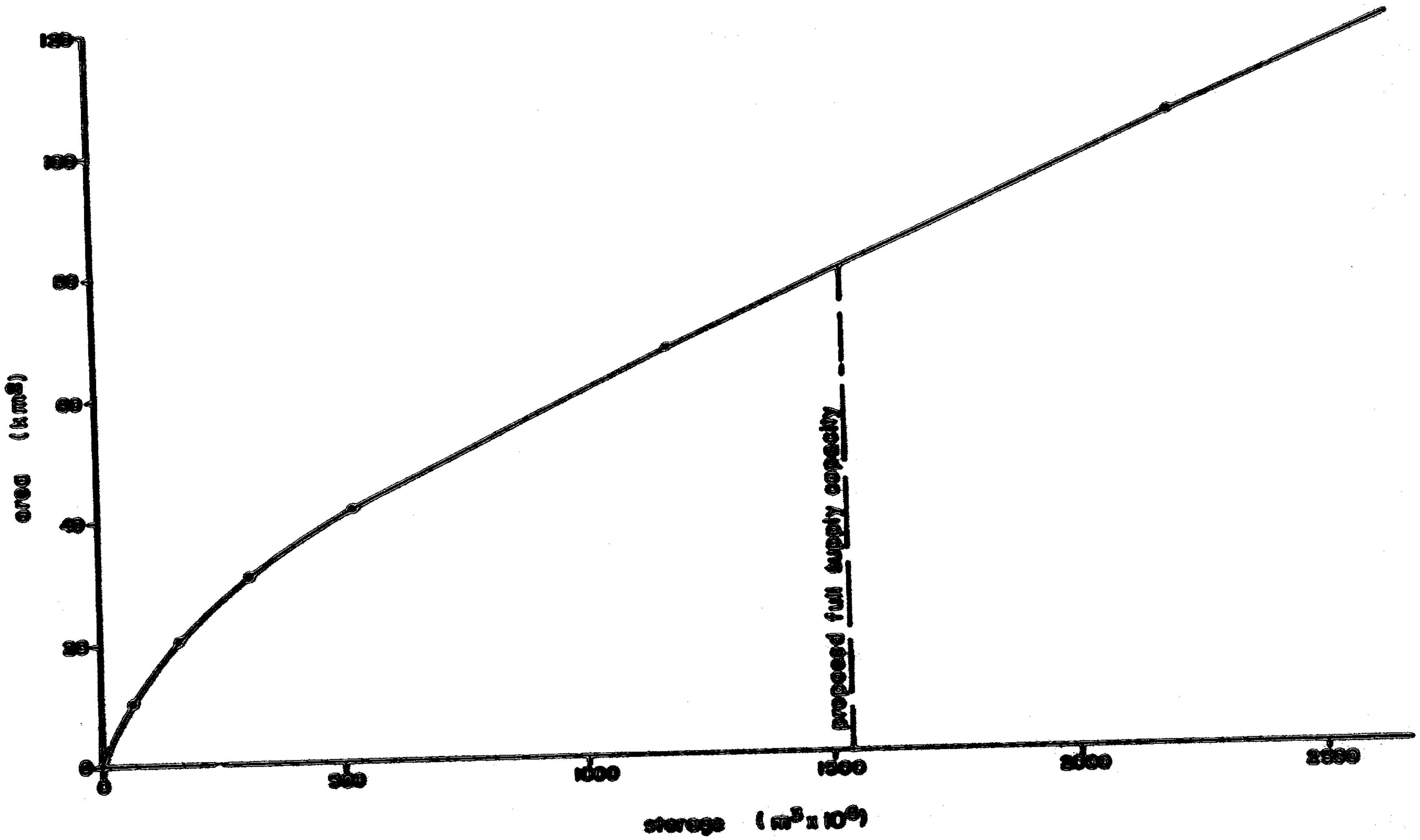

Fig.A7: Storage-area curve for Welkom Dam Site at Schoemansdrift

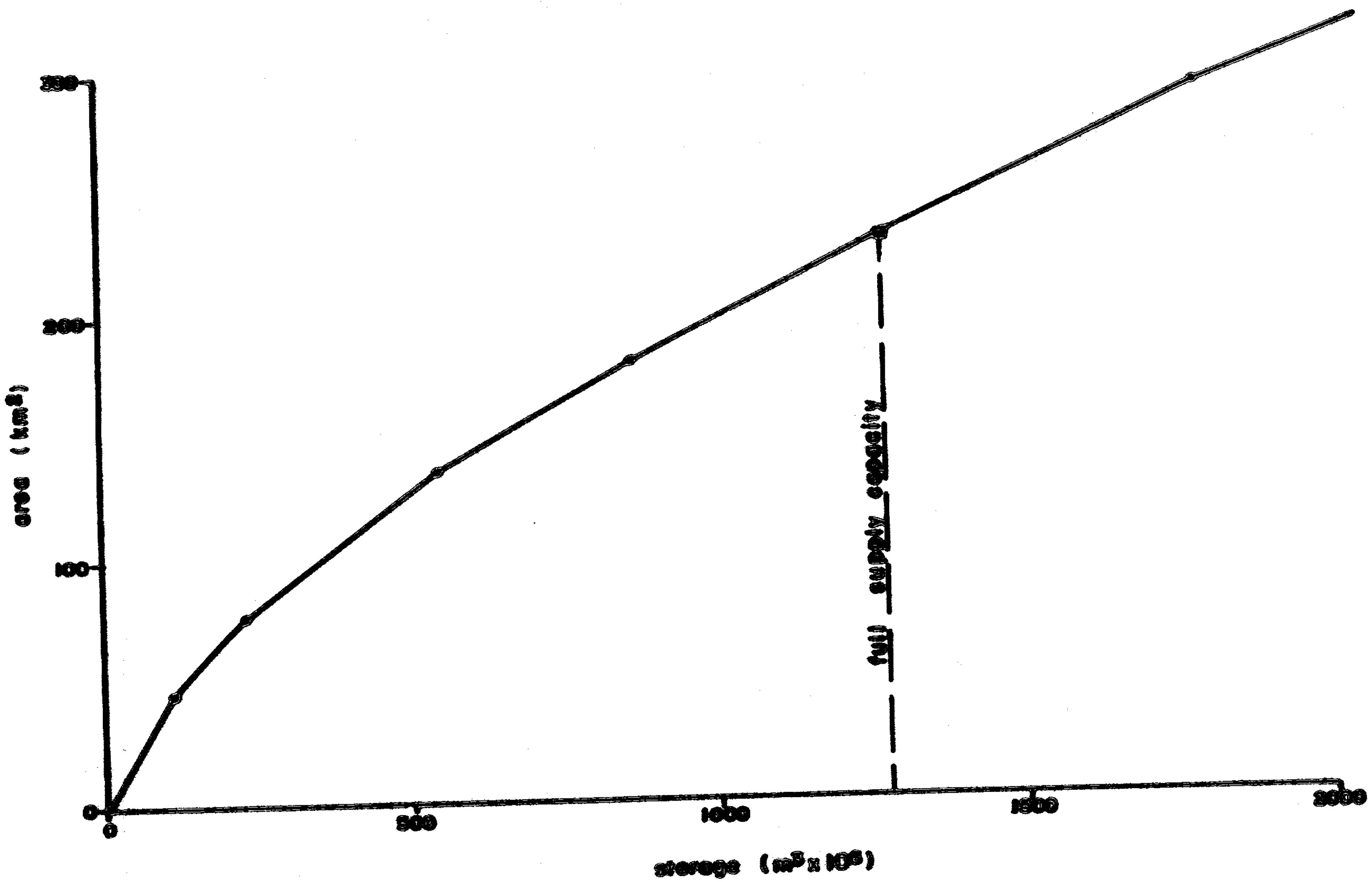

Fig.A.8: Storage-area curve for Bloemhof Dam as at April 1976

A.3 Rainfall and evaporation data

Fig. A.1 shows the location of rainfall stations used for each reservoir while Table A.6 gives details for the gauges.

Table A.6 : Details of rainfall stations used for each reservoir

Reservoir	Rainfall gauge no.	Latitude deg.	Latitude min.	Longitude deg.	Longitude min.	MAP (mm)	Period of record
Sterkfontein Dam	333/317	28	17	29	11	776	1905-1954
	333/226	28	16	29	8	665	1955-1976
Grootdraai Dam	441/523	26	43	29	18	668	1905-1949
	441/309	26	39	29	11	742	1950-1976
Vaal Dam	439/764	26	44	28	26	699	1905-1920
	439/389	26	59	28	13	555	1921-1976
Welkom Dam	437/834	26	54	27	24	646	1905-1976
Bloemhof Dam	362/159	27	39	25	36	489	1905-1976

Mean monthly Symons pan evaporations were derived from the maps produced by Pitman (1973). These pan evaporations were converted to equivalent lake evaporations using the relationship suggested by Pitman (1973), i.e. a factor of unity for the months November to June and 0,8 for the months July to October. The equivalent lake evaporations for each reservoir are given in Table A.7. Mean monthly gross evaporations for the proposed new dam site upstream of Grootdraai Dam were assumed to be the same as those at Grootdraai.

Table A.7 : Mean monthly lake evaporations (mm)

Location	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.
Sterkfontein Dam	110	138	138	138	110	119	90	80	60	56	80	97
Grootdraai Dam	128	155	168	161	141	122	99	81	70	58	82	97
Vaal Dam	150	186	200	193	157	147	112	92	74	64	94	127
Vaal Barrage	140	177	188	188	150	140	105	83	65	58	83	114
Welkom Dam	144	178	191	183	150	133	106	85	68	61	87	110
Bloemhof Dam	166	225	227	222	172	162	118	90	67	69	93	130

A.4 : Catchment runoffs

a) Grootdraai Dam catchment: Grootdraai Dam was commissioned only in 1979. Catchment runoffs prior to this date were obtained from the flow record at the DWA weir, station C1M01, near Standerton immediately downstream of the Grootdraai Dam. Flow records from 1905 are available.

b) Vaal Dam catchment: Prior to 1923 flow records were patched using the records at DWA weirs C1M01, C1M02 and C2M10. From 1923 to 1936 flow records are available at C2M03 (Engelbrechtsdrift weir, immediately downstream of Vaal Dam). Vaal Dam was commissioned in 1936 and after that date catchment runoffs were computed from the Vaal Dam mass balance. The records thus obtained apply, however, to the total Vaal catchment upstream of Vaal Dam (as Grootdraai Dam was built only in 1979). Runoffs for the Vaal Dam catchment (between Grootdraai and Vaal Dam) therefore had to be adjusted by subtracting Grootdraai Dam catchment runoffs. (This was necessary for all simulations of future conditions).

c) Vaal Barrage catchment: Vaal Barrage catchment runoffs (i.e. the catchment between Vaal Dam and Vaal Barrage) had to be simulated using the daily washoff model (Herold, 1981a). Historical records could not be used because considerable urban development has taken place in the Barrage catchment, leading to increased runoff efficiency. This factor alone renders the historical record inappropriate. Furthermore, the rating curves for the weirs situated in the tributaries of the southern PWV catchment are valid only for low flows (Herold, 1981a) and the increasing effluent discharges tend to mask the base flows.

The Barrage catchment was divided into twelve sub-catchments (see Fig. A.9) and the daily washoff model was calibrated for each for the period 1970/71 to 1978/79 (Herold, 1981a). The calibration is therefore valid for present-day (developed catchment) conditions. Daily runoffs for each of the twelve sub-catchments were then simulated using available rainfall and evaporation data for the period 1923 to 1979. Daily values for each sub-catchment were then aggregated into monthly totals for the entire Barrage catchment. Due to inadequacies in the daily rainfall data record the runoff prior to 1923 had to be simulated using the monthly model developed by Pitman (1973).

d) Bloemhof Dam catchment: Owing to inadequacies in the available flow record, runoff from the catchment between Vaal Barrage and Bloemhof Dam had to be simulated using the Pitman monthly model (Hydrological Research Unit, 1981).

A.5 : Catchment salt washoffs

(a) Grootdraai Dam and Vaal Dam catchments: Monthly salt loads washed off the whole Vaal Dam catchment (i.e. the Vaal Dam catchment prior to the commissioning of Grootdraai Dam) were simulated using the monthly salt washoff model described in HRU Report No. 1/80 (Herold, 1980). The model was calibrated for the period 1969/70 to 1977/78. Runoff data for the period 1905 to 1976 were then used to generate a record of monthly salt concentrations. Details of the calibration for the Vaal Dam catchment are given in HRU Report No. 1/80 (Herold, 1980).

It was assumed that the Vaal Dam catchment, which is largely undeveloped, would remain in a stationary condition with respect to water quality. This assumption may be overthrown, however, as a result of the recent rapid growth of petro-chemical industries at Secunda in the eastern Transvaal.

Monthly salt concentrations for washoff from the Grootdraai catchment and that between Grootdraai and Vaal Dam were assumed to be identical to those simulated for the entire Vaal Dam

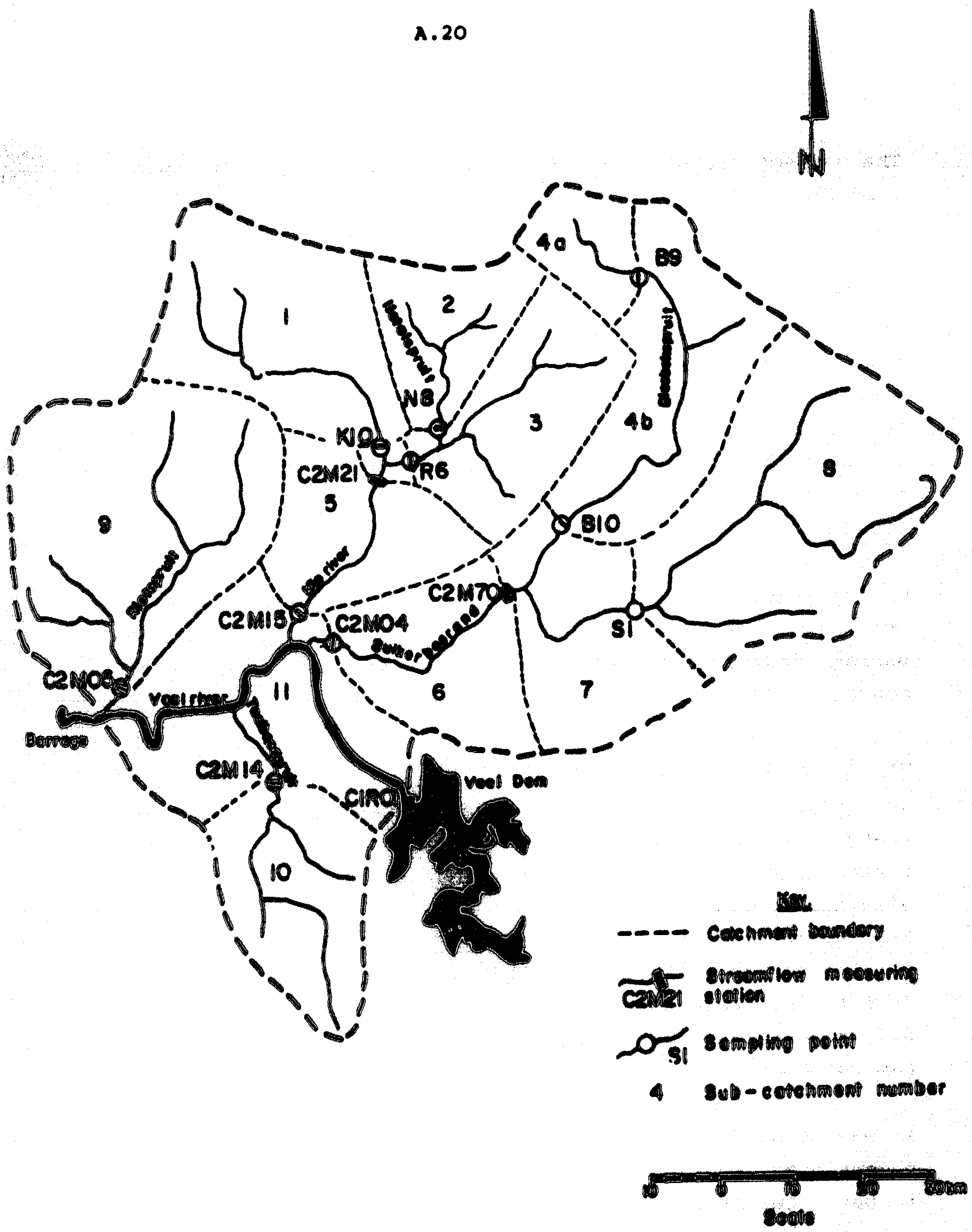

Fig A.9: Map showing sub-catchments and monitoring points.

catchment (i.e. the area upstream of Vaal Dam was assumed to be homogeneous).

b) Vaal Barrage catchment: The water quality component of daily washoff model (Herold, 1981a) was calibrated for the year 1977/78 and verified for the years 1973/74 to 1976/77 and 1978/79. A strong correlations was found between the calibrated diffuse source salt generation rate and the industrial water supply to each of the twelve sub-catchments (Herold, 1981a).

Industrial water demands for the period 1970/71 to 1979/80 within each of the twelve sub-catchments are available. These are given in Table A.8.

Table A.8 : Annual industrial water consumption within each sub-catchment ($m^3 x10^6$)

Sub-catchment	Hydrological year									
	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979
1	12,0	12,8	13,5	14,3	14,4	15,5	16,6	17,7	17,6	16,6
2	16,2	17,5	18,0	20,1	23,0	25,5	26,9	26,7	28,9	29,8
3	3,3	3,3	2,9	3,4	4,0	3,8	3,6	14,0+	24,6	22,0
4a	8,6	8,6	9,4	9,8	10,3	10,9	11,6	11,8	12,1	12,3
4b	9,5	9,4	9,9	10,3	10,7	11,0	10,9	10,9	11,0	11,5
5	10,3	10,0	9,4	9,2	9,3	10,1	10,3	8,6	11,3	11,1
6 - 8	0	0	0	0	0	0	0	0	0	0
9	18,2	22,3	23,6	26,2	30,4	33,1	29,7	28,9	33,2	33,3
10	0	0	0	0	0	0	0	0	0	0
11	59,3	55,9	59,5	60,0	59,5	61,8	60,8	68,1	73,5	70,6
Total	137,4	139,8	146,2	153,3	161,6	171,6	170,3	186,7	209,2	207,1

+ the sharp rise in demand in sub-catchment 3 is attributable to the commissioning of the ERGO mine dump re-processing plant.

Annual industrial water demands for the entire Barrage catchment were expressed as percentages of the total water supply. These percentages are plotted in Fig. A.10. Linear and power regression equations are also shown in Fig. A.10. Table A.9 gives details of the regression equations.

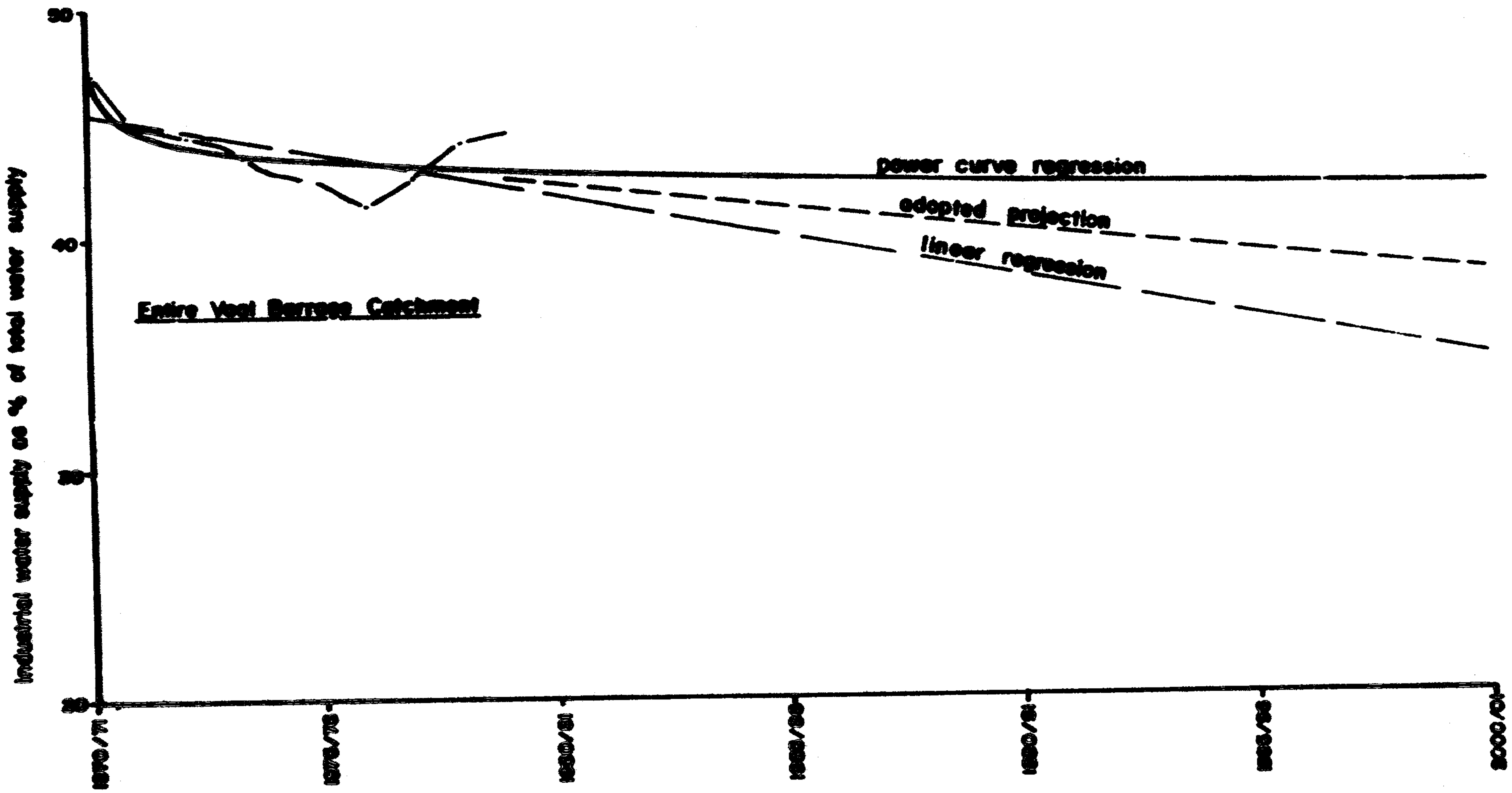

Fig.A.10: Industrial water supply as percentage of total water supply for the Barrage catchment

Table A.9 : Regression equations for industrial water supply as percentage of total water supply

Equation type	Equation	Linear correlation co-efficient
Linear	Percentage = 782,3 - 0,3740.Year	0,599
Power	Percentage = 44,734.(Year-1969,92)^{0,02066}	0,779

The average between the linear and power regressions was used as the projection (the broken line in Fig. A.10). The estimated southern PWV catchment total water demands given in Table 3.4 were then used in conjunction with the projected percentages to predict annual industrial water demands for the period 1980/81 to 2000/01. These values were then used to project the industrial water demands in sub-catchments 1-5, 9 and 11, assuming that the rate of development within each sub-catchment would be identical to that for the entire catchment. Annual industrial water demands derived in this fashion are given in Table A.10. It was assumed that sub-catchments 6-8 and 10 would remain undeveloped. (i.e. The diffuse source salt generation rate as calibrated for the year 1977/78 (Herold, 1981a) was assumed to remain constant).

The industrial demands shown in Table A.10 for the years 1964/65 to 1979/80 are the best-fit regressions fitted to the annual demands for each individual sub-catchment given in Table A.8.

The regression equation relating diffuse-source salt generation rate to industrial water supply derived by Herold (1981a) was then used to compute growth factors for each sub-catchment. These are given in Table A.11.

The daily washoff model was then run for each of the twelve sub-catchments for the hydrological sequence 1923/24 to 1958/59 corresponding to the demand sequence 1964/65 to 1999/2000. Diffuse-source salt generation rates for the year 1964/65 were assumed to be the same as those calibrated in HRU Report No. 3/81 (Herold, 1981a). Salt generation rates for subsequent years were assumed to grow according to the growth factors given in Table A.11. Daily salt loads were then aggregated into monthly totals for the entire Barrage catchment.

Table A.10 : Projected annual industrial water demands ($m^3 x 10^6$)

Hydro-logical year	Sub-catchment number								
	1	2	3	4a	4b	5	9	11	total
1964	8,4	5,6	2,4	5,3	4,9	9,4	3,9	56,0	96,0
1965	9,0	7,3	2,6	5,8	5,8	9,4	6,3	56,0	102,2
1966	9,6	9,0	2,7	6,3	6,9	9,5	8,6	56,0	108,5
1967	10,2	10,7	2,8	6,9	7,6	9,5	10,9	56,0	114,6
1968	10,8	12,4	2,9	7,4	8,3	9,6	13,2	56,0	120,5
1969	11,4	14,1	3,0	7,9	8,8	9,6	15,6	56,1	126,5
1970	12,0	16,0	3,1	8,4	9,3	9,7	18,1	55,7	132,1
1971	12,8	17,5	3,2	8,9	9,7	9,7	22,3	57,3	141,2
1972	13,5	19,0	3,3	9,4	10,0	9,8	24,8	58,9	148,6
1973	14,1	20,6	3,4	9,9	10,3	9,8	26,7	60,5	155,3
1974	14,8	22,2	3,6	10,3	10,5	9,9	28,3	62,1	161,7
1975	15,5	23,9	3,7	10,8	10,7	10,0	29,5	63,6	167,8
1976	16,1	25,6	3,8	11,3	10,9	10,2	30,7	65,2	173,8
1977	16,8	27,4	12,7	11,7	11,1	10,3	31,7	66,8	188,5
1978	17,5	29,2	19,3	12,1	11,2	10,4	32,0	68,4	200,7
1979	18,1	31,0	25,9	12,5	11,4	10,5	33,4	69,9	212,8
1980	18,9	32,3	27,0	13,1	11,9	11,0	34,9	72,9	222,0
1981	19,7	33,8	28,2	13,7	12,4	11,5	36,5	76,2	232,0
1982	20,7	35,4	29,6	14,[illegible]	13,0	12,0	38,2	79,8	243,0
1983	21,6	37,0	30,9	15,0	13,6	12,6	39,9	83,4	254,0
1984	22,5	38,6	32,2	15,6	14,2	13,1	41,6	87,[illegible]	265,0
1985	23,7	40,6	34,0	16,4	14,9	13,8	43,8	91,7	279,0
1986	25,0	42,8	35,8	17,3	15,7	14,6	46,2	96,6	294,0
1987	26,6	45,6	38,1	18,4	16,8	15,5	49,2	102,8	313,0
1988	28,1	48,0	40,2	19,4	17,7	16,4	51,9	108,4	330,0
1989	29,4	50,4	42,1	20,4	18,5	17,2	54,4	113,7	346,0
1990	30,8	52,7	44,1	21,3	19,4	17,9	56,9	118,9	362,0
1991	32,2	55,2	46,1	22,3	20,3	18,8	59,5	124,5	379,0
1992	33,7	57,6	48,2	23,3	21,2	19,6	62,2	130,1	396,0
1993	35,3	60,4	50,5	24,5	22,2	20,6	65,2	136,3	415,0
1994	36,9	63,2	52,8	25,6	23,2	21,5	68,2	142,6	4[illegible]4,0
1995	38,6	66,1	55,2	26,7	24,3	22,5	71,3	149,1	454,0
1996	40,5	69,3	57,9	28,0	25,5	23,6	74,8	156,4	476,0
1997	42,5	72,6	60,7	29,4	26,7	24,7	78,4	163,9	499,0
1998	43,5	74,1	62,2	30,1	27,4	25,3	80,3	167,9	511,0
1999	46,6	79,8	66,7	32,3	29,4	27,2	86,1	180,0	548,0
2000	48,8	83,5	69,8	33,8	30,7	28,5	90,2	188,6	574,0

The monthly washoff model (Herold, 1980) was then calibrated so as to mimic the monthly salt loads simulated by the daily model for the period 1939/40 to 1958/59 (corresponding to the demand period 1980/81 - 1991/2000). Fig. A.11 shows the fit achieved between monthly salt loads simulated by the daily and monthly models. (The monthly washoff model is, after all, a simplified version of the daily washoff model). Table A.12 provides a statistical comparison. In view of the good fit achieved between monthly salt loads simulated by the daily and monthly models, it was assumed that the calibration parameter values used in the monthly model would be equally valid for any other hydrological

Table A.11 : Diffuse-source salt generation rate growth factors used in program NACLØ1

Hydro-logical year	Sub-catchment number 1	2	3	4a	4b	5	9	11	total
1964	49,4	61,0	38,4	83,2	35,4	68,9	33,2	176,5	65,2
1965	51,1	72,1	39,1	89,1	37,4	68,9	38,6	176,5	67,5
1966	52,8	83,3	39,7	94,9	39,9	69,4	44,0	176,5	69,9
1967	54,6	94,4	40,4	100,7	41,7	69,4	49,4	176,5	72,1
1968	56,4	105,6	41,0	106,4	43,2	69,9	54,7	176,5	74,4
1969	58,3	116,7	41,6	112,1	44,5	69,9	60,1	176,5	76,5
1970	60,1	129,5	42,3	117,9	45,6	70,3	66,0	176,5	78,9
1971	62,3	139,1	43,0	123,6	46,4	70,3	75,7	179,9	81,9
1972	64,4	149,2	43,6	129,1	47,1	70,8	81,5	184,3	84,5
1973	66,5	159,6	44,2	134,4	47,8	70,8	85,9	188,6	87,0
1974	68,5	170,4	44,9	139,7	48,3	71,3	89,4	193,0	89,3
1975	70,5	181,4	45,5	144,8	48,8	71,9	92,4	197,3	91,6
1976	72,5	192,7	46,2	149,8	49,2	72,5	95,0	201,6	93,9
1977	74,5	204,2	98,4	154,6	49,6	73,2	97,3	205,8	107,3
1978	76,4	216,0	136,8	159,4	50,0	73,8	99,4	210,1	117,8
1979	78,4	227,9	175,2	164,1	50,4	74,4	101,4	214,3	128,2
1980	80,7	236,7	181,7	170,1	51,5	76,6	104,7	222,5	132,4
1981	83,2	246,3	188,8	176,7	52,7	78,9	108,3	231,4	136,9
1982	86,0	256,8	196,6	183,9	54,1	81,5	112,3	241,3	141,9
1983	88,8	267,3	204,4	191,2	55,5	84,1	116,3	251,1	147,0
1984	91,6	277,9	212,3	198,4	56,8	86,7	120,3	260,9	152,0
1985	95,2	291,3	222,2	207,6	58,6	90,0	125,4	273,4	158,4
1986	99,0	305,6	232,8	217,5	60,4	93,6	130,8	286,8	165,3
1987	103,9	323,8	246,3	230,0	62,7	98,1	137,7	303,8	174,0
1988	108,2	340,1	258,4	241,2	64,8	102,1	143,9	319,0	181,8
1989	112,3	355,4	269,8	251,7	66,8	105,9	149,7	333,3	189,1
1990	116,4	370,7	281,1	262,2	68,8	109,6	155,5	347,6	196,4
1991	120,7	387,0	293,2	273,4	70,9	113,7	161,7	362,8	204,2
1992	125,0	403,3	305,3	284,6	73,0	117,7	167,9	378,0	212,0
1993	129,9	421,5	318,3	297,1	75,3	122,2	174,8	395,0	220,7
1994	134,7	439,7	332,2	309,6	77,7	126,7	181,7	411,9	229,3
1995	139,8	458,8	346,4	322,7	80,2	131,4	188,9	429,8	238,5
1996	145,4	479,9	362,1	337,2	82,9	136,6	196,9	449,5	248,6
1997	151,3	501,9	378,4	352,3	85,7	142,0	205,3	470,0	259,1
1998	154,3	513,4	386,9	360,2	87,2	144,8	209,6	480,8	264,6
1999	163,8	548,8	413,2	384,5	91,8	153,6	223,1	513,8	281,5
2000	170,4	573,7	431,6	401,7	95,0	159,7	232,5	537,1	293,4

sequence. The monthly model was then used to simulate monthly salt loads for the hydrological sequence 1914/15 to 1933/34, corresponding to catchment conditions projected for the period 1980/81 to 1999/2000. (The daily model could not be used to simulate this hydrological sequence due to the poor distribution of rainfall gauges prior to 1923.)

Table A.12: Statistical comparison of monthly salt loads simulated using the daily and monthly washoff models

Statistical parameter	Unit	Daily model	Monthly model	Percentage error
Mean	$tx10^3$	58,100	58,071	-0,05
Standard deviation	$tx10^3$	79,940	78,423	-1,90
Linear correlation coefficient	-	0,976		

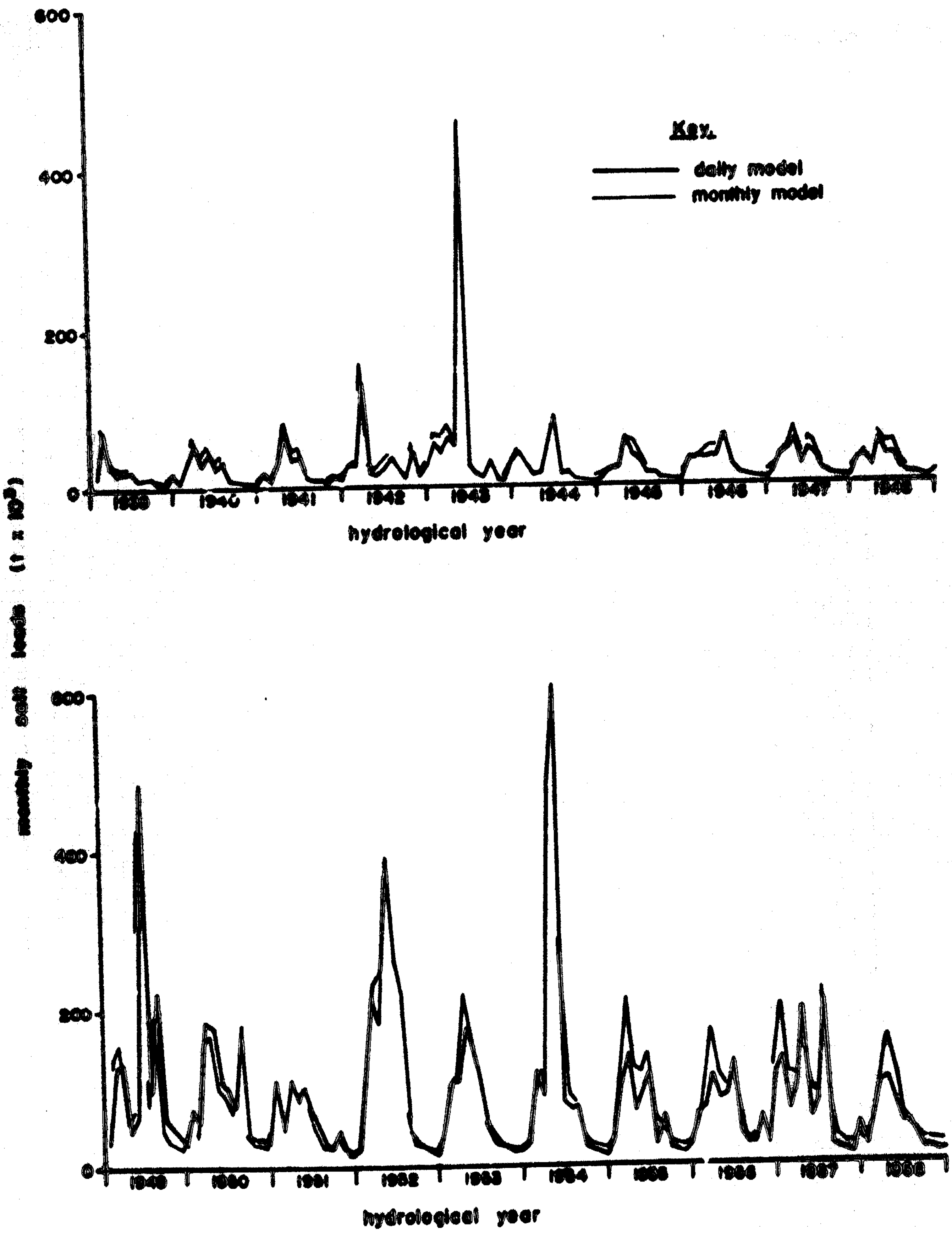

Fig.A.11: Monthly salt loads simulated by the monthly and daily washoff models : 1939/40 – 1958/59

c) Bloemhof Dam catchment: It was not possible to calibrate either the daily or monthly washoff models for the catchment between Vaal Barrage and Bloemhof Dam owing to the paucity of water quality data. For simulating the options described in this report it was assumed that the salt generation rate per unit area for the Bloemhof catchment would be approximately equal to that for the Vaal Dam catchment. Monthly salt loads for the period 1914/15 to 1933/34 were then simulated using the monthly washoff model assuming a stationary catchment condition (i.e. assuming that the salt generation rate does not change with time).

This assumption may not be entirely appropriate in view of the expansion of the urban and industrial (particularly mining) development taking place throughout the catchment. It would have been futile, however, to incorporate growth factors because of the uncertainties associated with the first assumption (vis. that the salt generation rate per unit area is identical to that for the Vaal Dam catchment).

No account has been taken of effluent discharges in the Bloemhof catchment, due to the lack of data. Several mines operate in this region and are known to discharge saline water pumped from their workings.

It is clear therefore that the Bloemhof catchment has not been adequately modelled and it is strongly recommended that a comprehensive monitoring system be established as a preparatory step to the comprehensive study of the region.

PART III

THE MONTHLY FEEDBACK MODEL

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SYNOPSIS

This report embodies the documentation of a numerical model designed to simulate the daily fluctuations of discharge and salt concentration at any point in the tributaries that drain the southern PWV region as well as in the Vaal Barrage and in the Vaal river between the Barrage and Bloemhof Dam. Daily salt concentrations in the water supplied to the 27 sub-regions into which the southern PWV region has been divided are also computed, as well as daily water and salt storages in each of the major impoundments of the Vaal basin. The feed-back effects of return flows of mineralised effluent which re-enter the water supply system are taken into account, as well as the effects of saline mine water pumpages. The tributary routing element of the model accounts for channel bed losses, irrigation abstractions and return seepage as well as the influence on the movements of both water and salt of storage in the extensive reed swamps.

Inputs to the model comprise:

- output from the monthly and daily washoff models described in HRU Reports 1/80 and 3/81
- modelled or observed daily runoffs from the Grootdraai and Vaal Dam catchments
- modelled monthly runoffs from the Bloemhof Dam catchment
- annual water demands on each reservoir
- monthly water demands on Vaal Barrage
- physical characteristics of the reservoirs
- annual quantities of effluent return flow
- mine water pumpages and associated salinities
- monthly rainfalls on reservoir surfaces and
- model parameters defining the assumptions made in the simulation.

The model is designed in such a way that a wide variety of management and planning options can be modelled with the minimum of programming changes. Recommendations on how the model can be used to compare the effectiveness of water pollution abatement strategies are made and illustrated by way of example.

A comprehensive user manual is provided for guidance in the use of the various programs.

CHAPTER 1 INTRODUCTION

1.1 Motivation

The Pretoria-Witwatersrand-Vereeniging (PWV) complex is the most economically important region in southern Africa. This complex is currently supplied with water abstracted from Vaal Dam and from the Vaal Barrage. Some of the water abstracted from the Barrage is derived from runoff contributed by the catchment downstream of Vaal Dam, some from return flow of used water from the system, plus mine pumpage, and the balance is made up of water released from Vaal Dam. Vaal Dam water thus enters the system both directly and via the Barrage. The quantities, and hence the qualities, of these different waters therefore depend not only upon the demand situation and the hydrology but also upon the policy adopted for operating the reservoir system, the major components of which are given in Fig. 1.1. The position is further complicated by the relationship between the quality of water supplied and that of the effluents discharged to the tributaries of the Vaal Barrage (viz. the Klip and Suikerbosrand - see Fig. 1.1).

It is not surprising that increasing mineralization of the water resources has become a cause for deep concern. Clearly, the major source of water supply (Vaal Barrage) is also the sink for much of the generated pollution.

In 1975 the Water Research Commission initiated a study of the PWV complex with special reference to existing and potential problems of water supply, waste water management and pollution control. In particular, mineral pollution was singled out as being the problem requiring the most urgent attention, both because of the danger to public health and because of the high costs associated with treatment and damage to industrial and domestic equipment. The Hydrological Research Unit of the University of the Witwatersrand, funded by the Water Research Commission, undertook to develop a set of

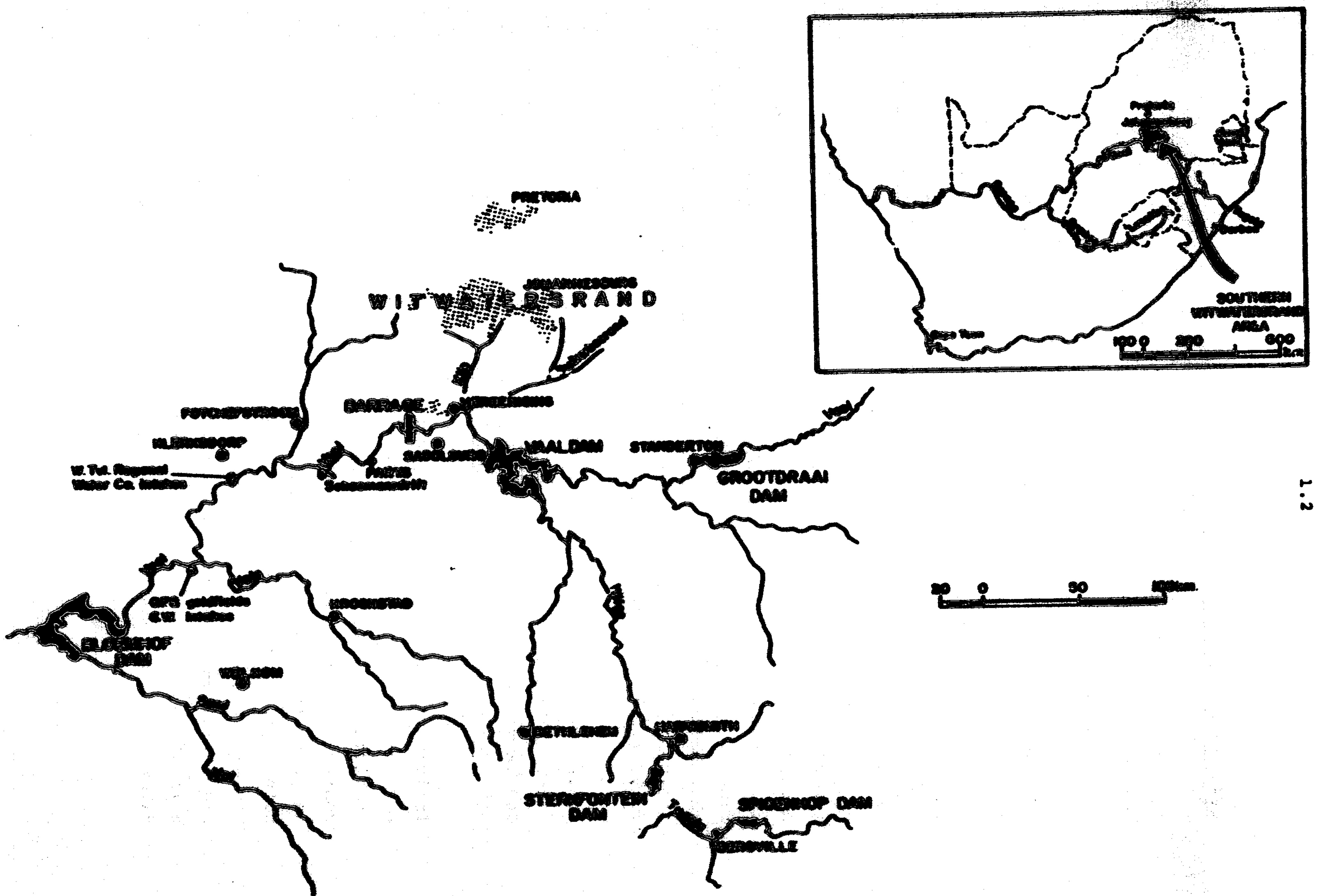

Fig.1.1: Location of PWV region and major reservoirs of the Vaal basin

numerical models which could be used to simulate the fluctuations of salinity at key points in the system and to provide a means of comparing various proposals for ameliorating undesirable future salinity conditions. For the sake of completeness, the models that were developed are briefly outlined in the following paragraphs.

1.2 The models

The components of the suite of models developed to simulate the PWV water supply system are described in turn.

1.2.1 The monthly catchment washoff model

The monthly catchment washoff model (Herold, 1980) simulates monthly total dissolved solids (TDS) concentrations associated with monthly runoff volumes (either observed or generated by means of the monthly catchment model (Pitman, 1973). The Pitman model simulates monthly runoffs from observed meteorological data. The output of the washoff model provides the input to a monthly feed-back model (Herold, 1981b)as well as to the daily feed-back model described in this report. The primary purpose of the washoff model is to create long synthetic sequences of monthly salt concentrations associated with runoff and thereby to simulate fluctuations in the mass balances of water and salt in the major impoundments of the Vaal basin. Monthly values of salt concentration are adequate for this purpose because attenuation in the large volumes of storage is appreciable.

1.2.2 The monthly feed-back model

The monthly feed-back model (Herold, 1981b) is used to simulate average monthly salt concentrations at key points in the system. Basic inputs are projected demands for, say, the next two decades with a large number of possible hydrological sequences. Functions relating the salt concentrations in the water supply to the operation and maintenance costs to consumers in various sectors of the economy were derived by Heynike (1980) and these have been built into the model. Frequency distributions of monthly TDS concentrations at key points in the system at different time horizons, together with the associated annual running costs to consumers, can be used as the basis for comparing the effectiveness of various management and planning proposals aimed at improving the mineral quality of the water supply. The monthly feed-back model can, at relatively low cost, be used to test a number of options, so that the most favourable ones can be singled out for detailed analysis.

1.2.3 The daily catchment washoff model

The daily catchment washoff model (Herold, 1981a) simulates daily catchment runoffs and associated daily salt concentrations using meteorological data as the basic input. Provision is made for both surface and sub-surface storage, movements of water and salt across the catchment, channel routing and storage effects of the large reed swamps. This model is used to patch and extend flow and water quality records, where these are deficient, and to simulate daily runoffs and salt concentrations resulting from any sequence of historical rainfall and evaporation data for present-day and assumed future states of catchment development.

1.2.4 The daily feed-back model

The daily feed-back model, which is the subject of this report, is designed to simulate the day-to-day fluctuations of TDS concentration in the water supplied to users situated in various demand centres in the Vaal basin, particularly those in the southern PWV region, arising from any given hydrological sequence and set of assumed water demands and for a wide variety of planning and management options. In order to accomplish this it is necessary to simulate daily spillages from Vaal Dam (which must be in phase with the hydrological data used as input to the model for the PWV region). This in turn necessitates simulating the behaviour of upstream impoundments (Grootdraai and Sterkfontein dams) as well as the downstream Bloemhof Dam which, depending on the option being simulated and the assumed demand levels, may make calls on Vaal Dam. Water released from Vaal Dam radically alters the quality of water supplied from the Vaal Barrage to the PWV region. Provision is made for a proposed new dam at Schoemansdrift on the farm Welkom (see Fig. 1.1). Inputs to the dam simulation portion of the model comprise: modelled or observed daily runoffs (monthly runoffs in the case of the Bloemhof catchment which has not yet been studied in sufficient detail for daily runoffs), modelled monthly salt concentrations in catchment runoff (provided by the monthly washoff model), observed monthly rainfalls, mean monthly evaporations, physical characteristics of the reservoirs and projected demands.

The Vaal Barrage creates a long, narrow lake with headwaters extending nearly as far upstream as Vaal Dam. Plug-flow conditions prevail in this reach of the Vaal river, from which 64% of the total PWV demand is at present abstracted at nine different points. Water qualities at the various abstraction points differ markedly from one another and considerable temporal variations occur because of the fluctuations in the discharges from the major tributaries of the southern PWV region (the Klip and Suikerbosrand) and from Vaal Dam. Accordingly a cell-type level-pool model of the Barrage was developed by Joubert and Mileikowsky (Mileikowsky, 1980) to simulate daily salt concentrations. This model is incorporated in the daily feed-back model under discussion here. This model requires as basic external input a matrix of monthly demands at the nine abstraction points. Other inputs, such as Vaal Dam spillages, downstream water requirements and tributary inflows, are provided internally by the other models of the suite.

There is a marked variation in the quality (in terms of mineral content) of the water supplied to different demand centres in the PWV region. This is due to the characteristics of the distribution network which result in differing mixes of water delivered to each demand centre from the various abstraction points (each with different water quality). The mixing proportions for each demand centre have been carefully estimated and constitute part of the input to the feed-back element of the model which computes daily water supply salt concentrations using the cell salinities simulated by the Barrage model. Characteristic of each demand centre is a change in salt concentration resulting from usage. These changes are estimated from historical water quality data. Average values are used to compute salt concentrations in effluents discharged by the major users to various points in the southern PWV tributary system. These daily salt concentrations, together with effluent discharge quantities and mine pumpage rates with their salt concentrations (specified as part of the input to the model) are then fed into the tributary routing component of the model.

The purpose of the tributary routing model element is to route catchment washoffs (both water and salt) along with point discharges, through the tributaries draining the southern PWV catchment (i.e. the Vaal catchment between Vaal Dam and Vaal Barrage). The southern PWV tributaries have been discretized into 25 connected river reaches. Model input comprises daily runoffs and salt concentrations from each of the 12 southern PWV sub-catchments the behaviour of which had been simulated by the daily washoff model, daily point inputs to each river reach (i.e. outputs from the feed-back element), rainfall and evaporation data (also provided by the daily washoff model) and model parameters defining channel geometry, reed swamp areas, bed losses, irrigated areas and friction factors for each river reach.

Simulated daily tributary discharges and salt concentrations then provide input to the Barrage model element which in turn computes new cell salinities (which become input to the feed-back element for the next computational time step), Barrage spillages and/or calls on Vaal Dam (input to the dam simulation routine for the next time step).

Several changes to the system (such as redistribution of water demands, changes in the mixing proportions, increased storage in the distribution network, centralization of waste water treatment works, diversion from the catchment of mine pumpage and/or effluent discharges and introduction of a dam at the Welkom Dam site) can be incorporated in the model simply by changing the input data. Other options (such as desalination of sewage effluents, blending of water supplies so as to meet improved water quality objectives and pumping water back from Welkom Dam to meet demands in the PWV region) can be introduced by effecting minor changes to the program coding. More complex options (such as the building of holding dams on the Klip and Suikerbosrand tributaries to detain the highly saline first-flush at the start of the rainy season) would require the incorporation of new model elements. The tributary routing subroutine, however, is flexible enough to accept such elements without undue difficulty.

Chapter 2 describes the model structure while Chapter 3 gives the results of a test to verify the adequacy of the model. Model applications are demonstrated by way of an example in Chapter 4. Conclusions and recommendations follow in Chapter 5. Details of the data used in the simulations described in Chapters 3 and 4 are given in Appendix A. A comprehensive user manual is to be found in HRU report No. 5/81 (Herold, 1981c).

CHAPTER 2 MODEL STRUCTURE

2.1 Introduction

The model described in this report comprises four distinct components which have been amalgamated to run interactively. They are:

a) The Barrage model: This is essentially a one-dimensional cell-type representation of the Barrage reservoir. The structure of this model is described in detail in HRU Report No. 4/80 (Mileikowsky, 1980).

b) The tributary routing model: The purpose of this component is to account for the storage and movement of water and salt through a system of linked river channels (Herold, 1981a)

c) The dam simulation model: This model simulates the storage states of water and salt in the major reservoirs of the Vaal river basin.

d) The feed-back model: The feed-back model closes the cycle between the Barrage model and the tributary routing model.

Fig. 2.1 depicts the interaction of the model components. Starting storages of water and salt are first defined at all points in the system. For each day simulated the model computes spillages from all reservoirs upstream of Vaal Barrage (viz. Grootdraai, Sterkfontein and Vaal Dam) and calculates water requirements downstream of Vaal Barrage. Using salt concentrations at Vaal Barrage intake and in Vaal Dam the feed-back model computes concentrations of salt in point discharges to each river reach. This information is then transferred to the tributary routing model which routes catchment runoffs and point inputs through the tributaries of the southern PWV catchment. Modelled discharges and salt loads entering the Vaal Barrage are then fed into the Barrage model. The Barrage model uses Vaal Dam spillages, tributary inflows, downstream requirements and specified demands at each abstraction point to solve for Barrage cell salinities and Barrage releases. The dam simulation model is again activated, this time to solve for the storage states of reservoirs downstream of Vaal Barrage.

2.2

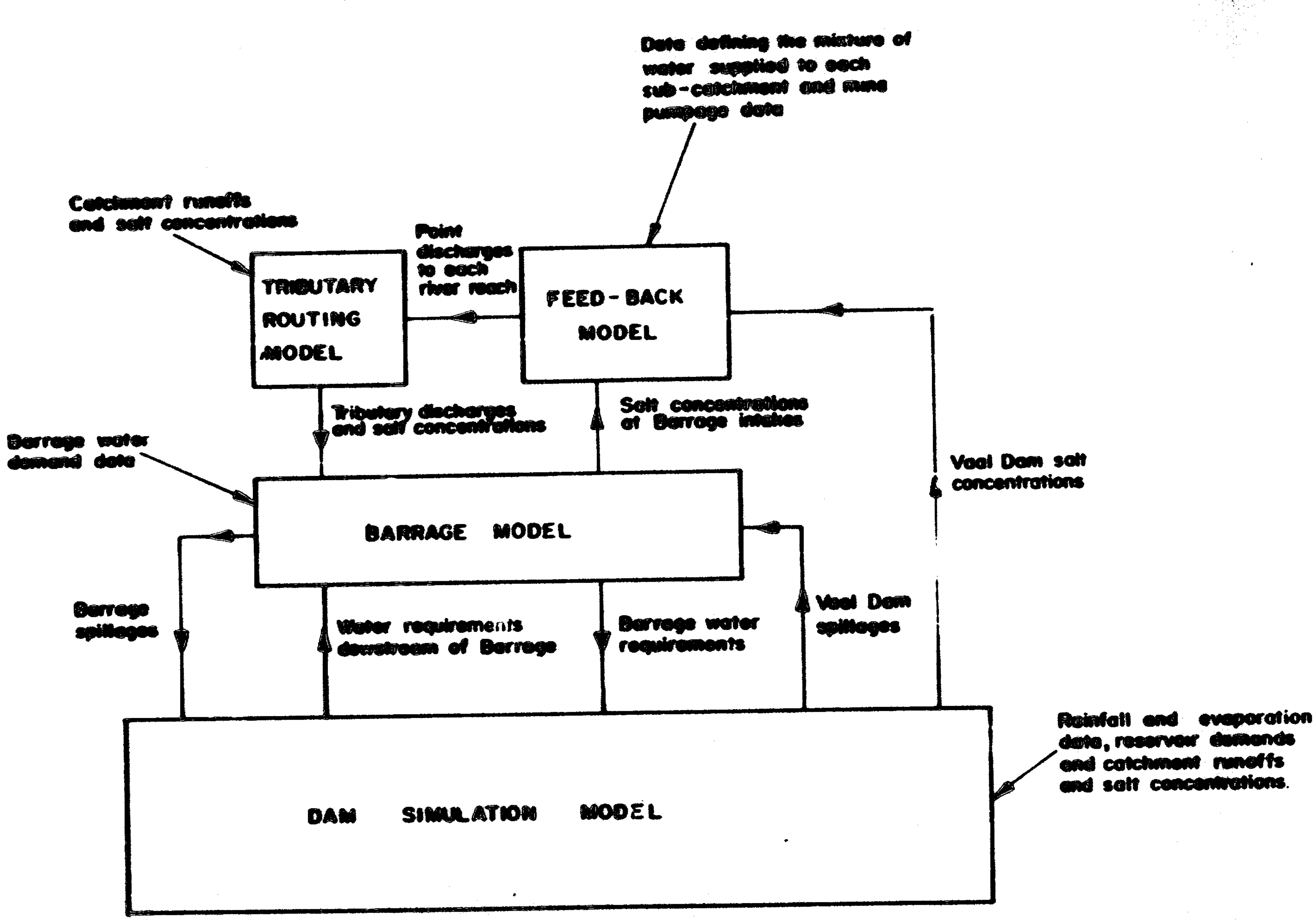

Fig.2.1: Interaction of the model components

The entire process is repeated for each day.

Sections 2.2 to 2.5 describe the structure of each of the four models.

2.2 The Barrage model

It is not the intention to give a detailed description of the model structure as this has been fully documented elsewhere (Mileikowsky, 1980). A brief description ought to suffice. Developed originally by Joubert and modified by Mileikowsky, the Barrage model is a one-dimensional level-pool representation of the Vaal Barrage reservoir.

The reservoir is approximately 50 km long, 200 m wide for most of its length and varies from 4m to 8m in depth. For the purposes of routing salt the reservoir was divided into 57 cells which are modelled as being completely mixed. The main mode of salt transfer between cells is by advection. Dispersion equations, however, have also been included in the model. Fig. 2.2 shows the locations of the nine Vaal Barrage abstraction points as well as the confluences of the four main tributaries draining the southern PWV catchment. Originally Joubert incorporated 131 cells, the object being to facilitate modelling of future possible changes to the system. Mileikowsky reduced the number to 57, and in fact showed that considerably fewer cells could be used without loss of accuracy (Mileikowsky, 1980).

2.3 The tributary routing model

Tributary routing is handled by introducing one or more interlinked channel reaches which are treated as linear reservoirs. Each reach is assumed to comprise a central channel as well as a flood plain. Discharges in the channel and through the flood plain are computed according to the Manning formula and provision is made for lateral flow between channel and flood plain. Each reach accepts at its head the outflow from up to three upstream reaches together with effluent point flows and part of the runoff from the catchment within which the reach is situated. The remainder of the catchment runoff enters the river reach laterally via the flood plain.

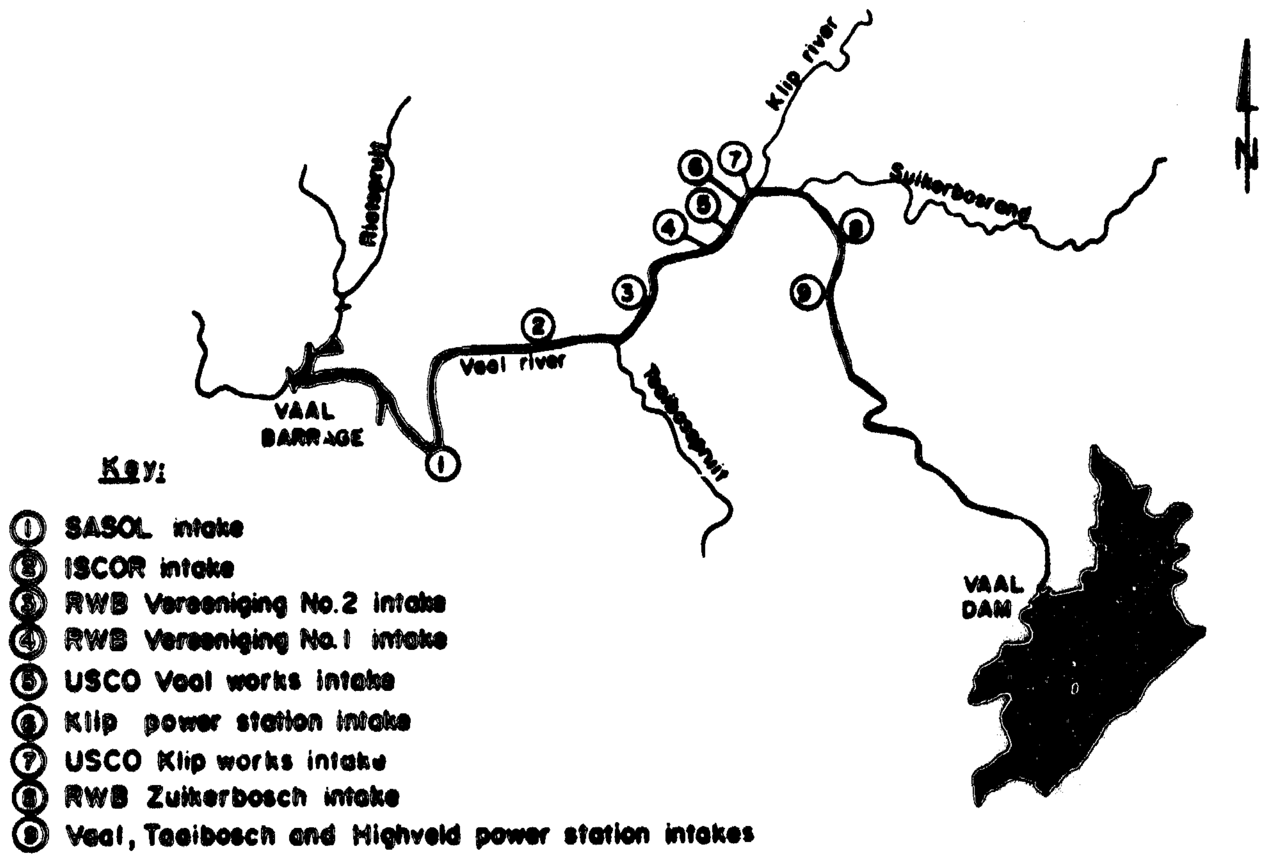

Fig.2.2: Location of Vaal Barrage abstraction points

That portion of the inflow which enters the upstream end of the channel section of the reach is aggregated to form a new cell. These cells are then advected through the reach. At the downstream end of the reach the cells are progressively destroyed, their contents then contributing towards the input to the following reach.

Lateral flows to and from the channel are fed into, or removed from, each cell in proportion to the cell volumes (i.e. the channel is assumed to be uniform in cross-section) Allowance is made for bed seepage losses, irrigation abstractions and return seepage, as well as evaporation from free water surfaces and evapotranspiration from reed beds.

A full description of the structure of this model is contained in HRU Report No. 3/81 (Herold, 1981a).

2.4 The dam simulation model

Fig. 1.1 shows the locations of the major impoundments of the Vaal system. Grootdraai, Sterkfontein, Vaal and Bloemhof dams are included in the dam simulation model. In addition to these provision is made for the inclusion of a new dam at Schoemansdrift on the farm Welkom (referred to hereafter as Welkom Dam). The dams subroutine can be by-passed entirely if so desired. In such event, boundary conditions for the Barrage model must be provided in the form of records of daily Vaal Dam releases and salt concentrations and daily Vaal Barrage discharges. The dam simulation model is usually by-passed when calibrating or verifying the catchment washoff model (Herold, 1981a) which in turn is used to simulate runoffs and associated salt washoffs from the sub-catchments of the southern PWV region. For most simulations, however, it is necessary to invoke the dam simulation model in order to ensure that the reservoirs (in particular Vaal Dam) spill in phase with the hydrology of the Barrage catchment for the given pattern of demand conditions being simulated. Fig. 4.5 of Chapter 4 clearly illustrates the drastic changes in Vaal Barrage salt concentrations brought about by imposing differing water demands on the system even though the hydrological inputs were unchanged.

The dam simulation subroutine is called twice for each day; first, for solution of the mass balance equations for Grootdraai, Sterkfontein and Vaal Dam in that order and then, after solution of the water and salt balance for Vaal Barrage (with subroutine SUBBAR) the dam simulation subroutine is again entered to solve the mass balances for Welkom Dam and Bloemhof Dam.

The water and salt mass balances for Grootdraai Dam are solved independently of the other reservoirs. Inputs to Grootdraai Dam comprise daily catchment runoffs (recorded flows at weir C1M01) as well as water transferred from the Usutu basin. Water transferred from the Usutu basin is assumed to have a constant salt concentration. The salt concentrations associated with catchment runoffs from the Vaal catchment upstream of Vaal Dam were computed on a monthly basis using the monthly washoff model (Herold, 1980 and Herold, 1981b). Average monthly salt concentrations were considered sufficiently accurate in view of the narrow range within which salt concentrations fluctuate (80 to 150 mg/l) and the attenuation effects of the large storage elements involved. The same modelled monthly salt concentrations were adopted for the Vaal Dam catchment upstream as downstream of Grootdraai Dam. The need to model daily discharges from Vaal Dam could not be avoided, however, because of the profound effect that spillages from Vaal Dam have on day-to-day salinities in the Vaal Barrage (from which most of the water supplied to the PWV region is currently abstracted). The timing of fresh water spillages from Vaal Dam in conjunction with runoffs from the polluted tributaries of the Vaal Barrage is therefore crucial to the accuracy of the modelling.

A daily mass balance at Grootdraai Dam was therefore also needed because spillages from Grootdraai form part of the input to Vaal Dam. Spillages are lagged four days to account for the time taken to flow to Vaal Dam.

The negligible runoff from the small Sterkfontein catchment has been ignored. The sole input (other than net rainfall) is therefore the water pumped from the Tugela basin. Pumping is assumed to continue after Sterkfontein is full, the spillage going downriver to Vaal Dam. Water is released only when Vaal Dam falls below the specified reserve level. A six-day lag is allowed from Sterkfontein Dam to Vaal Dam and allowance is made for transmission losses. (Transmission losses are not allowed for in routing water between Grootdraai and Vaal Dam, however, because these are already implicitly accounted for in downstream requirements specified in the Grootdraai Dam demand matrix). Any supply shortfalls experienced by Sterkfontein Dam are accumulated, recorded and assumed to be made good from an unspecified external source. Apart from calls by Vaal Dam, no other water demands are made on Sterkfontein Dam.

Vaal Dam has three primary sources of water, namely, spillages from Grootdraai Dam, spillages and releases from Sterkfontein

Dam and catchment runoffs. The daily catchment runoffs into Vaal Dam are supplied to the model in the form of observed discharges at the gauging weir C2M03 (immediately downstream of Vaal Dam) for the period prior to the commissioning of Vaal Dam. After the commissioning date, daily inflows were computed using a daily reverse mass balance for Vaal Dam. The record described above represents total Vaal Dam catchment runoffs with no dam at Grootdraai. (The dam was commissioned only in 1979). All simulations of the system behaviour for various planning and management strategies, however, have to take account of the presence of Grootdraai Dam and the catchment runoffs directly entering Vaal Dam must be derived only from that portion of the catchment downstream of Grootdraai. The model computes these inputs to Vaal Dam by subtracting suitably lagged observed daily discharges at C1M01 from calculated historical daily inflows to Vaal Dam.

Outflows from Vaal Dam (other than evaporation losses) comprise demands made directly on the dam plus spillages and calls made on Vaal Barrage.

Before returning to the main program, SUBDAM computes the water requirement between Vaal Barrage and Bloemhof Dam.

The spillages from Vaal Dam during the day being simulated, together with the current Vaal Dam salt concentration and the water requirement downstream of Vaal Barrage, are then passed to subroutine SUBBAR which computes spillages from Vaal Barrage and additional water requirements from Vaal Dam. The Barrage mass balance is simulated under the assumption that the additional water requirements from Vaal Dam are met on the same day that the call was made (at the current Vaal Dam salinity). The call is not deducted from Vaal Dam storage, however, until the following day has been simulated. This procedure obviates having again to call SUBDAM and re-adjust the Vaal Dam mass balances. This approximation is fully justified by the fact that the call which can be made on Vaal Dam during any single day, even under end-of-century demand conditions, is very much smaller than the reserve storage. A result of this assumption is that when Vaal Dam is drawn down to reserve storage the call on Sterkfontein Dam will be delayed by one day. There is in any event a six-day lag before the arrival of Sterkfontein releases and the Vaal Dam reserve storage has to be able to withstand this delay with a comfortable margin of safety. Recreational constraints, too, will probably dictate a minimum storage requirement of several million cubic metres.

The daily release from Vaal Barrage is then fed back into subroutine SUBDAM which solves the water and salt balance for Welkom Dam. (For options not envisaging a Welkom Dam, the storage capacity is set at an arbitrary small value.) The catchment between Vaal Barrage and Welkom Dam is small and for the purposes of modelling has been incorporated in the catchment downstream of the dam site. This assumption can be revised once a more detailed study of the Bloemhof catchment has been made.

Inputs to Welkom Dam comprise releases from Vaal Barrage and effluent return flows (provided by subroutine SUBFBK) from municipalities and industries discharging downstream of Vaal Barrage. Outflows comprise demands made directly on the dam plus spillages, releases made to satisfy downstream requirements and calls made by Bloemhof Dam.

The total release from Welkom Dam becomes the contents of a day-sized cell of water and salt released from Vaal Barrage. A seven-day time lag is allowed for each cell to reach Bloemhof Dam, i.e. the cells are assumed to move at a constant rate. This simplified assumption was adopted in view of the paucity of data available for the Bloemhof Dam catchment. In particular runoffs from the Bloemhof catchment are in the form of monthly volumes simulated using the Pitman monthly catchment model (Pitman, 1973, and Hydrological Research Unit, 1981). Salt concentrations associated with monthly runoffs were modelled using the monthly washoff model (Herold, 1980) with the assumption that the salt generation rate per unit of catchment area is the same as that calibrated for the Vaal Dam catchment. Both of these assumptions can be improved upon, but only after a comprehensive monitoring program has been embarked upon followed by detailed modelling of the Bloemhof Dam catchment. The accuracy of the assumption of a fixed 7-day lag is patently of little consequence when it is considered that average monthly catchment runoff volumes had to be used.

Daily modelling of water qualities abstracted from the Vaal river between Welkom and Bloemhof Dam is still desirable in order to provide an indication of likely salinity fluctuations caused by variations in the quantity and quality of the polluted water released from Vaal Barrage. Actual peak salt concentrations should be higher than those modelled for this river reach because of the artificial damping caused by the constant catchment runoffs used for each month.

Catchment runoffs are added to each cell in proportion to the cell volumes at the start of the day. Abstractions and river losses are then deducted from each cell in proportion to the new cell volumes (after adding runoffs).

Finally the water and mass balance of Bloemhof Dam is computed. Other than rainfall the only input is derived from the last cell in the river reach between Welkom and Bloemhof, the contents of which are emptied into the dam. (Each cell is composed of both spillages from Welkom Dam and catchment runoffs). Losses from the dam include evaporation, spillage and demands (including downstream requirements and transmission losses). If storage falls below the reserve level, a call is made on Welkom Dam.

A description of the equations controlling the water and salt mass balances follow.

2.4.1 Storage-area relationship

The storage-area relationship for each reservoir is defined by a table of surface areas corresponding to various storages. Surface areas for any given storage are interpolated linearly between the specified values. From Fig. 2.3 it can be seen that the surface area, A (km^2) for storage S ($m^3 \times 10^6$) is given by:

$$A = A_n + (A_{n+1} - A_n) \cdot \frac{(S - S_n)}{(S_{n+1} - S_n)} \quad \text{.......................(2.1)}$$

where A_n, A_{n+1}, S_n and S_{n+1} are defined in Fig. 2.3.

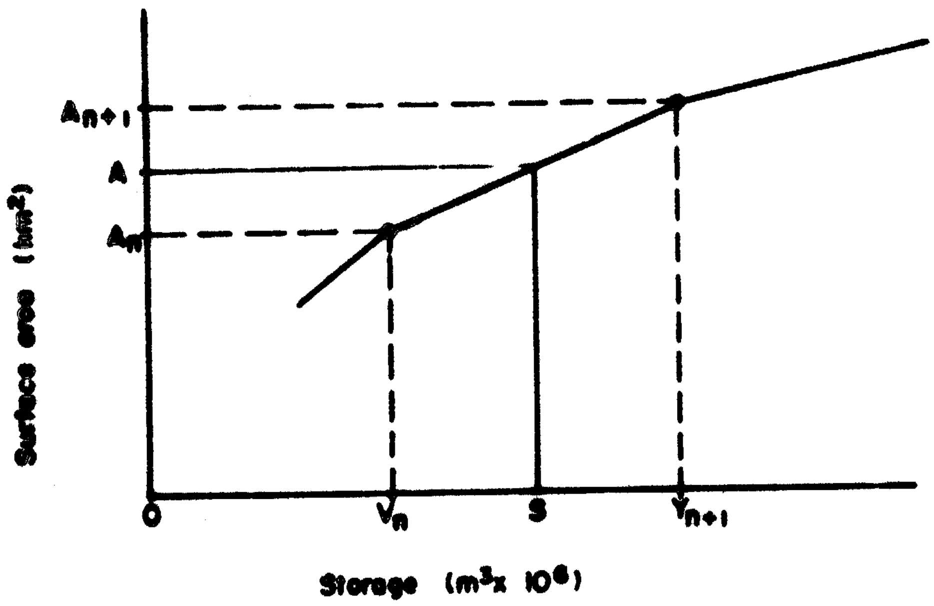

Fig. 2.3: Reservoir storage-area relationship.

2.4.2 Evaporation

The evaporation loss during any given day is very small compared with the total storage and consequently the change in surface area during the day has a negligible effect on the computed evaporations. The storage at the start of the day can therefore be substituted in equation 2.1 to obtain the surface area used to calculate evaporative loss.

The net evaporation, E ($m^3 x 10^6$), is given by:

$$E = (PE - R) \cdot \frac{A}{ND} \cdot 10^{-3} \quad \text{..............................(2.2)}$$

where PE = mean monthly potential lake evaporation (mm)

R = rainfall during current month (mm)

ND = number of days in curient month

2.4.3 Water demands

For each reservoir, annual demands (including downstream requirements) are read as input data and these are disaggregated according to a specified annual pattern. Demands are assumed constant during each month. Daily demands during each month, D ($m^3 x 10^6$), are thus given by:

$$D = PMONTH_i . \frac{DAMD_j}{ND.100} \quad \text{.......................... (2.3)}$$

where $PMONTH_i$ = mean monthly demand during month i as percentage of annual demand

$DAMD_j$ = annual demand for year j ($m^3 x 10^6$)

2.4.4 Water balance equations

The water balance for the day is given by:

$$S' = S + QUP + QCAT - E - D - CALLD \quad \text{............... (2.4)}$$

where S' = storage at end of day ($m^3 x 10^6$)

S = storage at start of day ($m^3 x 10^6$)

QUP = total spillage and releases (suitably lagged) from upstream reservoirs less transmission losses during day ($m^3 x 10^6$)

QCAT = catchment runoff during day ($m^3 x 10^6$)

CALLD = call made by downstream reservoir during previous day ($m^3 x 10^6$)

If S' calculated from equation 2.4 is greater than DAMCAP, the reservoir capacity, then the spillage from the reservoir, SPILL ($m^3 x 10^6$), is given by:

$$SPILL = S' - DAMCAP \quad \text{................................ (2.5)}$$

and S' is set equal to DAMCAP.

If S' as given by equation 2.4 is less than DAMRES, the reservoir reserve storage, then CALLU is given by:

$$CALLU = DAMRES - S' \quad \text{................................ (2.6)}$$

where CALLU is equal to CALLD for the next upstream reservoir. This call will be released from the upstream reservoir when the next day is simulated. After the release has been made CALLD is set equal to zero.

2.4.5 Reservoir salt mass balance

The salt mass balance is solved in two steps. First, inflows are added:

$$SS'' = SS + SUP + QCAT.CCAT \quad (2.7)$$

where
SS" = intermediate salt storage (t)
SS = salt storage at start of day (t)
SUP = salt load (suitably lagged) released from upstream reservoirs (t)
CCAT = salt concentration of catchment runoff (mg/l)

Next the losses are deducted:

$$SS' = SS'' - (D + CALLD + SPILL).DAMC \quad (2.8)$$

where
SS' = salt storage at end of day (t)
DAMC = salt concentration during day (mg/l)

$$= \frac{SS''}{S+QUP+QCAT-E} \quad (2.9)$$

Equations 2.8 and 2.9 imply that the contents of the reservoir are assumed to be completely mixed.

2.4.6 Water and salt balance equations for Vaal river between Welkom Dam and Bloemhof Dam

Water released from Welkom Dam is assumed to take 7 days to reach Bloemhof Dam. Routing is modelled as a train of cells moving at uniform rate. During each day a new cell, containing all water and salt released from Welkom Dam, is created at the upstream end of the reach, while one cell is removed from the downstream end of the reach, the contents of the destroyed cell being emptied into Bloemhof Dam.

The highly simplified assumption of discrete cells moving at uniform rate is justified by the coarse time step of the Bloemhof catchment runoff data that have to be used as input to the model. Once this catchment has been studied in greater detail it will be possible to use the tributary routing model (subroutine SUBTRI) to route both water and salt through this reach of the Vaal river with a greater degree of accuracy.

Catchment runoffs are added to each cell in proportion to its storage:

$$V_i'' = \frac{V_i}{VT} .QCAT + V_i \quad \text{.......(2.10)}$$

where V_i'' = intermediate storage of cell i (m^3x10^6)

V_i = storage of cell i at start of day (m^3x10^6)

VT = total storage in river reach at start of day (m^3x10^6)

$$= \sum_{i=1}^{7} V_i \quad \text{.......(2.11)}$$

The final cell storages are then computed by deducting water demands and transmission losses from each cell in proportion to its intermediate storage:

$$V_i' = \frac{V_i'' . D}{VT+QCAT} \quad \text{.......(2.12)}$$

where V_i' = cell storage at end of day (m^3x10^6)

D = demand and transmission loss between Welkom and Bloemhof Dam during day (m^3x10^6)

The salt balance equations are solved in a similar manner. The intermediate storage is given by:

$$SV_i'' = SV_i + \frac{V_i}{VT}.QCAT.CCAT \quad \text{.......(2.13)}$$

where SV_i'' = intermediate salt storage for cell i (t)

SV_i = salt storage of cell i at start of day (t)

Final cell salt storages are then given by:

$$SV_i' = SV_i'' = \frac{SV_i'' . D}{VT + QCAT} \quad \text{.......(2.14)}$$

where SV_i = salt storage of cell i at end of day (t)

The average salt concentration of water abstracted from the river during the day is given by:

$$CABS = \frac{1}{VT+QCAT} \cdot \sum_{i=1}^{7} SV_i'' \qquad (2.15)$$

where CABS = average salt concentration of water abstracted from the Vaal river between Welkom and Grootdraai dams (mg/l)

Inaccuracies in the method of routing the movement of salts released from Grootdraai and Sterkfontein dams are not critical as no significant abstractions are made direct from the Vaal and Wilge rivers upstream of Vaal Dam. (Daily fluctuations of salt concentration are therefore irrelevant). The timing (within a few days) of the arrival of salt loads at Vaal Dam is of little importance in view of the attenuation associated with the large storage volume.

2.5 The feed-back model

The function of the feed-back model (subrou FBK) is to compute, for each day simulated, the salt c ations of water supplied to each sub-region of the sc... PWV catchment and the salt concentrations of effluents discharged in each region. The equations controlling this subroutine are discussed below.

The tributaries of the southern PWV catchment have been divided into 25 river reaches for the purposes of routing water and salt through the system. These reaches are shown in Fig. 2.4. Each reach receives inputs of water and salt from upstream reaches plus effluent discharges, mine pumpages and runoffs from the adjacent sub-catchments. All of these inputs, with the exception of effluent discharges, are completely independent of water supply qualities. The salt concentrations of effluents discharged to stream are obviously related to the salt concentrations of water supplied to users. By making use of known pumping rates, the quality of water abstracted from the 9 Barrage abstraction points (see Fig. 2.2) and from Vaal

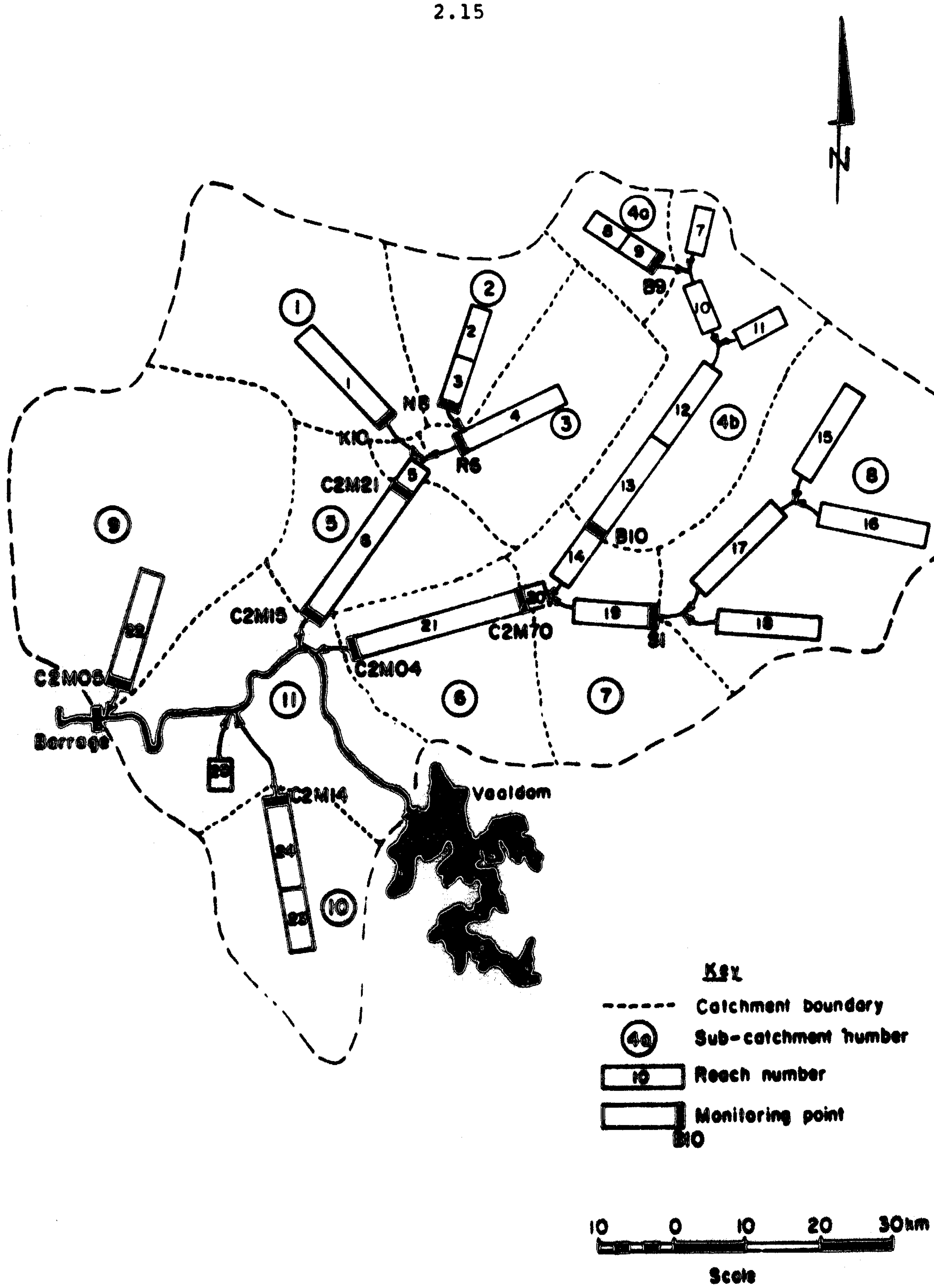

Fig.2.4 : Map showing tributary reaches.

Dam and known qualities of water delivered to various Rand Water Board supply regions (Rand Water Board, 1978), it has been possible to estimate the proportions of water from each abstraction point supplied to each of the major water users (see Fig. A.1 and lists in Appendix A). This information is fed into subroutine SUBFBK in the form of proportions of water from up to five Barrage cells (water from Vaal Dam is defined as cell number 0) specified for the aggregated water supply to all users discharging effluent return flow to each of the 25 river reaches.

Attenuation of water quality variations due to storage in the water supply network is accounted for by specifying a retention storage, RETEN (days), for each supply sub-region. (A supply sub-region is the one embracing all users that discharge effluent to a given river reach. The supply sub-regions bear the same numbers as the river reaches into which they drain. It should be noted that a supply sub-region need not be contiguous with its river reach.)

Usage of the water is assumed to raise the TDS concentration of the water returned by a constant amount, CADD (mg/l). This increase in TDS has been estimated for each of the major users and the flow-weighted mean for each supply sub-region has been calculated (see Appendix A).

The mass balance for salt stored in the supply network for each supply sub-region is given by:

$$SSTOR' = SSTOR + CSUP.Q - \left(\frac{SSTOR}{RETEN.Q}\right).Q \quad \ldots\ldots\ldots\ldots (2.16)$$

where

SSTOR' = salt storage in the network at the end of the day (t)

SSTOR = salt storage in the network at the start of the day (t)

CSUP = average salt concentration of water introduced to the supply network of the supply sub-region during the day (mg/l)

Q = water demand in the supply sub-region during the day ($m^3 x 10^6$)

CSUP is calculated as :

$$CSUP = \sum_{i=1}^{NCELL} PCELL_i . TDS_i \quad \text{.......................(2.17)}$$

where NCELL = number of Barrage cells contributing water to the supply sub-region

$PCELL_i$ = proportion of water derived from the ith contributing cell

TDS_i = salt concentration of i th Barrage cell during current day (as computed by sub-routine SUBBAR) (mg/l)

The salt concentration of water stored in the supply network at the end of the day, CSTOR' (mg/l), can be computed by dividing SSTOR' by the stored water volume, Q.RETEN. Hence from equation 2.16:

$$CSTOR' = CSTOR.(1 - \frac{1}{RETEN}) + CSUP.(\frac{1}{RETEN}) \quad \text{..........(2.18)}$$

where CSTOR = salt concentration of stored water at start of day (mg/l)

The salt concentration of the effluent return flow for the following day is then given by:

$$CRET' = CSTOR' + CADD \quad \text{.............................(2.19)}$$

From equations 2.18 and 2.19 we have:

$$CRET' = FAC1.CRET + FAC2.(CSUP + CADD) \quad \text{............(2.20)}$$

where $FAC1 = 1 - \frac{1}{RETEN}$

$FAC2 = \frac{1}{RETEN}$

For each year simulated the average annual effluent return flow rate, QRET (Ml/d), the average annual mine pumpage rate, QMINE (Ml/d) and the average mine pumpage salt concentration, CMINE (mg/l), are specified for each supply sub-region. The mine pumpage rates and mine water salt concentrations are assumed to remain constant throughout the year. Effluent return flow rates, however, are assumed to vary according to a seasonal pattern.

The total point discharge entering each river reach during each day simulated, QEFF (m^3x10^6), is therefore given by:

$$QEFF = (QRET.SEASON_j.10^{-2} + QMINE).10^{-3} \qquad (2.21)$$

where $SEASON_j$ = average effluent return flow during month j as a percentage of the annual average flow rate

The corresponding salt load entering the river reach, SEFF (t), is given by:

$$SEFF \quad RET.SEASON_j.CRET.10^{-2}+QMINE.CMINE).10^{-3} \qquad (2.22)$$

CHAPTER 3 MODEL VERIFICATION

Most of the model components have already been tested and verified in isolation and the results are available in previous reports. (The Barrage model was tested and the calibration parameter values optimized and verified by Mileikowsky (1980). The tributary routing component of the model is based on program NACLØ2 and has already been verified (Herold, 1981a).)

The reservoir simulation subroutine merely models the water and salt mass balances for each impoundment and as such has no model parameters that need to be calibrated. The mass balances have been checked manually for errors and the program routinely prints summaries of water and salt fluxes, thereby enabling a manual check to be made after every simulation, if so desired. The accuracy of the mass balances is dependent entirely on the accuracy of available input data.

The only remaining model component that has not previously been tested is the feed-back element which closes the water supply/effluent return flow/water supply cycle. Check calculations have, however, been made to ensure that this model component operates in accordance with the assumptions made (see section 2.5). The remainder of this chapter is devoted to a description of the tests made to verify the adequacy of these assumptions.

In HRU Report 3/81 (Herold, 1981a) the daily catchment washoff model was calibrated for each of the 12 sub-catchments of the southern PWV region (see Fig. 3.1) for the period September 1977 to August 1978. On the basis of the calibrated parameters and the relationship established between the calibrated diffuse source salt generation rates and industrial water demands, it was possible to model daily catchment runoffs and salt concentrations for the period September 1973 to August 1979. Output from NACLØ1 (the daily washoff model) together with observed point discharges provided the inputs to the tributary routing model (program NACLØ2). Output from NACLØ2 in turn

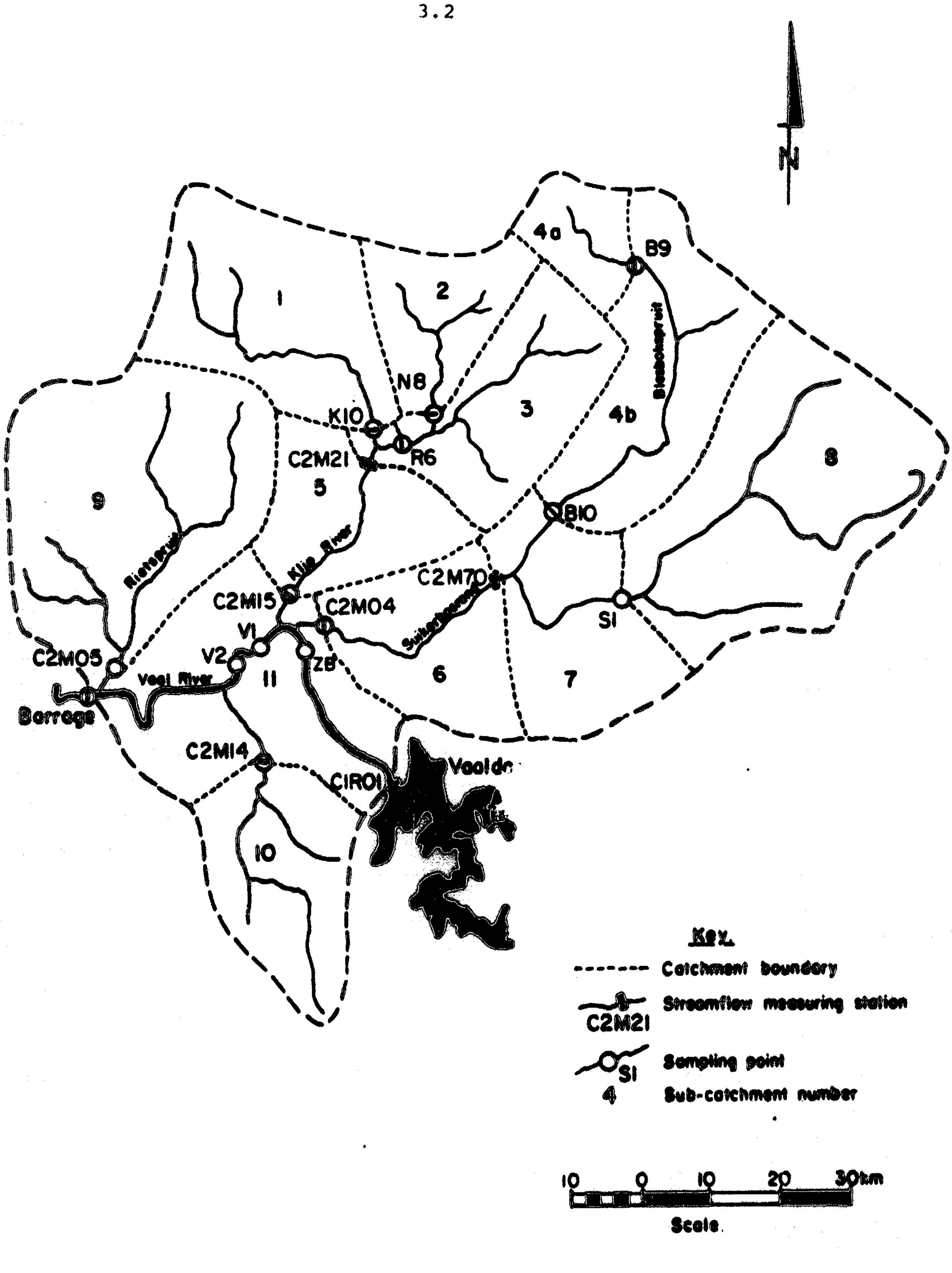

Fig 3.1: Map showing sub-catchments and monitoring points.

provided input to the Barrage model (Mileikowsky, 1980) which, using observed monthly abstraction data and observed daily Vaal Dam releases, simulated daily salt concentrations in each Barrage cell plus daily discharges and salt loads at the Barrage outlet. The acceptable fit between modelled and observed daily salt concentrations (at four points in the Barrage, including the Barrage outlet) and discharges (at the Barrage wall) served to verify the parameter values (calibrated for the year 1977/78) used in program NACLØ1 for each sub-catchment and also served to verify the adequacy of all three models involved (NACLØ1, NACLØ2 and the Barrage model) as well as the hypothesized relationship between industrial water demands and diffuse source salt generation.

The operation described in this chapter goes one step further than the foregoing and now also verifies the water quality feed-back element. Program NACLØ9, the combined daily PWV model described in this report, was used to simulate daily discharges and salt concentrations throughout the system for the six hydrological years 1973/74 to 1978/79. (The South African hydrological year is 1 October to 30 September). In this simulation daily effluent return flow water qualities were computed internally, based on simulated Vaal Dam and Vaal Barrage cell salinities.

Modelled and observed daily salt concentrations at the three RWB Vaal Barrage intakes (Zuikerbosch, Vereeniging No. 1 and Vereeniging No. 2 intakes, corresponding to abstraction points 8, 4 and 3 of Fig. 2.2) and at the Barrage wall were compared, as also were modelled and observed daily water and salt releases from the Barrage. These are plotted in Figs. 3.2 to 3.7 and statistical comparisons are made in Table 3.1. Parameters E_1, E_2, r and N of Table 3.1 are used to denote percentage error between modelled and observed daily values, percentage error between the standard deviations of modelled and observed daily values, correlation coefficient and sample size respectively.

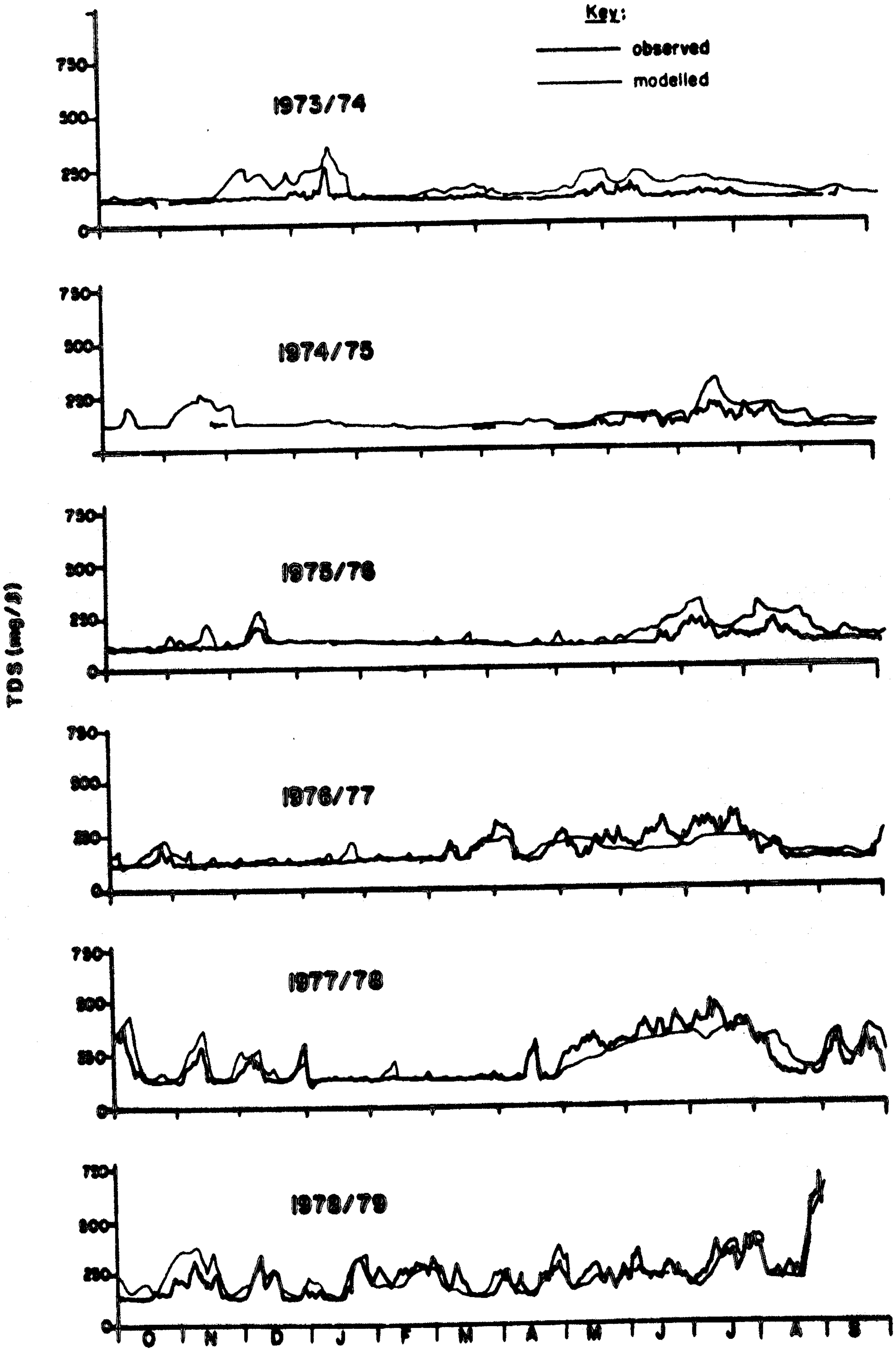

Fig.3.2 : Modelled and observed daily salt concentrations of RWB Zuurberg intakes

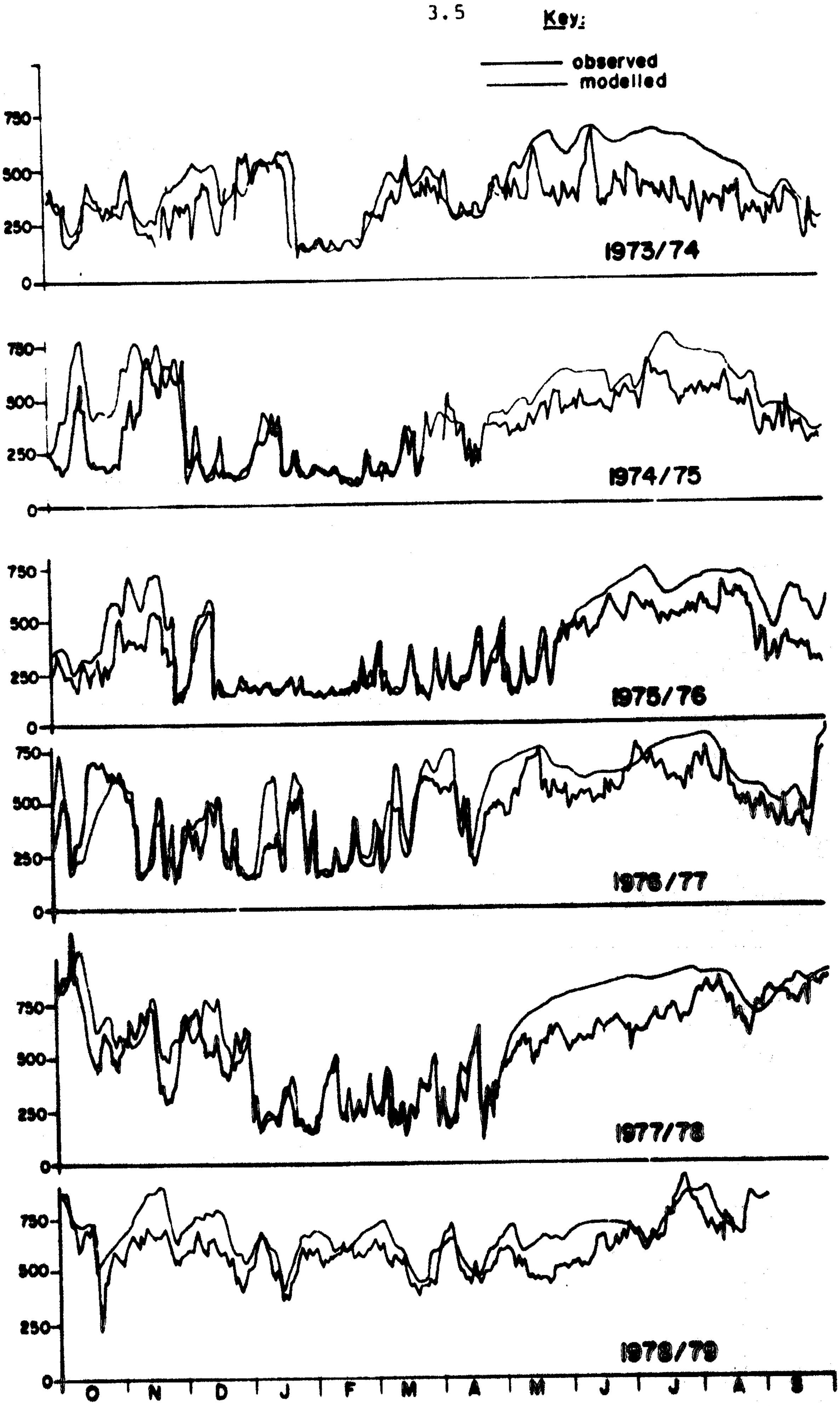

Fig.3.3. Modelled and observed daily salt concentrations at RWB Vereeniging no.1 intakes

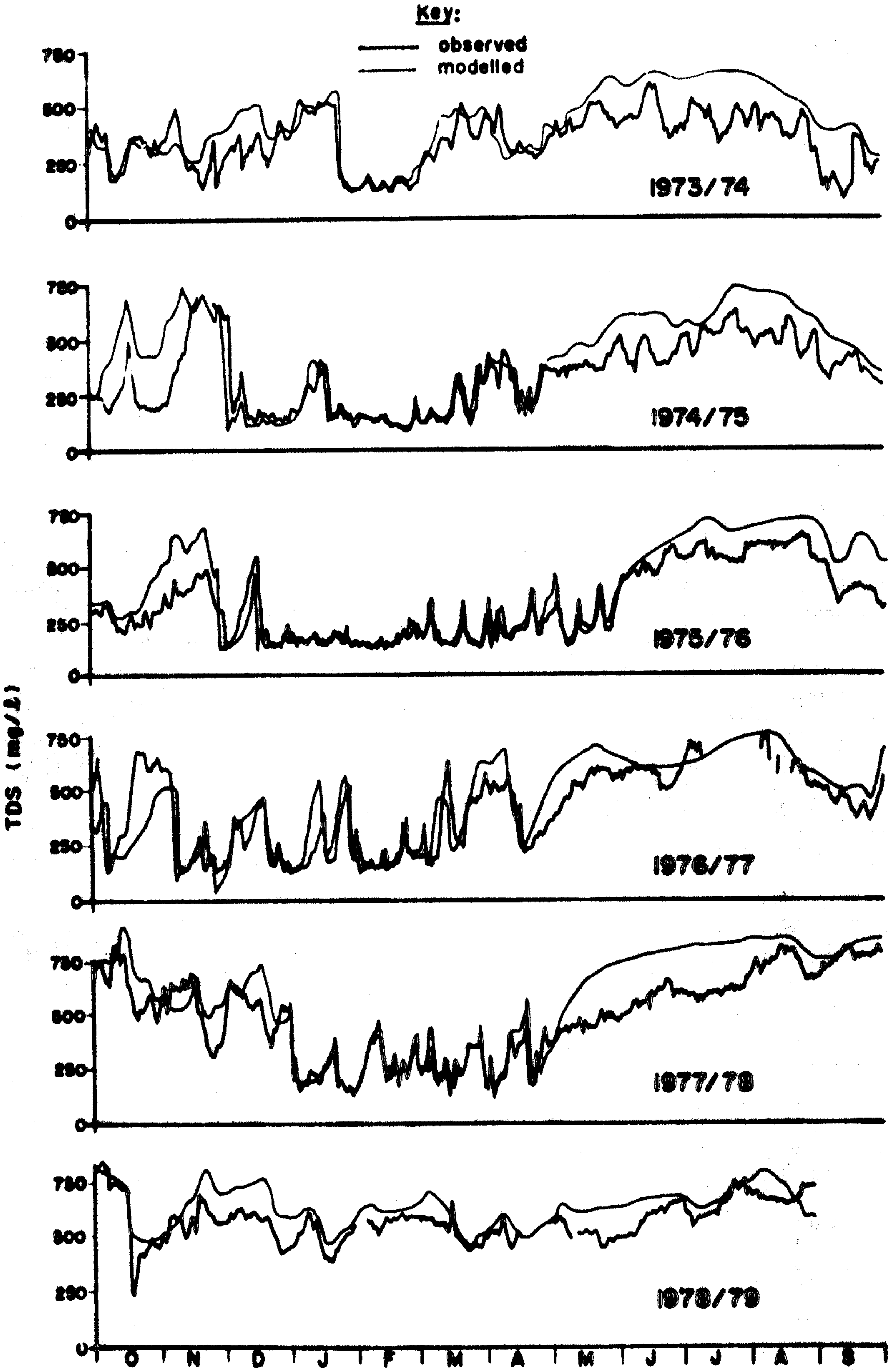

Fig.3.4: Modelled and observed daily salt concentrations at RWB Vereeniging No.2 intake

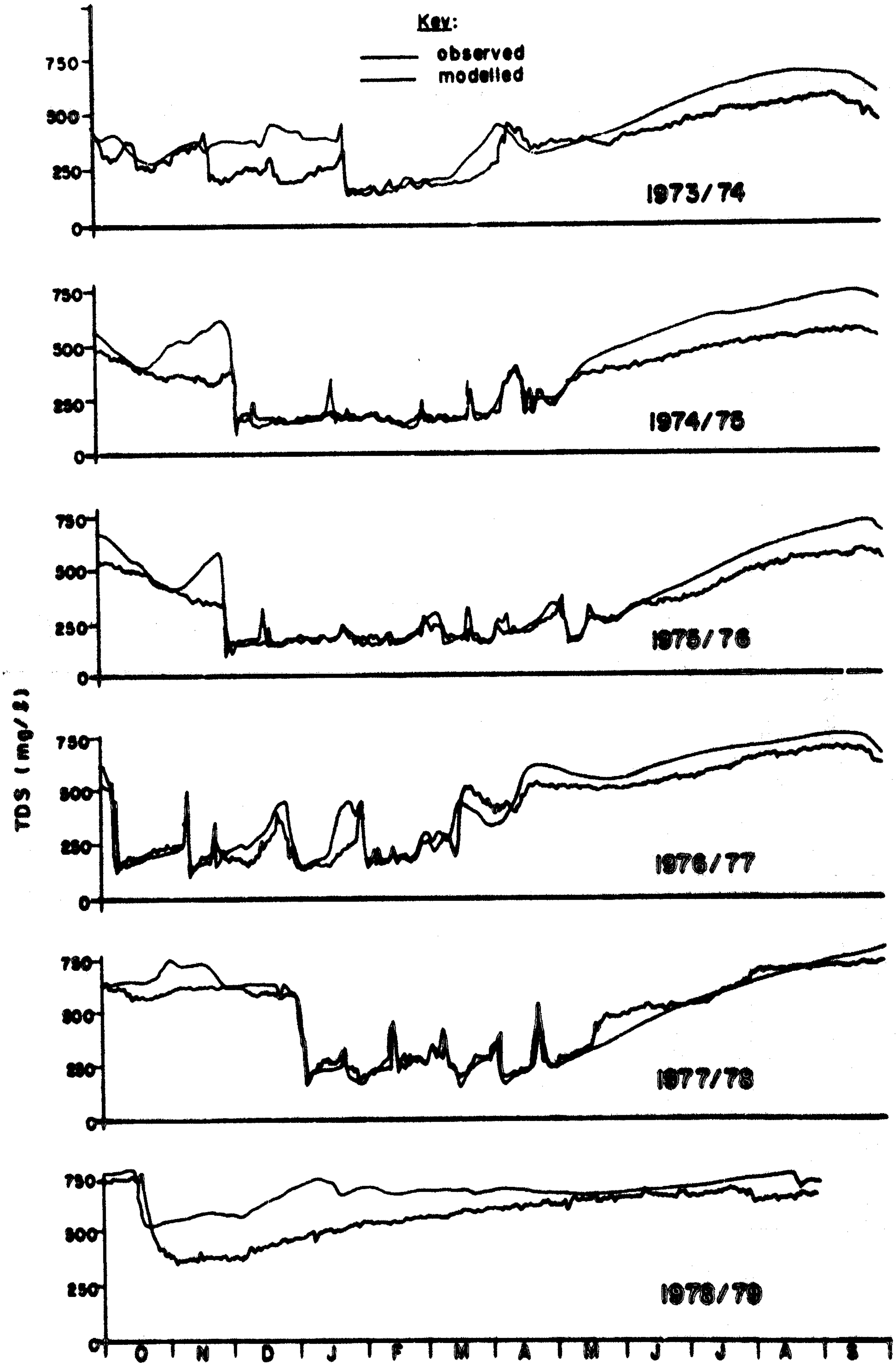

Fig.3.5: Modelled and observed daily salt concentrations at Barrage outlet

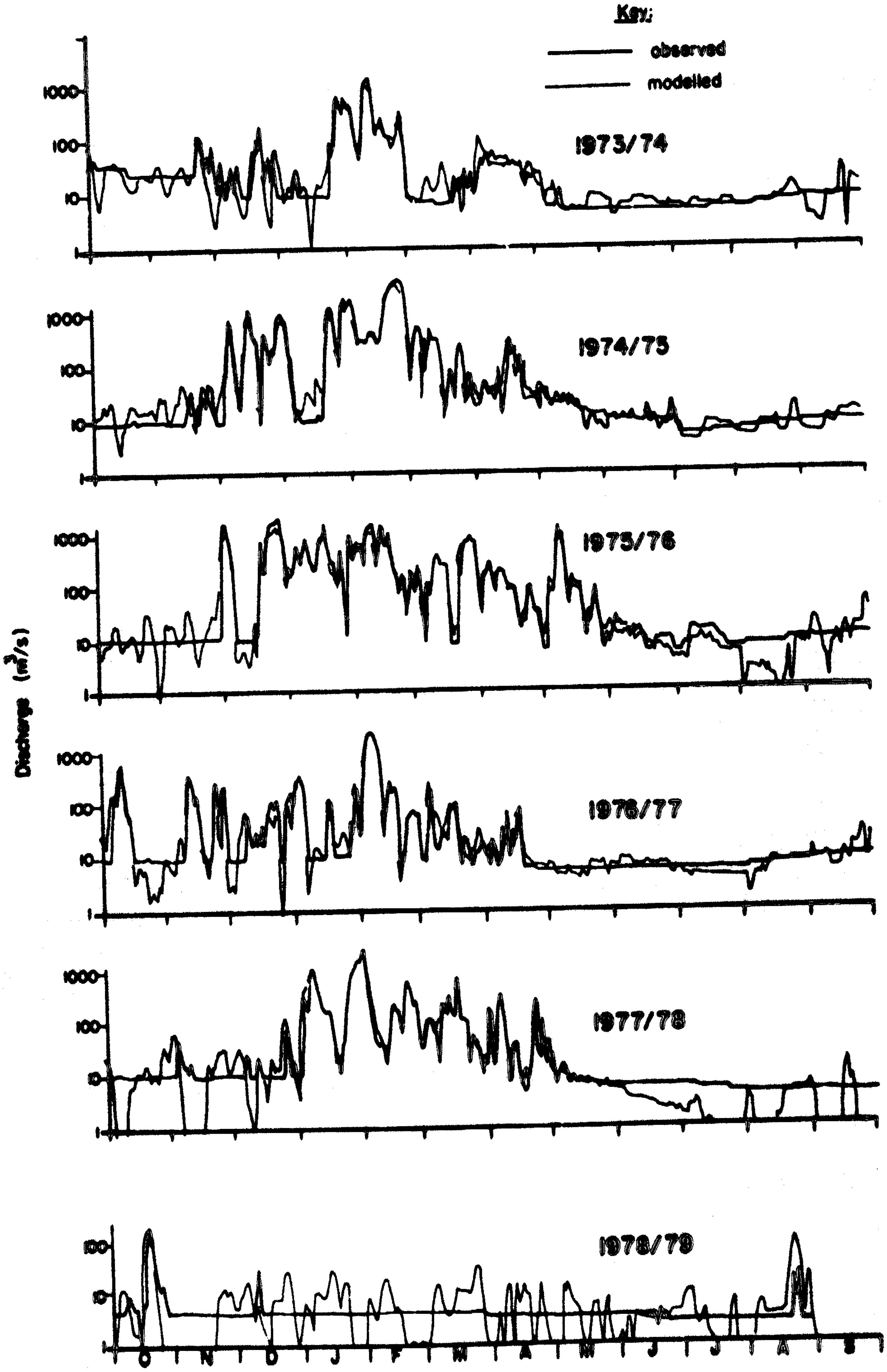

Fig.3.8 : Modelled and observed daily discharges from Vaal Barrage

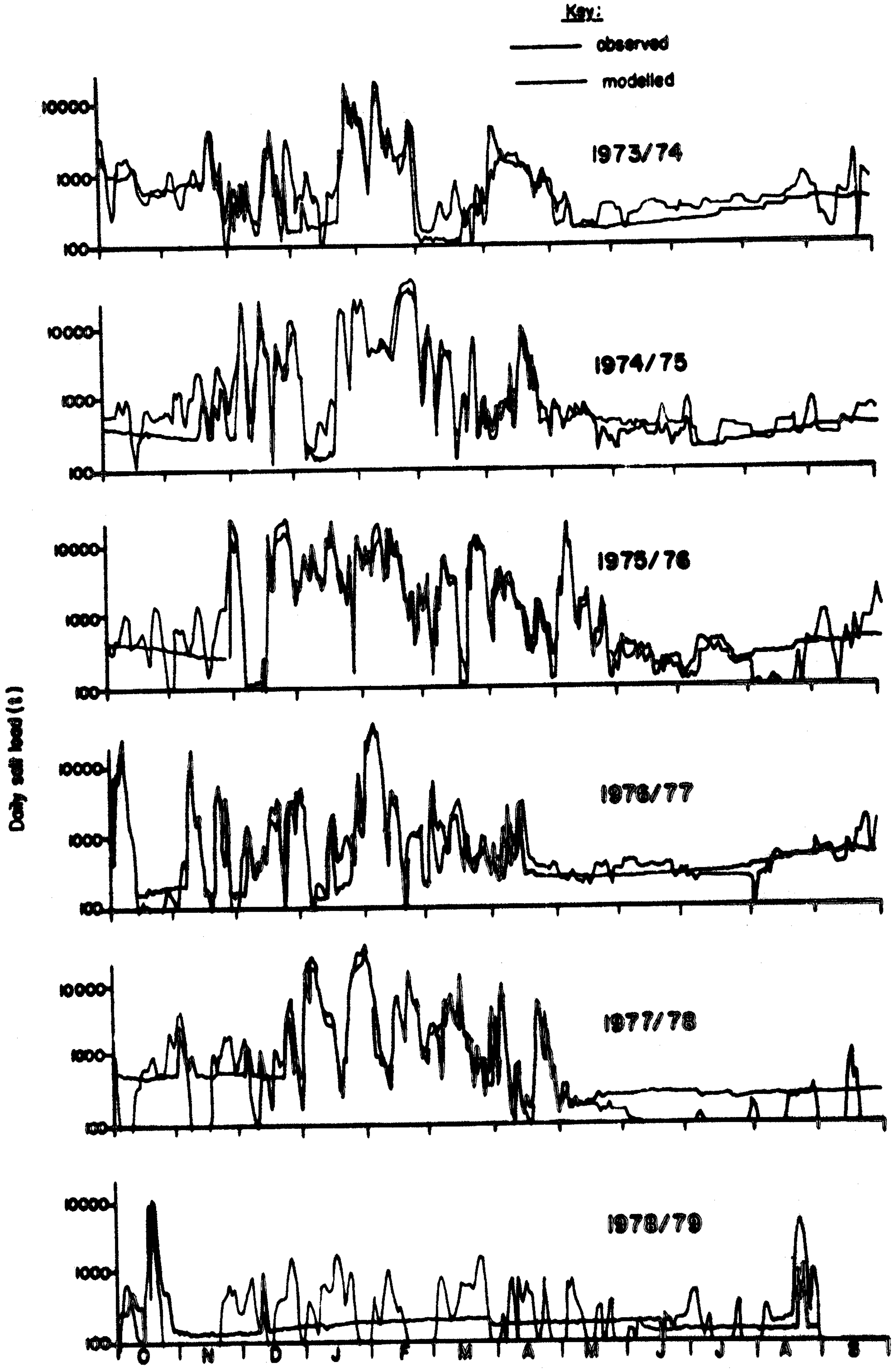

Fig.3.7: Modelled and o' . .rved daily salt loads discharged from .'3ai 3arr : ve

Table 3.1 Modelled and observed daily salt concentrations, salt loads and discharges at key points in the Vaal Barrage: 1973/74 - 1978/79

Location	Parameter	Units	Observed		Modelled		E_1	E_2	r	N
			mean	standard deviation	mean	standard deviation				
Zuikerbosch	TDS	mg/l	166,4	75,2	182,5	70,0	9,7	-6,9	0,805	1949
Vereeniging no. 1	TDS	mg/l	434,4	186,8	501,9	218,0	15,5	16,7	0,873	2132
Vereeniging no. 2	TDS	mg/l	410,9	180,0	476,4	211,3	15,9	17,4	0,886	2105
Barrage wall	discharge	m^3/s	102,6	335,4	97,2	297,0	-5,3	-11,4	0,986	2160
	TDS	mg/l	411,9	177,2	456,9	204,2	10,9	15,2	0,933	2158
	TDS	t/d	1808	4818	1724	3942	-4,6	-18,2	0,945	2157

Table 3.1 and Fig. 3.6 indicate a reasonably good fit between modelled and observed daily discharges. The error in the modelled mean of -5,3 percent is well within the accuracy with which the flow control structures can be rated. It should be noted that the rainfall-runoff parameters of the daily washoff model, program NACLØ1, were calibrated for each subcatchment for the period September 1970 to August 1978 with an error in the modelled mean of -1,1 per cent (Herold, 1981a). Due to variations in rainfall intensity during each day simulated (the catchment washoff model uses daily rainfall totals as basic input), and in the small errors of estimation of observed discharges from Vaal Dam and Vaal Barrage during large floods, it is possible for the error between modelled and observed values to fluctuate from year to year.

Base flows during the 1977/78 and 1978/79 hydrological years are not well represented (see Fig. 3.6). The logarithmic scale makes the fit appear poorer than it actually is and furthermore Fig. 3.6 does not reflect the Barrage abstractions, which averaged 16,5 m^3/s during the 1978/79 season. For example, if the abstraction of 16,5 m^3/s is added to both the modelled and

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Fig. 3.8 shows that the modelled seasonal distribution of monthly discharges is in fact in very close agreement with that observed. If the Barrage abstractions are taken into account, then the percentage error between the modelled and observed mean July discharges of -21,3% falls to only -6,3%.

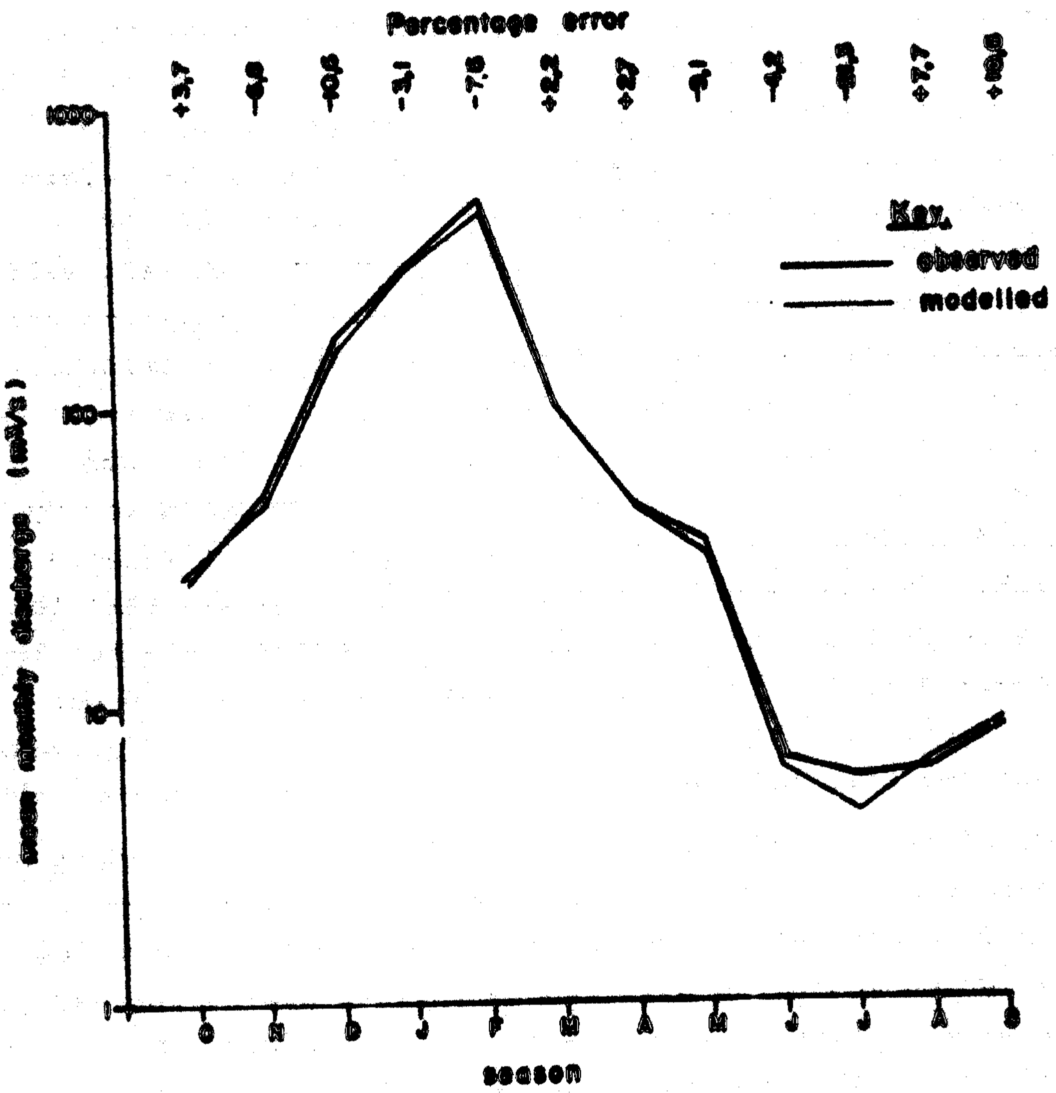

Fig.3.8: Comparison between modelled and observed mean monthly discharges of Barrage wall.

From Fig. 3.6 it can be seen that the observed daily discharges are much smoother than those modelled. This is because the Barrage storage level was assumed to be kept constant, whereas in fact significant fluctuations of level do occur. The fit between modelled and observed values during 1978/79 is not as poor as is indicated by Fig. 3.6. (The log scale accentuates errors during small runoff events). For example, the error between modelled and observed mean discharges (taking account of Barrage abstractions) during the 1978/79 hydrological year is only 10,3% and the corresponding error between modelled and observed standard deviations 15,6%.

Figs. 3.2 to 3.5 and Table 3.1 show a satisfactory fit between modelled and observed daily salt concentrations, particularly during the wet season. During the drier months, however, there is a tendency for salt concentrations downstream of the infalls of the Klip and Suikerbosrand rivers to be over-estimated while those at the Zuikerbosch intakes are under-estimated. This is due in part to the inability of the Barrage model adequately to mimic the mechanism whereby salts move upstream from the Klip and Suikerbosrand infalls to the Zuikerbosch intakes under conditions of stable low tributary discharge and reduced releases from Vaal Dam. Under such conditions stratification occurs, resulting in increased upstream advection (Mileikowsky, 1980) not accounted for by the one-dimensional cell-type model. This is particularly noticeable in the 1976/77 and 1977/78 hydrological years for which modelled salt concentrations at Zuikerbosch are too low. The modelled salt loads passing downstream of the Klip and Suikerbosrand are therefore higher than those observed because the modelled salt load abstracted at Zuikerbosch was too high.

Records of salt concentrations of water pumped from underground workings by mines in the southern PWV catchment are sparse and in most instances had to be estimated on the basis of a few grab samples which indicated salt concentrations during the early 1970's of the order of 10 000 mg/l. It has since come to the author's attention, however, that some of the ions present in the underground water become insoluble when oxidised and precipitate out soon after being discharged to the tributaries of the PWV region. (This is not applicable under present-day conditions as the major mines have since installed treatment works with aeration and lime-slaking plants which oxidise ions such as Fe_2 and raise the pH of the acid underground water before discharge. In the case of the ERPM gold mine the treatment processes reduced the TDS of shaft water from 8200 mg/l to 5800 mg/l during 1976/77. It is therefore likely that natural processes in the tributaries had a similar effect on salt concentrations prior to the commissioning of the treatment works). Moreover the mine pumpage rates for the earlier years were based on estimates made by Clausen (1976) which in turn were based on records of electrical energy consumption. There is evidence, however, that these estimates could have been too high (Herold, 1981a).

It is therefore probable that the so-called observed salt loads discharged by the mines during the earlier years are too high. The predominance of mine pumpage (which is most likely over-estimated) during this period (when more mines were operative and domestic effluent discharges relatively smaller) is therefore likely to result in modelled salt concentrations that are too high during the drier winter months.

The runoff from the southern PWV catchment during November 1978 simulated by the catchment washoff model (program NACLØ1) was slightly low (see Fig. 3.6) and as a result the Barrage salt concentrations are not sufficiently diluted (see Figs. 3.3 to 3.5). The modelled salt concentrations at the Barrage wall require several months to recover to the correct value because the discharges at the Barrage outlet during the exceptionally dry 1978/79 season are small compared with the residual Barrage storage.

Fig. 3.7 and Table 3.1 indicate good agreement between modelled and observed daily salt loads passing through the Barrage sluices. This is especially significant in view of the fact that more than 60% of the salt load entering Vaal Barrage during the six-year period simulated emanated from the southern PWV region (of which 47% originated from diffuse sources, 27%

from effluent discharges and 26% from mine shaft water). Hence 44,4% of the salt load represented in Fig. 3.7 has been simulated by the suite of models (the remaining 55,6% comprising observed discharges from Vaal Dam and from the mines). It is clear therefore that the fit obtained between simulated and observed daily salt loads is highly satisfactory. As with daily Barrage discharges the logarithmic scale and the large Barrage abstractions tend to bias the plotted results for daily salt loads during low flow conditions (Fig. 3.7). The fit between modelled and observed total daily outflows of salt from the Barrage (as opposed to outflows only via the Barrage sluices, plotted in Fig. 3.7) is again much better. For example, in July 1978 the error between modelled and observed mean monthly salt loads released from the Barrage sluices is -74% whereas the error in total Barrage salt outflows (including abstractions) is of the order of -18%. (This value could not be accurately estimated as water quality data are not readily available for all of the privately-owned Barrage abstraction points).

The accuracy of the modelled output is not significantly different from that obtained when observed effluent discharge water qualities were used (Herold, 1981a). It is therefore concluded that the assumptions made in the feed-back element of the model (subroutine SUBFBK) are satisfactory.

CHAPTER 4 MODEL APPLICATIONS

4.1 Philosophy

The daily feed-back model described in this report is designed to be used in conjunction with the monthly feed-back model described in HRU report 4/81 (Herold, 1981b). HRU 4/81 outlines in some detail how the two models can be used to complement one another.

In brief, the procedure is as follows: The monthly model is used to simulate average monthly salt concentrations of water supplied to the larger demand centres of the system using projected demands and salt generation rates for, say, the next twenty years with several 20-year hydrological sequences as basic input. For each hydrological sequence simulated the monthly model computes the equivalent present-value annual running costs to users , i.e. the costs attributable to high TDS in the water supply.

From the annual costs computed for each hydrological sequence simulated, a frequency distribution of annual running costs can be constructed from which the most likely running cost (as well as the extremes) associated with the option being tested can be identified.

The frequency distribution of daily TDS levels likely to arise is, however, also of importance. In particular the design capacity (and hence the capital cost) of industrial water purification plant is generally determined by the peak TDS concentration likely to occur. The monthly model is obviously incapable of modelling daily fluctuations of TDS concentration. One is obliged to fall back on the daily feed-back model.

There are two possible approaches to the use of the daily model. In the first instance, the daily model could be used in an identical manner to that just described for the monthly model, the only difference being that the system is disaggregated into much smaller components which are modelled more accurately at daily time-step. The drawback to this approach, however, is that the daily model is very much more expensive to run than is the monthly model and the data requirements are far more exhaustive. It would be extremely wasteful to run the daily model for several 20-year sequences. A more economical approach is therefore recommended whereby the daily model is run for, say, 10 carefully selected different one-year hydrological sequences and for a few selected demand horizons. For instance, the 1980 demand horizon might be simulated using hydrological input corresponding to the years 1933, 1938, 1943,.... 1978. Starting conditions in each of the reservoirs for each of the ten simulations would correspond to actual conditions observed as at the beginning of the 1980 hydrological year. Ten duration curves of daily TDS concentration could then be constructed for each point of interest in the system for 1980 (present-day)conditions. Each exceedance level on the duration curve will then have associated with it a frequency distribution. Fig. 4.1 illustrates how the most likely duration curve of daily TDS concentration at some point in the system could be constructed for a given demand horizon. Confidence limits can also be calculated if so desired.

For each point of interest in the system similar duration curves can be constructed for other demand horizons using the same ten hydrological sequences as input data. It is not necessary to use the daily model to simulate the years between the selected demand horizons, however, as the monthly model can be used to provide starting conditions in the major impoundments. For instance, should duration curves be desired for the demand year 1990 with hydrological input for the year 1933, the monthly model can be run for the hydrological years 1923 to 1932, corresponding to projected demands and salt generation rates for the period 1980 to 1989 with starting reservoir storages and salt concentrations as at the beginning of 1980.

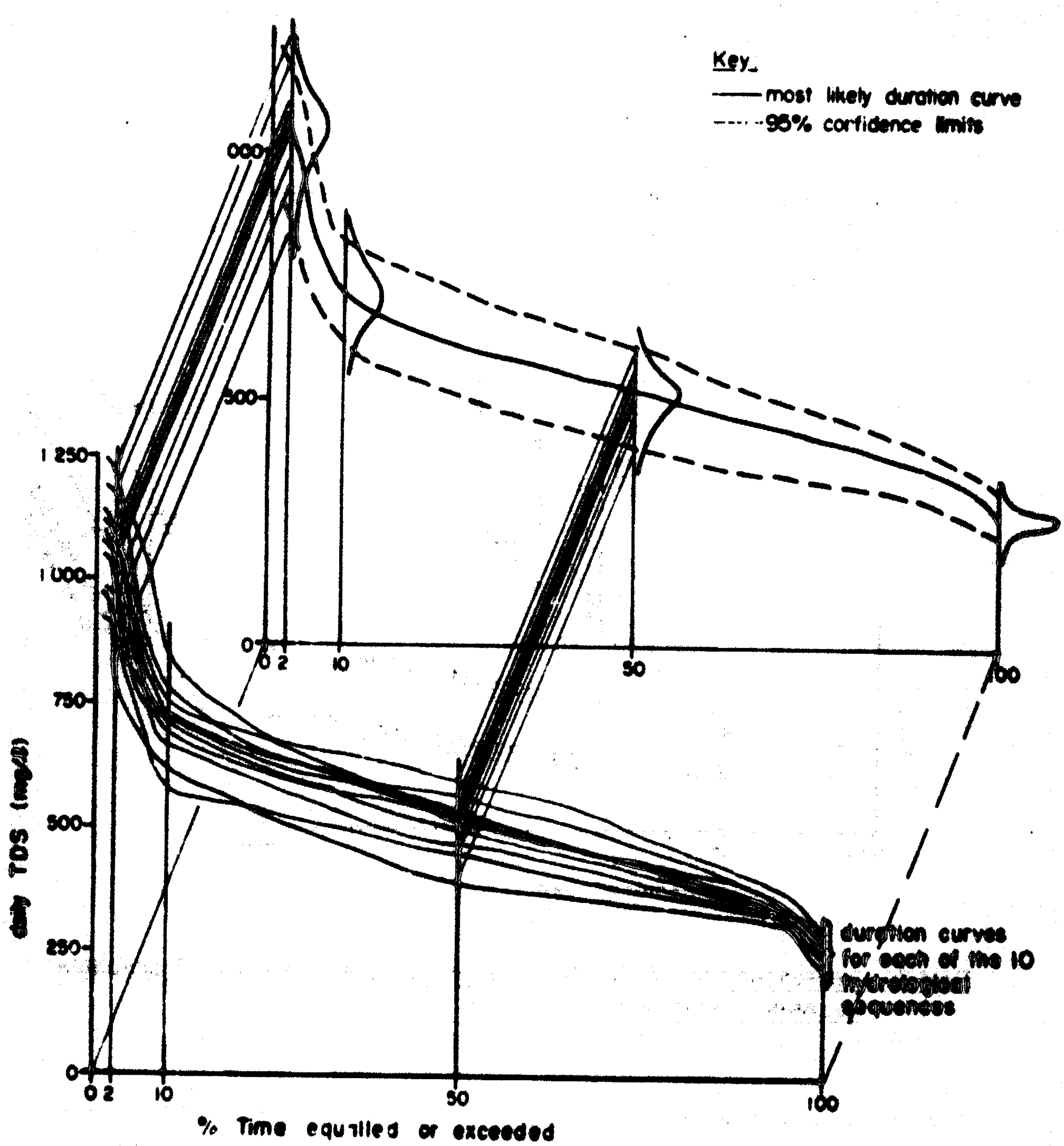

Fig.4.1: Illustration of how the most likely exceedance levels and confidence limits can be established

The daily model is then run for the hydrological year 1933 (corresponding to demand year 1990). Starting reservoir storages and salt concentrations are set equal to those simulated by the monthly model at the end of 1932. A similar procedure is adopted for the remaining nine simulations using hydrological input for the years 1938, 1943, 1958, ... 1978.

If the daily model has been used to construct representative duration curves for, say, demand years 1980, 1990 and 2000, then the exceedance levels most likely to arise in the intervening years can be interpolated to yield curves similar to those in Fig. 4.2 for each key point in the system.

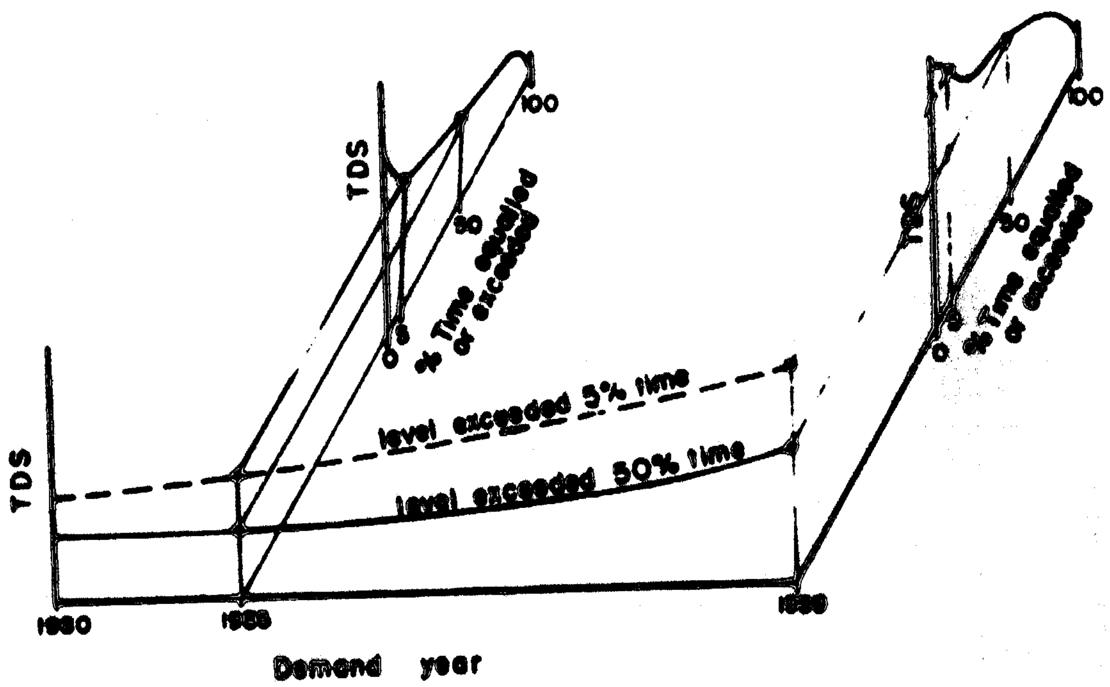

Fig.4.2: Representation of duration curves as a time series of probable exceedance levels

The method suggested in Chapter 3 of HRU Report 4/81 (Herold, 1981b) can then be used to estimate the capital investment in water treatment plant required in each water supply sub-region during the period 1980 to 2000.

The entire procedure outlined above is repeated for each option to provide estimates of the total annual costs to users. Implementation costs can then be estimated for the more promising of the options and benefit-cost analyses can be performed to permit objective comparisons to be drawn.

Once a planning option has been chosen, the model can be used in the design stage to optimize the sizing of proposed structures and can also be used to establish the optimum operating rules to be adopted. Finally, curves such as those in Fig. 4.2 can be constructed for each user sub-region. These can be distributed to industrialists and other interested parties to assist them in their forward planning. (If this is not done, industrialists will probably continue to base their plant designs on present-day frequency distributions and much of the benefit resulting from improved water quality will be lost).

4.2 Demonstration of model use

In order to demonstrate applications of the model, daily salinities in the various impoundments were simulated for demand horizons 1980, 1990 and 2000, using hydrology for the year October 1933 through September 1934. The status quo option (i.e. option no. 1 of HRU Report 4/81) was assumed to hold for each instance. Table 4.1 shows the adopted starting reservoir storages and salt concentrations.

Table 4.1 Initial reservoir storages and salt concentrations

Reservoir	Initial storage ($m^3 x10^6$)			Initial TDS (mg/l)		
	1980	1990	2000	1980	1990	2000
Sterkfontein Dam	508	2600	1666	70	76	77
Grootdraai Dam	108	257	71	100	121	115
Vaal Dam	1782	600	300	130	135	79
Welkom Dam*	5	5	5	500	869	871
Bloemhof Dam	631	366	284	300	575	611

* Welkom Dam does not exist in this simulation. The storage capacity has therefore been set at an arbitrary small value of $5x10^6 m^3$ and the TDS values are those in the river at the dam site.

A one-month running-in period was allowed, to damp out errors in the assumed starting salinities in Vaal Barrage. (This was necessary because the monthly model cannot provide starting salt concentrations in each of the 57 Barrage cells. A running-in period, lasting one month, has been found to be adequate for warming up the model). The starting values given in Table 4.1 therefore apply to the starting date of the warming-up period (corresponding to the hydrological date 31 August 1933). Simulated salinities for the month of September 1933 (the warming-up period) were discarded.

Initial storages used in the simulation for the 1980 time horizon were those observed at the start of September 1980 (Louw, 1981). Starting values for the 1990 and 2000 simulations were generated by the monthly feed-back model (Herold, 1981b) in the following manner:

With observed starting storages as at 30 September, 1980 the monthly model was used to simulate the behaviour of the system for the time frame 1980 - 1989 with 1923 - 1932 hydrology. Modelled storages and salt concentrations at the end of August 1932 then provided the 1990 starting values (shown in Table 4.1) for the daily model. Monthly storages and salt concentrations simulated by the monthly model are shown in Fig. 4.3. Similarly, the observed storages and salt concentrations as at 30 September, 1980, were used as starting conditions for the monthly model to simulate conditions for the time frame 1980 - 1999, with 1913 - 1932 hydrology. Modelled values are shown in Fig. 4.4 and the ending reservoir storages and salt concentrations are given in Table 4.1.

Daily salt concentrations at various points in the system have been plotted for each of the three demand horizons modelled. Fig. 4.5 shows daily values in the Vaal Barrage at the RWB Zuikerbosch and Vereeniging No. 1 intakes and in the Vaal river at the Welkom Dam site and at the Western Transvaal Regional Water Company intakes, while Fig. 4.6 shows daily salt concentrations in the water supplied to users in water supply sub-regions 1, 3, 22 and 25. As might be expected the salt concentrations modelled for 1990 demand conditions are considerably higher than those for 1980 demand conditions. This is attributable to three primary factors:

(i) Projected diffuse-source salt generation rates will be higher in 1990. (The salt generation rate is

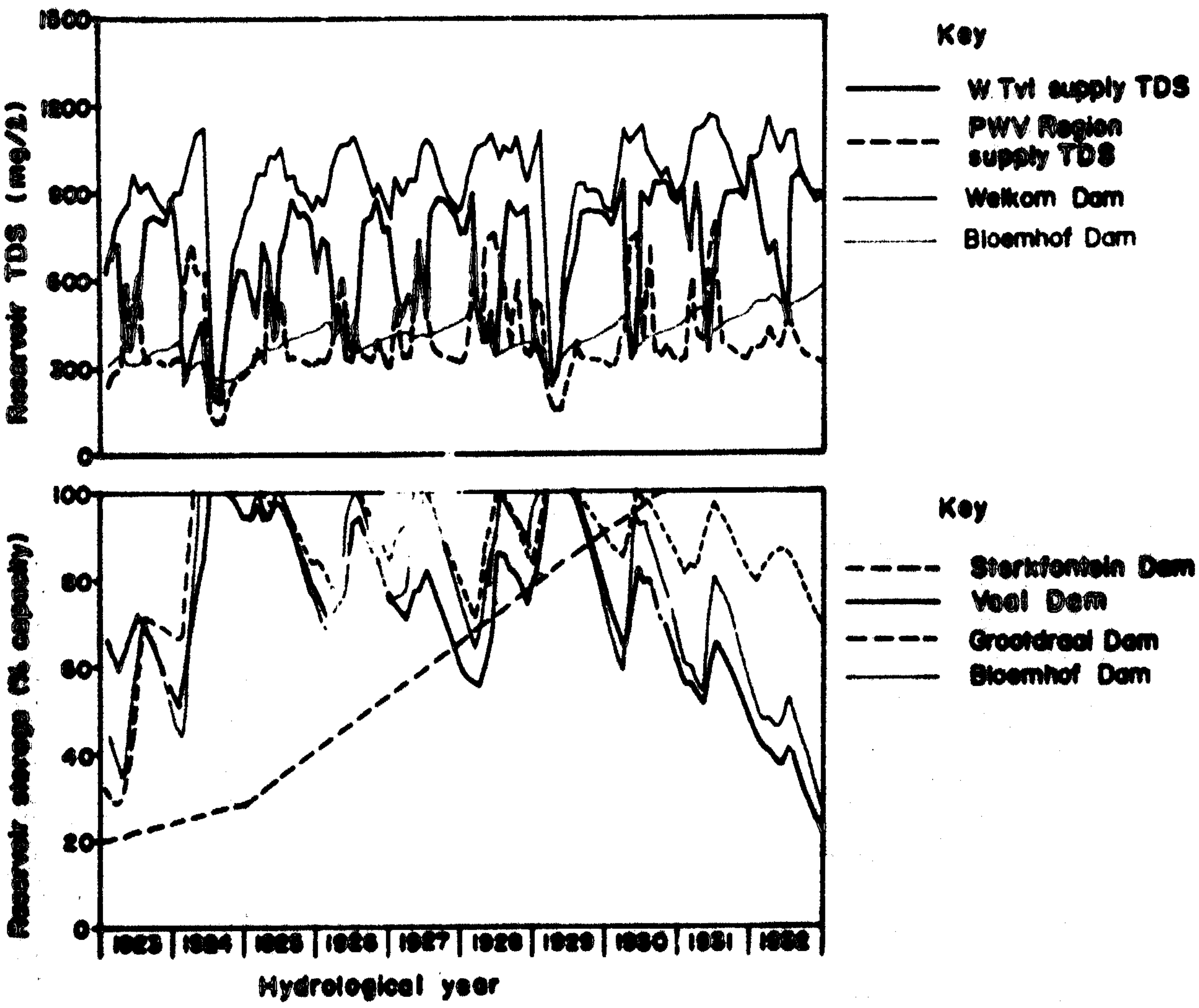

Fig.4.3: Monthly storage states and average monthly TDS concentrations for option I (Time frame: 1980-1989)

assumed to grow in proportion to the industrial water demand (Herold, 1981a)),

(ii) Higher water demands in 1990 result in proportionately higher effluent return flows, and

(iii) Higher demands in the antecedent years result in lower storages in the reservoirs at the start of the simulation and hence spillage at Vaal Dam (which occurs in early January 1934 under 1980 demand conditions) is delayed by about 40 days and the total volume of water spilled is greatly reduced. Spillage of fresh water from Vaal Dam is accompanied by a dramatic reduction in salt concentrations (see Figs. 4.5 and 4.6).

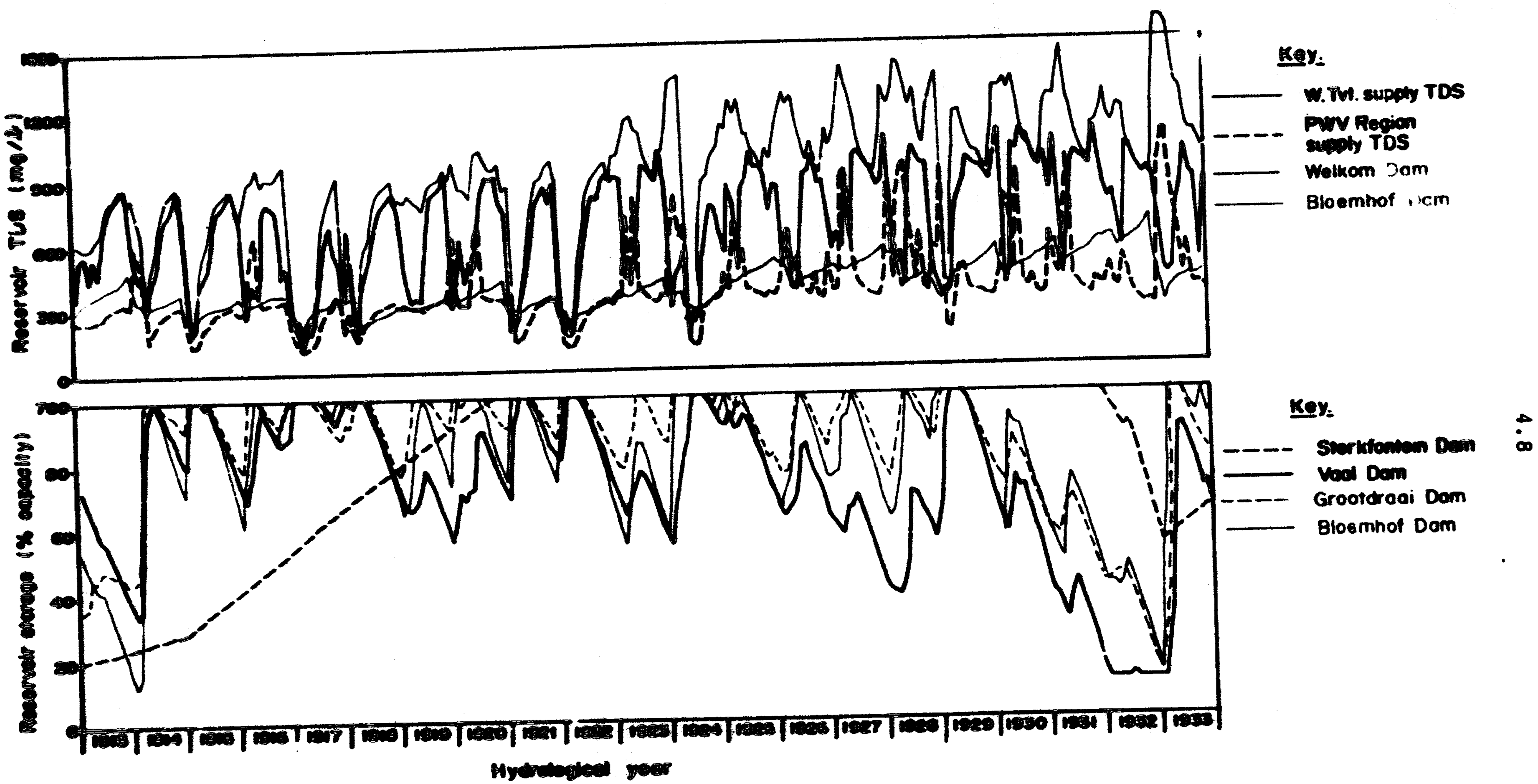

Fig. 4.4: **Monthly storage states and average monthly TDS concentrations for Option I (time frame 1980-1999)**

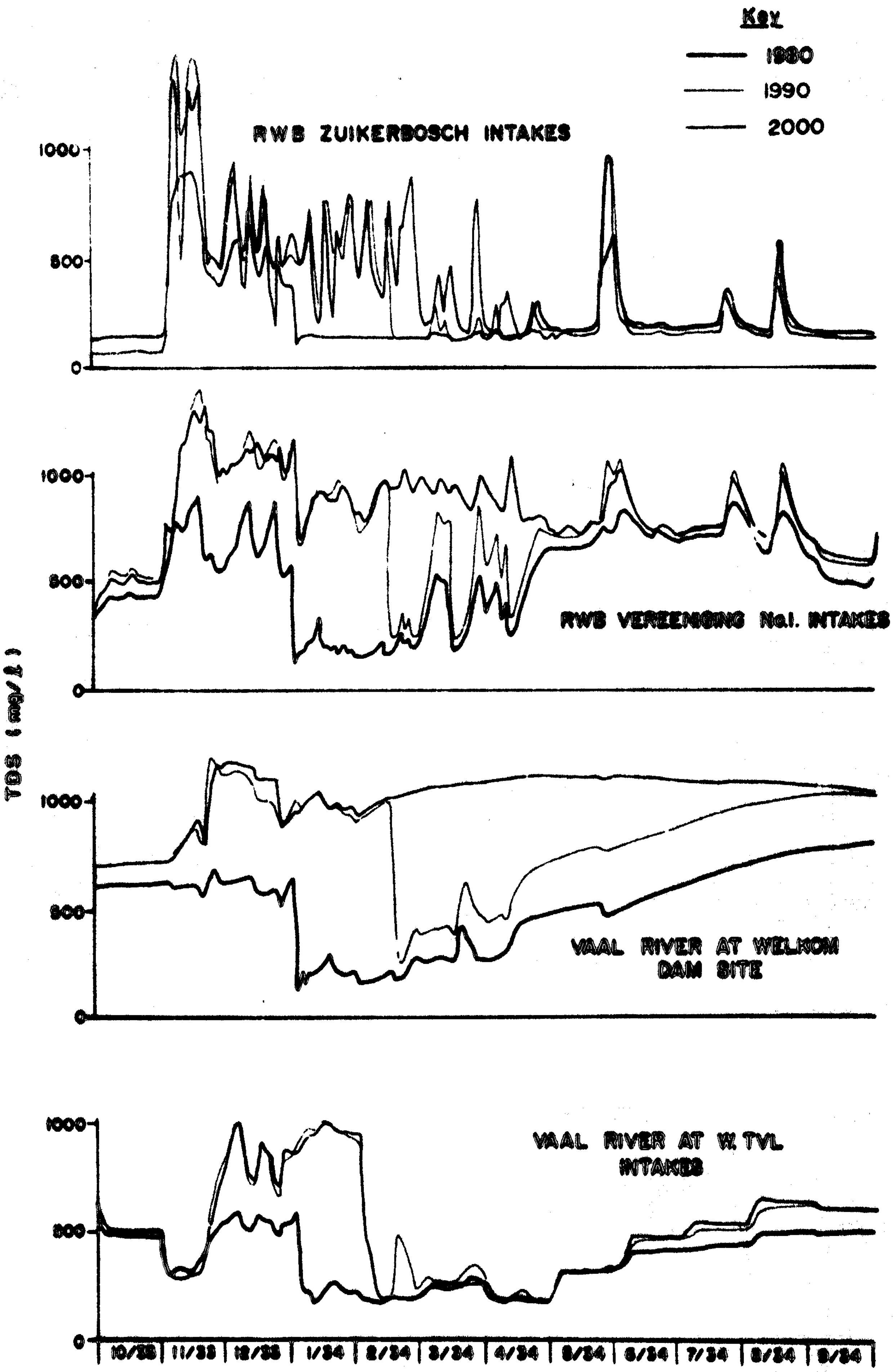

Fig.4.5: Modelled daily salt concentrations at various points in the Vaal River for time horizons 1980, 1990 and 2000.

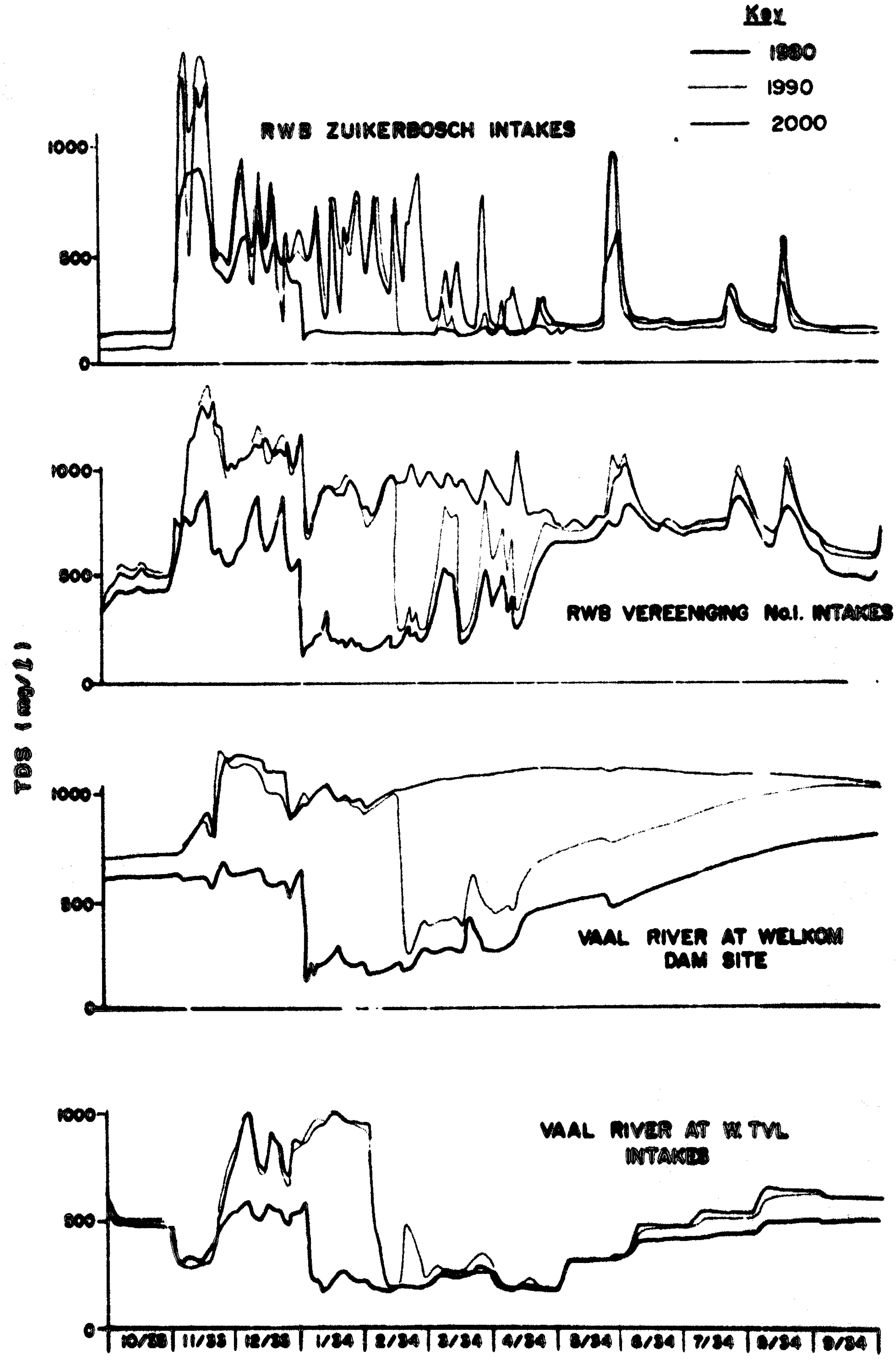

Fig. 4.5: Modelled daily salt concentrations at various points in the Vaal River for time horizons 1980, 1990 and 2000.

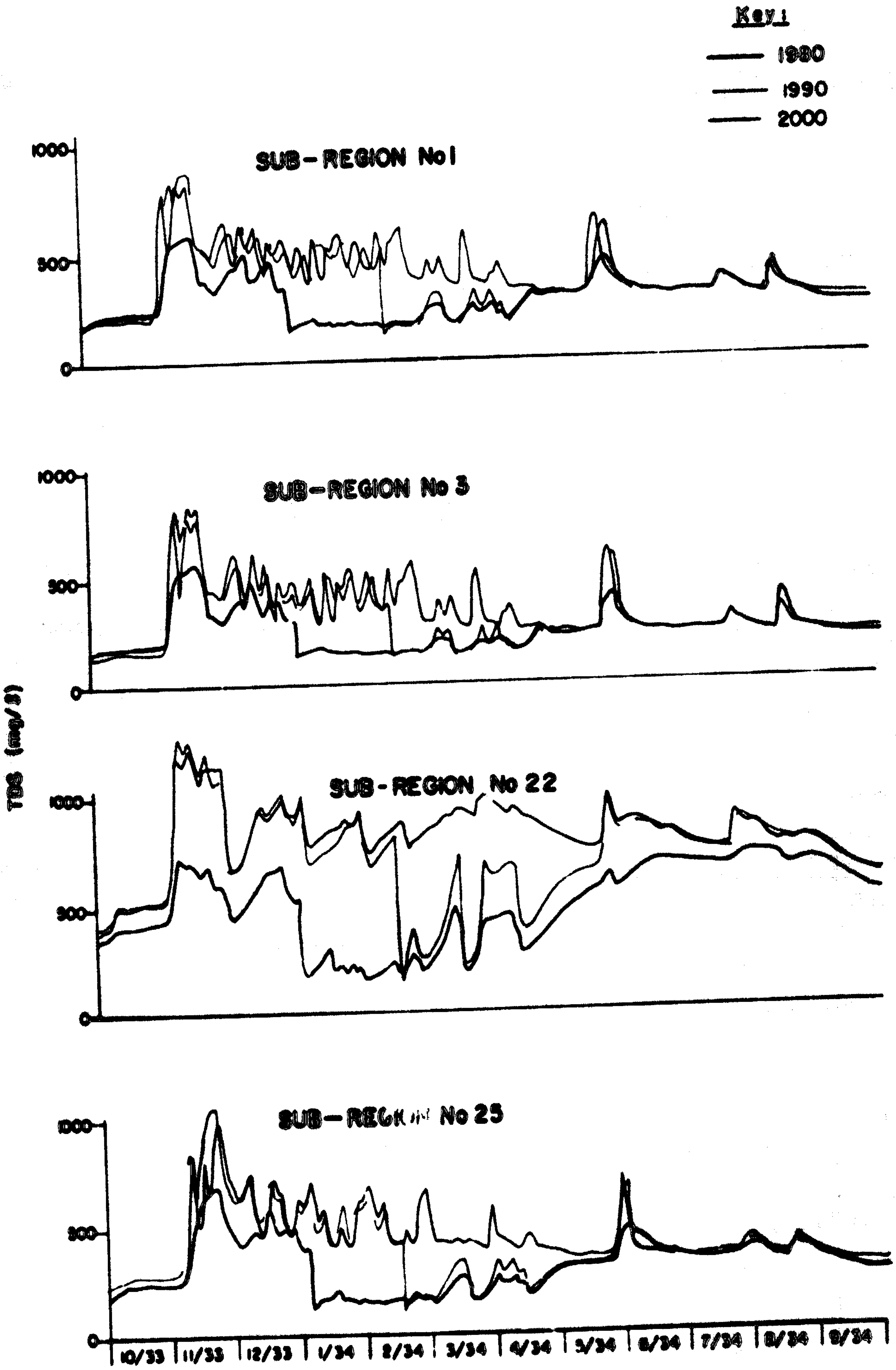

Fig.4.6: Modelled daily salt concentrations in various water supply sub-regions for time horizons 1980,1990 and 2000