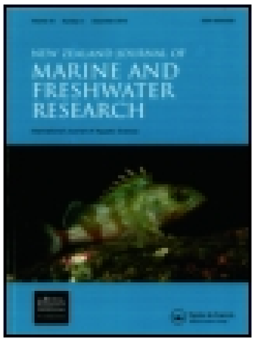

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PHYSICO-CHEMICAL FEATURES OF LAKE OTOTOA, A SAND-DUNE LAKE IN NORTHERN NEW ZEALAND

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ABSTRACT

Lake Ototoa is a warm monomictic lake at 36° 31′ S, 174° 14′ E. During a year's study (March 1969–March 1970), the lake became thermally stratified in November, the metalimnion being between depths of 12 m and 16 m. Surface temperatures ranged between 10.2°c (in August) and 25.2°c (in late January), and bottom temperatures between 9.7°c and 17.5°c. The annual heat budget was calculated to be 642 354 KJ.m^{-2} (15 500 cal.cm^{-2}) and the work of the wind in distributing the heat income 1.730 KJ.m^{-2} (1766 g.cm.cm^{-2}). Secchi disc transparencies ranged between 5 m and 9.2 m (mean 7.07 m) and were greatest in the summer. Light transmission per metre was also high, ranging between 61% and 87%. Surface waters were normally supersaturated with oxygen, but during summer stratification oxygen concentrations in the bottom waters dropped to a minimum of 2.3 mg.litre^{-2} and a positive heterograde distribution of oxygen with depth was found. The oxygen deficit was 0.015 mg.cm^{-2}.day^{-1} and showed the lake to be oligotrophic. Mean surface pH was 7.82, and the ionic composition of the waters was similar to that of other small New Zealand and Australian lakes located near the sea. Compared with other New Zealand lakes PO_4–P concentrations (range 1.00–10.20 μg.litre^{-1}) were low and NO_3–N concentrations (range 0.12–0.60 mg.litre^{-1}) high.

INTRODUCTION

New Zealand is well endowed with lakes, ranging in type from the large deep glacial lakes of the South Island to the many small lowland and sand-dune lakes characteristic of the northern and western coastlines of the North Island. Yet despite studies by Flint (1938), Cunningham *et al.* (1953), Bayly (1962), Jolly (1968), Stout (1969), Barker (1970), Mitchell (1971), McColl (1972) and Green (1974), there is much of their limnology to be described. This paper describes the physical and chemical features of Lake Ototoa, one of the North Island sand-dune lakes. The seasonal cycles of the phytoplankton and zooplankton in this lake will be discussed in other papers.

LAKE OTOTOA

Lake Ototoa lies about 80 km (50 miles) north of Auckland at 36° 31′ S and 174° 14′ E in the extensive series of sand dunes which border much of the west coast of the North Island. It is situated on the south head of the Kaipara harbour, a peninsula of land separating

TABLE 1—Some morphometric parameters of Lake Ototoa. The volume of each stratum was calculated using the equation $V = h/3\ (a_1 + \sqrt{a_1 a_2})$, where h = the depth of the stratum, a_1 = area of the upper surface, a_2 = area of lower surface. The value (12.29 m) for mean depth ($\bar{z}$) was calculated using, $\bar{z} = V/A$, where V = total volume, A = surface area (.. = negligible)

DEPTH (m)	AREA OF CONTOUR ($m^2 \times 10^6$)	VOLUME OF STRATUM ($m^3 \times 10^6$)	(% of total)
0	1.623	3.072	15.39
2	1.451	2.791	14.99
4	1.340	2.574	12.90
6	1.234	2.339	11.72
8	1.106	2.092	10.49
10	0.987	1.857	9.31
12	0.871	1.629	8.17
14	0.759	1.362	6.83
16	0.605	1.021	5.12
18	0.421	0.673	3.37
20	0.258	0.368	1.85
22	0.119	0.140	0.70
24	0.037	0.033	0.16
26	0.005	..	..
Total volume		19.951	

the Tasman Sea from the harbour itself, and to the west, north, and east the lake is never more than 5 km from the sea.

Ferrar (1934) believes that the dunes in the region of the Kaipara harbour are of two series, both formed during the Pleistocene. The older (Kaihu) series to the east have become consolidated as a yellow, sandy soil which is now extensively farmed, while the younger, darker and less consolidated series near the coast is being covered by drifting sand. Toetoe, *Cortaderia conspicua*, and spinifex, *Spinifex hirsutus*, have been planted in an endeavour to consolidate the dunes, but in many places they are still constantly encroaching eastwards.

The whole coastline is characterised by the formation of lakes where the valleys of streams draining the consolidated dunes have been blocked by advancing sands. The lakes tend to be elongated and orientated with their longest axis in a north–south direction. The valley sides are steep, and often there are dendritic side branches where small stream valleys have been flooded. Lake Ototoa is the largest and deepest of these lakes, many of the others being shallower because of filling by wind-blown sand (Cunningham *et al.* 1953).

A bathymetric map of Lake Ototoa compiled in 1970 from echo sounding traverses (Irwin 1973) is shown in Fig. 1. A 4-m contour interval has been used in this figure, but the areas and volumes enclosed by 2-m isobaths have been calculated from the original chart with a compensating polar planimeter (Welch 1948) (Table 1).

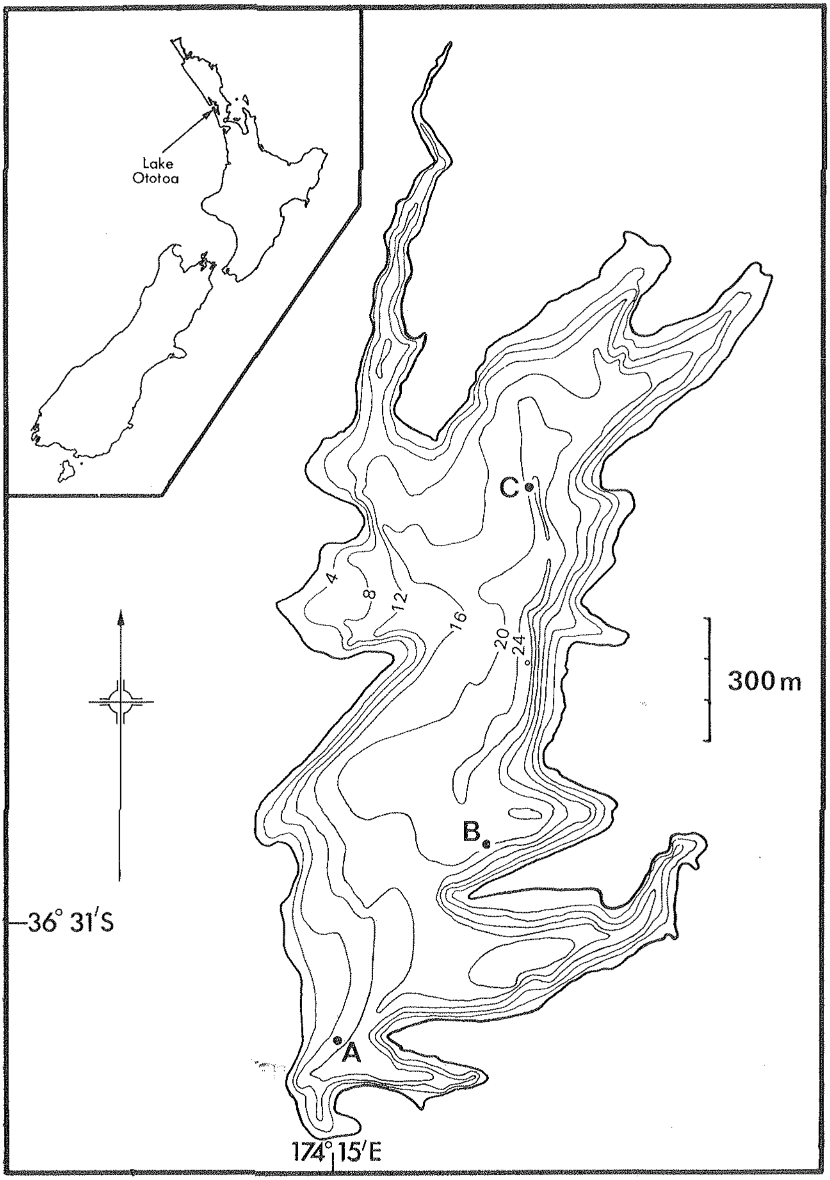


FIG. 1—Hydrographic map of Lake Ototoa, showing the location of the sampling stations. The contour interval is 4 m. The location of Lake Ototoa, on the south head of the Kaipara Harbour in the North Island of New Zealand, is shown in the inset.

The lake is rectangular in shape, and the deepest regions are located to the east where the basin slopes steeply down from the Kaihu sands, while there is a much more gentle slope up towards the western dunes. The conformation of the basin probably results from gradual filling by an inflow of sand from the west. There are steep hills or dunes on the east and west sides which funnel winds along the N–S axis of the lake.

The lake is apparently fed by seepage and a few small seasonal rivulets, and there is no outlet. The lake level dropped by about 1 m over the summer of 1969–70.

The littoral vegetation consists mainly of a narrow band of the sedge *Eleocharis sphacelata,* which is most common in the less steeply sloping and shallower parts of the lake, in the northern and eastern arms and along the dune face to the west. As well, *Chara australis* is abundant along the southern edge to depths of 10–15 m.

The small goby *Gobiomorphus australis* is common in the shallower bays and present all over the deep central basin, the floor of which is covered by loose sandy mud. The mussel *Hyridella menziesii* and the freshwater crayfish *Paranephrops planifrons* are also common, and a smelt, *Retropinna retropinna,* was also seen on one occasion.

CLIMATE

Lake Ototoa is subject to a temperate–subtropical oceanic climate, and meterological observations from the area, made at the nearby Woodhill Forest about 20 km to the south of Lake Ototoa, are summarised in Fig. 2. Temperatures are mild, winds frequent, moderately strong and variable. Most rain fell in autumn and winter, the yearly rainfall being 113.1 cm.

METHODS

Sampling was carried out, generally weekly, between March 1969 and March 1970 at stations marked in Fig. 1. Initially, samples were taken from one station only (B) centrally located in one of the deepest areas of the lake, but after April 1969 two more stations (A and C) were established at the south and north ends of the lake respectively (Fig. 1).

Temperatures were measured at metre intervals from the surface to the bottom with a thermistor thermometer. Transparency was measured with a 20 cm secchi disc divided into black and white quadrants (Welch 1948), and between September and November light intensity was measured at metre depth-intervals using a light meter.

Water samples were taken with a 1.1-litre Ogawa-Seiki reversing Nansen bottle. Surface samples for oxygen and pH analysis were collected at 2- or 3-weekly intervals and during the summer samples were also taken of the bottom waters. Oxygen and pH were measured at

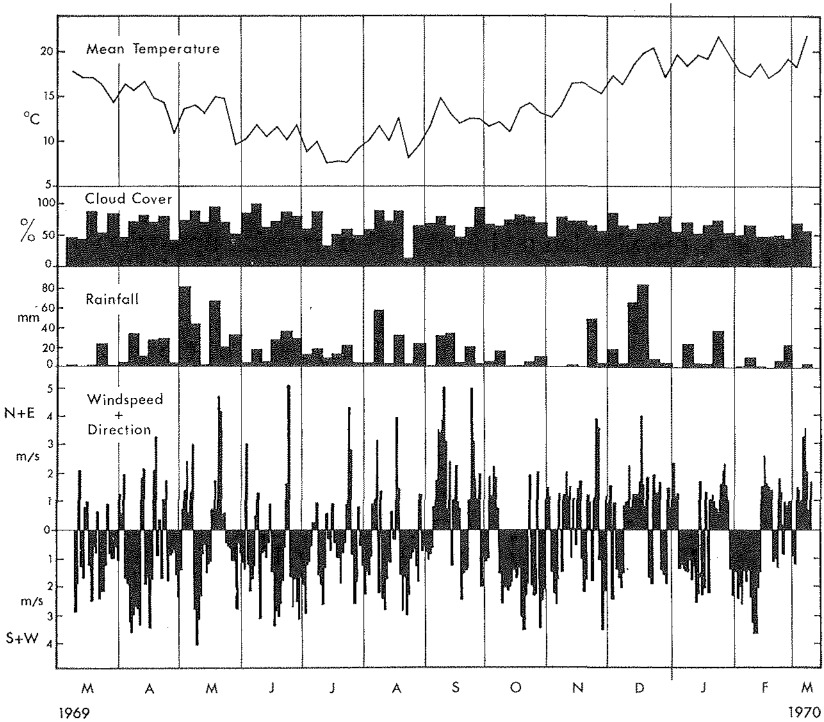


FIG. 2—Weather March 1969–March 1970 at the Woodhill Forest meteorological station, to the south of Lake Ototoa.

depths of 0, 3, 6, 9, 12, 15, 18, and 21 m on 12 January 1970 during summer stratification. After June 1969, monthly 1-litre samples for chemical analysis were taken from a depth of 1 m at stations A and C, and transported to the laboratory in polythene containers which had previously been treated with iodine to reduce bacterial uptake of phosphate and nitrate on their inner surfaces (Mackereth 1963).

All estimations were made according to Mackereth (1963) immediately on returning to the laboratory. Oxygen was determined by unmodified Winkler method, pH on a Radiometer model 22 pH meter, sodium and potassium on an EEL flame photometer and calcium, nitrate, and reactive phosphate by spectrophotometric methods using a Beckman DB spectrophotometer. Alkalinity was determined by titration to pH 4.5 and cation ion-exchange methods were used to estimate total anionic concentration, chlorides, and sulphate (Mackereth 1955). Magnesium was estimated approximately by subtracting the equivalent sum of sodium, potassium and calcium from the total anionic concentration. Organic matter was analysed by acid dichromate oxidation (Maciolek 1962) before and after filtration through a millipore filter of 0.8 μm pore size.

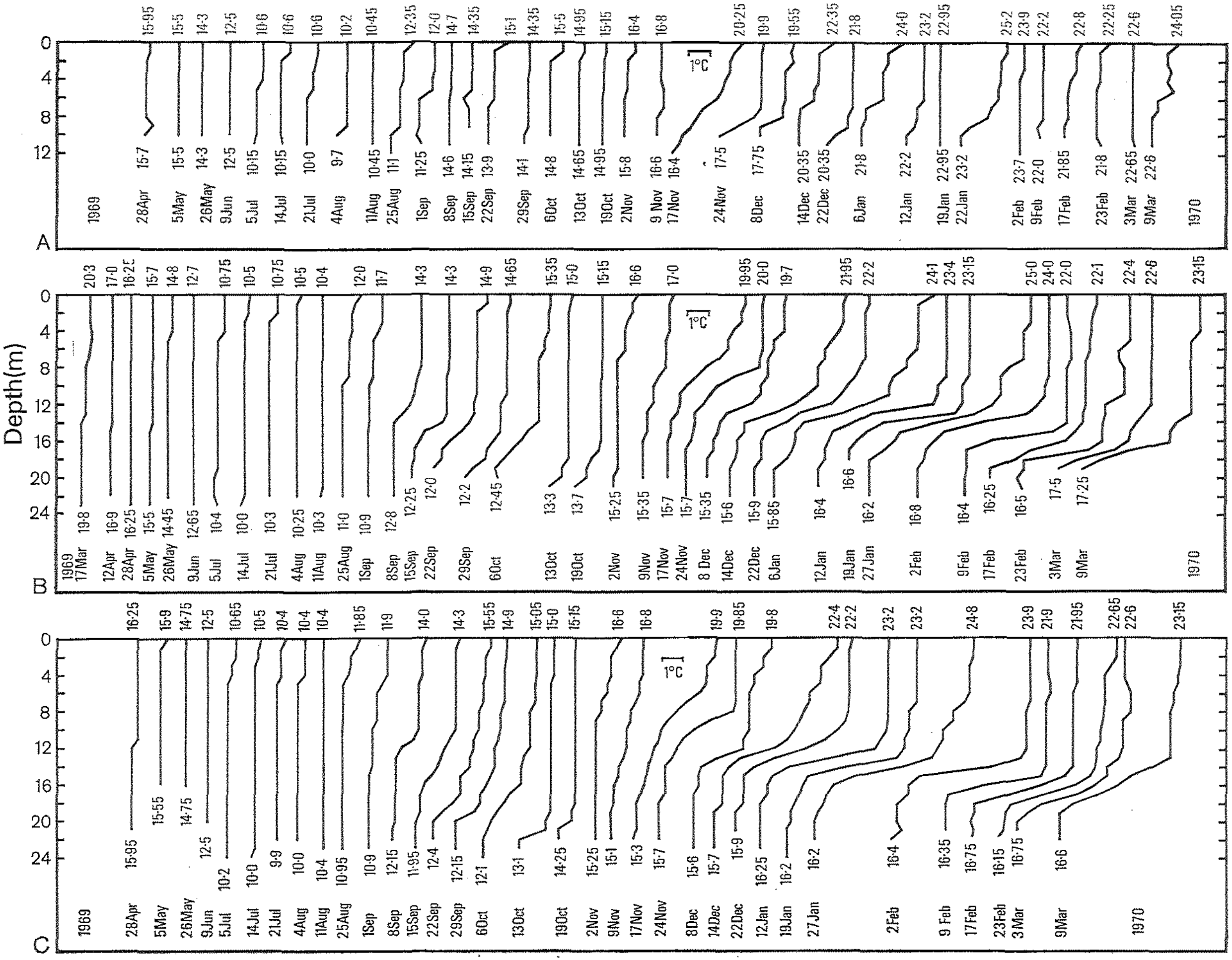
TEMPERATURE

From March to early September 1969 Lake Ototoa was homothermal (Fig. 3), with temperatures reaching their lowest values in August (9.7°C on 4 August). During warm weather in September a weak thermocline developed which, although surface heating continued, was gradually broken down by strong north and east winds later in the month. Stratification reformed in November and was strongly developed to the end of the sampling period. During most of December and January the epilimnion, metalimnion and hypolimnion occupied approximate depth ranges of 0–12 m, 12–16 m, and 16–23 m and comprised 72.8%, 15.0% and 12.2% of the total lake volume respectively. The depth of the thermocline increased in February and March as the epilimnion cooled and finally the hypolimnion comprised only 5.9% of the lake volume. As there is only one circulation period during the year, and temperatures are always well above 4°C, Lake Ototoa may be classified as a warm monomictic lake (Hutchinson 1957).

A feature of the curves in Fig. 3 is the small temperature irregularities in the epilimnion on many occasions, which often show similar patterns at all three stations (e.g., 17 November 1969, 1 December 1969, 8 December 1969, 6 January 1970, 19 January 1970, 27 January 1970). These microstratifications probably result from surface heating and subsequent incomplete mixing by the wind. Epilimnetic temperatures followed the trend in air temperatures, and were highest in late January (maximum 24.2°C). Those at stations B and C were similar, while those at station A, which was shallower and more sheltered, were often higher. During the summer the greatest drop in temperature through the metalimnion was 6.4%, which is similar to that found in other New Zealand lakes (Jolly 1968, Barker 1970, Fish 1970). The range in temperature of the bottom waters over the year was 6.5°C and is somewhat greater than that found for other shallow, stratified lakes in New Zealand (Jolly 1968, Fish 1970).

Patterns of stratification recorded on similar dates in 1950 (Cunningham *et al.* 1953), 1969 (a preliminary visit by the author before beginning this study) and 1970 indicate that the thermal régime of Lake Ototoa varies from year to year (Fig. 4). Cunningham *et al.* found only weak stratification, but believed that a previous stronger stratification had been broken down a short time before their visit. In 1969, a distinct thermocline was present, but it was not as deep as that in the present study and the temperature difference between epilimnion and hypolimnion was smaller. The summer of 1970 was warmer than average, and this probably explains the stronger stratification.

The annual heat budget of Lake Ototoa was calculated using Birge's (1915) method to be 642 354 KJ.cm^{-2} (15 500 cal.cm^{-2}) (Table 2). For a monomictic lake this value represents summer heat income (θ_{bs}). Mean temperatures used for this calculation were a maximum of 22.7°C on 27 January 1970, and a minimum of 10.1°C on 4 August 1969. Heat



G. 3—Distribution of temperature with depth at the three sampling stations in Lake Ototoa; the surface and bottom temperatures are shown for each trace.

TABLE 2—Annual heat budgets of New Zealand and Australian lakes. Data from (¹) Fish (1975), (²) Barker (1970), (³) Timms, & Midgely (1969), (⁴) Bayly (1962). Surface area (A_0), mean depth ($\bar{z}$) and total volume (V) are also given for each lake.

	θ_{ba}		A_0	$\bar{z}$	V
	(cal.cm^{-2})	(kJ.m^{-2})	(m^2 × 10^4)	(m)	(m^3 × 10^6)
Okataina[1]	19 950	826 772	1 049.4	45.5	477.25
Pupuke[2]	16 000	663 000	85.7	34.0	29.23
Ototoa	15 500	642 354	162.3	12.3	19.95
Okaro[1]	9 306	385 661	32.95	11.1	3.65
Ngapouri[1]	9 496	393 535	22.34	12.1	2.72
Borumba[3]	7 963	330 004	501	8.5	42.6
Aroarotamahine[4]	6 000	248 653	10.2	12.2	1.25
Rotoehu[1]	5 296	219 478	791.24	8.2	64.53

budgets of other New Zealand and Australian lakes are given for comparison in Table 4, and all are low by world standards. The amount of work done by the wind (B) in distributing the heat absorbed by Lake Ototoa was calculated by Birge's (1916) method to be 1.730 KJ.m^{-2} (1766 g.cm.cm^{-2}). The unit work of the wind (the amount of work needed to distribute each calorie of the heat budget, ie., B/θ_{bs}) was 0.114 g.cm.cal^{-1}. These two values are rather high by world standards (Hutchinson 1957)

OPTICAL PROPERTIES

Average Secchi disc transparencies over the sampling period are plotted in Fig. 5; transparencies at the three stations were similar on any one date. There was no marked seasonal pattern, and little relationship between Secchi depth and total numbers of phytoplankton ($r = 0.08$, $n = 26$, N.S.) or total organic matter (Fig. 5), although high phytoplankton concentrations during August and September, and during late December and early January coincided with lower Secchi depths. Also the decrease in transparency in October and the gradual increase in the following 2 months coincided with an increase in organic matter during October, followed by a decrease during November.

Irregular variations in transparency may have resulted from variable light reflection from the large colonies of *Botryococcus braunii* which were always present. These appear much brighter in higher light intensities, especially if concentrated in the upper waters on a clear calm day. Windblown material from nearby dunes may also have caused variations in Secchi transparency since windspeed and Secchi transparencies were negatively correlated (Secchi depth is significantly correlated with windspeed in the previous 5-day period; $r = -0.406$, $P < 0.02, n = 35$; Fig. 6).

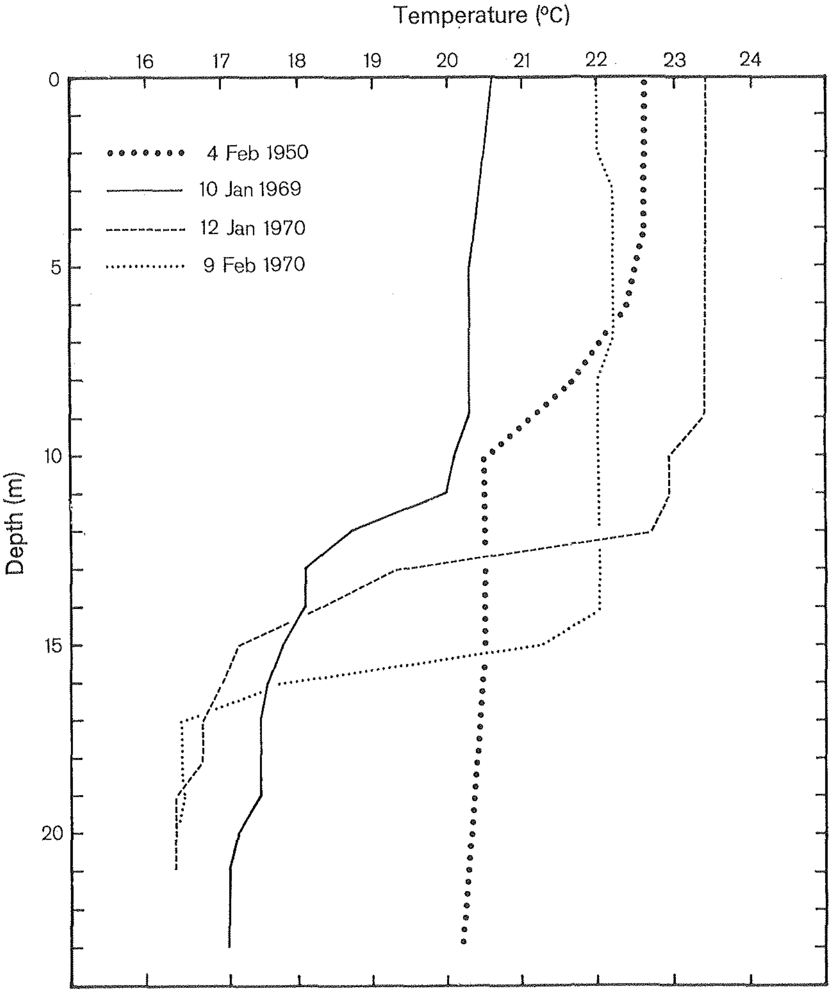


FIG. 4—Thermocline depth in Lake Ototoa during the summers of different years: 1950 from Cunningham *et al.* (1953); 1969 from a preliminary visit by the author; 1970 from the present study.

Lake Ototoa has clearer water than many other small New Zealand lakes described in the literature (Haydon unpublished 1967, Donovan unpublished 1968, Jolly 1968, Mitchell 1971, Green 1974). Many shallower sand dune lakes have much lower transparencies (Cunningham *et al.* 1953) probably as a result of disturbance of silt and bottom sediments by wind.

The photometer readings are shown in Fig. 7. The slopes of these lines are a measure of the absorption of light by the water, which may

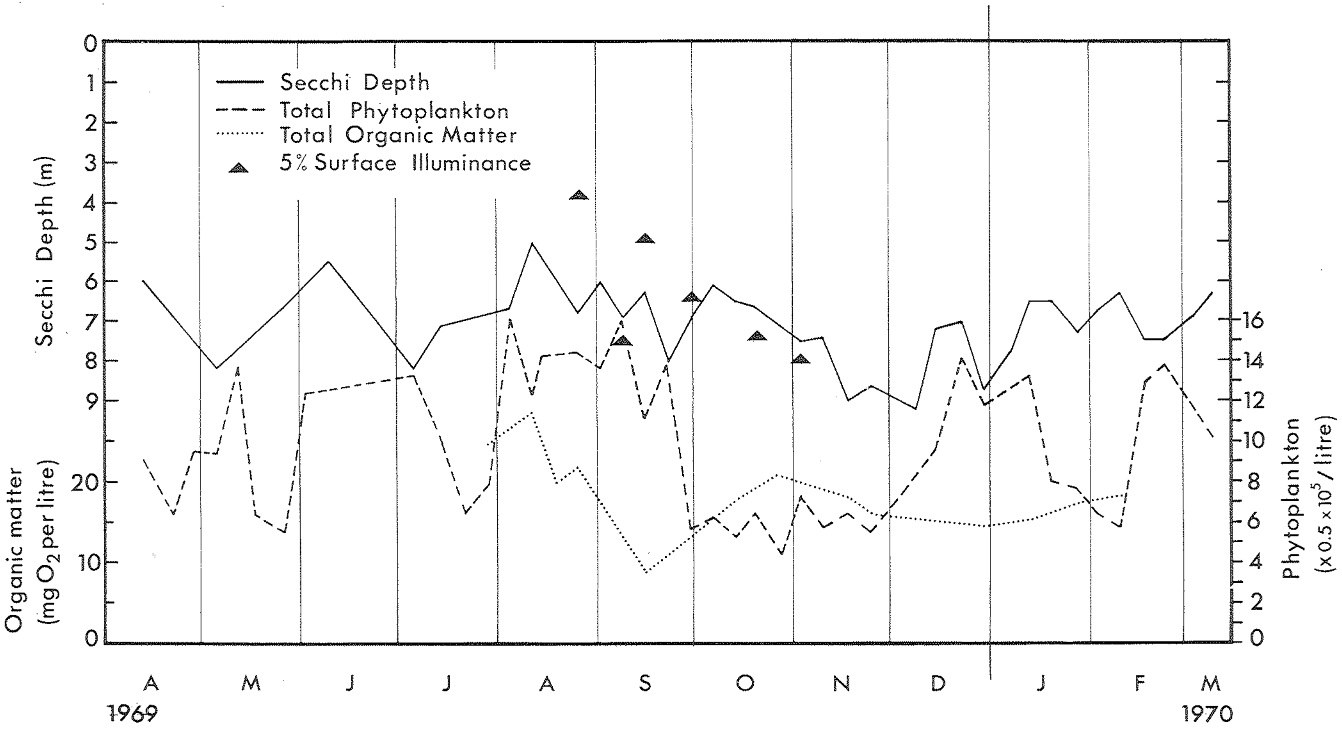


FIG. 5—Seasonal changes in Secchi depth in Lake Ototoa. Total phytoplankton numbers (cells per 2 ml), organic matter, and depth of 5% surface illuminance are also shown.

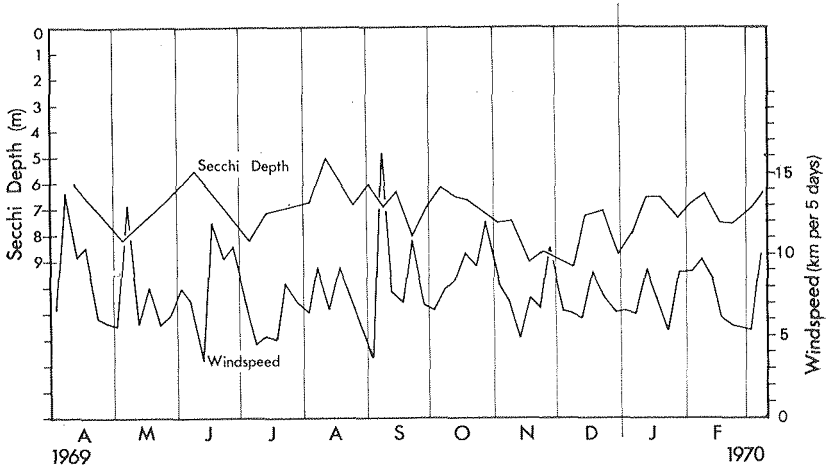


FIG. 6—Seasonal changes in Secchi depth in Lake Ototoa, and windspeed at the neighbouring Woodhill Forest meteorological station. Windspeed is expressed as the number of kilometres run in a 5-day period. Secchi depth is significantly correlated with windspeed in the previous 5-day period ($r = -0.406$, $P < 0.02$, $n = 35$).

be expressed by the vertical extinction co-efficient (η'') or the percentile transmission per metre (Hutchinson 1957). The vertical extinction coefficient is given by:

$$\eta'' = \frac{\ln I_a - \ln I_b}{z_b - z_a}$$

where I_a and I_b are light intensities at depths z_a and z_b respectively, when z_a is less than z_b.

The percentile transmission ($\mathrm{Pt{\cdot}m^{-1}}$) is given by:

$$\mathrm{Pt{\cdot}m^{-1}} = 100e^{-\eta''}$$

The results (Table 3) emphasise the clarity of the water in Lake Ototoa. Many of the light absorption curves (Fig. 7) demonstrate an increase in transmission below about 11 m. Similarly, in Table 3, the percentile transmission between 6 m and 11 m is generally less than that between 11 m and 16 m or between 11 m and 21 m depth. This suggests that seston was denser nearer the surface.

DISSOLVED OXYGEN

Dissolved oxygen concentrations and saturations at the surface differed little between the three stations, and the average values have been plotted in Fig. 8. The mean values from the bottom waters at stations B and C are also shown.

TABLE 3—Light extinction co-efficients (η'') and percent transmissions (Pt.m^{-1}) in Lake Ototoa, 1969 (– = station depth only 11 m; .. = no data)

DATE	DEPTH RANGE (m)	STN A		STN B		STN C	
		(η'')	(Pt.m^{-1})	(η'')	(Pt.m^{-1})	(η'')	(Pt.m^{-1})
25 August	1–6	0.445	64.07	0.392	67.6	0.333	71.7
	6–11	0.270	76.3	0.247	78.1	0.323	72.4
	11–16	–	–	0.220	80.3	0.242	78.5
	16–21	–	–	0.269	76.4	0.277	75.8
8 September	1–6	0.265	76.7	0.315	73.0	0.253	77.6
	6–11	0.239	78.8	0.372	68.9	0.278	75.8
	11–16	–	–	0.139	87.1	0.240	78.7
	16–21	–	–	0.220	80.3	0.352	70.3
15 September	1–6	0.277	75.8	0.225	79.8	0.281	75.5
	6–11	0.250	77.9	0.247	78.1	0.254	77.6
	11–16	–	–	0.222	80.1	0.208	81.3
	16–21	–	–	0.175	83.9	0.245	78.3
29 September	1–6	0.220	80.3	0.196	82.2	0.153	85.8
	6–11	0.300	74.1	0.257	77.4	0.292	74.7
	11–16	–	–	0.226	79.8	0.247	78.2
	16–21	–	–	0.213	80.8	0.220	80.3
19 October	1–6	0.226	79.8	0.298	74.2	0.328	72.1
	6–11	0.496	60.9	0.305	73.7	0.299	74.2
	11–16	–	–	0.222	80.1	0.217	80.5
	16–21	–	–	0.223	80.0	0.212	80.9
2 November	1–6	0.371	69.0	0.229	79.6	..	..
	6–11	0.285	75.2	0.255	77.5	0.268	76.5
	11–16	–	–	0.257	77.3	0.255	77.5
	16–21	–	–	0.198	82.1	0.204	81.5

Oxygen concentrations were highest in winter, and tended to drop gradually during spring and summer. However, oxygen saturation increased during spring and summer, reached maximum levels in December (121% on 22 December), and then tended to decline prior to another small increase in February. Surface waters were supersaturated with oxygen on all occasions except once, in May 1969. Higher saturation levels during spring and summer possibly resulted from increased photosynthesis by phytoplankton which was more abundant in December and February.

During the summer, both oxygen concentration and saturation gradually dropped in the bottom waters reaching minimum levels of 2.3 mg.litre^{-1} and 24% saturation on 3 March 1970. The small increases in February and March may have been caused by mixing of epilimnetic waters into the hypolimnion. Oxygen was measured at depths of 0, 3, 6, 9, 12, 15, 18, and 21 m at station B on 12 January 1970 (Fig. 9) and a weakly developed positive heterograde curve was found, suggesting that algal photosynthesis was occurring in the stable metalimnetic layers

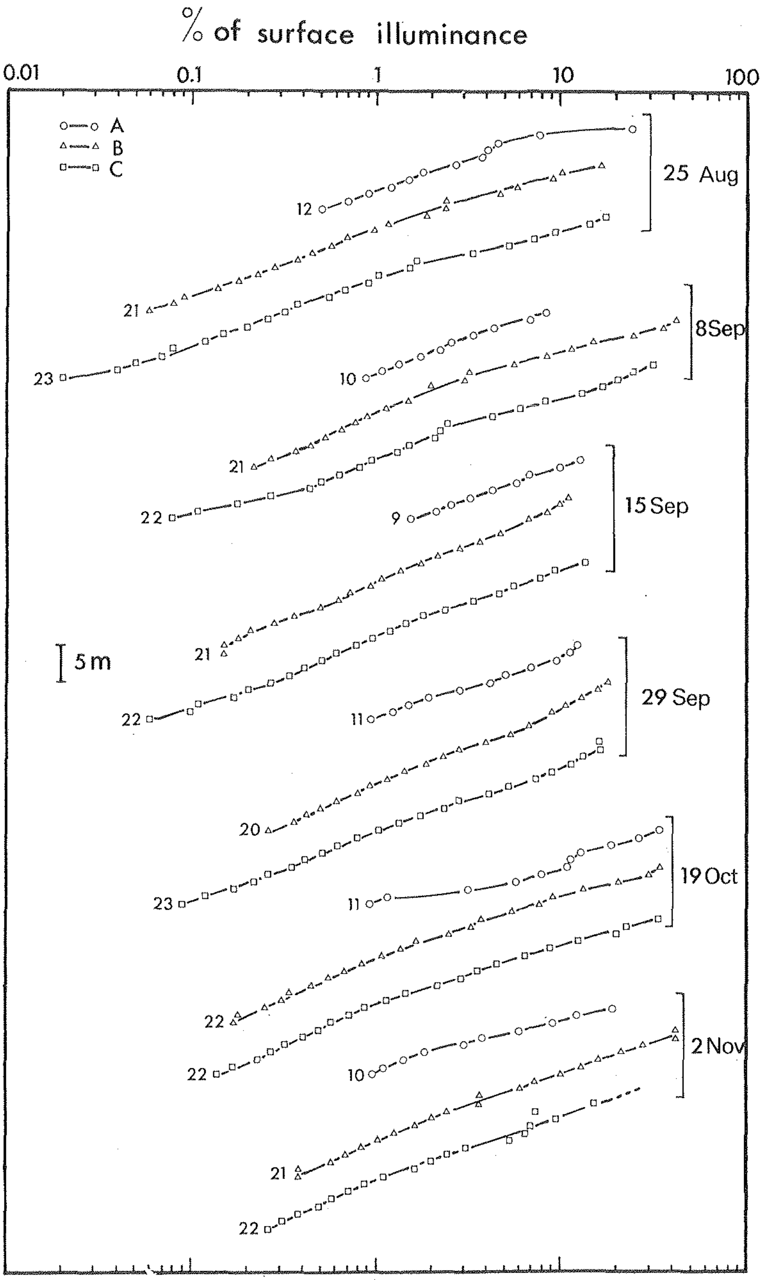


FIG. 7—Transmission of light in Lake Ototoa. Light intensity at each depth has been expressed as % of surface illuminance. The slopes of these lines give a measure of the vertical extinction coefficient, a steeper slope indicating greater light transmission.

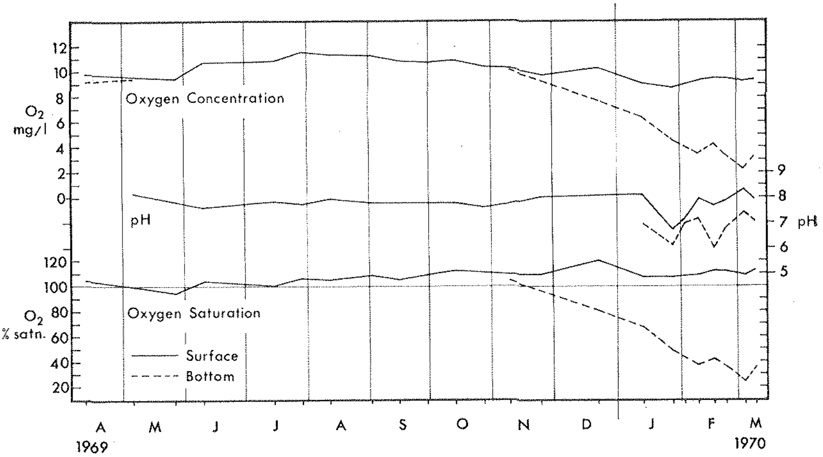


FIG. 8—Changes of oxygen concentration, % oxygen saturation, and pH of the surface waters of Lake Ototoa throughout the year, and of the bottom waters during the summer. The surface values are the averages of those from all stations and the bottom values are those from stations B & C.

(Hutchinson 1957). On 12 January 1970, for example, the thermocline lay between 12 m and 14 m where the illumination was probably about 1% of surface light intensity, which is thought to be approximately the lower limit for the occurrence of photosynthesis (Clarke 1954).

Surface oxygen concentrations in January 1970 (Fig. 9) were similar to those found on 4 January 1950 by Cunningham *et al.* (1953) when there was weak thermal stratification between 6 m and 10 m depth (see

TABLE 4—Hypolimnetic oxygen deficits of some New Zealand lakes. Data from (1) Fish (1970); (2) Barker (1970); (3) McColl (1972); (4) Green 1974 (– = no data)

LAKE	AREAL DEFICIT (mg.cm^{-2}.day^{-1})	AREAL DEFICIT (mg.cm^{-2})	VOLUMETRIC DEFICIT (g.m^{-3})	VOLUMETRIC DEFICIT (g.m^{-3}.day^{-1})
Ngapouri[3] (1970–71)	0.106	19.2	12.0	0.066
Rotoma[3]	0.091	13.3	2.01	0.014
Rotokakahi[3]	0.065	11.9	6.59	0.036
Okaro[3] (1970–71)	0.058	10.5	11.6	0.064
Okataina[3] (1970–71)	0.046	6.6	1.01	0.0068
Ngapouri[1] (1962–66)	0.044	8.4	9.7	0.050
Okataina[1] (1962–66)	0.042	7.6	2.3	0.013
Okaro[1] (1962–66)	0.034	6.3	10.0	0.054
Pupuke[2]	0.032	–	–	–
Okareka[3]	0.028	5.1	2.53	0.016
Ototoa	0.015	0.96	2.44	0.033
Auxiliary Nihotupu[4]	0.013	–	–	–
Tikitapu[3]	0.0077	1.1	0.86	0.0059

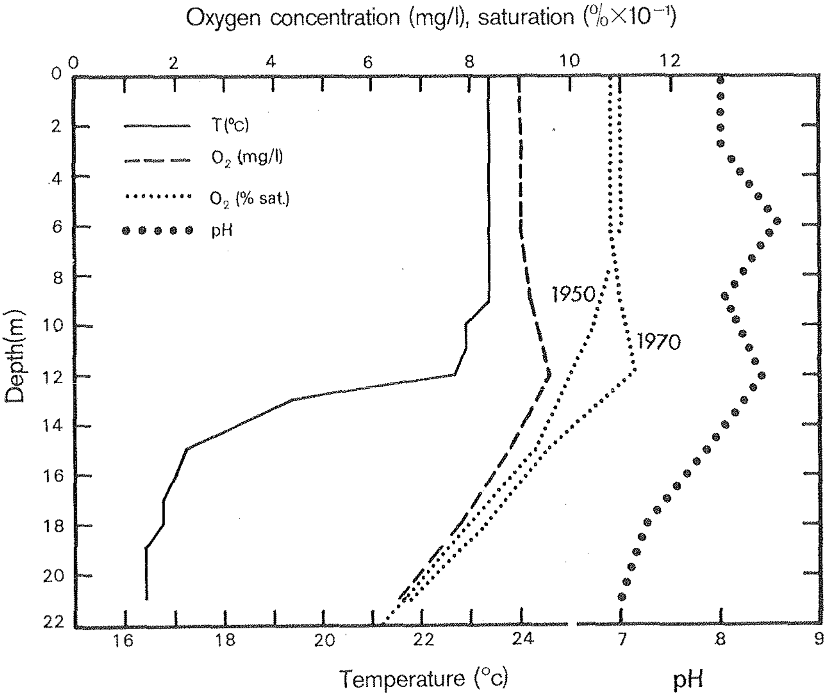


FIG. 9—Distributions of temperature, pH, oxygen concentration, and oxygen saturation with depth at station B during mid summer (12 January 1970). Oxygen saturation on 4 January 1950 defined by Cunningham *et al.* (1953) are also shown.

Fig. 4). A positive heterograde oxygen distribution was not found by Cunningham *et al.* but oxygen saturation was 55% at 25 m (3.0 mg.litre^{-1}), which is comparable with the results found in the present study.

OXYGEN DEFICIT

The relative hypolimnetic areal oxygen deficit (the difference between the amounts of oxygen dissolved in the hypolimnion during spring circulation and summer stagnation expressed per unit area of the hypolimnetic surface, Hutchinson 1957) was calculated for Lake Ototoa using the data presented in Fig. 9 and the oxygen concentrations determined on 9 November. Because stratification had only just begun to form, and the bottom waters were still supersaturated (see Fig. 8), it was assumed that the bottom value (10.2 mg.litre^{-1}) approximated to oxygen concentrations in the whole of the hypolimnion.

A deficit of 0.96 mg.cm^{-2} over 64 days, or 0.015 mg.cm^{-2}.day^{-1}, was calculated for Lake Ototoa, which is considerably lower than the deficits of most other New Zealand lakes (Table 4). Cubic deficits for Lake

TABLE 5—Major ionic constituents per litre of water in Lake Ototoa. (– = not determined)

DATE	Na^+ (mg)	Na^+ (me)	Mg^{2+} (mg)	Mg^{2+} (me)	Ca^{2+} (mg)	Ca^{2+} (me)	K^+ (mg)	K^+ (me)	Cl^- (mg)	Cl^- (me)	HCO_3^- (mg)	HCO_3^- (me)	SO_4^{2-} (mg)	SO_4^{2-} (me)	TOTAL STRONG ACIDS (me)	TOTAL ANIONS (me)	SALINITY (mg)
14.7.69	–	–	–	–	–	–	–	–	–	–	–	–	–	–	1.40	–	–
11.8.69	23.0	1.00	12.2	1.00	3.0	0.15	2.43	0.06	–	–	50.5	0.83	–	–	1.38	2.21	–
22.9.69	24.5	1.07	10.3	0.85	4.60	0.23	2.53	0.07	–	–	50.5	0.83	–	–	1.39	2.22	–
26.10.69	28.5	1.24	8.4	0.69	4.66	0.24	2.50	0.06	–	–	50.6	0.83	–	–	1.39	2.22	–
17.11.69	23.8	1.03	–	–	4.40	0.22	2.45	0.06	–	–	–	–	–	–	1.37	–	–
29.12.69	25.1	1.09	10.7	0.88	3.13	0.16	2.43	0.06	44.4	1.25	50.6	0.83	4.99	0.10	1.36	2.19	141.3
27.1.70	32.25	1.40	7.1	0.58	3.85	0.19	2.60	0.07	48.05	1.36	51.8	0.85	4.04	0.08	1.39	2.24	149.7
17.2.70	32.75	1.42	7.3	0.60	3.53	0.18	2.50	0.06	47.40	1.34	51.8	0.85	4.23	0.09	1.41	2.26	149.0
27.2.70	34.75	1.51	6.3	0.52	3.73	0.19	2.80	0.07	46.55	1.31	52.4	0.86	5.52	0.12	1.43	2.29	152.0
9.3.70	34.75	1.51	6.1	0.50	4.51	0.23	2.28	0.06	46.40	1.31	53.7	0.88	5.43	0.11	1.42	2.30	153.2
Mean	28.8	1.25	7.3	0.71	3.93	0.20	2.50	0.06	46.55	1.31	51.5	0.84	4.84	0.10	1.39	2.24	149.0

TABLE 6—Minor ionic constitutents of Lake Ototoa (– = not determined)

DATE	NO^3–N (mg.litre^{-1})	PO_4–P (μg.litre^{-1})
11 August 1969	0.6	–
22 September 1969	0.5	5.95
26 October 1969	0.3	1.00
17 November 1969	0.17	10.20
29 December 1969	0.37	3.15
27 January 1970	0.36	3.15
17 February 1970	0.46	2.65
23 February 1970	0.31	–
9 March 1970	0.12	–
Mean	0.35	4.35

Ototoa are also shown in the table. The figures for Ototoa may be a little too low since oxygen produced photosynthetically in the upper metalimnion may have been transferred into the upper hypolimnion by turbulent mixing.

IONIC COMPOSITION

pH

In Lake Ototoa there was little seasonal variation in the pH of the surface waters (see Fig. 8): slightly higher values were found in December and early January than during the rest of the year and the lowest surface pH's were in late January and early February (minimum 7.2) when phytoplankton stocks were low. The pH of Lake Ototoa falls in the range for other New Zealand lakes (Flint 1938, Barker 1970, Mitchell 1971, and McColl 1972), and as in most stratified lakes the bottom waters had slightly lower pH values during the summer (see Fig. 8). On 12 January 1970 (see Fig. 9) high pH at 6 m and high pH and oxygen concentration at 12 m may have been related to algal photosynthesis. Below the thermocline pH's dropped gradually and reached neutrality in the bottom waters.

Ionic composition varied little between stations, and the mean values of the major and minor ions are set out in Tables 5 and 6.

MAJOR IONS

The salinity of Lake Ototoa is typical of the series of Northland lakes studied by Dr M. A. Chapman, Waikato University, and myself (unpublished data) which are considerably more saline than the dilute waters of the Canterbury mountain lakes (Stout 1969), and central North Island lakes (McColl 1972), yet more dilute than Aroarotamahine (Bayly 1962), Pupuke (Barker 1970) and Tomahawk Lagoon (Mitchell 1971) (Table 7). Between August 1969 and March 1970, values of sodium, chloride, bicarbonate, and sulphate increased, as the lake level was lowered by evaporation during the summer. However, concentrations of calcium and magnesium decreased, perhaps as a result of biological deposition during photosynthesis (Horie 1968).

Previous analyses of water from Lake Ototoa by Cunningham *et al.* (1953) gave concentrations for chloride of 58.2 me.litre^{-1} and for silicate of 4 me.litre^{-1}. Analyses of samples from Lake Ototoa carried out by the Government Analyst at Auckland on 27 April 1964 gave the following results: pH 7.6, chloride 55 me.litre^{-1}, total solids 130 me.litre^{-1}, and alkalinity 50 me.litre^{-1}. These differ from those of 1969–70 only in the sightly higher chloride concentrations.

Ionic proportions from Lake Ototoa are shown in Table 8 together with those of typical seawater, world average freshwater, and a number of New Zealand and Australian lakes and groups of lakes. The ionic sequence in Ototoa is $Na > Mg > Ca > K$ for the cations, and $Cl > HCO_3 > SO_4$ for the anions, compared with the order for typical freshwater of $Ca > Na = Mg > K$ and $HCO_3 > SO_4 > Cl$. Such enrichment

TABLE 7—Comparison of the chemical composition of some New Zealand Lakes. Data from (1) Barker (1970); (2) Author's unpublished data; (3) Bayly (1962); (4) Stout (1969); (5) Mitchell (1971); (– = not given)

LAKE	CONCENTRATIONS (mg. litre $^{-1}$) Na^+	Mg^{2+}	Ca^{2+}	K^+	Cl^-	CONCENTRATIONS (me. litre $^{-1}$) HCO^{3-}	SO_4^{2-}	TOTAL ANIONS
Ototoa	28.8	7.3	3.95	2.5	46.55	51.5	4.84	2.24
Pupuke [1]	35.0	14.7	8.50	2.16	44.0	96.7	23.7	3.30
Northland dune lakes [2]	20.7	8.5	1.7	1.4	38.7	16.0	4.9	–
Aroarotamahine [3]	125.0	1.2	0.9	4.0	76.0	102	4.0	1.00
Canterbury lakes [4]	1.75–8.0	0.33–1.50	2.2–13.5	0.05–1.2	3–8	0.33–0.99	–	–
Tomahawk [5]	–	12.3–24.3	30.8–88.6	–	278–580	–	–	–
Mahinerangi [5]	–	0.2–1.0	0.9–2.0	–	4–5	–	–	–
Waipori [5]	–	0.3–2.1	0.8–2.5	–	2.5–35	–	–	–

TABLE 8—Comparison of mean proportions of major ions in Lake Ototoa with those of other waters: (1) Conway (1942); (2) Barker (1970); (3) Bayly (1964); (4) Timms (1969); (5) Stout (1969); (6) Bayly (1962); (7) Author's unpublished data; (8) Cunningham *et al.* (1953); (8) McColl (1972) (– = not given)

WATER	IONIC PROPORTIONS (me % of total cations or anions) Na^+	Mg^{2+}	Ca^{2+}	K^+	Cl^-	HCO^{3-}	SO_4^{2-}	$Na^+ : Cl^-$	SALINITY (mg.litre $^{-1}$)
Ototoa	56.3	32.0	9.0	2.7	58.4	37.2	4.4	0.97	149
Seawater [1]	77	18	3	2	90	0.4	9	0.86	35 000
Mean fresh water [1]	16	17	64	3	10	73	16	1.60	146
Pupuke [2]	49.0	35.6	13.8	1.6	36.9	48.8	14.3	1.33	225
Queensland–New South Wales dune lakes [3]	78	16	4	2	82	2	16	0.95	39
Wooli lakes [4]	80	14	5	1	75	17	8	1.07	74
Canterbury lakes [5]	31	11	55	2	–	–	–	–	–
Aroarotamahine [6]	96	2	1	2	38	62	1	2.52	–
Northland dune lakes [7]	56.1	36.7	4.9	2.4	68.5	13.9	6.1	0.82	–
Northland dune lakes [8]	60	24	13	3	–	–	–	–	147
Central North Island lakes [9]	52.0	19.4	18.3	10.3	28.4	55.0	16.6	1.83	57.3

of sodium, chloride and magnesium is widespread in Australasian lakes and typical of those near the sea. The ratios of calcium and bicarbonate are however relatively higher in Ototoa than if only atmospheric supply of ions was important. These two ions, and possibly also some magnesium, are most likely introduced by solution of limestones, shells, etc., in the consolidated Kaihu dunes. The low concentrations of calcium in Ototoa are similar to those of most other New Zealand lakes (2–8 me.litre^{-1}) which are characteristically soft (Fish 1969) or "poor" in the sense of Ohle (1934).

MINOR IONS

Nitrate concentrations were highest in mid-winter (0.6 mg.litre^{-1}, see Table 6), and decreased during spring to 0.17 mg.litre^{-1}. Concentrations rose in the summer but declined again in March to the lowest value found. In Lake Ototoa nitrate was highest at times of increased phytoplankton densities. Nitrate concentrations tended to be higher than those in other New Zealand lakes (e.g., Mitchell 1971, McColl 1972), and in the West Coast dune lakes Cunningham *et al.* (1953) found nitrate concentrations varying between zero and 0.24 mg.litre^{-1} (0.20 mg.litre^{-1} in Lake Ototoa) which are a little lower than the values recorded in this study.

Phosphate concentrations ranged between 1.00 μg.litre and 10.20-μg.litre^{-1} (see Table 6) and tended to be highest in late winter and in spring. The high mean value recorded on 17 November 1969 (10.2 μg.litre^{-1}) resulted from a high concentration of 16.7 μg.litre^{-1} at Station C, possibly caused by aerial topdressing with superphosphate of farmland around the north of the lake as the sample was being collected. Phosphate concentrations tend to be lower than many reported from other New Zealand lakes. Cunningham *et al.* (1953) found values ranging from a trace to 30 μg.litre^{-1} (16 μg.litre^{-1} in Ototoa); Jolly (1968) found 0–360 μg.litre^{-1} in the large North Island lakes; Fish & Chapman (1969) recorded trace to 100 μg.litre^{-1} in Lake Rotoiti, while Mitchell (1971) found 2.1–133.0 μg.litre^{-1} in Tomahawk Lagoon, 0.5–3.0 μg.litre^{-1} in Lake Mahinerangi, and 1.7–8.7 μg.litre^{-1} in Lake Waipori. Of the lakes studied by McColl (1972), phosphate concentrations in Okaro and Ngapouri were higher than in Ototoa, while those in Rotokakahi, Okareka, Tikitapu, Okataina, and Rotoma were similar to those in Ototoa.

ORGANIC MATTER

Total organic matter fluctuated throughout the year (Fig. 10), and most organic matter was always contained in the fraction passing a 0.8 μm membrane filter, and was presumably composed mainly of dissolved organic material and small non-living detrital particles. From September onwards this fraction underwent a seasonal fluctuation which was the reverse of that of total phytoplankton (see Fig. 5). The increases in November and February may have been caused by the breakdown of dead phytoplankton; the low values during September and December may indicate the subsequent incorporation of this material into new algal stocks.

Organic matter larger than 0.8 μm probably corresponds to the living phytoplankton and larger detrital particles; the large amounts in August may be related to the *Dinobryon* bloom which occurred at that time. However, later changes did not seem to be related to any significant changes in phytoplankton numbers.

The only other determinations of organic matter in Australasian waters by similar methods to those used in this study appear to be those of Fish (1966) and Bayly (1964) whose data for New South Wales dune lakes during August and September 1963 do not differ significantly from those in Lake Ototoa.

DISCUSSION

The characteristics of Lake Ototoa are typical of a temperate–subtropical lake close to the sea. Winter temperatures are favourable for algal growth, and the annual range of temperatures is small. Thus most heating occurs at relatively high temperatures, and because of the greater density change of water per degree Celsius at higher temperatures, distribution of heat into the lake requires a considerable amount of work, as shown by the rather high value for the work of wind ($B/\theta_{bs} =$ 0.114 gm.cm.cm^{-2}).

Warm monomictic lakes might therefore be expected to have lower heat budgets than those of dimictic lakes. However, heat budgets of Ototoa, Okataina, Pupuke, and Ngapouri, for example, are not as low as expected and are comparable with the annual budgets of many of the Northern Hemisphere lakes (Hutchinson 1957, Schlindler 1971). Two factors associated with an oceanic climate are probably responsible for higher uptake by some New Zealand lakes: greater exposure to persistent, variable, and moderately strong winds; and a lower rate of heating between maximum and minimum temperatures, resulting in a lower average daily temperature increase of the surface waters. This will facilitate their mixing by the wind deeper into the lake, with the consequent development of a deeper thermocline and thus a higher summer heat income. In New Zealand, heat is acquired over similar periods of time to lakes in Northern and Continental countries, yet the range of temperature of the surface waters is much less: c.f. 10–25°C in Ototoa with 0–22°C in the Canadian ELA lakes (Schindler 1971). In Lake Ototoa the large increase in bottom temperatures during the year is indicative of the efficient transfer of heat into the deeper regions of the lake by these processes, and the divergence found between the patterns of stratification of 1970, and those of the summers of 1950 and 1969 emphasise the variability of wind rather than temperature in the oceanic environment.

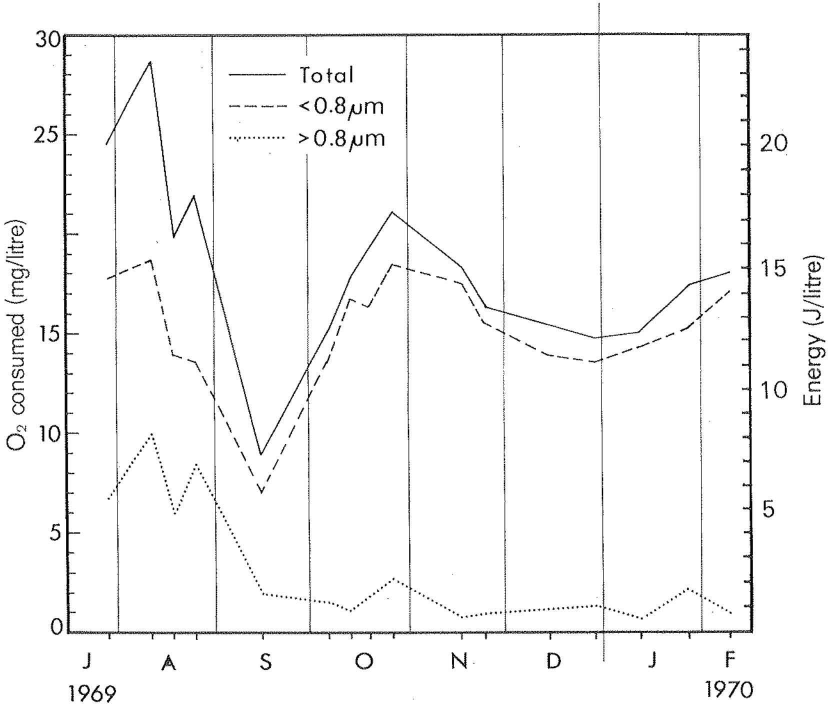


FIG. 10—Seasonal changes in the concentration of organic matter in Lake Ototoa. The total amount of organic matter is shown, as well as fractions for particles smaller and larger than 0.8 μm in diameter.

Oxygen deficits were calculated in an attempt to determine the trophic status of Lake Ototoa. Hutchinson (1957) regarded lakes which lost oxygen at a rate of up to 0.033 $mg.cm^{-2}.day^{-1}$ as oligotrophic and those in which the rate was 0.05–0.14 $mg.cm^{-2}.day^{-1}$ as eutrophic. Mortimer (1942) suggested slightly different values of 0.025 $mg.cm^{-2}.day^{-1}$ as an upper limit for oligotrophy and 0.55 $mg.cm^{-2}.day^{-1}$ as a lower limit for eutrophy. These classifications use the terms eutrophy and oligotrophy in the edaphic rather than the typological sense, trophic condition being assessed in terms of amounts of production under unit surface area rather than by the intensity of biological processes.

The oxygen deficit calculated for Lake Ototoa was 0.015 $mg.cm^{-2}.day^{-1}$ and thus on the basis of Mortimer's classification the lake must be regarded as oligotrophic, in the edaphic sense. This low deficit was developed even though there was a thick epilimnion much of which could have been trophogenic because of the clear water. The reduction of oxygen which did occur in the hypolimnion during the summer resulted from the small volume of water below the thermocline, which constituted only 12% of the lake volume. Although the deficit may be a little low because of metalimnetic oxygen production, it would seem that of the lakes in the North Island which have been studied in detail Lake Ototoa is one of the least productive. This is also suggested by the water clarity, relatively low soluble phosphate concentrations, and also by the small concentrations of chlorophyll and phytoplankton numbers (Green unpublished 1973).

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LITERATURE CITED

BARKER, M. A. 1970: Physico-chemical features of Lake Pupuke, Auckland, *N.Z. Journal of Marine and Freshwater Research 4*: 406–30.

BAYLY, I. A. E. 1962: Ecological studies on New Zealand lacustrine zooplankton with special reference to *Boeckella propinqua* Sars (Copepoda: Calanoida). *Australian Journal of Marine and Freshwater Research 13*: 143–97.

——— 1964: Chemical and biological observations on some acidic lakes of East Australian sandy coastal lowlands. *Australian Journal of Marine and Freshwater Research 15*: 56–72.

BIRGE, E. A. 1915: The heat budgets of American and European lakes. *Transactions of the Wisconsin Academy of Arts Sciences and Letters 18*: 166–213.

——— 1916: The work of the wind in warming a lake. *Transactions of the Wisconsin Academy of Arts Sciences Letters 18*: 341–91.

CHAPMAN, M. A. 1972. *Calamoecia lucasi* (Copepoda: Calanoida) and other zooplankters in two Rotorua, New Zealand lakes. *Internationale Revue der gesamten Hydrobiologie 58*: 1–18.

CLARKE, G. L. 1954: "Elements of Ecology". Wiley, New York. 560 pp.

CONWAY, E. J. 1942: Mean geochemical data in relation to oceanic evolution. *Proceedings of the Royal Irish Academy (Series B) 48*: 119–59.

CUNNINGHAM, B. T., MOAR, N. T., TORRIE, A. W., & PARR, P. J. 1953: A survey of the western coastal dune lakes of the North Island, New Zealand. *Australian Journal of Marine and Freshwater Research 4*: 343–86.

DONOVAN, W. F. unpublished 1968: The zooplankton of Lake Waikare. IIIB project lodged in Zoology Department, Auckland University. 31 pp.

FERRAR, H. T. 1934: The geology of the Dargaville-Rodney Subdivision. *N.Z. Geological Survey Bulletin 34*. 85 pp.

FISH, G. R. 1966: Some effects of the destruction of aquatic weeds in Lake Rotoiti, New Zealand. *Weed Research 6*: 350–8.

——— 1969: The oxygen content of some New Zealand lakes. *Verhandlungen Internationale Vereinigung fur Theoretische und Angewandte Limnologie 17*: 392–403.

——— 1970: A limnological study of four lakes near Rotorua. *N.Z. Journal of Marine and Freshwater Research 4*: 165–94.

——— 1975: Lakes Rotorua and Rotoiti, North Island, New Zealand; their trophic status and studies for a nutrient budget. *N.Z. Ministry of Agriculture and Fisheries, Fisheries Research Bulletin 8.* 72 pp.

FISH, G. R. & CHAPMAN, M. A. 1969: Synoptic surveys of lakes Rotorua and Rotoiti, New Zealand. *N.Z. Journal of Marine and Freshwater Research 3*: 571–84.

FLINT, E. A. 1938: A preliminary study of the phytoplankton of Lake Sarah (New Zealand). *Journal of Ecology 2*: 353–8.

GREEN, J. D. unpublished 1973: Ecological stdies on Lake Ototoa with special reference to the copepod *Calamoecia lucasi*. D. Phil. thesis lodged in library of University of Waikato. 225 p.

——— 1974: The limnology of a New Zealand reservoir with special reference to the life histories of the copepods *Boeckella propinqua* Sars and *Mesocyclops leuckarti* Claus. *Internationale Revue der gesamten Hydrobiologie 59 (4)*: 441–87.

HAYDON, G. A. unpublished 1967. Some aspects of the zooplankton of the Lower Nihotupu Reservoir. IIIB project lodged in Zoology Department, University of Auckland. 40 pp.

HORIE, S. 1968: Limnological studies on Lake Yogo-ko. III. *Bulletin of the Disaster Prevention Research Institute, Kyoto University 17*: 21–8.

HUTCHINSON, G. E. 1957: "A Treatise on Limnology". Vol. 1. Wiley & Sons, New York. 1015 pp.

IRWIN, J. 1973: Lake Ototoa provisional bathymetry. 1:5544. *N.Z. Oceanographic Institute Chart, Lake Series.*

JOLLY, V. H. 1968: The comparative limnology of some New Zealand Lakes. 1. Physical and chemical. *N.Z. Journal of Marine and Freshwater Research 2*: 214–59.

McCOLL, R. H. S. 1972: Chemistry and trophic status of seven New Zealand Lakes. *N.Z. Journal of Marine and Freshwater Research 6*: 399–447.

MACKERETH, F. J. H. 1955: Ion exchange procedures for the estimation of (1) total ionic concentration (II) total ionic concentration (II) chlorides and (III) sulphates in natural waters. *Mitteilung Internationale Vereinigung fur Theoretische und Angewandte Limnologie 4*: 1–16.

——— 1963: Some methods of water analysis for limnologists. *Freshwater Biological Association Publication 21.* 70 pp.

MACIOLEK, J. A. 1962: Limnological organic analyses by quantitative dichromate oxidation. *Research Report of the U.S. Fisheries and Wildlife Service 60*: 1–61.

MITCHELL, S. F. 1971: Phytoplankton productivity in Tomahawk Lagoon, Lake Waipori and Lake Mahinerangi. *N.Z. Marine Department Fisheries Research Bulletin 3.* 87 pp.

MORTIMER, C. H. 1942: The exchange of dissolved substances between the mud and water in lakes. *Journal of Ecology 30*: 147–201.

OHLE, W. 1934: Chemische und Physicalische untersuchungen Norddeutscher Seeen. *Archive fur Hydrobiologie 26*: 386–464.

SCHINDLER, D. W. 1971: Light, temperature and oxygen regimes of selected lakes in the experimental lakes area, north-western Ontario. *Journal of the Fisheries Board of Canada 28*: 157–69.

STOUT, V. M. 1969: Lakes in the mountain region of Canterbury, New Zealand. *Verhandlungen Internationale Vereinigung fur Theoretische und Angewandte Limnologie 17*: 404–13.

TIMMS, B. V. 1969: A preliminary limnological survey of the Wooli lakes, New South Wales. *Proceedings of the Linnean Society of New South Wales 94*: 105–12.

TIMMS, B. V. & MIDGELY, S. H. 1969: The limnology of Borumba Dam, Queensland. *Proceedings of the Royal Society of Queensland 81*: 27–42.

WELCH, P. S. 1948: "Limnological Methods". Blakiston Press. Philadelphia. 381 pp.