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Water levels, balance, and chemistry of Lake George, New South Wales

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The marked water-level fluctuations of Lake George, a closed lake in southern New South Wales, have long been a subject of speculation. Monitoring over a 20-year period (1958-77) shows that the fluctuations are a response to seasonal and long-term variations in rainfall, evaporation and inflow of streams. An approximate water balance for the lake has been computed and shows marked seasonal characteristics; increases in water volume between May and October correspond with high inflows and low evaporation, while decreases in water volume between November and April correspond with low inflows and high evaporation. The long-term fluctuations reflect climatic variability. Salinity of the lake water, which is a sodium chloride type, varies inversely with water volume. A substantial net loss in salt was observed during a recessive phase of the lake in 1973.

Introduction

Lake George is a closed lake in a basin of internal drainage covering 932 km^2 in the Southern Tablelands of New South Wales (Fig. 1).

The lake was 'a splendid sheet of water' when first discovered by European colonists in 1820, but by 1839 'was dry enough to drive a team across the middle (historical sources quoted by Russell, 1887). The considerable fluctuations in the water level of Lake George have created a good deal of interest ever since. Thus, Griffith Taylor wrote in 1907—

> 'The lake is now portioned into grazing leases, and fences run nearly across the bed. The local sheep-breeders for the most part much prefer the lake dry, since many extra sheep can be carried on their runs . . . At the same time the neglected boathouses,

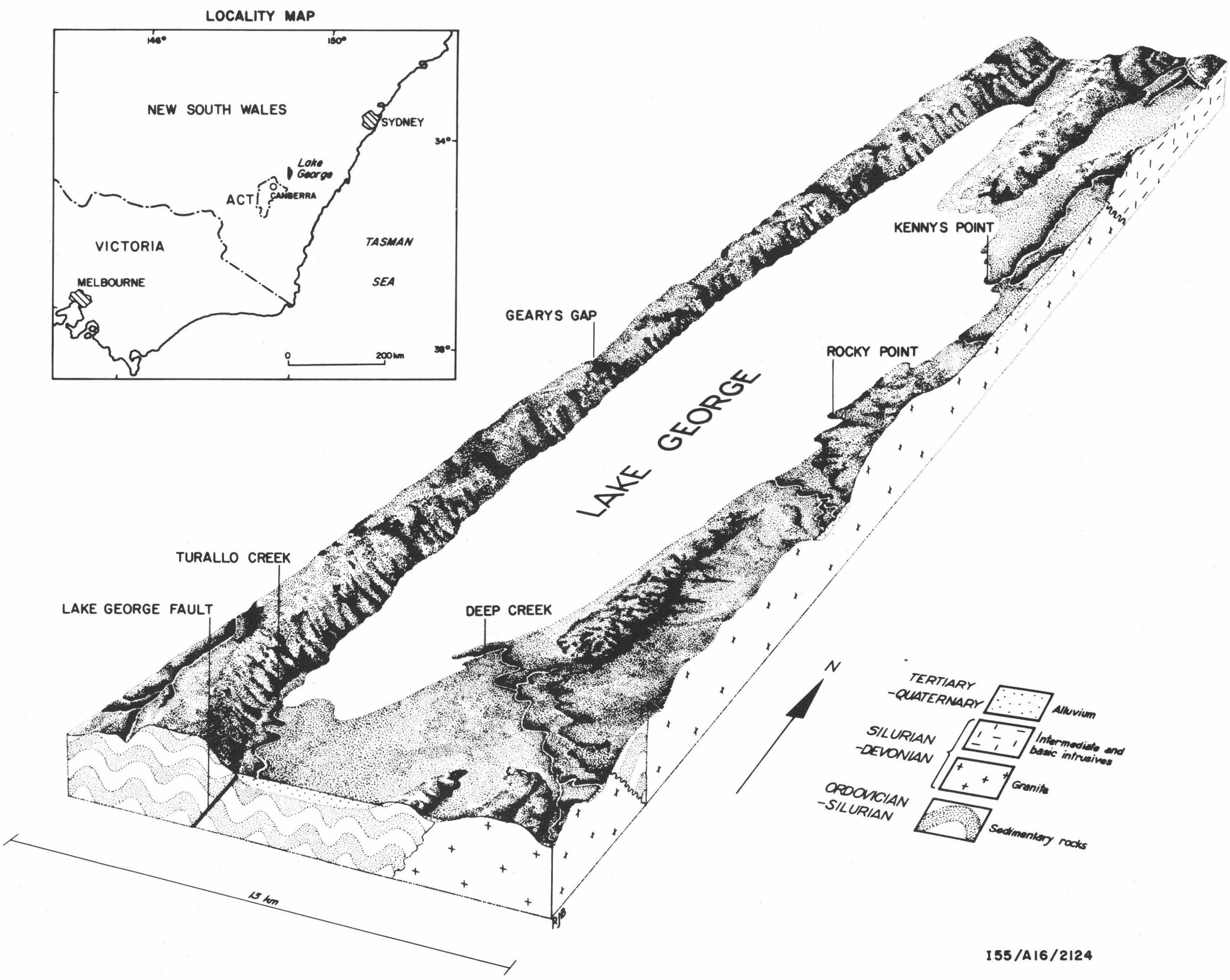

Figure 1. Block diagram illustrating the geological setting of Lake George.

Figure 2. Lake George looking southeast from Geary's Gap, March 1978.

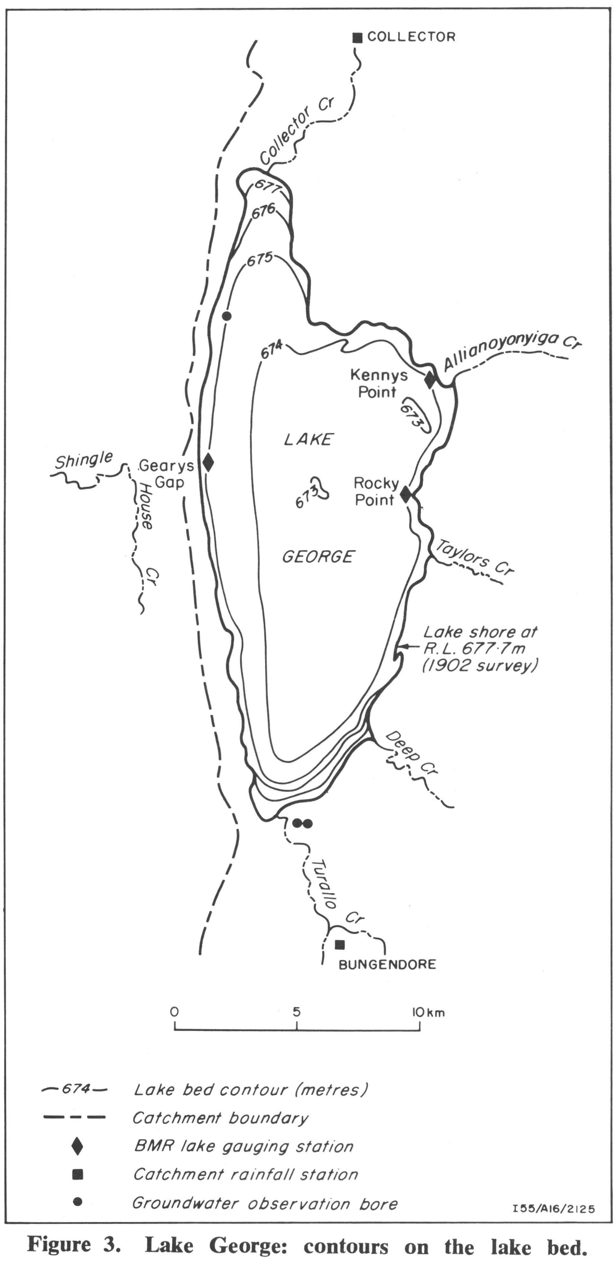

Figure 3. Lake George: contours on the lake bed.

jetties, and decaying boats and launches which are to be seen near Bungendore, recall the good old times when the lake teemed with Murray cod . . .'

A substantial body of myth has grown up to explain the appearing and disappearing waters of Lake George. Popular theories have included the draining of lake water through a fissure and its subsequent refilling from an underground spring! Recently, because of the lake's proximity to Canberra, possible recreational and water storage uses have been mooted for it, and the study of its fluctuations is thus of economic importance.

The hydrographic record of Lake George extends over 160 years and is one of the longest in Australia. The first official gauge at Lake George was set up in 1885 by H. C. Russell, the Government Astronomer of New South Wales (Russell, 1887). Levels were gauged by the New South Wales Department of Works until the lake dried up in 1930. BMR has gauged Lake George since 1950 (Noakes, 1951) and detailed monitoring for computation of the water balance has been undertaken since 1958 (Burton, 1972; Burton & Wilson, 1973).

This paper summarises the results of BMR monitoring of the lake over the last 20 years.

Geological setting

The geological setting of Lake George is shown in the block diagram (Fig. 1).

The lake is underlain by Tertiary-Quaternary alluvium which overlies deeply weathered Palaeozoic bedrock. Geophysical surveys (Polak & Kevi, 1964), and drilling to the south of the lake, have shown that the alluvium is 45-50 m thick; it consists of interbedded sand, clay and gravel. A drillhole in the lake bed near the north end of the lake was completed in mainly clayey alluvium at a depth of 71 m. The alluvium around the lake is an important source of sand and gravel for Canberra development, and contains aquifers which supply water to the town of Bungendore and the Woodlawn mine.

Geophysical surveys have shown that bedrock beneath the lake is weathered to depths of up to 130 m. The bedrock consists mainly of Ordovician and Silurian sedimentary and granitic rocks (Garretty, 1936). These rocks are separated from less weathered Ordovician rocks to the west by the Lake George

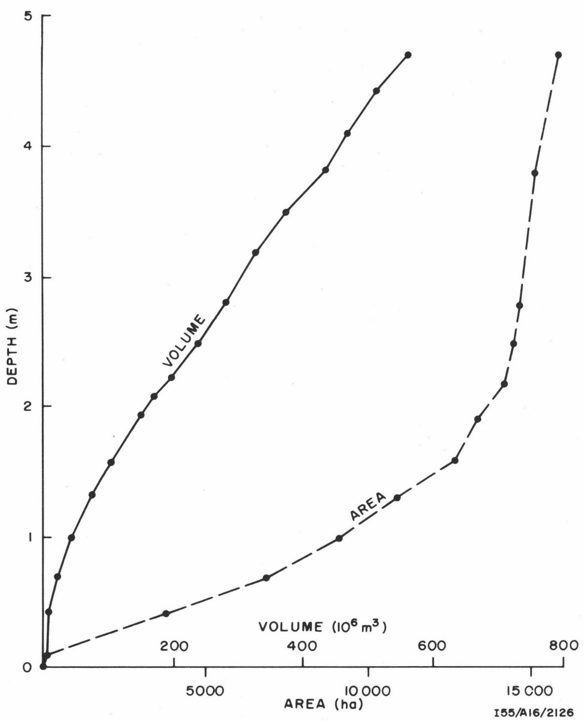

Figure 4. Area and volume of water in Lake George as a function of maximum depth.

Fault, a steeply dipping, meridional, reverse fault (Noakes, 1957). The escarpment on the west side of the lake is probably the result of post-Palaeozoic movement on the Lake George Fault, and the lake probably originates from disruption of a pre-existing drainage system by this movement (Jennings, Noakes & Burton, 1964).

Abandoned shoreline features up to 37 m above the lake bed indicate a history of substantial water-level fluctuations dating back beyond 20 000 years B.P. (Coventry, 1976). Above this height, the lake would have overflowed to the west through a saddle in the escarpment known as Geary's Gap. Pollen studies of lake bed cores up to 9 m deep, by Dr G. Singh of the Australian National University, have extended the history of vegetation and lake conditions back possibly 100 000 years (Bowler & others, 1976; Churchill & others, 1978).

Water-level fluctuations

Monitoring of water levels, temperature and salinity has been carried out monthly from one or more of the three gauging stations, Geary's Trig., Kenny's Point, and Rocky Point (Fig. 3). The lake is subject to fluctuations caused by wind-generated seiches with an amplitude of up to 15 cm and a period of up to 2 hours (Burton, 1972).

The lake bottom is smooth with the lowest point just below 673 m (Fig. 3). Lake-bed surveys in 1902 and 1973 showed only slight changes of up to 15 cm due to sedimentation during this time. The lake area and volume depend on the shape of the basin and are related to maximum depth as shown on the graph in Figure 4.

The results of monitoring of the water-level fluctuations of Lake George between 1958 and 1977 are shown in Figure 5. There are regular seasonal changes in lake level in response to rainfall and evaporation, typically with maxima in October and minima in April. The seasonal fluctuations are superimposed on long-term variations with a period of several years. The highest level reached during the period of measurement was 677.29 m, a maximum depth of 4.41 m, in October 1963; this corresponded to a lake area of 15 400 hectares, and a volume of just over 500 million cubic metres. The lowest level reached was 673.47 m, a depth of 0.59 m in July 1973. This corresponded to a lake area of 4 300 hectares and volume of 7 million cubic metres, and was the culmination of a low stage lasting several years.

The composite lake hydrograph based on historical records from 1818 to 1977 is shown in Figure 6. Depths of more than 7 m were recorded in 1820-23 and 1873-75 (Russell, 1887). Rainfall records are available for Bungendore from the 1880's. From the rainfall variation graph (Fig. 6), it is evident that the periods of 1904-12 and 1930-45—when the lake was dry or nearly dry—were periods of below average rainfall in the catchment.

Water balance

The water balance derived from Lake George is based on the simplified equilibrium equation for closed lakes,

$$I + P\,(A_L) = E\,(A_L)$$

where I is inflow from the catchment, P is precipitation on the lake surface, E is the gross evaporation rate, and A_L is the lake surface area (Langbein, 1961). Variations in inflow, precipitation, and evaporation produce fluctuations in water level with corresponding changes in lake area and volume. This can be represented by the equation

$$\Delta S = I - (E\text{-}P)\,A_L$$

where ΔS is the change in lake volume.

Groundwater seepage into and from Lake George is thought to be only a minor component of the water balance, and has not been taken into account in computations. Piezometric levels in two observation bores about one kilometre south of the lake are generally 6-7 m above lake level, which indicates a net groundwater inflow to the lake.

The approximate water balance for Lake George has been calculated for the past 20 years (Table 1). The data used for computation are precipitation and evaporation which are based on meteorological station data, and the monthly change in lake level obtained at the gauging stations in the lake. Inflow from the catchment is not gauged, but is estimated by difference; any errors in the components of the water balance are thus incorporated into the inflow component.

Precipitation is taken as the average monthly rainfall for two rain gauges in the catchment at Bungendore and Collector. The mean annual precipitation on the lake is estimated as 749 mm; the annual precipitation has fluctuated between 392 mm (1967) and 1119 mm (1974). Precipitation is distributed fairly evenly throughout the year, with a maximum in October. The total precipitation on the lake is estimated as about 100 million m^3 annually.

The evaporation component is based on monthly measurements at the Canberra meteorological station, 30 km to the southwest of Lake George. Until February 1967 Canberra evaporation was measured with an Australian Sunken Tank; Burton (1972) established that these measurements are very close to the actual lake evaporation. After February 1967, Canberra

	Monthly rainfall (mm)	Change in lake level (mm)	Change in lake volume (million m³)	Volume of rain on lake (million m³)	Evaporation from lake Volume (million m³)	Evaporation from lake Depth (mm)	Inflow to lake (million m³)
January	69	— 83	—10.59	9.13	23.56	177	3.83
February	66	— 42	— 8.21	8.40	18.47	138	1.85
March	47	— 70	— 9.21	6.22	15.98	121	0.56
April	56	— 24	— 2.46	7.00	10.02	77	0.56
May	51	+ 2	+ 0.96	6.61	5.82	45	0.17
June	43	+ 40	+ 4.51	5.73	3.76	28	2.54
July	56	+ 79	+ 9.32	7.63	4.20	32	5.89
August	69	+ 85	+11.26	9.02	6.36	47	8.59
September	65	+ 40	+ 9.14	9.12	9.42	70	9.45
October	97	+ 70	+ 7.33	13.42	14.80	109	8.71
November	65	— 30	— 5.97	8.76	21.68	157	6.95
December	65	—121	—13.10	8.84	24.22	183	2.28
Annual Total	749	— 54	— 7.02	99.88	158.29	1184	51.38

Table 1. Approximate mean monthly water balance, 1958-77.

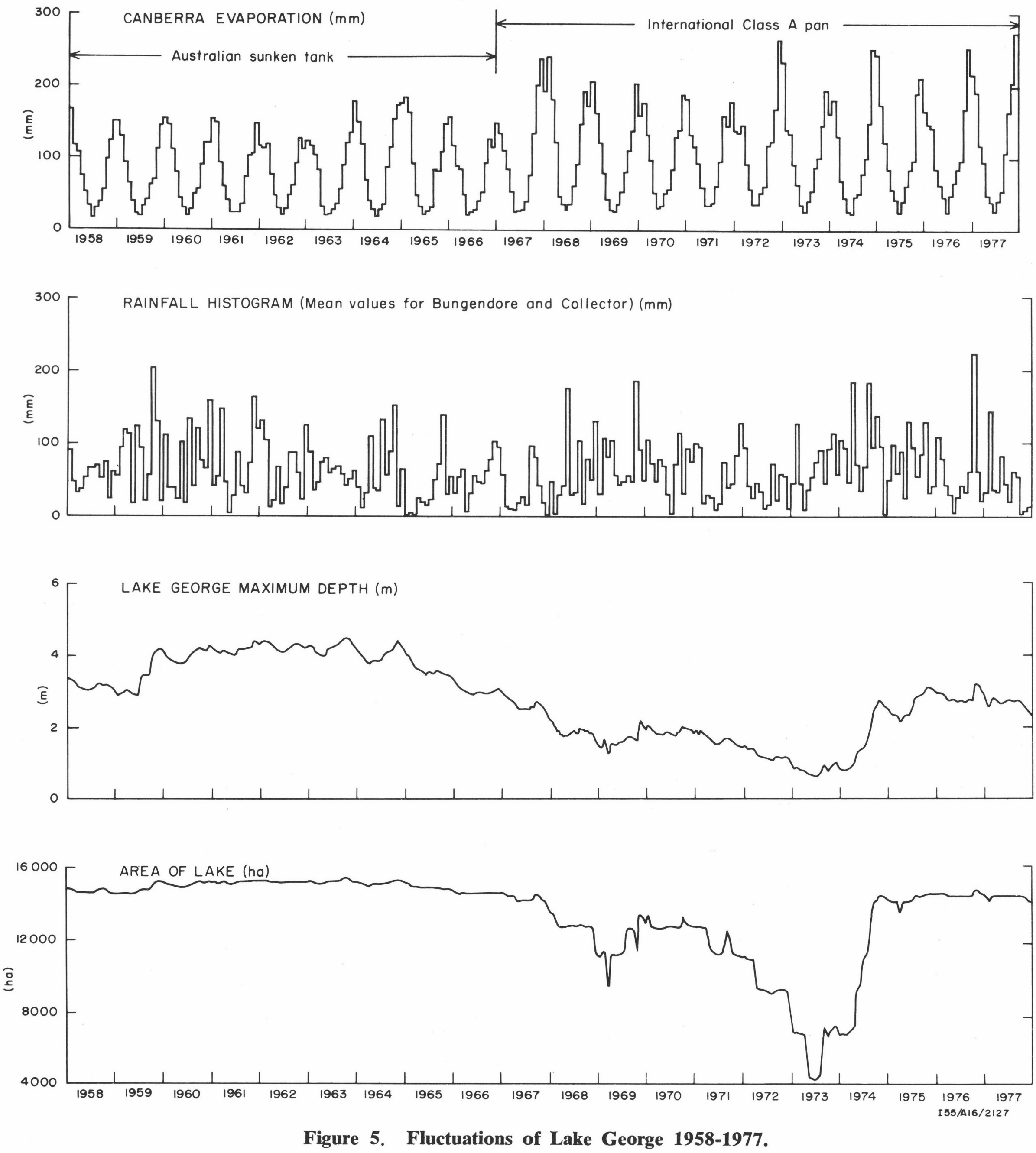

Figure 5. Fluctuations of Lake George 1958-1977.

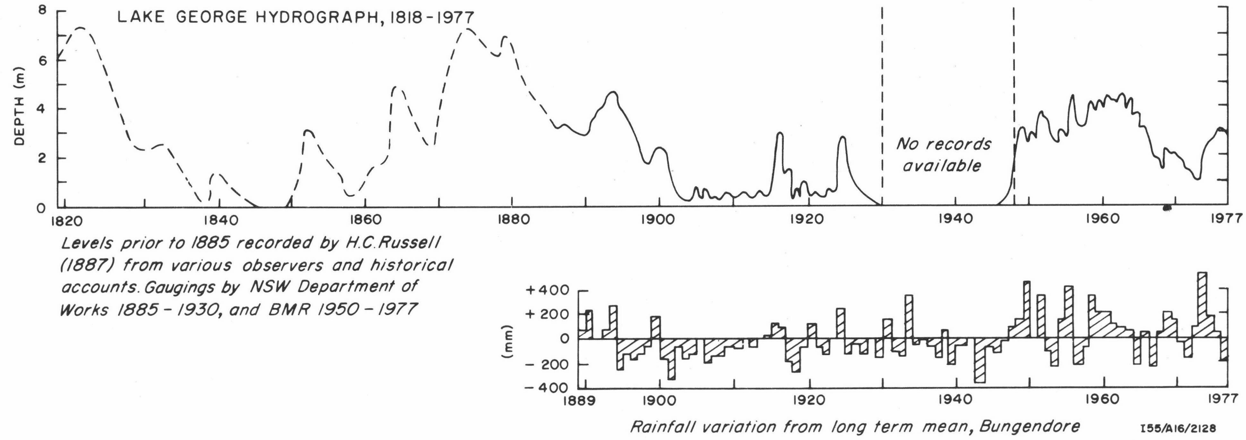

Figure 6. The Lake George Hydrograph 1818-1977.

evaporation was measured with an International Class A pan, and a correction factor of 0.85 has been applied to these pan measurements to estimate the lake evaporation. This value is the mean of experimentally determined annual pan coefficients, relating pan to lake evaporation at two water storages in New South Wales (Hoy & Stephens, 1977). A birdguard was added to the pan in April 1975; to allow for this a correction factor of 0.90 has been applied to more recent pan measurements.

The mean annual evaporation from the lake is estimated as 1184 mm per year and has ranged between 987 mm in 1963 and 1650 mm in 1977. The lake water losses from evaporation are estimated as 158 million m^3 annually, equivalent to the total volume of the lake at a level of 2.00 m.

The mean annual inflow of streams is estimated by subtraction from the water balance as about 51 million m^3. Of the streams that flow into Lake George two, Deep Creek and Collector Creek (Fig. 3), have nearly permanent flows; the other three, Taylors Creek, Turallo Creek, and Allianoyonyiga Creek, flow only after heavy rain.

The aggregate loss in water volume between 1958 and 1977 was about 7 million m^3, and the annual volume change fluctuated between a loss of 86 million m^3 in 1967 and a gain of 211 million m^3 in 1974.

Table 1 illustrates the marked seasonal influence on lake volume: from May to October the lake volume generally increases with the relatively high inflows during a time of low evaporation, whereas from November to April the lake volume decreases, with low inflows during the period of high summer evaporation.

Water chemistry

The relationship of the salinity of Lake George to the volume of lake water is illustrated in Figure 7, which is based on monthly electrical conductivity readings at the BMR gauging stations over the past 20 years. The salinity, in terms of total dissolved solids expressed as milligrams per litre, is related to electrical conductivity measured in microsiemens per centimetre at 25°C, by a factor ranging from 0.53 to 0.84—as shown by numerous chemical analyses of the lake water. For purposes of computation the ratio of total

Location / *Date*	*Lake George Geary's Trig Jan. 1969*	*Lake George Kenny's Point Jan. 1969*	*Lake George Geary's Trig Feb. 1973*	*Lake George Kenny's Point Feb. 1973*	*Lake George Geary's Trig Sept. 1976*	*Lake George Kenny's Point Nov. 1976*	*Lake George Geary's Trig Nov. 1976*	*Deep Creek Nov. 1976*	*Collector Creek Nov. 1976*	*Bore South end Lake George Nov. 1976*
pH	8.9	8.9	8.9	8.9	8.5	8.0	7.8	7.4	7.5	8.0
TDS	9893	7163	44800	38900	2018	1627	1730	205	406	432
EC	16250	11900	54052	45953	3601	3071	3251	337	844	854
Ca	18	22	35	35	53	19	22	14	38	42
Mg	205	152	860	740	42	36	38	15	39	21
Na	3506	2504	15900	13700	670	553	585	37	57	103
K	17	13	47	40	6	5	6	2	1	2
Fe	—	—	0.5	0.35	—	0.20	0.10	0.55	0.15	—
Mn	0.02	0.03	0.17	0.17	—	—	—	—	—	0.13
B	—	—	0.9	1.3	—	0.20	0.20	0.15	—	—
F	1.88	1.54	1.1	1.05	—	0.45	0.50	0.20	0.10	0.65
Cl	4995	3535	23005	20160	977	781	830	40	157	103
SO_4	470	325	2823	2391	114	92	97	43	33	11
HCO_3	1085	930	1565	1515	279	251	263	101	148	302
CO_3	66	33	565	450	11	—	—	—	—	—
PO_4	0.94	1.01	1.09	1.04	—	—	—	—	—	—
SiO_2	4.56	3.14	4.5	1.3	—	3	2	13	5	17
NO_3	0.16	0.10	0.25	0.25	7	8	13	3	8	1
NO_2	—	—	0.03	0.03	—	—	—	—	—	—
Br	23	16	100	90	—	6	7	—	—	—
Al_2O_3	—	—	0.40	0.40	—	0.20	0.15	0.58	0.08	—
Cu	0.02	0.02	0.10	0.05	—	—	—	0.04	—	—
Zn	0.04	0.01	0.07	0.12	—	0.01	0.01	0.01	0.02	0.36
Sr	0.75	0.72	2.70	2.35	—	0.35	0.35	0.10	0.20	0.40

Table 2. Chemical analyses of water samples.

Analyses in milligrams/litre with electrical conductivity (EC) in microsiemens/cm at 25°C.

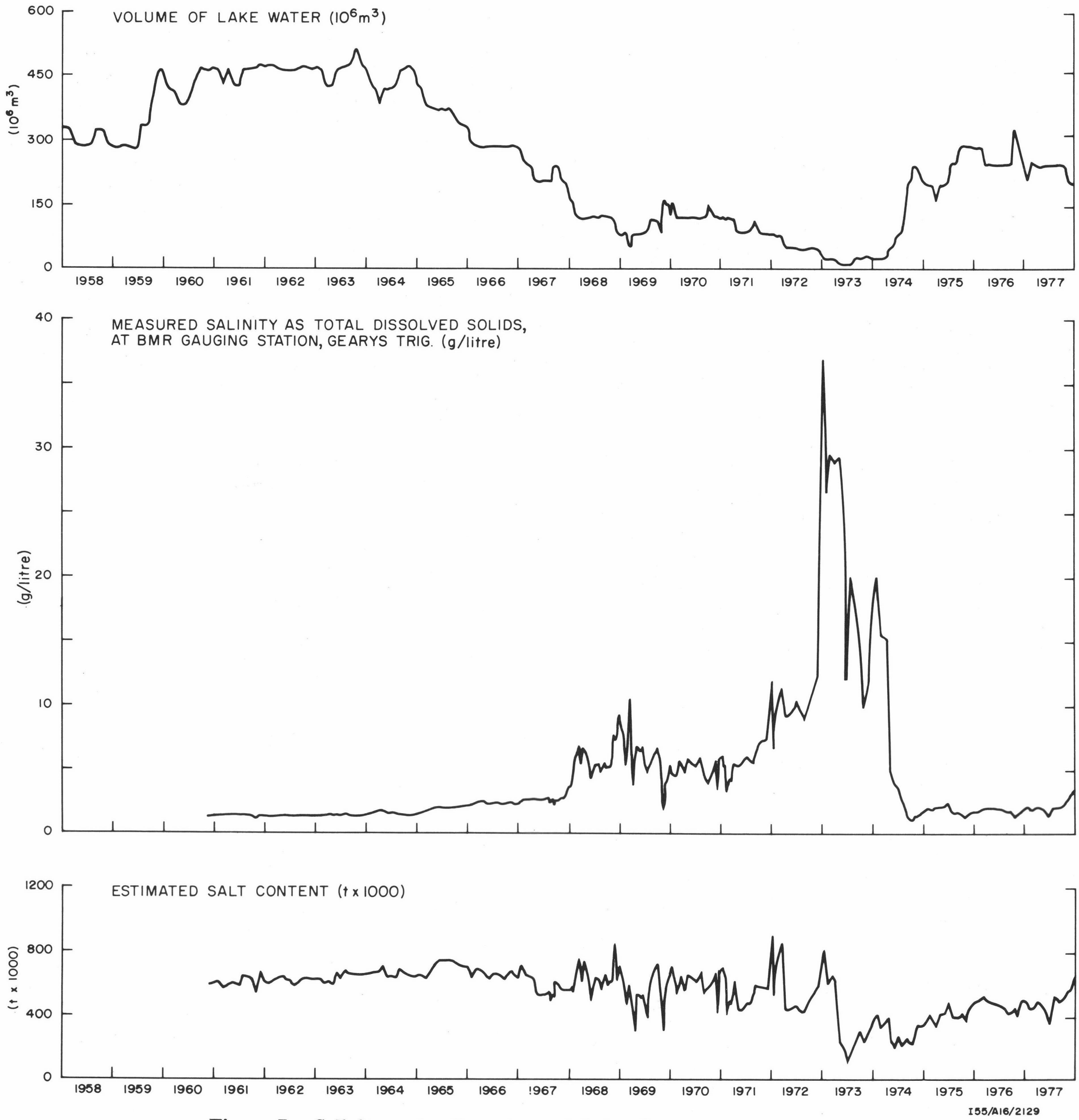

Figure 7. Salinity and salt content of Lake George waters 1958-1977.

dissolved solids to electrical conductivity has been taken as follows.

EC (microsiemens/cm)	TDS/EC
1- 5 000	0.58
5 001-20 000	0.64
20 001-40 000	0.74
40 001-60 000	0.84

Figure 7 shows that the salinity of the lake water increases as the depth and volume decrease, and seasonal fluctuations in salinity are superimposed on long-term trends. During the period for which regular measurements have been made the estimated salinity has ranged from 1183 mg/*l* total dissolved solids in October 1961, to 36 960 mg/*l* in January 1973.

Table 2 shows the results of chemical analyses of lake water at different salinity levels, and of creek water and groundwater. The lake water is generally more saline than creek water and groundwater in the catchments. It is a sodium chloride water, in contrast to the influent creek water which has relatively high concentrations of other ions. The ionic composition of the lake water varies slightly with changes in lake volume; as the lake volume decreases and salinity increases, the concentrations of sodium and chloride increase with respect to other ions.

Traverses across the lake in December 1970 and January 1971 showed an increase in salinity of 6 percent from east to west. Generally fresher water on the eastern side is attributed partly to greater depth and partly to the inflow of fresh runoff from the creeks on the eastern side. Samples recovered from different depths at particular localities showed no appreciable differences in salinity.

The total salt content of the lake (Fig. 7) has been calculated as the product of the weight of water and the estimated average concentration of dissolved solids. Figure 8 shows the variations in salt content of Lake George with changes in lake depth and volume from 1970 to 1977, during which period the lake fell to a

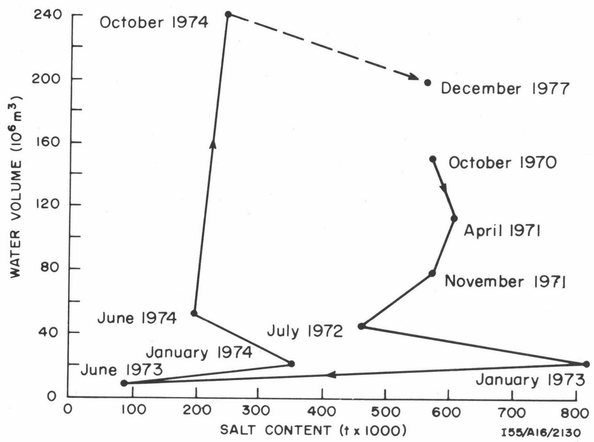

Figure 8. Lake George: relationship of water to volume to salt content, 1970-1977.

low level in July 1973 and then recovered. During the substantial decrease in lake volume from 1970 to 1972 the amount of salt in solution remained approximately constant, although salinity increased markedly during this time. In 1973 an additional small decrease in volume resulted in a marked decrease in the salt content of the lake, from 800 000 to 100 000 tonnes. With the recovery in lake volume during 1974 the amount of salt increased—but not to the same concentration as before the recession began. Subsequently, during the relatively stable phase of the lake from 1975 to 1977 the amount of salt in solution steadily increased from 250 000 to 600 000 tonnes.

The loss of salt during the recessive phase of the lake is attributed to its removal from dry salt flats by winds and dispersal over the surrounding area.

Discussion

The fluctuations in water level of Lake George can be considered on three time scales—daily, seasonal, and over a period of several years. The daily fluctuations are caused by wind-generated seiches. The seasonal fluctuations are due to high inflows and low evaporation raising the water level in the winter months, and low inflows and high evaporation lowering the water level in the summer months. The water-level fluctuations with a period of several years (Fig. 5) are caused by climatic changes, which alter the balance between inflow, evaporation, and precipitation.

Statistical analyses of rainfall data for southeast Australia have shown a general decrease in rainfall from the 1890's and a return to wetter conditions in the 1940's (Gentilli, 1971). These long-term rainfall fluctuations have been ascribed to changes in atmospheric circulation by Kraus (1955, 1962), who postulated a shift in the westerly wind belt towards the equator as the cause of the rainfall decrease in the 1890's. The long-term rainfall fluctuations correlate with two major events at Lake George in historical times—the drying up of the lake in the 1890's, and its refilling in the late 1940's (Fig. 5). The lake hydrograph is therefore an important indicator of gross climatic change.

Geomorphological evidence of high lake levels has enabled extrapolation of the Lake George hydrograph back into Quaternary time to form the basis of palaeoclimatic reconstructions. Thus, Galloway (1965) was able to deduce low evaporation during the last glacial stage and postulate a cooler drier climate than the present. Coventry (1976) has confirmed this, and dated the sequence of abandoned shorelines to plot a history of climatic fluctuations for the last 40 000 years.

Salinity of the lake water varies inversely with water volume, and seasonal fluctuations in salinity are superimposed on long-term trends. The total amount of salt in solution varies in a more complex manner with a cycle of accumulation, removal, and further accumulation (Fig. 8) which conforms closely to the idealised cycle for variations in the salt content of a closed lake postulated by Langbein (1961). The salt in Lake George is thought to be mainly cyclic salt (Burton, 1972), brought in by coastal rainfall. The predominantly sodium chloride composition of the lake water is similar to that of most other southern Australian lakes for which data is available (Williams, 1966).

Any disturbance of the natural hydrological system will require careful analysis and planning to ensure acceptable water level and salinity fluctuations.

Acknowledgements

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