WATER AUTHORITY
of Western Australia

WATER RESOURCES DIRECTORATE
Hydrology Branch

Hydrology of Lake Toolibin

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HYDROLOGY OF LAKE TOOLIBIN

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ABSTRACT

Lake Toolibin is a shallow, less than 4 km^2 surface area, ephemeral lake located in the wheatbelt of south-western Australia. As one of the few, relatively fresh water lakes in the region, Toolibin is an important habitat for indigenous fauna, particularly waterfowl. A deterioration in the vegetation in and around the lake during the dry years in the late 1970's gave cause for concern as to the continuing viability of the lake as a wildlife habitat. As part of a management response to this problem a water and salt balance study of the lake system was undertaken from 1977 to 1984.

The largest source of water and salt inflow to the lake was from surface streams draining the 95% cleared, partially salinized, 440 km^2 catchment. There was no evidence for a significant residual accumulation of salt in the lake. Below the overflow volume of 2.7 x 10^6 m^3 the salinity-volume relationship is one of concentration by evaporation.

Salt is lost from the lake waters during drying, possibly by leaching to the underlying groundwater or by storage in the unsaturated near surface soils of the exposed lake bed. Some of this may re-enter the lake water following rainfall, inflow and rising lake levels.

Surface water inflow to the lake occurs in about 7 in 10 years with filling occuring in 4 of these years. This results in the lake volume being greater than 1 x 10^6 m^3 (average depth of 1m) for about 70% of the time. Lake salinities are generally above 3000 mg/L for volumes less than 1 x 10^6 m^3.

Increased input of salt from the catchment is likely due to the delay between clearing and the full development of catchment salinization. This effect and/or a rise in groundwaters beneath the lake leading to reduced leaching could cause the lake to salinize.

ACKNOWLEDGEMENTS

The efficiency of the field and data processing groups of the Hydrology Branch of the Water Authority in the collection and processing of data is acknowledged. Agriculture Department staff at Narrogin have assisted in the collection of data.

Mr P.R. George of the Department of Agriculture and Mr M. Martin of the Geological Survey of Western Australia provided valuable discussion on the hydrology of the lake.

Mr D. Salim provided the computer code for the simulation of the catchment rainfall-runoff and Mr R. Pickett assisted with the production of the inflow probabilities using the catchment model.

Finally, the very valuable preliminary work of the late Mr P.D.K. Collins is gratefully appreciated.

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1. INTRODUCTION

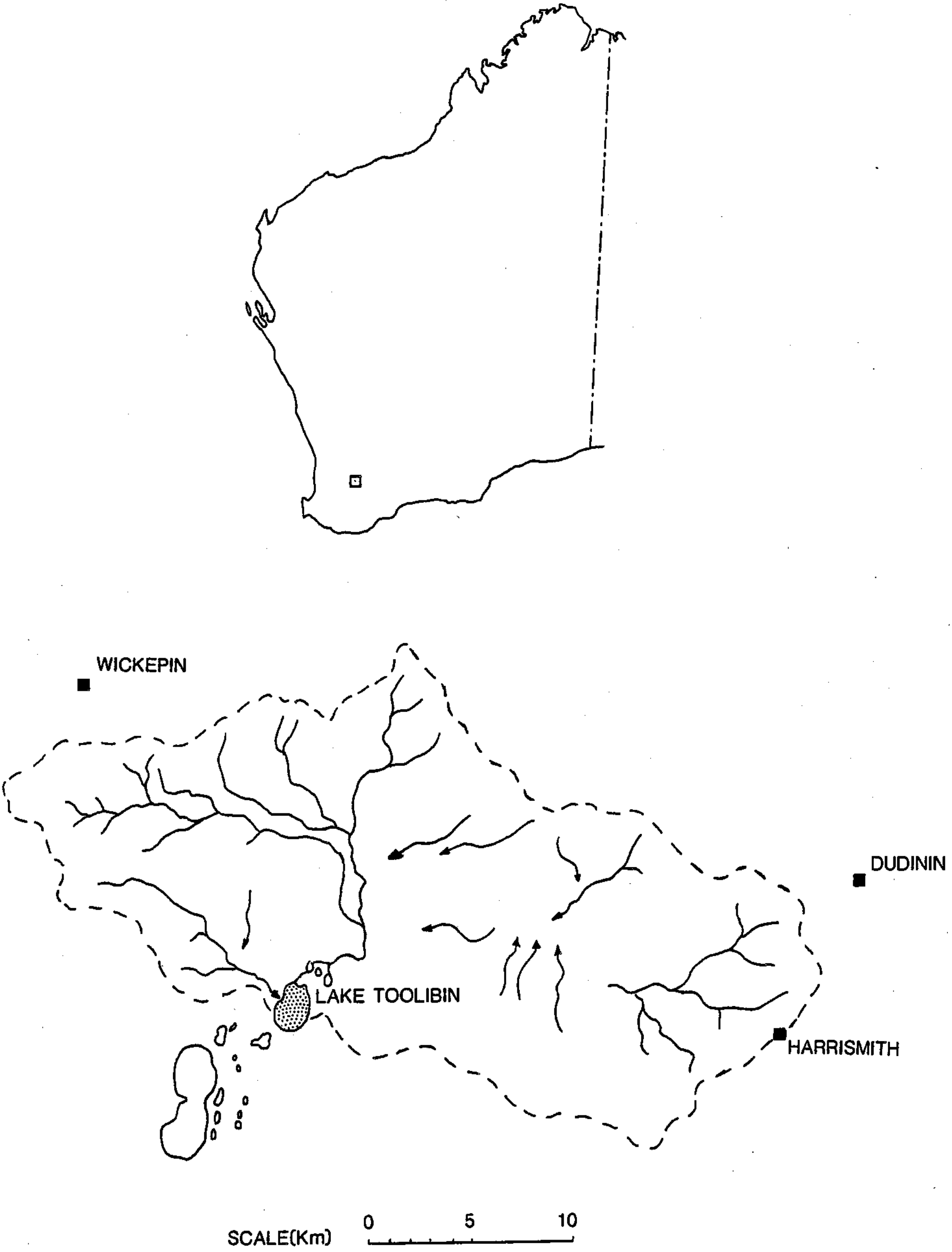
Lake Toolibin is at the head of a chain of lakes occupying a palaeodrainage valley which now forms part of the Arthur River system. The catchment to Lake Toolibin is about 440 km^2 in area, and extends from Dudinin in the east to Wickepin in the west (Figure 1). Lake Toolibin, as one of the few remaining 'non-saline' lakes in the wheatbelt, provides an important habitat for indigenous fauna, particularly waterfowl. It is a vital breeding area for a wide range of water birds, including some rare species such as freckled duck. A declining trend in the use of the lake by nesting waterfowl has been noted (N.A.R.W.R.C., 1978). Crucial to the survival of the lake as a nursery is its ability to sustain an adequate population of invertebrates which provide the necessary protein source for breeding adult waterfowl and their downy young. The food chain of aquatic plants and invertebrates can be adversely affected by increasing or rapidly fluctuating, salinity of the lake water.

The Committee for the Rehabilitation of the Northern Arthur River Wetlands (N.A.R.W.R.C.) was set up under the authority of the Minister of Fisheries and Wildlife in March 1977. The main purpose of the committee was to recommend measures to:-

a) preserve Lake Toolibin as a freshwater lake; and

b) rehabilitate other lakes and foreshores downstream from Toolibin to improve the carrying capacities, water quality and the wildlife value of the system.

This report investigates the hydrology of Lake Toolibin and considers the implications of the lake water and salt balance and possible management options.



LOCATION MAP

FIGURE 1

The study considers:-

(i) the lake water and salt balance
(ii) relative significance of sources of water and salt
(iii) future of the lake

2. HISTORY OF CATCHMENT AND LAKE

2.1 Catchment

Land in the lake catchment area was first taken up for farming during the late 1890's. As early practices were pastoral rather than cropping,there was little clearing of native vegetation, and most was confined to the dozen farms established south east of Lake Toolibin (NARWRC, 1978). Large scale clearing of the better class, clayey soils occurred after World War 1, and most of the heavy land had been put under cultivation by about 1934. Development of the lighter, sandier soils did not commence until the late 1940's or early 1950's. There are no precise figures available for the rate of agricultural clearing, but most of the heavier soils or one third of the catchment had been cleared by the mid 1930's. By 1962, aerial photography revealed that some 85% of the area was cleared, and this had increased to 90% by 1972.

One of the most noticeable effects of clearing has been the appearance and spread of salt encrusted land since the 1930's. At present about 3% of the total catchment is severly salt affected, and a further 2.6% in moderately salt affected. On one particular farm on the west bank of Lake Toolibin, the area of salinization has doubled in the sixteen years between 1961 and 1977.

2.2 Lakes

There are no long term records of the hydrology of Lake Toolibin. However a local farmer, resident since 1904, has reported that Lake Toolibin had not been consistently dry until the sequence of drought years in the 1970's. In average and above rainfall years the lake had filled, but only partially in below average years.

The history of Lake Taarblin immediately downstream of Lake Toolibin is indicative of the effect of clearing on lakes in the area. Lake Taarblin consisted of a series of swampy lagoons prior to 1926 when it was recorded to have completely filled for the first time. It was after this inundation that trees within the southern half of the lake were reported to have died. During the 1930's Lake Taarblin was mostly dry. Trees in the northern half were dead by the mid 1930's. The lake was flooded again in 1945 and 1955 when, as in 1926, the annual rainfall was some 200 mm above average. The dense thickets of Sheoak (C. obsea) round the perimeter of the lake regenerated above the 1955 highwater mark, and salt crusting became evident in the lake at about this time.

2.3 Groundwater

The catchment is underlain by granites of the Yilgarn Block which outcrop along the divides, but are generally mantled by lateritized deep weathering profiles. The broad, flat valleys have been infilled with fluviatile and aeolian deposits, on which playa lakes and associated dunes have developed.

Considerable stores of salt are known to exist in soil profiles such as these and groundwaters are often saline (>10 000 mg/L TSS). Some fifty seven bores were sunk within the catchments of lakes Toolibin and Taarblin between 1907 and 1913 (NARWRC, 1978). Most bores were between 25 to 30 m deep and bottomed on rock. About half the bores were dry, and in the others the water tables were deep and generally saline. At this time clearing was insufficient to affect the hydrologic regime. However since then the evidence is that groundwater levels, and perhaps salinity, have risen following clearing. The appearance and spread of salt affected land and available bore data reveal a rise of 12 to 15 metres in the water table in the past 50 to 60 years. Soaks used for stockwater were abandoned due to high salinity during the 1930's.

Previous investigations (NARWRC, 1978) have shown the lakes to be underlain by shallow, very saline groundwaters. Where surface salt crusting has occurred the water levels appear to be within 1.2m of the surface.

2.4 Lake Vegetation

Vegetation surveys of Lake Toolibin (NARWRC, 1978, 1982) found that the most stressed, unhealthy or dead trees were adjacent to salt scalds on cleared land located on the west bank of Lake Toolibin, and along the southern margin of the lake. This could indicate that Lake Toolibin is deteriorating into a salt lake such as Taarblin. It is probable that the gilgai formations with undulations up to 1.5 m high have done much to preserve the vegetation in the centre of Lake Toolibin.

3. LAKE CHARACTERISTICS AND DATA

3.1 Lake Characteristics

Lake Toolibin (Figure 2) is ephemeral, only filling in years of above average rainfall. When full the lake is about 3 km^2 in area and 2-3m deep. The lake volume and surface area relationships are shown in Figure 3. These were derived by calculation of a surface area-height relationship from a Lands and Surveys Department contour map of the lake and are of suspect accuracy at low volumes.

The lake bed is relatively flat with several shallow (<1m) depressions or lagoons and gilgai mounds in the centre of the lake. These mounds control circulation at low lake levels.

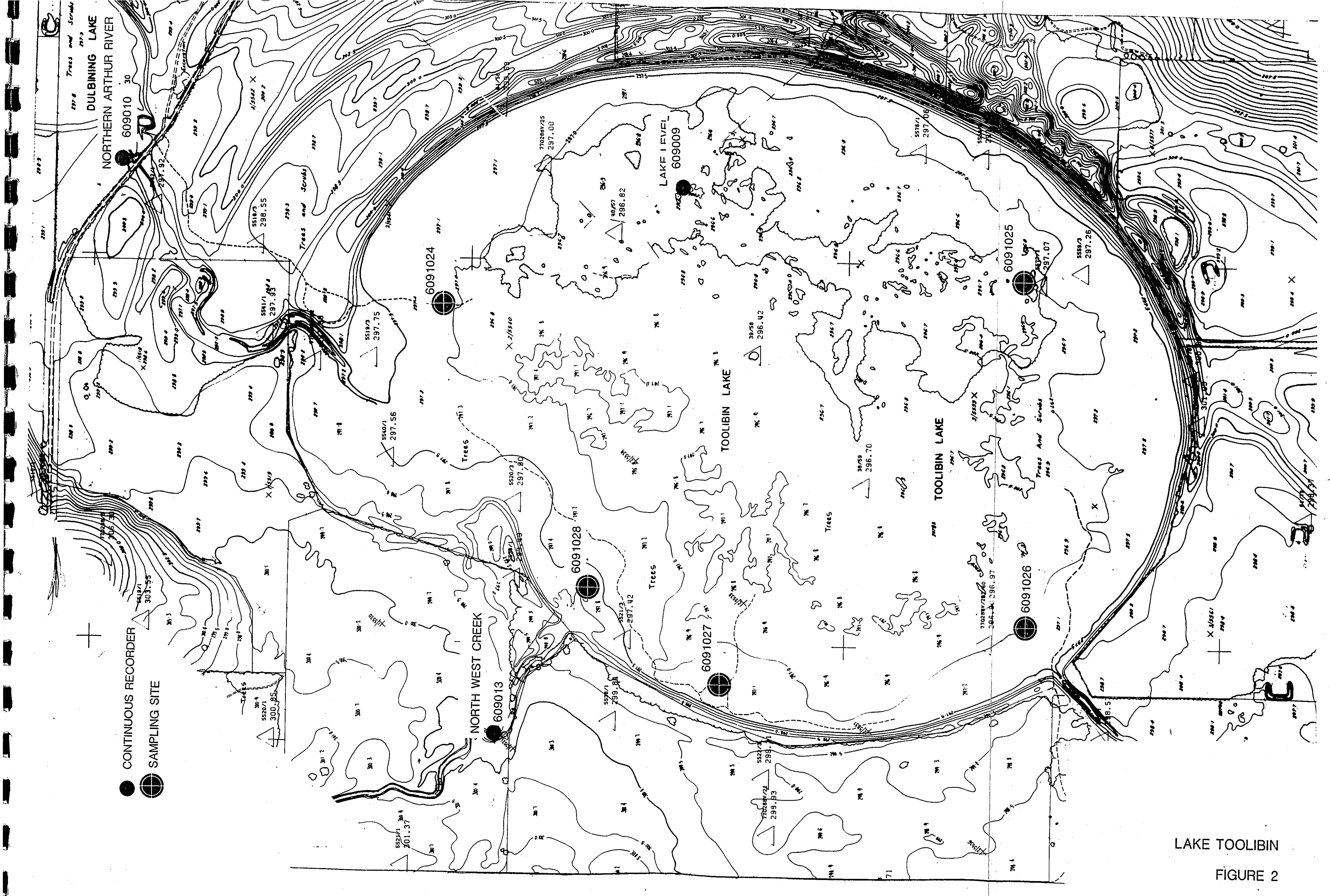
Surface water inflow to the lake is from the catchment of the Northern Arthur River (435 km^2) to the north of the lake and from the smaller catchment (41 km^2) of the North West Creek in the north west corner of the lake. Lake outflow as surface water loss occurs via an overflow channel to the south of the lake and drains via a series of smaller lakes to Lake Taarblin.

It is assumed that both groundwater inflow and outflow may occur to and from the lake.

3.2 Model of Lake

A model of the lake inputs and outputs is shown in Figure 4. The lake water balance equation is:-

$$V_t = V_{t-1} + I_1 + I_2 + I_3 + R + GD - GR - E - O \qquad 3.1$$



LAKE TOOLIBIN

FIGURE 2

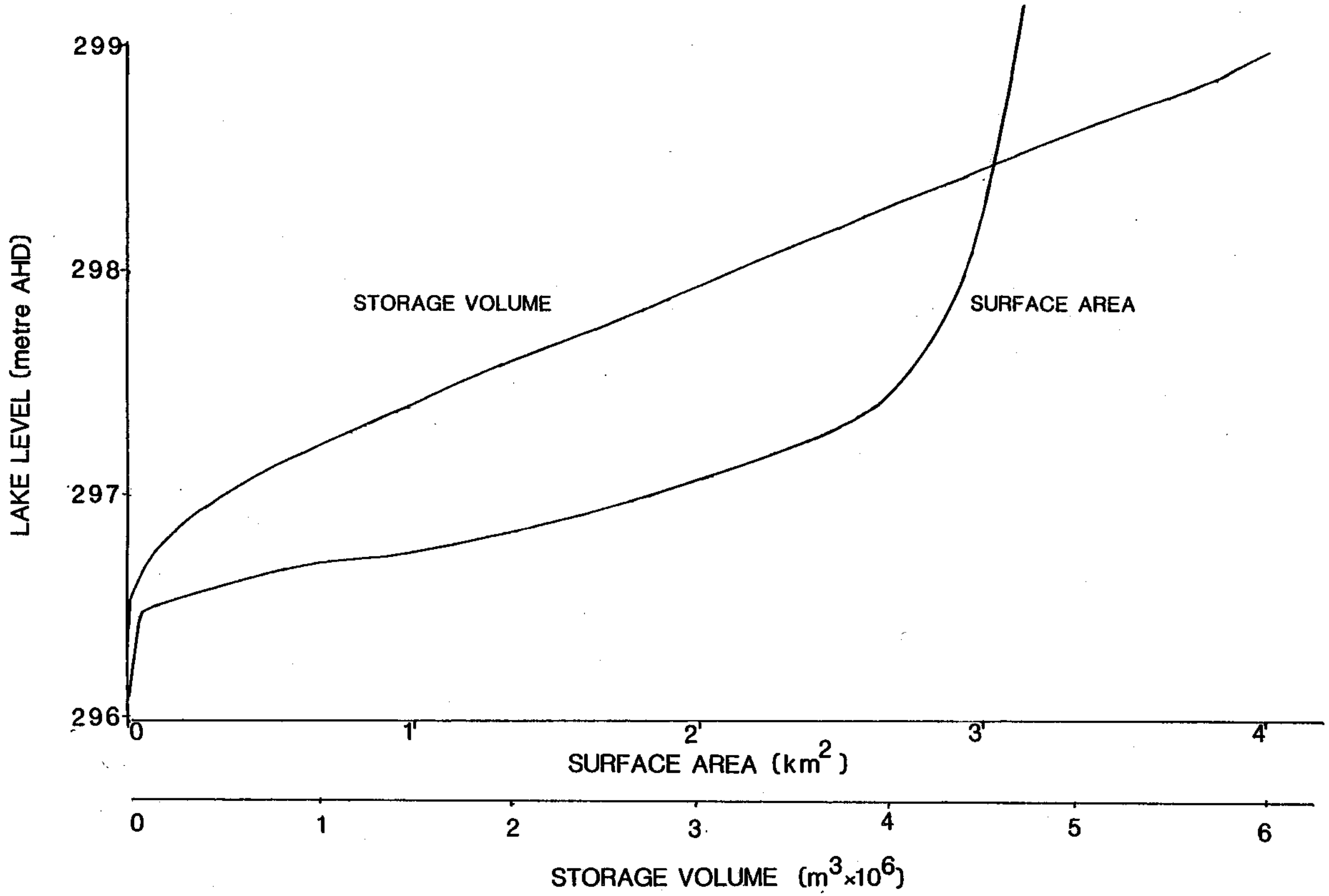
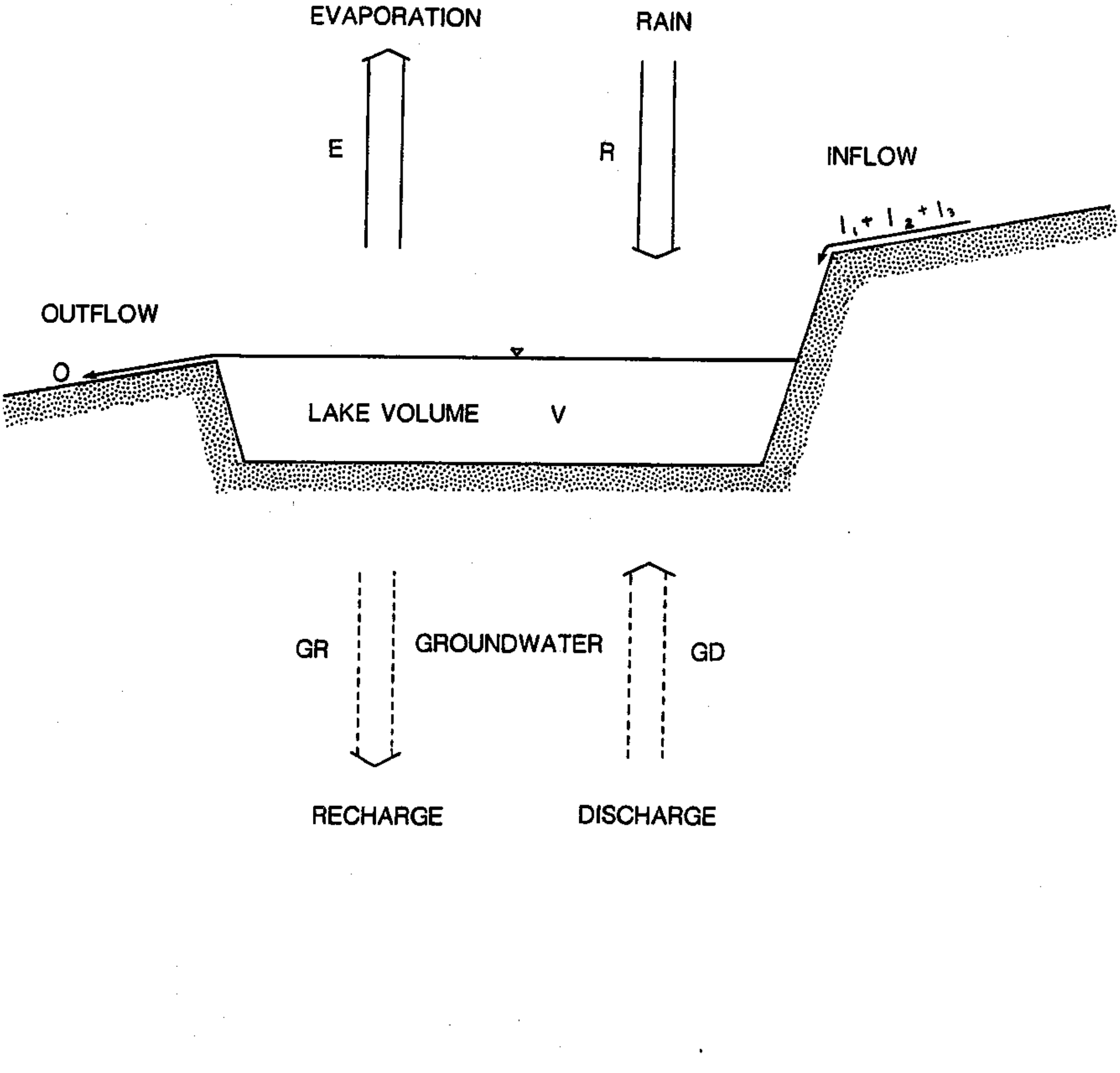

LAKE LEVEL (metre AHD)
299
298
297
296
STORAGE VOLUME
SURFACE AREA
0
1
2
3
4
SURFACE AREA (km²)
0
1
2
3
4
5
6
STORAGE VOLUME (m³×10⁶)

FIGURE 3



WATER BALANCE OF LAKE

FIGURE 4.

where

V	lake volume at time t, t-1
I_1	inflow from Northern Arthur River
I_2	inflow from North West Creek
I_3	inflow from drain
R	rainfall
GD	groundwater discharge into lake
GR	groundwater recharge from lake
E	evaporation (and transpiration)
O	overflow

collecting known (measured) and unknown terms:-

$$E + O - G + I_3 = V_{t-1} - V_t + R + I_1 + I_2 \tag{3.2}$$

where : $G = GD - GR$ is a general groundwater term.

The lake salt balance equation is:-

$$S_t = S_{t-1} + SI_1 + SI_2 + SI_3 + SG - SO \tag{3.3}$$

where :

S	lake salt load at time t, t-1
SI_1	salt load from Northern Arthur River
SI_2	salt load from North West Creek
SI_3	salt load from drain
SG	net groundwater salt load
SO	overflow saltload

Collecting knowns and unknowns:-

$$- SG + SO + SI_3 = S_{t-1} - S_t + SI_1 + SI_2 \tag{3.4}$$

Neither the overflow (O) nor some of the inflows such as I_3 and occasionally I_2 were measured during this study. Clearly therefore equations 3.2 and 3.4 cannot be solved because there are too many unknowns. However during periods of no overflow and no surface inflow the equations reduce to:-

$$E - G = V_{t-1} - V_t \qquad 3.5$$

and

$$-SG = S_{t-1} - S_t \qquad 3.6$$

Therefore changes in the salt load in the lake water may be interpreted from 3.6 as a loss or gain of salt to groundwaters. Evaporation (E) can be estimated from daily pan data so that the groundwater contribution (G) in 3.5 can be calculated. With an estimate of average groundwater salinity (Cg) then the G term can be cross-checked because:-

$$SG = Cg \times G \qquad 3.7$$

when groundwater contributes to the lake.

Conversely, an estimate of the rate of water and salt loss from the lake water can be calculated over a period by using an average lake salinity (Ca) and then from 3.6 :-

$$G = (S_t - S_{t-1}) \times 10^6/Ca \qquad 3.8$$

3.3 Availability of Data

The availability of data for the lake volume and inputs is shown in Figure 5. Site locations are shown in Figure 2.

3.3.1 Lake Volume : Derived from a continuous water level, float operated chart recorder situated in the lake since December 1977 (site number 609009). The level/ volume/surface area relationships were derived from 1:5000 scale map prepared by Department of Lands and Surveys with contours at 0.5 metre intervals.

Data are essentially complete for the period from April 1981 to March 1984. The Lake was dry from December 1977 to June 1981.

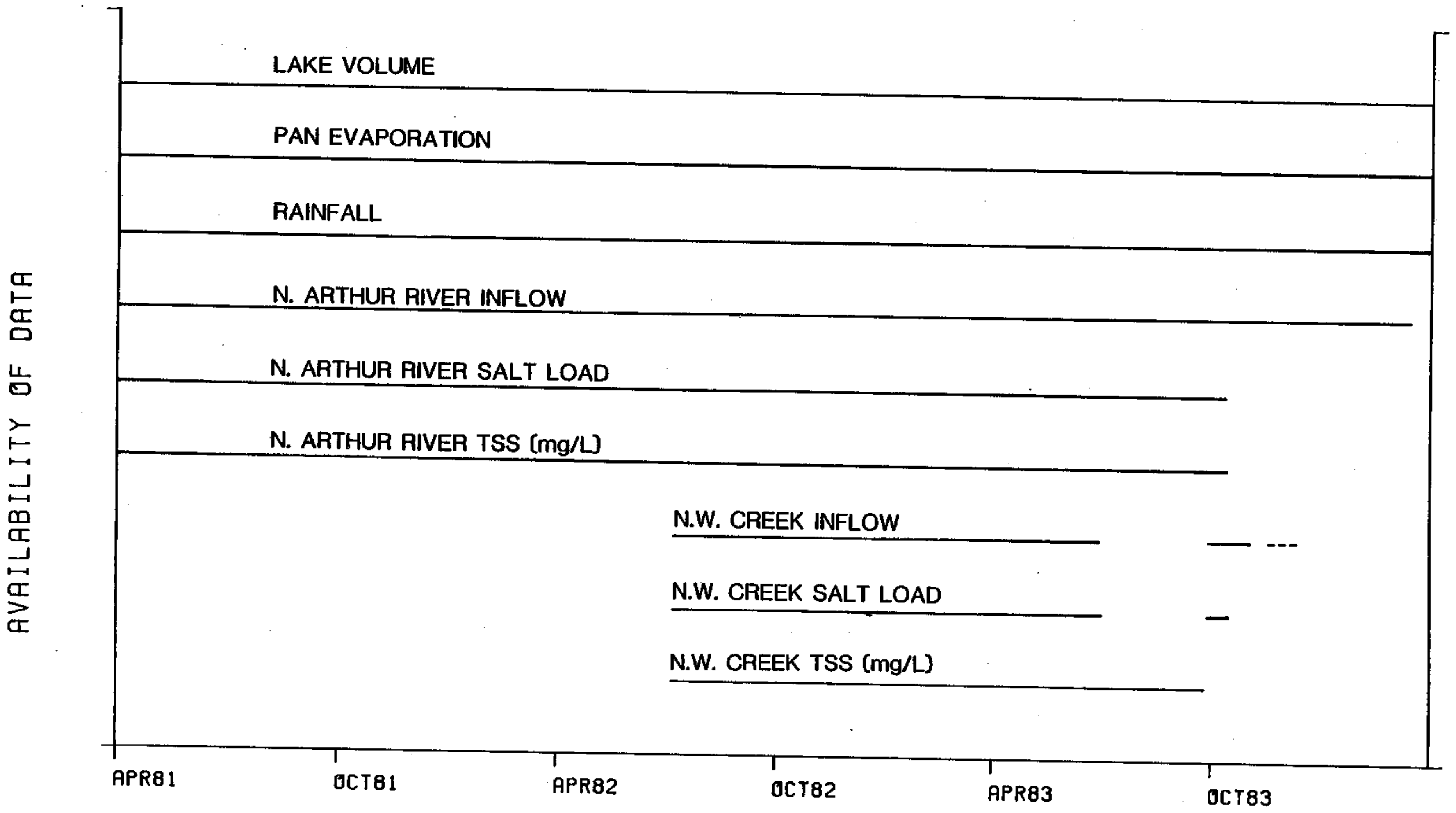
Wind caused oscillations can be as high as 20 mm but are normally in the order of 5-8 mm. These effects have been averaged at the digitising stage of processing.

The level/volume relationship is doubtful below 0.46 million cubic metres due to the flat bottomed nature of the lake.

3.3.2 Inflow : <u>609010 Northern Arthur River</u> This record is derived from a continuous water level float operated chart recorder. Also sited at this installation are another water level recorder monitoring tailwater effects from the lake and a continuous stream conductivity recorder.

The stage discharge relationship is derived from a combination of discharge measurements and theoretical rating of the culvert/road crossing control. The relationships are confirmed to approximately 90% of the total recorded flow yield (ie 30.5 m^3s^{-1}). The extrapolation to the maximum recorded flood level is very small and therefore considered reasonably accurate. Data are complete from April 1981 to March 1984.

Daily salt loads were derived from integration of the continuous flow and conductivity data.



AVAILABILITY OF OF DATA

FIGURE 5

: <u>609013 North West Creek</u>. The stage record for this site is also recorded on a continuous water level, float operated chart recorder. Data for this station commences in June 1982.

Flow records from this site are poor in quality as:

a) few discharge measurements were taken and the control was unstable.

b) the station was drowned by Lake Toolibin for the period 6/83 to 10/83.

Continuous conductivity was also recorded at this site and is available for the period when tailwater affected.

Daily salt loads were derived from integration of the continuous flow and conductivity data.

3.3.3 Rainfall : A pluviograph installation has been in operation (site number 510254) in conjunction with the main inflow measuring site.

Where record was incomplete, it was filled in using other nearby gauges. (site numbers 510253, 010839).

Long term data was from Wickepin (site 010654).

3.3.4 Evaporation : Data from April 1981 to February 1983 comes from the Bureau of Meteorology station in Narrogin (site 010614).

From March 1983 to March 1984 the data are from a PWD installation a short distance east of Lake Toolibin (site number 010839).

A comparison of overlap monthly data for these sites produced a reasonable 1:1 correlation.

4. WATER AND SALT INPUTS

4.1 Yearly Input

Inputs of water and salt from N. Arthur River and NW Creek are summarized in Table 1. In the 1981 winter, 2.1 x 10^6 m^3 of water and 2590 tonnes (t) of salt were input by N. Arthur River. Most of this occurred prior to the sampling of the lake salinity on 2/9/81; at which time the lake salt load is estimated to have been about 3330t. Therefore, by difference, some 750t of salt may have been contributed by NW Creek which was not monitored.

The January 1982 event produced 1.1 x $10^6 m^3$ and 450t from N. Arthur River. There is no evidence for surface overflow from the lake in 1981 or 1982.

Very little inflow occurred via N. Arthur River during the 1982 winter and the contribution from NW Creek was about 220t.

Large quantities of water and salt were input during the 1983 winter (Table 1). The volume of water input amounted to more than six times the lake volume at which overflow occurs. A salt load input of in excess of 10 000 t probably occurred.

A record of the quantities of water and salt input by NW Creek, relative to N. Arthur River, was not obtained because of problems with lake tailwater. However an estimate can be obtained from the relative catchment areas. The proportion of the catchment area of NW Creek to that of N. Arthur River is approximately 10%. Therefore it is reasonable, in the absence of flow records, to assume that in most good inflows that NW Creek contributes 10% of the N. Arthur River contribution.

Very little surface inflow was measured in the 1984 winter (Table 1) and an estimate of the salt input (not listed) was about 200t.

Table 1 Yearly Water and Salt Inflow

INFLOW PERIOD	N. ARTHUR RIVER WATER (10^3m^3)	TSS (tonnes)	TSS (mg/L)	N.W. CREEK WATER (10^3m^3)	TSS (tonnes)	TSS (mg/L)
WINTER 1981	2100	2590	1230	NA	NA	NA
JANUARY 1982	1100	450	410	NA	NA	NA
WINTER 1982	0.5	2	4000	36.7	220	6000
WINTER 1983	15600	8500	550	430.	1100	2500
WINTER 1984	10.7	NA	NA	2.5	NA	NA

NW Creek inflow incomplete in Winter 1983 because of rating problem.

NA: No record

4.2 Distribution of Input

Daily streamflow volumes and salinity are shown in Figures 6 a-d and Figure 7 for N. Arthur River and NW Creek. Streamflow occurs for relatively short periods, with little sustaintained baseflows. Runoff is generally of short duration, associated with the more intense rainfalls.

Streamflow salinities vary considerably with minima around 100 mg/L and maxima of 8000 mg/L. Concentrations during high flows are lower than either the first flows or the recession flows towards the end of winter. Flow-weighted salinities are shown on the salinity plots. As expected, average salinities are lower for higher runoff.

In 1981 and 1983, streamflow salinity for N. Arthur River was above the flow-weighted salinity from August in each year. For 1983 this meant that continuing inflow, of small though significant volume in terms of lake volume, increased lake salt storage by displacing earlier, fresher inflows by overflow.

Although the inflow from NW Creek could not be obtained in 1983 the inflow salinity (Figure 7) is available. During July to August concentrations varied from 100 mg/L to 4000 - 5000 mg/L with each flow event. At the beginning and end of period of flow, salinities were in excess of 10 000 mg/L. The dynamic range of salinities indicates substantial dilution of a saline groundwater baseflow by rainfall during an event. Relative to N. Arthur River, NW Creek flows are generally more saline and continue for a longer period of time.

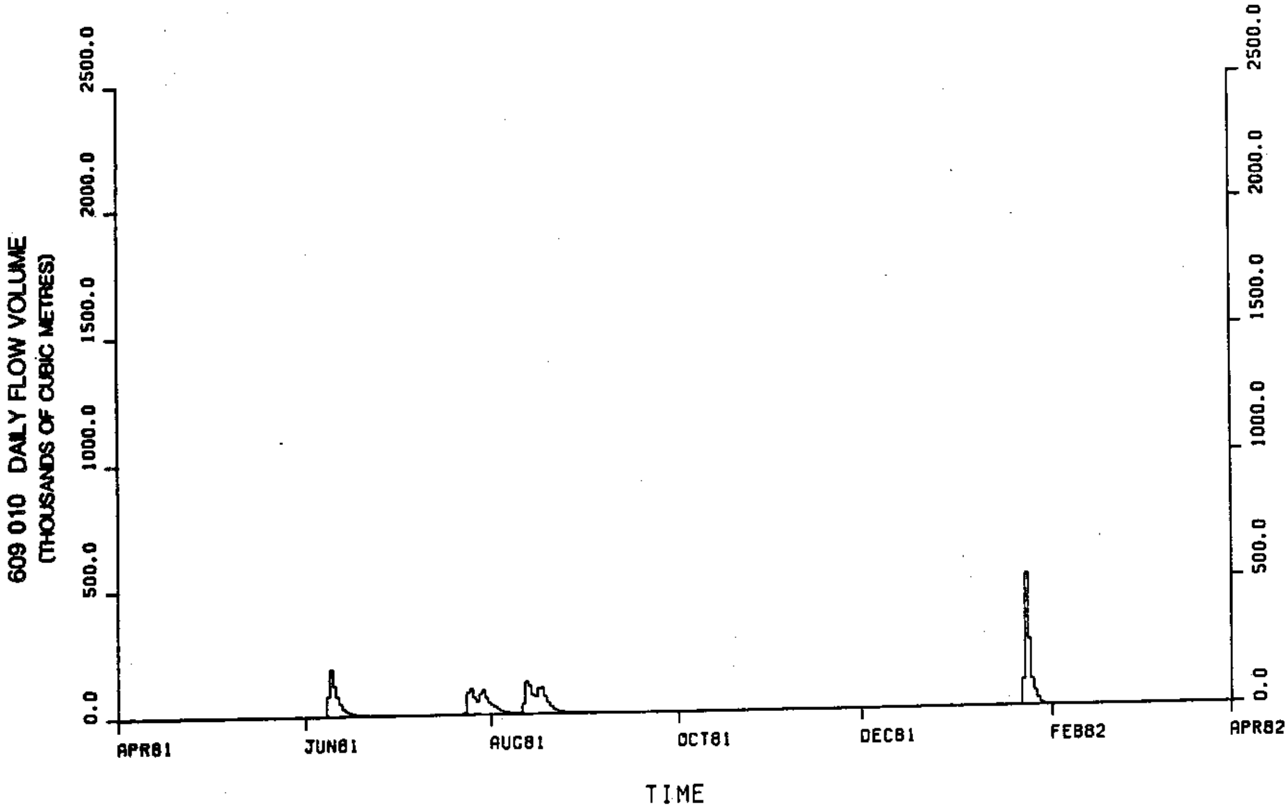


FIGURE 6a N. ARTHUR RIVER INFLOW : 1981

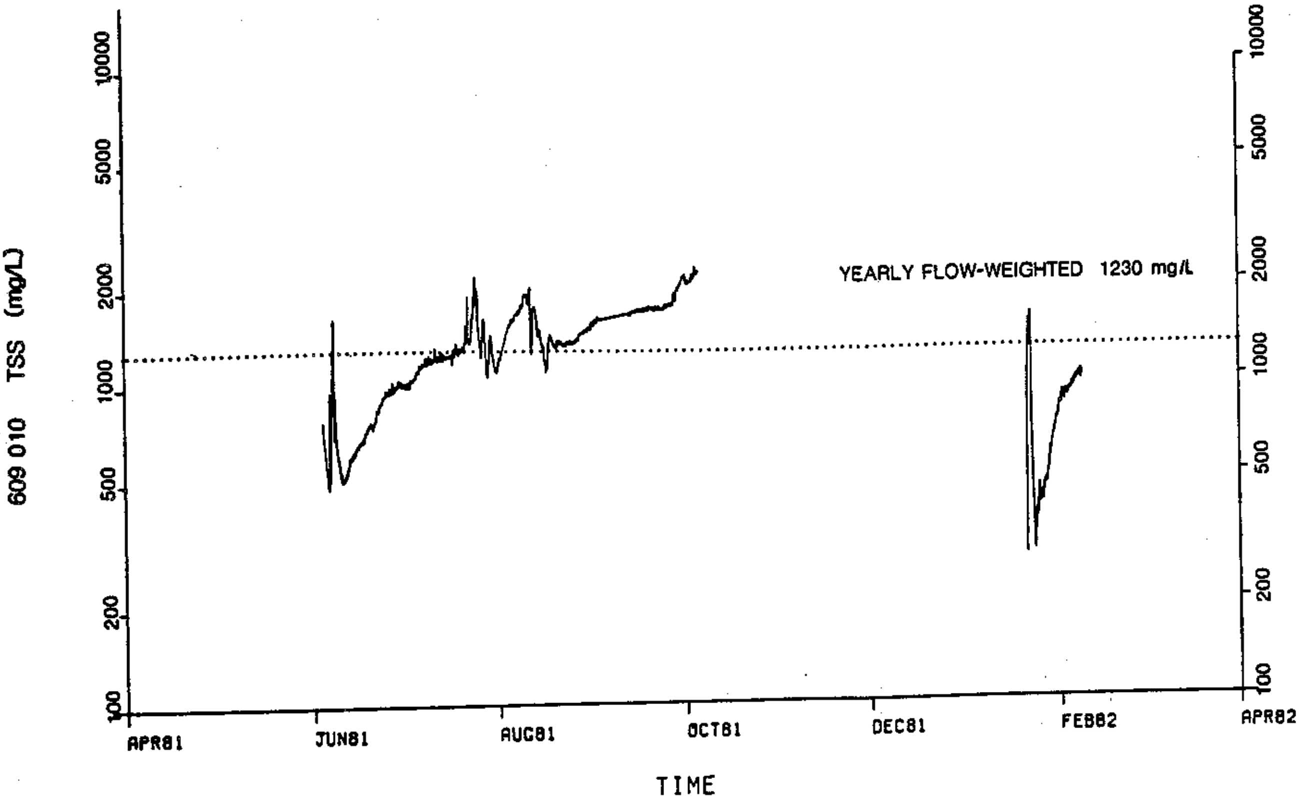


FIGURE 6b N. ARTHUR RIVER SALINITY : 1981

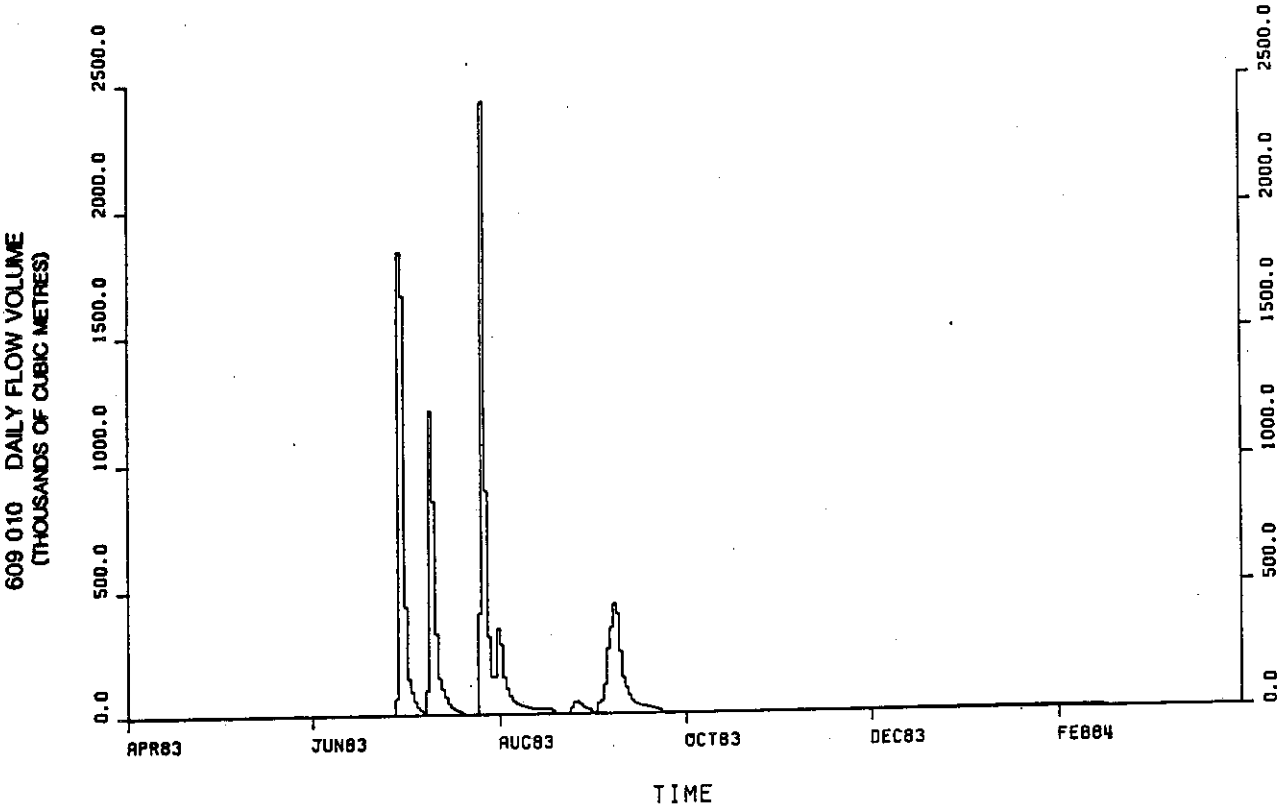


FIGURE 6c N. ARTHUR RIVER INFLOW : 1983

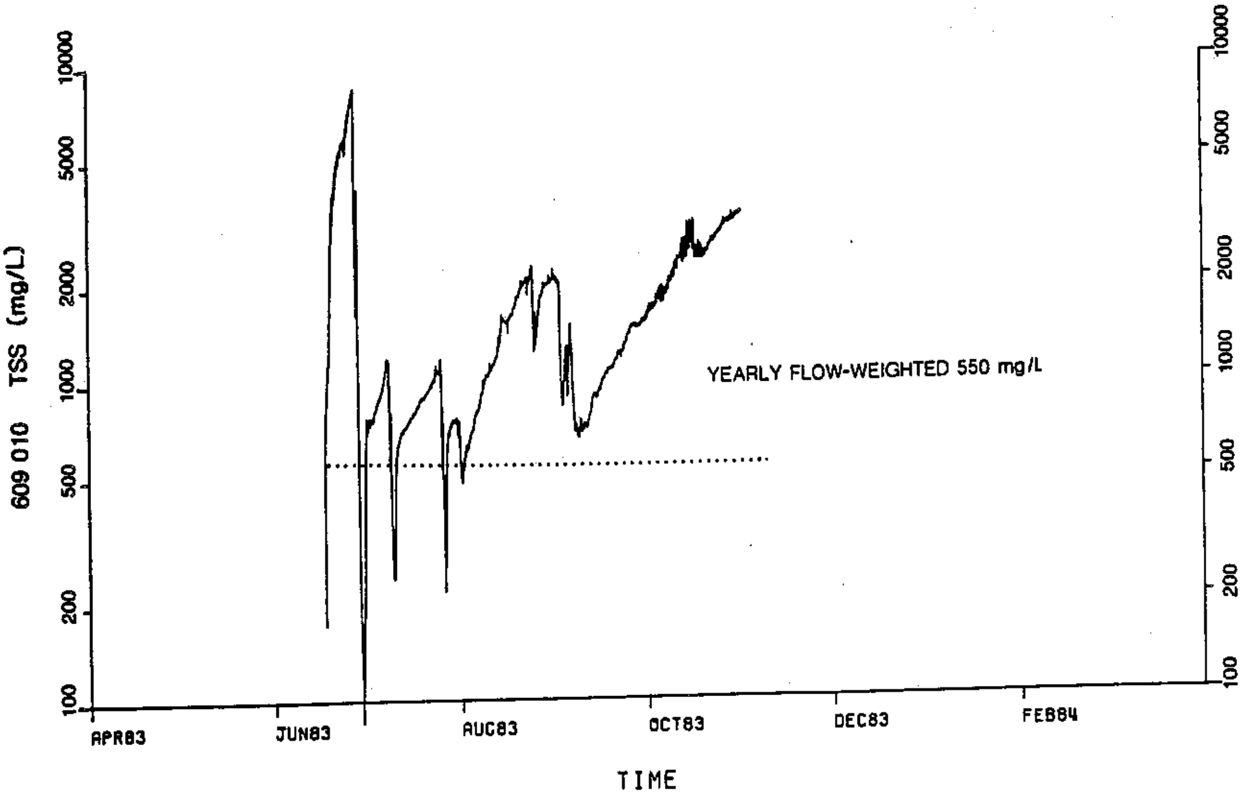


FIGURE 6d N. ARTHUR RIVER SALINITY : 1983

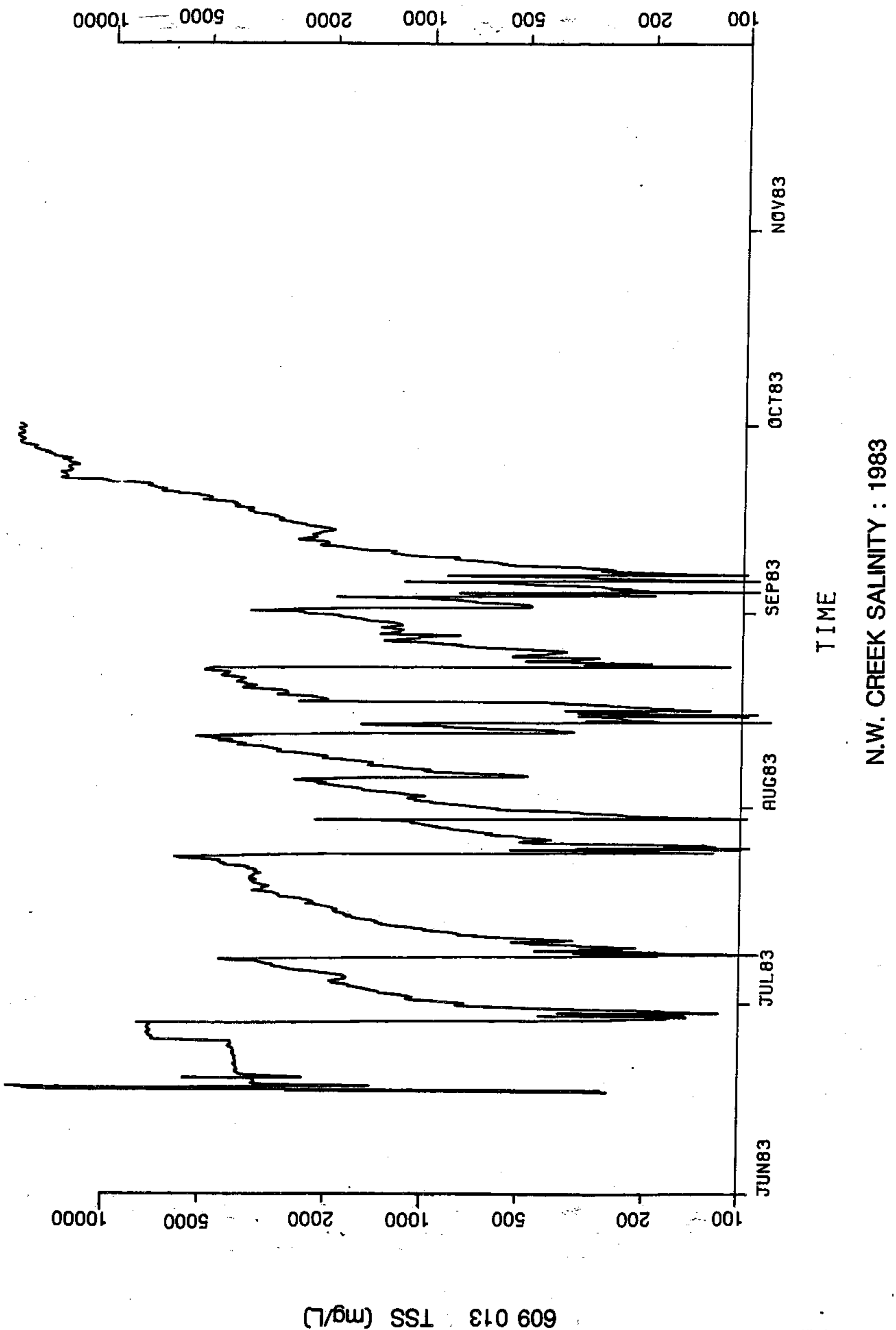

N.W. CREEK SALINITY : 1983
TIME
JUN83
JUL83
AUG83
SEP83
OCT83
NOV83
609 013 TSS (mg/L)
100
200
500
1000
2000
5000
10000

FIGURE 7

5. LAKE RESPONSE

5.1 Salinity Sampling

Six salinity sampling points were established on lake Toolibin (Figure 2). Two of these sample the lake close to the inflow points of the Northern Arthur River (6091024) and North West Creek (6091028). Sampling point number 6091026 is located close to the lake overflow point. The remaining sampling points are located around the edge of the lake; one on the western boundary (6091027), adjacent to where an agricultural drain enters the lake, one in the south east lagoon (6091026) and the third at the lake level recording station (609009).

Samples were taken at the lake surface and near the lake bottom. The salinities of these indicated little if any stratification in the lake.

Between July 1981 and January 1985 the lake salinity was sampled on 43 occasions. The total soluble salts (TSS), derived from electrical conductivity, for the six sample points are listed in Table 2. Salinity samples were not obtained for every sample point at each visit. On some occasions, such as 30/7/81, 3/8/82 and 30/6/83 only one or two samples were obtained.

The salinities vary between sample points and through time. Salinities of the samples from the western edge of the lake (6091027), 6091028) were generally higher than those from the east or near the overflow point. This is attributed to the relatively more saline inflows from NW Creek and the inflow from the interceptor channel near 6091027.

The value of 15638 mg/L for 6091028 on 22/9/81 is almost ten times higher (Table 2) than the salinities at the other sample points. This result may be an analysis error or an indication of the salinity of inflows from NW Creek.

TABLE 2 LAKE SALINITY SAMPLES

		SALINITY SAMPLE POINTS					
	DATE	6091024	609 009	6091025	6091026	6091027	6091028
1	01/07/81	2137	853	1016	N/S	3154	N/S
2	30/07/81	1610	N/S	N/S	N/S	N/S	N/S
3	05/08/81	1334	1387	1493	1970	1840	N/S
4	02/09/81	1557	1563	1587	1811	1746	N/S
5	22/09/81	1712	1706	1718	1999	1891	15638*
6	05/11/81	2152	2093	2199	3136	2641	2547
7	15/12/81	3407	2924	3124	4119	4472	3624
8	19/01/82	5457	4415	4796	6944	9116*	5598
9	26/01/82	465	1599	1323	777	1136	N/S
10	23/02/82	2152	2158	2170	2235	2270	2293
11	20/04/82	3177	2959	2959	2953	3136	3248
12	27/05/82	N/S	3271	3330	3418	3389	3147
13	03/06/82	3601	3359	3377	3471	3395	3383
14	24/06/82	3265	3242	3248	3418	3342	3312
15	29/07/82	3236	3242	3248	3318	3295	3259
16	03/08/82	227*	N/S	227*	N/S	N/S	N/S
17	26/08/82	3024	3094	3018	3094	3236	3059
18	28/09/82	3295	3271	3289	3301	3354	3295
19	27/10/82	4196	3948	3925	3931	4001	4013
20	08/12/82	6869	5527	5468	6121	6086	6863
21	19/01/83	N/S	15521	13224	N/S	N/S	N/S
22	30/06/83	N/S	N/S	N/S	642	N/S	N/S
23	01/07/83	N/S	221	380	389	335	N/S
24	06/07/83	N/S	412	N/S	377	N/S	N/S
25	13/07/83	N/S	N/S	N/S	446	N/S	N/S
26	19/07/83	N/S	N/S	N/S	464	N/S	N/S
27	03/08/83	N/S	N/S	N/S	494	N/S	N/S
28	17/08/83	N/S	627	N/S	632	N/S	623
29	08/09/83	N/S	793	813	795	N/S	N/S
30	23/09/83	N/S	849	849	851	853	856
31	12/10/83	N/S	914	917	918	N/S	N/S
32	10/11/83	N/S	1045	1055	1060	N/S	N/S
33	16/11/83	N/S	1065	N/S	1095	N/S	N/S
34	15/12/83	N/S	1232	1237	1268	N/S	1252
35	16/02/84	N/S	1940	1970	1988	N/S	2005
36	18/04/84	N/S	2570	2553	2582	N/S	2688
37	22/05/84	N/S	2603	2573	2709	N/S	N/S
38	21/06/84	N/S	2630	2600	2736	N/S	N/S
39	17/07/84	N/S	2688	N/S	N/S	N/S	N/S
40	16/08/84	N/S	2818	2812	2883	N/S	2830
41	17/10/84	N/S	3177	3189	3272	N/S	3407
42	29/11/84	N/S	4196	4473	4367	N/S	4732
43	15/01/85	N/S	8230	N/S	N/S	N/S	N/S

Total Soluble Salt (mg/L)
* : Suspect Sample
N/S: No sample taken

Following the major summer inflow event of January 1982 salinities at the sample points ranged from 465 mg/L (6091024) to 1599 mg/L (609009), less than a week after the inflow. This variation between sample points is unusual, particularly since sample point 609009 is 'downstream' of 6091024 and it might be expected that the salinities would be similar. Therefore these data may not be representative of the lake salinity.

The salinity for 3/8/82 was based on two, similar quality samples. The low salinity at this time is not consistent with the salinities of the preceeding (29/7/82) and following (26/8/82) sample times (Table 2). The lake volumes were very similar for these three times and no inflow was recorded for the N. Arthur River therefore these low salinities may also not be representative of the general lake salinities.

5.2 Calculation of Lake Salt Load

The quantity of salt in the lake waters can be calculated from the lake volume and an estimate of the lake salinity. As discussed the salinities vary from site to site in the lake as well as through time and this was attributed to variations in inflow and lake configuration. The calculation of lake salt load and average salinity will be influenced by this point-to-point variation.

A weighted average and an arithmetic average salinity were calculated from the salinity of the sample points (Table 4). The weighted salinity was obtained by the approximate proportion of the surface area of the lake around each sample point (polygon method). These weights are listed in Table 3.

There are only small differences between the lake salinities obtained by the two methods (Table 4). The arithmetic average is generally slightly higher, particularly in 1981 and 1982 when there were significant salinity differences between sample points.

Table 3 Weights for Salinity Samples

SALINITY SAMPLE POINT

	6091024	609 009	6091025	6091026	6091027	6091028
1	.2	.2	.3	0.0	.3	0.0
2	1.0	0.0	0.0	0.0	0.0	0.0
3	.2	.2	.2	.2	.2	0.0
4	.2	.2	.2	.2	.2	0.0
5	.2	.2	.2	.2	.1	.1
6	.2	.2	.2	.2	.1	.1
7	.2	.2	.2	.2	.1	.1
8	.2	.2	.2	.2	.1	.1
9	.2	.2	.2	.2	.2	0.0
10	.2	.2	.2	.2	.1	.1
11	.2	.2	.2	.2	.1	.1
12	0.0	.3	.2	.2	.1	.2
13	.2	.2	.2	.2	.1	.1
14	.2	.2	.2	.2	.1	.1
15	.2	.2	.2	.2	.1	.1
16	.4	0.0	.6	0.0	0.0	0.0
17	.2	.2	.2	.2	.1	.1
18	.2	.2	.2	.2	.1	.1
19	.2	.2	.2	.2	.1	.1
20	.2	.2	.2	.2	.1	.1
21	0.0	.7	.3	0.0	0.0	0.0
22	0.0	0.0	0.0	1.0	0.0	0.0
23	0.0	.4	.2	.2	.2	0.0
24	0.0	.7	0.0	.3	0.0	0.0
25	0.0	0.0	0.0	1.0	0.0	0.0
26	0.0	0.0	0.0	1.0	0.0	0.0
27	0.0	0.0	0.0	1.0	0.0	0.0
28	0.0	.4	0.0	.3	0.0	.3
29	0.0	.5	.2	.3	0.0	0.0
30	0.0	.3	.2	.2	.1	.2
31	0.0	.5	.2	.3	0.0	0.0
32	0.0	.5	.2	.3	0.0	0.0
33	0.0	.7	0.0	.3	0.0	0.0
34	0.0	.3	.2	.2	0.0	.3
35	0.0	.3	.2	.2	0.0	.3
36	0.0	.3	.2	.2	0.0	.3
37	0.0	.5	.2	.3	0.0	0.0
38	0.0	.5	.2	.3	0.0	0.0
39	0.0	1.0	0.0	0.0	0.0	0.0
40	0.0	.3	.2	.2	0.0	.3
41	0.0	.3	.2	.2	0.0	.3
42	0.0	.3	.2	.2	0.0	.3
43	0.0	1.0	0.0	0.0	0.0	0.0

Table 4 Lake Salinity and Salt Load

		LAKE VOLUME	LAKE SALINITY AND SALT LOAD WEIGHTED AVERAGE		ARITHMETIC AVERAGE	
	DATE	(m^3)	(mg/L)	(tonnes)	(mg/L)	(tonnes)
1	01/07/81	479050	1849	886	1790	858
2	30/07/81	991060	1611	1596	1611	1596
3	05/08/81	1156800	1605	1857	1605	1857
4	02/09/81	2014800	1653	3331	1653	3331
5	22/09/81	1943900	3180	6182	4111	7991
6	05/11/81	1508700	2435	3674	2462	3714
7	15/12/81	1063000	3525	3747	3612	3840
8	19/01/82	615890	5794	3569	6055	3729
9	26/01/82	1992300	1060	2113	1060	2113
10	23/02/82	1629500	2200	3584	2213	3607
11	20/04/82	1118200	3048	3409	3072	3435
12	27/05/82	1002700	3300	3309	3312	3321
13	03/06/82	980350	3440	3372	3432	3364
14	24/06/82	1028200	3300	3393	3305	3398
15	29/07/82	1038900	3264	3391	3267	3394
16	03/08/82	1041200	228	237	228	237
17	26/08/82	1098600	3076	3379	3088	3392
18	28/09/82	1041000	3296	3431	3301	3436
19	27/10/82	849240	4002	3398	4003	3399
20	08/12/82	523330	6092	3188	6156	3222
21	19/01/83	108230	14832	1605	14373	1556
22	30/06/83	3459200	642	2221	642	2221
23	01/07/83	4501700	310	1393	332	1493
24	06/07/83	4326300	402	1738	395	1708
25	13/07/83	4669700	446	2084	446	2084
26	19/07/83	4189200	465	1946	465	1946
27	03/08/83	4629400	495	2291	495	2291
28	17/08/83	3977300	628	2498	628	2498
29	08/09/83	4795100	798	3825	800	3838
30	23/09/83	3954600	852	3368	852	3370
31	12/10/83	3506100	916	3212	917	3214
32	10/11/83	3103100	1052	3263	1053	3269
33	16/11/83	3091200	1074	3321	1080	3340
34	15/12/83	2792900	1247	3482	1248	3485
35	16/02/84	1777100	1975	3510	1976	3511
36	18/04/84	1370400	2604	3568	2598	3560
37	22/05/84	1382600	2629	3635	2628	3633
38	21/06/84	1433900	2656	3808	2655	3807
39	17/07/84	1437800	2688	3865	2688	3865
40	16/08/84	1407000	2833	3986	2836	3990
41	17/10/84	1286300	3267	4202	3261	4195
42	29/11/84	912950	4446	4059	4442	4055
43	15/01/85	363730	8230	2993	8230	2993

The area-weighted salinities were adopted as probably more representative of lake conditions.

5.3 Lake Volume and Salinity

Lake Toolibin volume and salinities for the four years from April 1981 are shown in Figures 8 a-d.

The lake began filling in June 1981 for the first time since 1975. Storage was only about 0.5 x 10^6 m^3 for most of June and July 1981, increasing to just above 1 x 10^6 m^3 by 5/8/81. The lake bed was not fully covered until about 2/9/81 when the volume reached 2 x 10^6 m^3.

From the peak lake volume of about 2 x 10^6 m^3 in August-September 1981, the volume decreased with a steepening recession into summer, suggesting an increasing evaporation influence. The average daily decrease in lake volume over December 1981 - January 1982 was about 14 000 m^3. For a lake surface area of 2 km^2 this rate is approximately 7 mm day^{-1} which is more than 80% of the average daily pan evaporation rate.

During 1981 lake salinities were between 1000 and 2000 mg/L TSS until November-December when salinities increased sharply to more than 5000 mg/L as the lake volume decreased to less than 1 x 10^6 m^3 into January 1982 (Figure 8a).

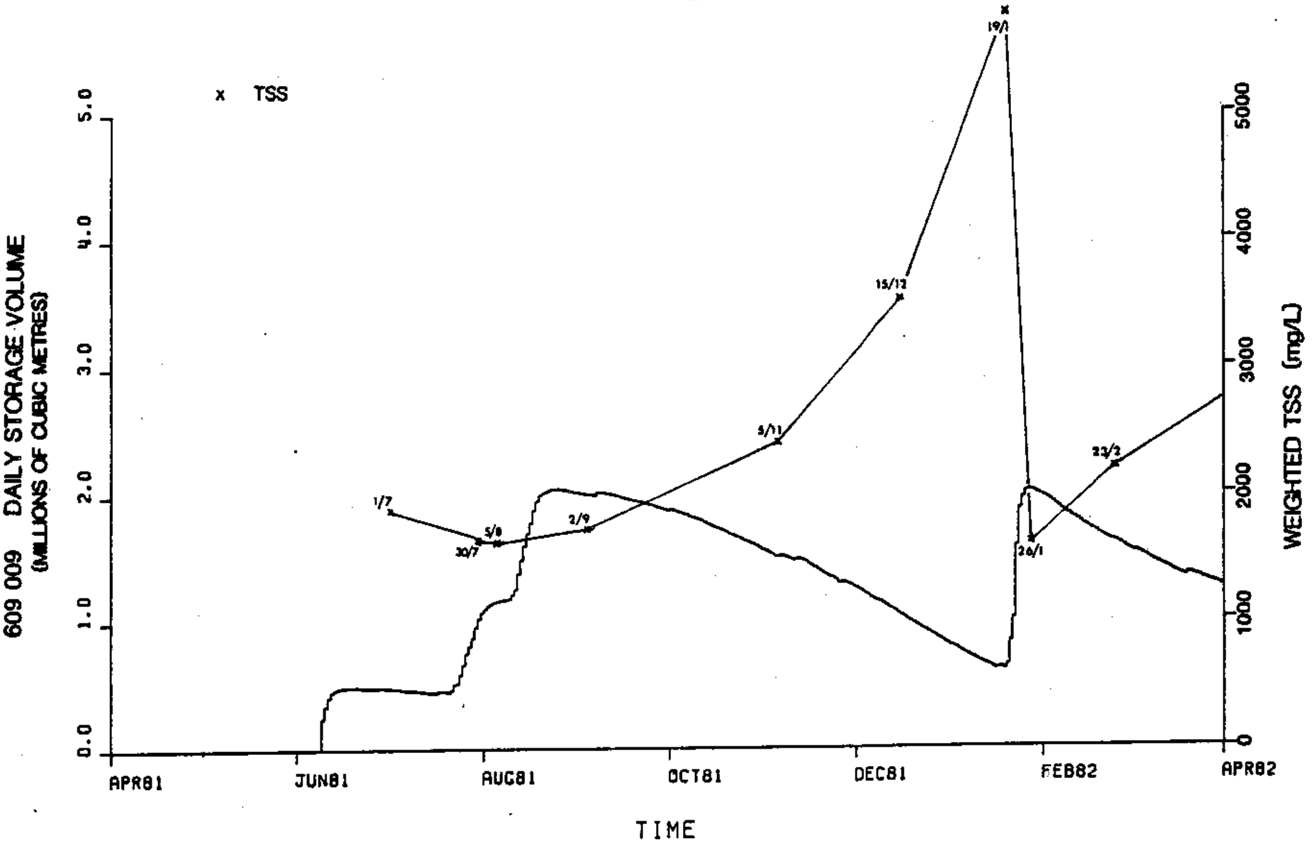


FIGURE 8a LAKE VOLUME:1981

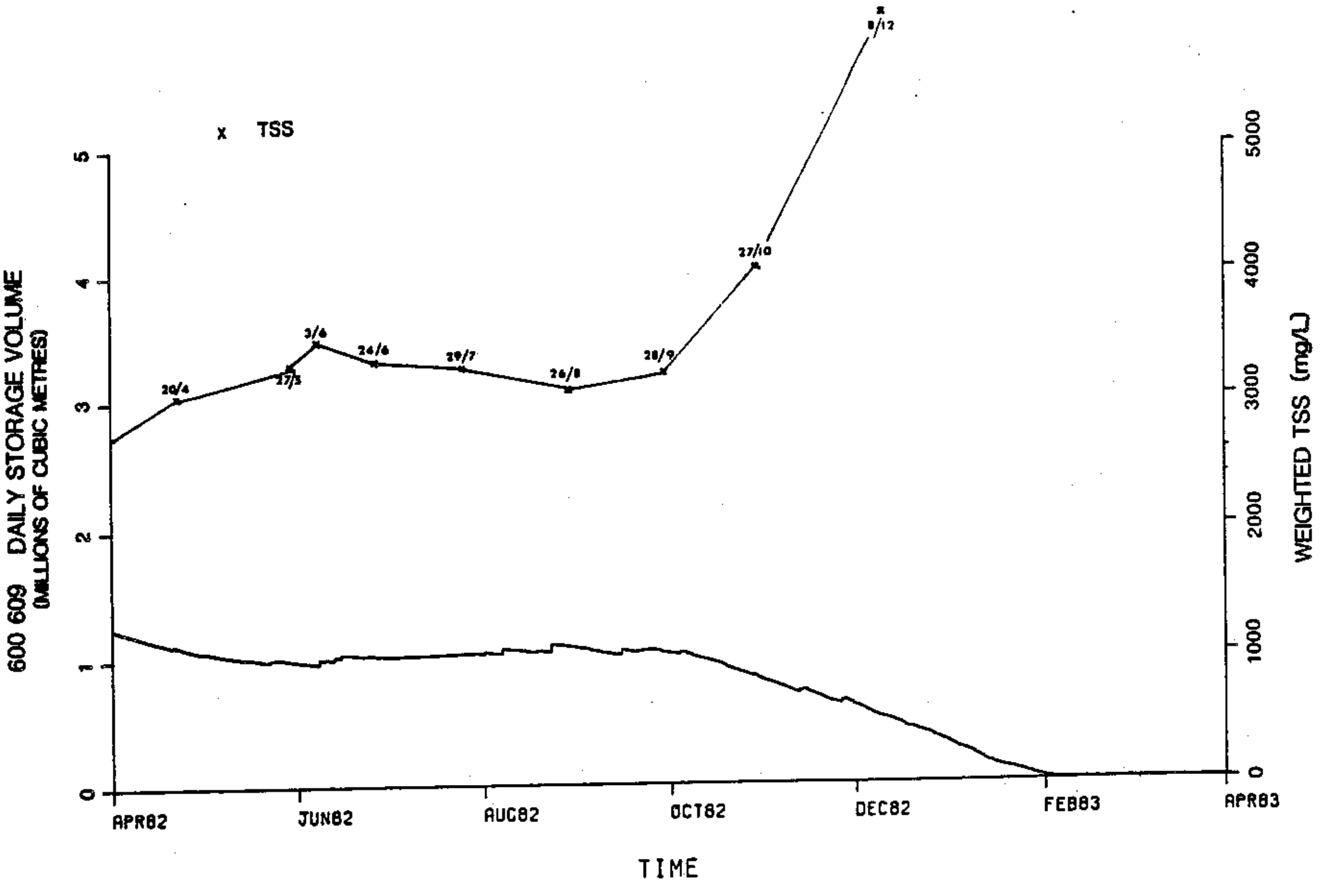


FIGURE 8b LAKE VOLUME:1982

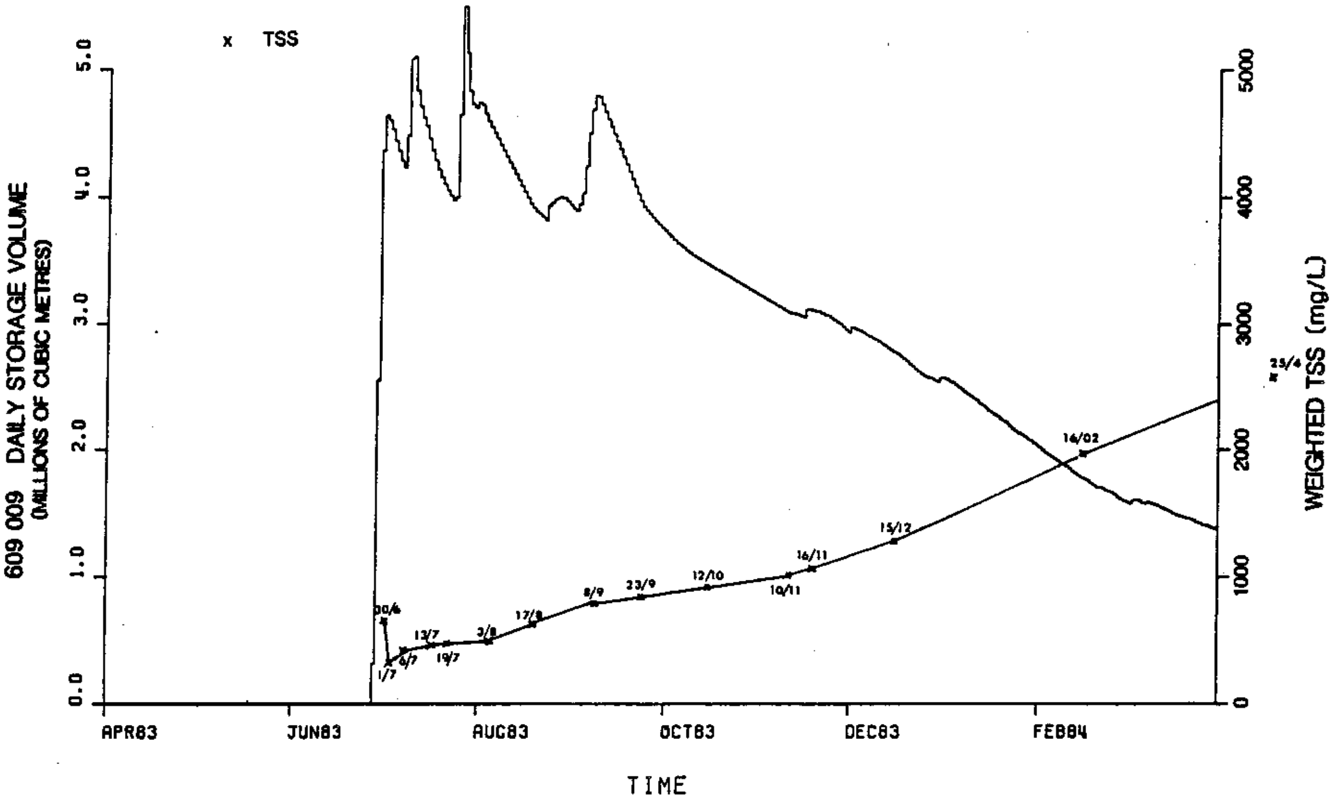


FIGURE 8c LAKE VOLUME : 1983

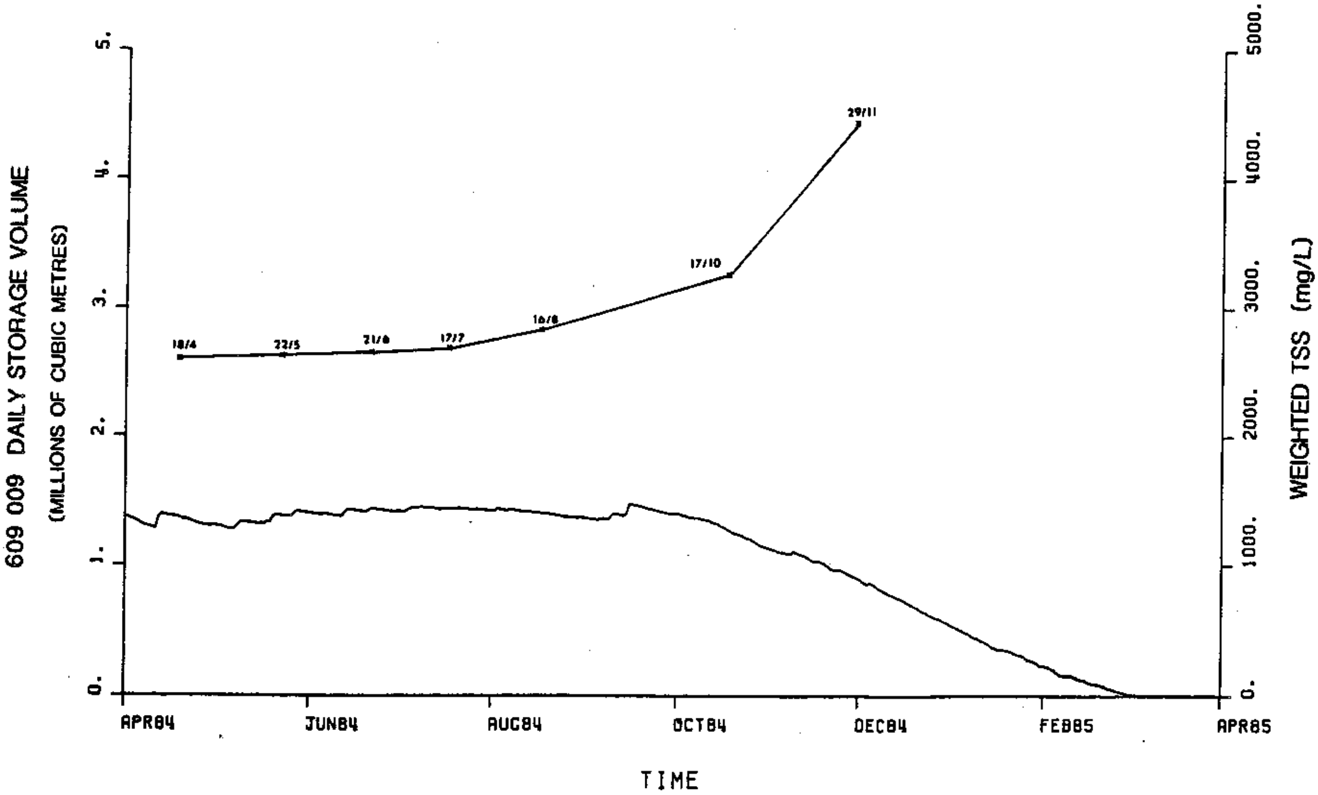


FIGURE 8d LAKE VOLUME : 1984

Widespread rainfall of cyclonic origin between 19-21 January 1982 produced an inflow of more than 1 x 10^6 m^3 with an average salinity of 410 mg/L. The salinities for 26/1/82 (Table 2) are suspect because a calculation using the lake volume and salt load on 15/12/81 and the January inflow volume and salt load yields a salinity higher than that sampled and more consistent with the results on 23/2/82. Since the lake did not overflow and the salt store should be largely conserved the data for 26/1/82 are not representative of lake conditions.

The lake volume remained at or just above 1 x $10^6 m^3$ during the 1982 winter (Figure 8b). The small fluctuations in storage can be attributed to rainfall and evaporation as very little surface water inflow was recorded. Salinities stabilized at around 3300 mg/L.

A recession commenced in October 1982 and at an average daily loss of about 8 400 m^3 the lake was dry by the beginning of February 1983, with salinities above 5000 mg/L by December 1982 and 15000 mg/L in January 1983.

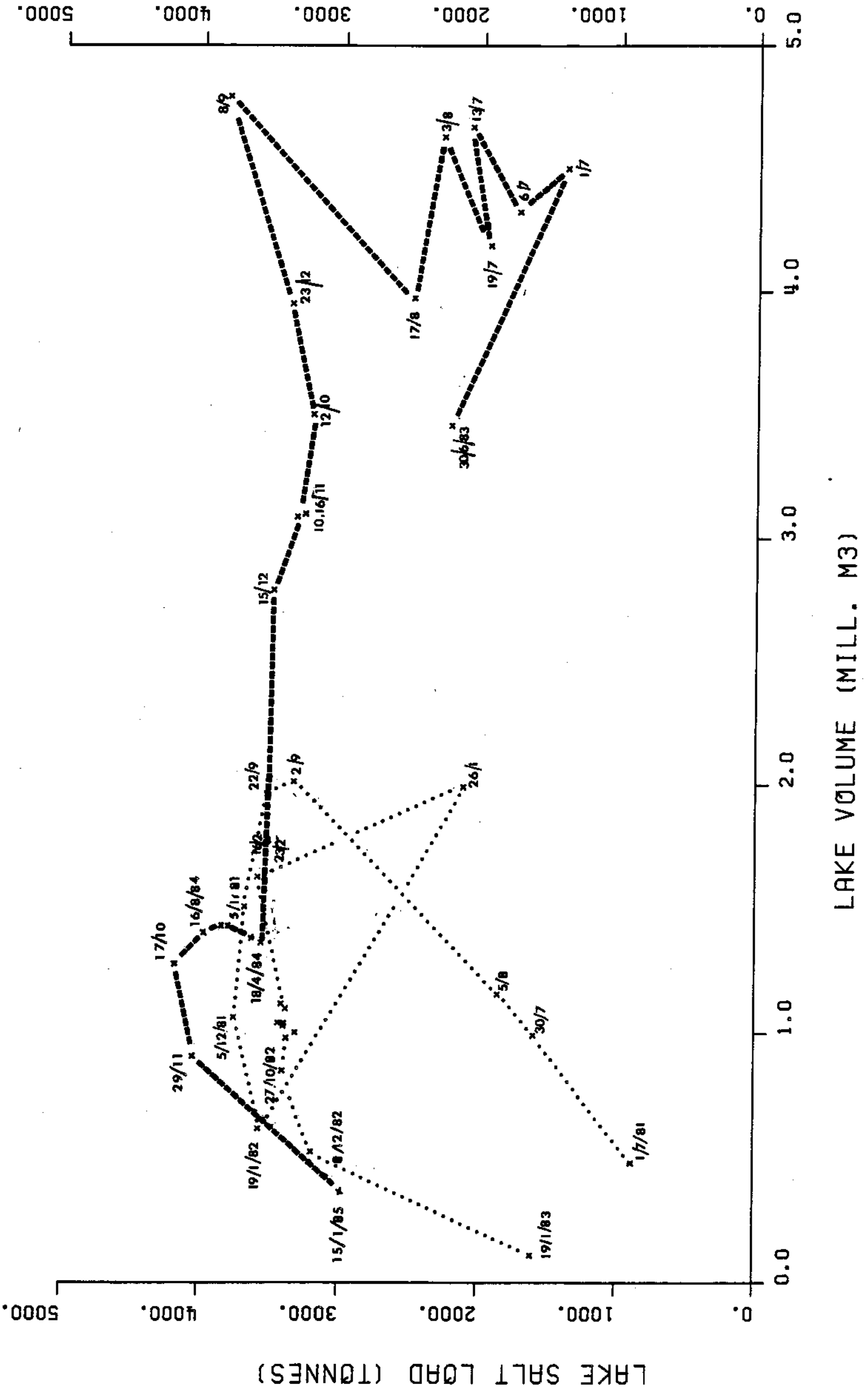
Large inflows, principally from N. Arthur River, produced lake volumes in excess of 4 x 10^6 m^3 for about 12 weeks from late June 1983. Peak volumes were 5.5 x 10^6 m^3, with steep recessions as the lake drained by overflow (Figure 8c). Overflow ceased by the middle of December 1983 and lake volume was 1.4 x 10^6 m^3 at the beginning of April 1984. Salinities increased from about 500 mg/L at the end of June 1983 to 2600 mg/L in April 1984 with a steepening of the rate of increase in summer.

During 1984 the lake response (Figure 8d) was fairly similar to 1982 with a recession into winter, an essentially constant volume through winter and a steepening recession into summer. The lake was effectively dry by late summer 1985.

5.4 Lake Volume, Salt Load, Salinity Relationships

The majority of the lake salt load-volume data plot between 3000 and 4000 tonnes (Figure 9). During the inflow periods in 1981 and 1983 the lake salt load increased with increasing volume. The difference between the amount of salt in the lake water and that in the measured inflows following a period of the lake being dry is a possible indication of residual salt storage in the lake. This difference was 500t in July 1981 and 720t in June 1983. However not all surface inflow sources were measured (such as North West Creek and the interceptor drain) and there may be an error in calculating the lake salt load from a few samples. Therefore any residual salt load was probably much less than the 500-700t indicated.

In 1983 the lake salt store increased by 1600t between the first measurement on 30/6/83 and the peak measurement on 8/9/83. Approximately 7200t was input by the N. Arthur River during this period. The steady increase in salt storage in the lake during a period of overflow probably results from the displacement of fresher, earlier inflow by more saline, later inflows (see Figure 6d).



LAKE SALT LOAD - VOLUME

FIGURE 9

Little increase in lake salt storage is evident during the periods of lake volume decline over the 1981/82, 1982/83 and 1983/84 summers (Figure 9). In most cases the load decreases as the lake volume declines below about 1.5-2 x 10^6 m^3.

The lake salt store increased by about 600t in the 1984 winter with little increase in volume. Only about 200t of salt was measured as inflow during this time so that about 400t may have been input from the interceptor drain on the western shore of the lake. Some of the increase may also be a result of solution of salt from the soils of the exposed lake bed by rainfall, inflow and increased lake volume.

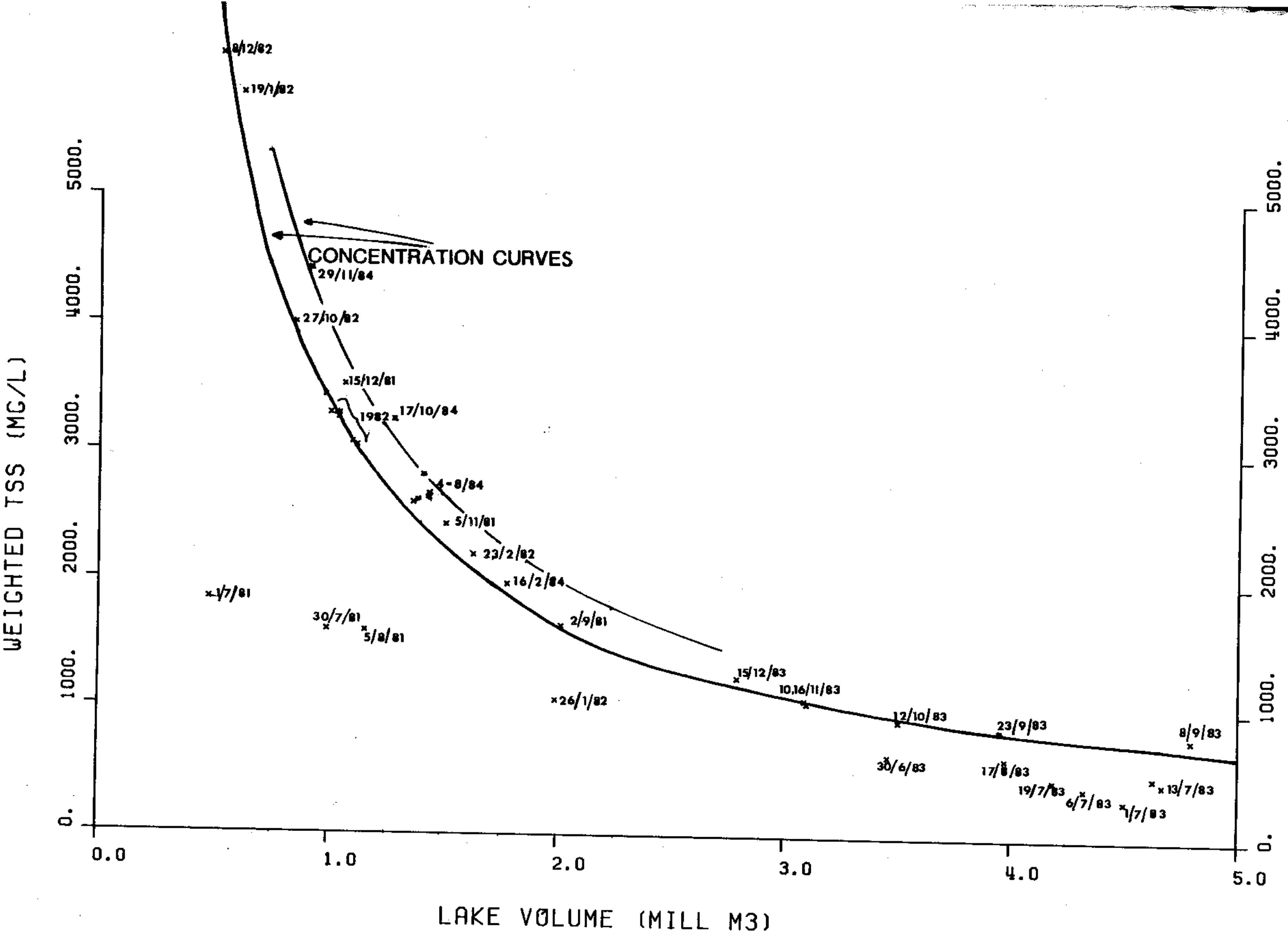
Lake salinities (Figure 10) increase from less than 1000 mg/L at volumes greater than 4 x 10^6 m^3, to more than 5000 mg/L at volumes less than 1 x 10^6 m^3. The variation of salinity with volume, particularly below the overflow volume, appear to follow an evaporation-concentration relationship, that is:-

$$C = L/V \qquad 5.1$$

where C : concentration (mg/L)
L : salt load (tonnes)
V : volume (10^6 m^3)

To illustrate this, an upper and lower bound curve were constructed (Figure 10) with salt loads of 4000t and 3340t selected from Figure 9.

The 1981/82, 1982/83 and 1984/85 recessions are generally represented by these two bounds, thus supporting the evaporation-concentration effect. However below about 0.5 x 10^6 m^3 this effect 'over-predicts' salinities, indicating, as does the data in Figure 9, that the salt load in the water of the lake is not constant as the lake dries.



LAKE SALINITY/VOLUME

FIGURE 10

5.5 Lake-Groundwater Interaction

Lake Toolibin does not overflow when lake volumes are less than about 2.7 x 10^6 m^3. During summer little inflow from the rivers occurs and the remaining inputs and outputs to the lake are evaporation, and possibly groundwater (equations 3.5 and 3.6).

The contribution of groundwaters will be most readily detectable, if at all, during periods of no surface inflow. Increases in lake salt storage may indicate such a contribution. The changes in lake salt storage over several such periods are listed in Table 5.

Six of the nine periods indicate a decrease or loss of salt from the lake. Of the three periods when an increase in lake salt storage occurred, two (5/11/81-15/12/81 and 15/12/83-16/2/84) almost certainly include small amounts of surface inflow. The third period, 16/2/84-18/4/84 also indicates some inflow because of the lake volume change. Therefore it is likely that these three increases are probably due to surface water inflow rather than groundwater. This is supported by the average daily change in the lake salt storage (Table 5) expressed in tonnes per day where the increases are all small relative to the decreases.

Most of the increases in lake salt storage can therefore be accounted for by surface water inflow. The lake-groundwater interaction appears to be one of the loss of water and salt from the lake rather than any net gain.

Estimates of the magnitude of this loss are given in Table 6. These were calculated (equation 3.8):-

$$G = (S_t - S_{t-1}) \times 10^6/C_a \qquad 5.2$$

where : G : recharge to groundwater (m^3)
S_t : lake salt load at time t (tonnes)
S_{t-1} : " " " " " t-1 (tonnes)
C_a : average lake salinity t to t-1 (mg/L)

The loss (G) is also given in m^3 day^{-1} and mm day^{-1}, the latter by using the average surface area of the lake between the times indicated.

The average loss was 950 m^3 day^{-1} (one standard deviation of 90), a remarkably consistent result. As an average depth, the values range between 0.3 mm day^{-1} and 0.55 mm day^{-1} with a mean of 0.4 mm day^{-1}. This rate is more than ten times less than the average daily pan evaporation rate during these periods. Therefore although most water is lost to the atmosphere, a very small seepage is apparently sufficient to reduce the store of salt in the water of the lake over summer.

Where this salt goes in the lake-groundwater system cannot be determined in this study. It may be leached through the unsaturated zone to the underlying groundwater or it may be stored in the soils of the exposed lake bed (Torgersen, 1984) for leaching or return into solution in subsequent inflows. Although there is insufficient evidence, the latter does not appear to be a dominant mechanism operating in Toolibin at this stage.

Table 5 Changes in Lake Salt Storage

PERIOD	CHANGE IN SALT LOAD (tonnes)	(%)	(tonnes day^{-1})
5/11/81 - 15/12/81	+73	+2	+1.8
15/12/81 - 19/1/82	-178	-5	-4.9
23/2/82 - 20/4/82	-175	-5	-3.1
20/4/82 - 27/5/82	-100	-3	-2.6
28/9/82 - 23/10/82	-33	-1	-1.1
27/10/82 - 8/12/82	-210	-6	-5.0
8/12/82 - 19/1/83	-1583	-50	-36.8
15/12/83 - 16/2/84	+28	+1	+0.4
16/2/84 - 18/4/84	+46	+1	+0.7
17/10/84 - 29/11/84	-143	-3	-3.3

Table 6 Losses to Groundwater

PERIOD	CHANGE LAKE VOLUME (m^3)	TSS (t)	AVERAGE TSS (mg/L)	LOSS TO GROUNDWATER (m^3)	(m^3 day^{-1})	(mm day^{-1})
11/12/81 - 19/1/82	447100	178	4660	38200	1060	0.5 (2.0)*
23/2/82 - 20/4/82	511300	175	3500	50000	860	0.3 (2.5)
20/4/82 - 27/5/82	115500	100	3175	31500	900	0.4 (2.25)
27/10/82 - 8/12/82	325900	210	5050	41600	970	0.55 (1.75)
17/10/84 - 29/11/84	373400	143	3856	37085	852	0.34 (2.5)

* value in brackets is average surface area of lake (km^2)

6. LONG TERM LAKE RESPONSE

6.1 Inflow

Approximately 6mm of runoff from the catchment is required to fill Lake Toolibin to the point of overflow and this represents a runoff of 1.5% of average rainfall. In the winter of 1981, 5mm of runoff, followed by 2.5mm in January 1982 failed to fill the lake. However in 1983 total runoff was 36 mm with a maximum daily inflow of 5.6mm. Very little runoff occurred in the winter of 1982 and little has occurred to September 1984.

Since the record of lake level commenced in December 1977 the lake received little or no inflow between 1978 and 1980. Therefore since 1978, only in two of the last seven years (1981 and 1983) has the lake received substantial inflows.

As there are no long term records of lake level or inflow, the probability of inflow must be inferred from long term rainfall records. A 78 year (1907-1984), composite daily rainfall record from Wickepin and Narrogin was obtained for use in this study.

6.2 Simulation of Inflow

To assist in the estimation of the likelihood of filling Lake Toolibin, a simple, daily rainfall-runoff water balance model developed by Sukvanachaikul and Laurenson (1983) was applied to the N. Arthur River catchment. Daily rainfall is added to a single store from which evaporation and runoff are calculated.

An approximate calibration was obtained for the 1981-1983 data period. Although the model overpredicted runoff in 1983, no runoff was predicted for the winter of 1982 which was considered to be the important response to simulate.

6.3 Probability of Inflow

The calibrated model was run on the 78 years of daily rainfall, producing monthly runoff. These monthly runoff were then classed into no inflow, inflow insufficient to fill the lake and runoff sufficient to fill the lake. The time series of this classification is shown in Figure 11.

Inflow sufficient to fill the lake probably occurred in 33 of the 78 years (42%) with no inflow in 22 of the years (29%). In the remaining 29% of the years inflow was probably insufficient to fill the lake. Inflow therefore occurs in 7 out of 10 years.

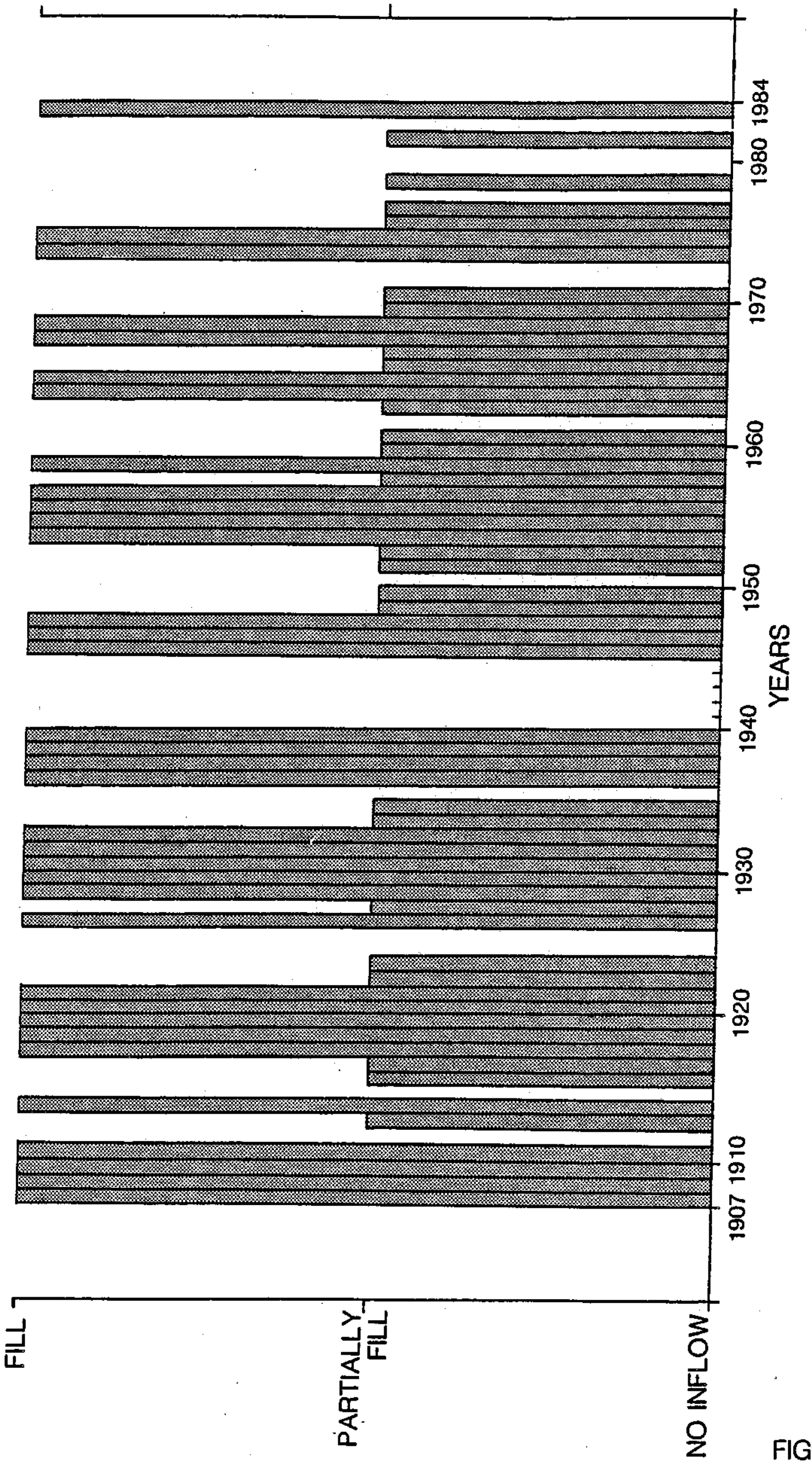
Sequences of no inflow and filling are shown in Figure 11. Substantial inflows occurred between 1926 and 1932 (7 years) with partial filling in 1933 and 1934.

A five year sequence of no inflows occurred between 1940 and 1944 which appears to be the most severe on record; followed by the four years 1977-1980. (The rainfall-runoff model predicted some inflow for July 1978, which is not verified by the record of lake level). Other sequences of little or no inflow include 1922-25 (4 years), 1948-52 (5 years), 1959-62 (4 years) and 1969-72 (4 years).

Lake Toolibin probably has water of more than 1 m depth (10^6 m^3) for more than 70% of the time because of the carry-over effect of previous wet years. However in the context of present salinities this water may be above 3000 mg/L.

6.4 Inflow Salinity

The long term inflow salinity will be crucial to the viability of Lake Toolibin as a wildlife habitat. The current salinity of inflow, from the small data set, provides a baseline against which increases in salinity can be compared.



INFLOW TO TOOLIBIN

FIGURE 11

The flow weighted N. Arthur River inflow salinity was 1230 mg/L in 1981 and 550 mg/L in 1983. Runoff and salt loads were 4.8 mm and 2590t in 1981 and 36mm and 8500t in 1983. With these two data points a relationship between the salinity of inflow (C) and inflow volume (Q) was derived:-

$$C = 1656 / Q^{0.4} \qquad 6.1$$

where : C : inflow salinity (mg/L)
Q : inflow volume (10^6 m^3)

This is shown in Figure 12. For an inflow of 2.7 x 10^6 m^3 to just fill the lake this relationship produced a salt load input of 3000t.

The relationship has been derived using only two data points and therefore must be used with caution. From experience with saline catchments elsewhere in the south west the salinities appear low for small inflows (less than 3000 mg/L for 0.5 x 10^6 m^3).

The salinity of inflow over the next decades cannot be predicted. However it is unlikely to decrease and may well increase as a result of the delayed effects of the extensive clearing of the lighter, upslope soils during the late 1940's and early 1950's. The time scale for the development of the full effects of clearing on groundwaters in this area may well be of the order of at least 50 years. This is based on modelling of groundwater recharge-discharge in other areas of south western Australia (P.G. Lutz, personal communication, 1984).

An approximate salt balance for the N. Arthur River catchment for 1981 and 1983 produced output to input ratios of 0.8 and 2.2 respectively. Those are low relative to salinized catchments in higher (600 mm) rainfall areas of the south west where output to input ratios of more than twenty have been recorded. It is considered unlikely that Toolibin ratios will approach these because of lower recharge.

Soil salinity surveys and particularly hydrogeologic investigations in the catchment have apparently indicated the potential for a significant increase in the area of saline land. If this resulted in a doubling in salt load into the lake for example, without much additional water, the lake salinity would also at least double and evaporation would then further increase lake salinities.

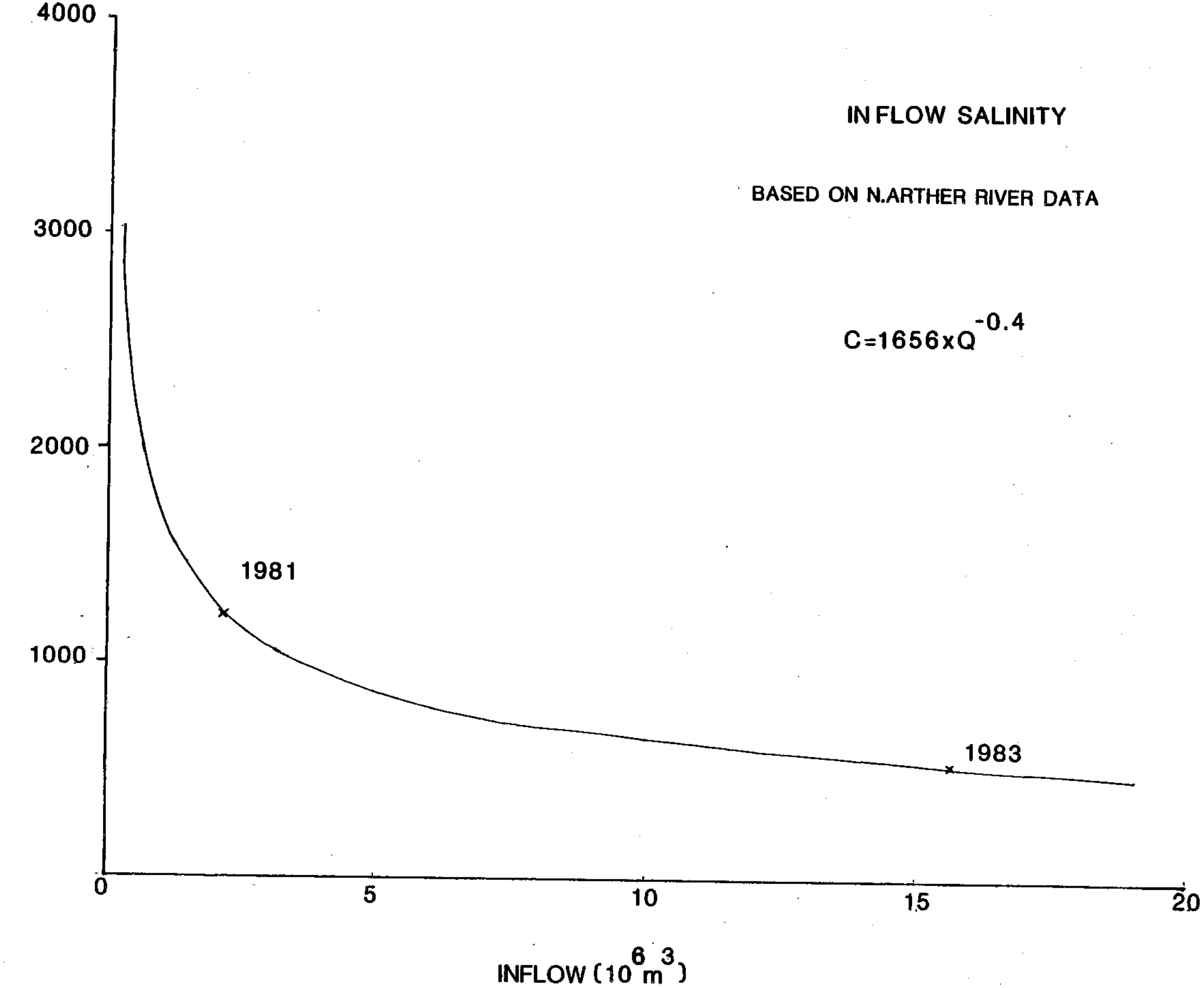

INFLOW SALINITY
BASED ON N.ARTHER RIVER DATA
C=1656xQ-0.4
Salinity (mg/L)
4000
3000
2000
1000
0
5
10
15
20
INFLOW (10 6 m 3)
1981
1983

FIGURE 12

7. MANAGEMENT OF LAKE SALINITY

7.1 Summary of Hydrology

Most of the lake water and salt is input by N. Arthur River and North West Creek. NW Creek contributes about 10% of N. Arthur River inputs, flows for a longer time, particularly in dry years and has higher baseflow salinities. In dry years little surface runoff enters the lake from N. Arthur River, partly because of the lakes upstream which contain the small amounts of saline runoff. This has a beneficial effect on the salinity of the lake. Surface water inflow occurs in approximately 7 out of 10 years and is probably sufficient to fill in 4 of these years.

Salt is apparently lost from the lake water thereby reducing the lake salt load and reducing the increase in salinity as the lake concentrates by evaporation. High groundwater levels on the west of the lake are probably:-

(i) contributing to soil salinization and tree mortality when the lake is low or dry

(ii) reducing the efficiency of the leaching when the lake is full.

Under current hydrologic conditions, lake salinities are above 3000 mg/L, through the concentrating effects of evaporation, when the lake volume reduces to about a million cubic metres (average depth of 1m).

The salinity of Lake Toolibin may become more serious if the input of salts from the catchment increases and/or the leaching process decreases due to rising groundwaters under the lake.

7.2 Ameliorative Measures

Clearly the solutions are to reduce inputs of salt and/or to increase the output of salt. This would involve any or all of the following:-

(i) Rehabilitation of the catchment. A decrease in the salt load and/or increase, of better quality, runoff from the catchment may be possible through better management. A large scale tree planting programme, similar to that on the Collie catchment, is impracticable because of the area involved.

(ii) Diversion of inflows. Diversion of some of the low, saline inflows from N. Arthur River and NW Creek would reduce the input of salt at the start and end of the flow period. Works required would include diversion structures on both streams and a channel of several kilometres with a sump and pump to lift water downstream.

Most of the salt load input to the lake occurs at higher flows and it would be difficult to divert these. Water would also then be diverted from the lake which may otherwise have improved the value of the lake as a wildlife habitat. There would also be problems of operating the diversion of flows. For these reasons diversion does not appear to be a practicable option.

(iii) Lowering Groundwaters. Pumping of groundwaters, particularly on the western half of the lake, would reduce soil salinization and enhance leaching. However the area involved and the hydraulic properties make this an impractical proposition.

(iv) Control of lake volume. Emptying the lake when salinities rise to 3000 mg/L would require pumping about a million cubic metres.

(v) Tree planting. A belt of trees, say 200m wide along the western bank may have an effect on the local groundwaters in addition to improving the local habitat.

8. CONCLUSIONS

This study has shown that the salinity problem of Lake Toolibin is caused by the input of salt from the salinized agricultural catchment. Limited data indicates that the quantities of salt and water draining into the lake are possibly already sufficient, on average, to result in lake salinities above 1000 mg/L TSS and often above 3000 mg/L TSS. It is possible that the full salinity effects of clearing in the catchment have not yet developed.

Salt is being lost from the lake water, presumably to a groundwater system beneath the lake, in sufficient quantities to effectively remove most of the salt held in the lake at volumes less than the overflow of 2.7×10^6 m^3. This loss is an important process in the continued survival of the lake as a wildlife habitat.

There is insufficient evidence to confidently predict future salt load inflows to Lake Toolibin or groundwater levels beneath the lake. However the trends are for both salt inflows and groundwater levels to increase and on this basis it is probable that the salinity of Lake Toolibin will also continue to increase.

9. REFERENCES

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