TRANSACTIONS

OF THE

ROYAL SOCIETY OF NEW ZEALAND

GENERAL

VOL. 2 NO. 5 JANUARY 30, 1968

Some Hydrological Observations in Auckland and Otago Harbours

By D. J. SLINN

[Received by the Editor, April 10, 1967.]

Abstract

RESULTS are presented, basically in the form of monthly means, of temperature, salinity, oxygen and nutrients (nitrate, nitrite, phosphate and silicate) in water from Auckland and Otago Harbours during 1963. Some data from other years are also incorporated into this account. Sea surface temperatures are compared with local air temperatures, and salinity with rainfall. In both harbours fresh water influence is small in summer, but more marked in winter. Nutrients are, in general, low in summer and high in winter, although phosphate does not seem to have a well defined pattern. There seems to be little chemical evidence of organic pollution in either harbour. It is concluded that Auckland Harbour is vertically well-mixed as a result of tidal currents, and this may also apply to Otago Harbour.

INTRODUCTION

MUCH of the information available on the hydrology of New Zealand waters relates to temperature and salinity, and a general account based on data collected prior to 1955 has been prepared by Garner (1962). Garner (1961) has described investigations, made in 1955, into the temperature and salinity distribution within New Zealand coastal waters. There have also been some more localised investigations. For example, Cassie (1960) gives a broad picture of temperature and salinity in the Hauraki Gulf during summer and winter, while Hounsell's observations (Hounsell, 1935) on Auckland Harbour provide data on temperature, salinity and pH as well as various metereological factors. Linzey (1944) has given some figures of salinity and other factors (e.g., silicate, phosphate and pH) in the Heathcote and Avon Estuary at Christchurch. More recent are the observations in Wellington Harbour by Maxwell (1956) and Brodie (1958). The latter, although dealing primarily with the current systems, includes some information on temperature and salinity. Skerman (1958) has summarised information on temperatures within New Zealand harbours during the years 1952–55 inclusive.

Apart from the temperature data in Skerman's paper, there seems to have been relatively little hydrological information collected from New Zealand coastal localities on a regular basis. This paper presents data collected mainly during 1963 on the distribution of temperature, salinity, dissolved oxygen and nutrients (phosphate, silicate, nitrate and nitrite) in Auckland and Otago Harbours.

Published by the Royal Society of New Zealand, c/o Victoria University of Wellington, P.O. Box 196, Wellington.

Sample Collection and Storage

Surface samples were collected in a polythene bucket, and temperatures taken by means of mercury in glass thermometers read to the nearest 0.1° C (duplicate thermometers were used in Auckland Harbour). Near-bottom samples were collected by Nansen reversing bottle fitted with reversing thermometers.

Samples for oxygen determination were taken in duplicate in ground-glass stoppered bottles. Samples for nutrient estimation were either filtered (silicate and phosphate) through a well-washed No. 2 Whatman paper or centrifuged (nitrate and nitrite) to remove suspended matter.

Silicate samples were stored in polythene bottles with 2 drops concentrated hydrochloric acid for every 100ml filtrate (Mullin and Riley, 1955a). Samples for the determination of other nutrients were kept in glass bottles, phosphate samples being preserved with chloroform and nitrate–nitrite samples with *ca* 2ppm mercuric chloride. Samples were either stored in a domestic refrigerator or deep frozen at *ca* —20° C until it was convenient to carry out the analysis (2–3 days for samples stored in a refrigerator, up to 3 weeks for those in deep freeze). Samples for salinity determination were stored in 6oz medicine bottles into which waxed corks had been rammed.

Analytical Procedure

Salinity samples from Prince's Wharf (Auckland) and Portobello Marine Station Wharf (Otago) were titrated with silver nitrate (standardised against Copenhagen standard sea water) using potassium chromate as indicator (Oxner and Knudsen, 1920). A Knudsen pattern burette and pipette were used, with a magnetic stirrer to break up the silver chloride precipitate. The standard deviation of the method (seven estimations) was found to be 0.076%. Other salinity estimations were made according to the procedure recommended by Harvey (1955: 127) in which 10ml of the sea water sample is titrated against a solution containing 27.25g silver nitrate per litre; in this case results are expressed only to the nearest $0.1^{0}/_{00}$.

The standard Winkler technique (Jacobsen, Robinson and Thompson, 1950) was used to determine dissolved oxygen. Manganous sulphate and alkaline iodide were added when the sample was collected, and concentrated sulphuric acid prior to titration. Samples from Prince's Wharf were usually titrated within an hour or two of collection. The standard deviation of the method (10 estimations) was found to be 0.34%.

Nutrients, in the water samples collected and stored as described earlier, were estimated colorimetrically: silicate by the method of Mullin and Riley (1955 b), and phosphate by a molybdenum blue method (Slinn, 1956) based upon the procedure of Harvey (1948) and Armstrong (1949). Nitrate and nitrite were determined as described in Strickland and Parsons (1960) but using sulphanilic acid and α–naphthylamine for the diazotisation and coupling reaction (Mullin and Riley, 1955 c). The optical density of the coloured solution was measured in a Schimadzu XK–50 spectrophotometer with a cell of appropriate length (2cm for silicate and nitrate; 10cm for phosphate and nitrite). Calibration curves were constructed for all components using standard solutions, and a salt error correction applied where necessary.

Auckland Harbour

General Description

Auckland Harbour (also known as the Waitemata Harbour) has been described as a typical example of a drowned river valley, modified by wave action, and now

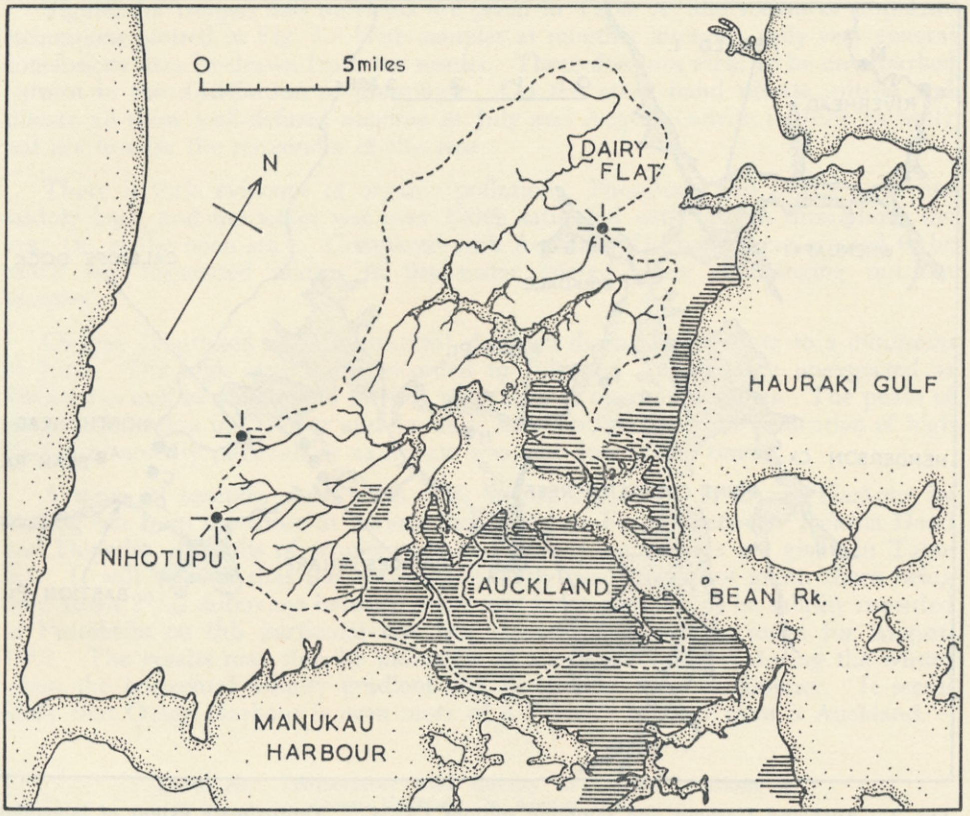

FIG. 1.—Auckland Harbour (catchment area outlined by dotted line).

containing extensive intertidal mudflats (Bartrum, 1917). In this investigation, only an area to the west of a line drawn from North Head–Bean Rock–Bastion Point (see Figs. 1 and 2 for place-names) has been considered. This is rather smaller than the official limits of the harbour as defined, for example, in Hounsell (1935).

The approximate catchment area of the harbour (as defined above) is outlined in Fig. 1. Fresh water drains into the harbour from a number of small creeks, the principal flows entering at Riverhead and Henderson Creek. These are not large, however, and the harbour was regarded by Powell (1937) as a virtually tidal harbour.

Apart from the main channel, the harbour is very shallow being mostly 1 fathom or less. Below Kauri Point the main channel averages about 7 fathoms (with several depressions of over 10 fathoms) but shallows to some 3–4 fathoms above. Fuller details will be found on Chart N.Z. 5322 of the R.N.Z.N. Hydrographic Branch.

Sublittoral deposits have been described by Powell (1937) and are also indicated on Chart N.Z. 5322 (see above). In general, they are of mud or muddy sand (with or without shell debris) except where tidal scour is too great for the finer deposits to settle. Intertidal deposits grade from muddy sand to mud in sheltered bays and creeks, with occasional outcrops of rock. The most outstanding (and ecologically important) of the latter is Point Chevalier Reef which extends from the south bank of the harbour to within $\frac{1}{2}$ mile of Kauri Point.

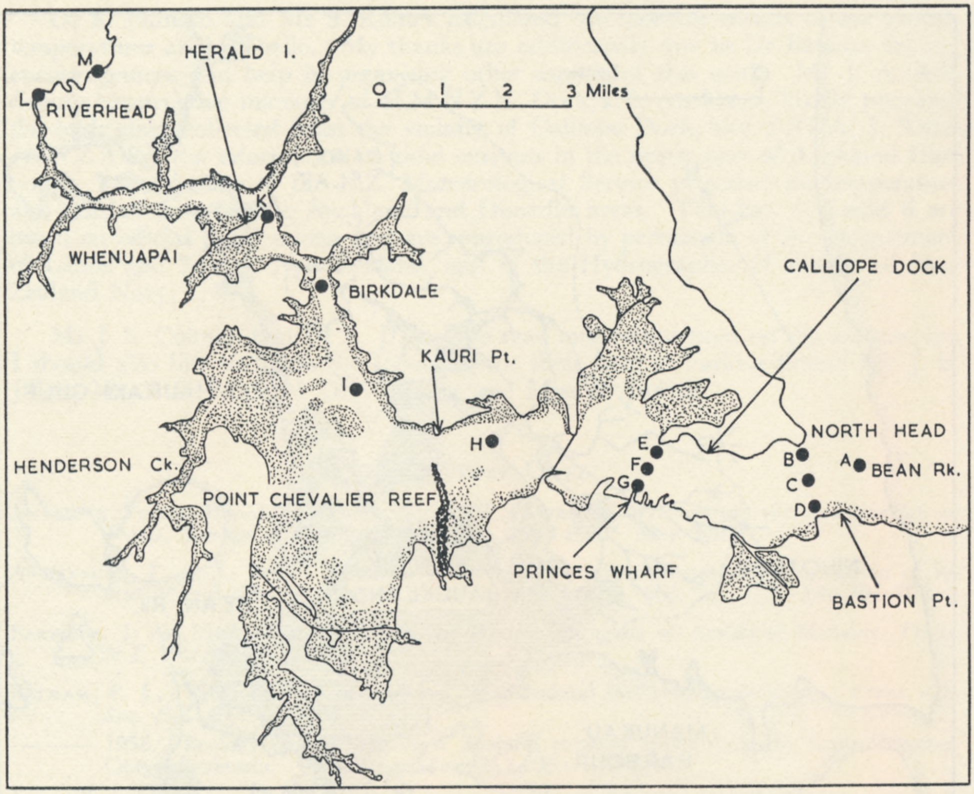

Fig. 2.—Auckland Harbour and sampling stations (A–M). Approximate extent of intertidal flats shown by stippling.

Tides are semi-diurnal with a range at Auckland of about 6.4ft at mean neaps and 9.6ft at mean springs (N.Z. Tide Tables for 1964). According to Hounsell (1935), there is little difference in tidal levels between the Port of Auckland and Birkdale, but upstream of this point the much narrower channel results in the height of spring tides at Riverhead being 18in greater than at Queen's Wharf (Auckland).

Currents are mainly tidal. Chart N.Z. 5322 (see above) indicates about 2 knots at springs between Bean Rock and the bridge, and 3–4 knots off Kauri Point. Average figures of $1\frac{3}{4}$–2 knots have been recorded between Kauri Point and Herald Island with up to $2\frac{3}{4}$ knots at spring tides off the Herald Island jetty (Tiller, pers. comm.). It seems likely that the funnelling effect of Point Chevalier Reef (exposed at half tide) helps to bring about the strong currents off Kauri Point.

Sampling, etc., in Auckland Harbour

Water samples for analysis were collected as follows (stations are indicated in Fig. 2) during 1963:

1. Surface samples from the end of Prince's Wharf, Auckland. Temperature and a salinity sample were taken approximately three times per week at 1300 hours. Samples for oxygen and nutrients were taken at the same time once per week. Temperature and salinity samples were also collected in December, 1962.

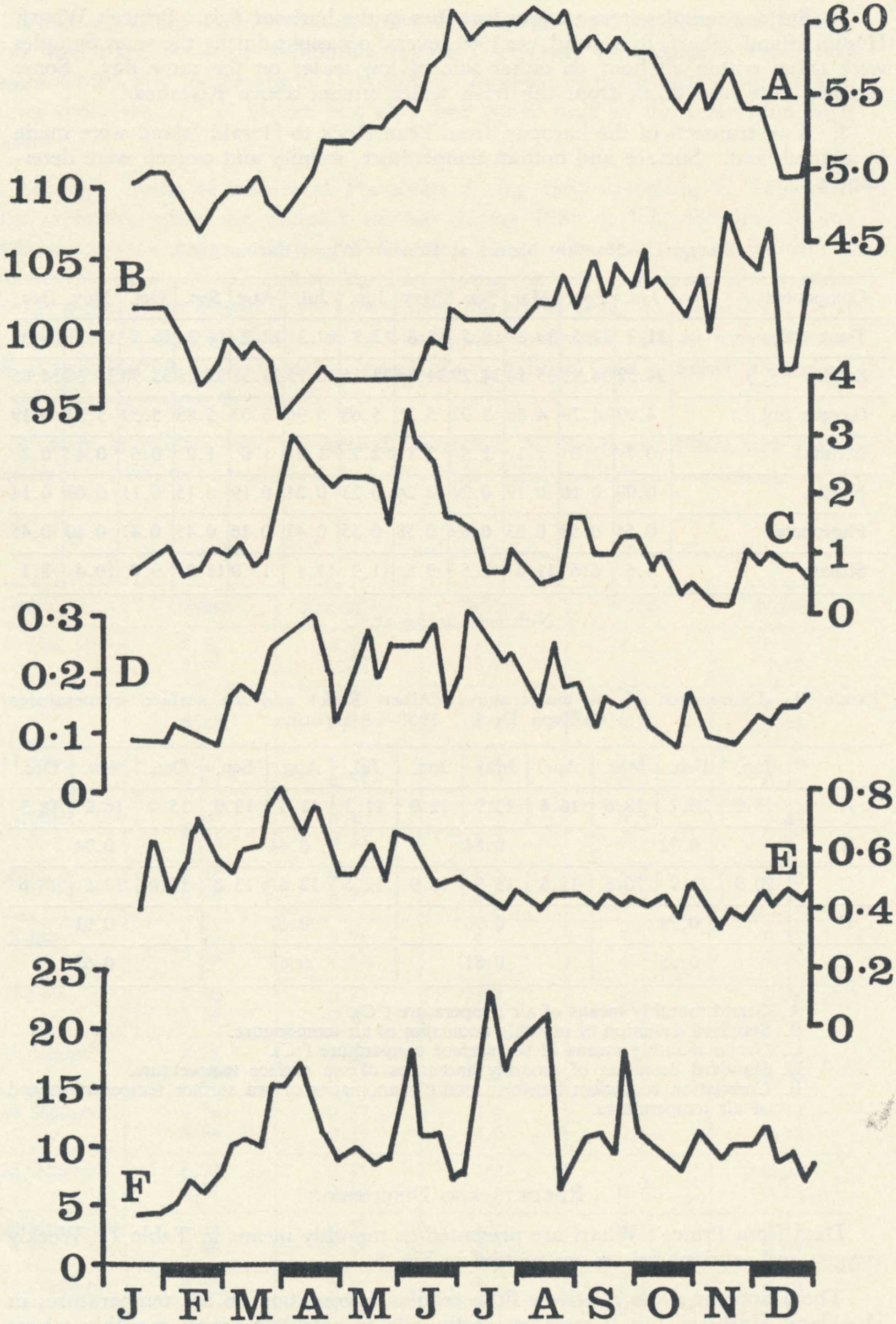

FIG. 3.—Auckland Harbour: weekly oxygen and nutrients during 1963. (A) oxygen, ml/l. (B) oxygen, % saturation. (C) nitrate. (D) nitrite. (E) phosphate. (F) silicate. (C–F as μg–at./l).

2. Surface samples from various localities in the harbour (viz.: Prince's Wharf, Herald Island Wharf, Riverhead, etc.) on several occasions during the year. Samples were taken within an hour on either side of low water on the same day. Some samples were also taken from the fresh water stream above Riverhead.

3. Two transects of the harbour, from Bean Rock to Herald Island were made in a small boat. Surface and bottom temperature, salinity and oxygen were determined.

Table I.—Monthly Means at Prince's Wharf during 1963.

Component	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
Temp (°C)	21.7	22.5	20.8	18.5	15.8	13.9	12.3	12.2	14.2	16.1	17.2	18.9
Salinity (°/₀₀)	34.52	34.95	35.14	34.29	34.38	33.15	32.75	33.31	33.28	33.90	34.86	34.85
Oxygen (ml./l.)	4.99	4.79	4.89	5.02	5.31	5.60	5.96	6.03	5.85	5.59	5.52	5.19
Nitrate	0.7	1.0	1.1	2.5	2.1	2.7	1.2	1.0	1.2	0.6	0.4	0.8
Nitrite	0.09	0.10	0.19	0.24	0.24	0.23	0.24	0.19	0.15	0.11	0.09	0.14
Phosphate	0.54	0.58	0.63	0.69	0.58	0.55	0.47	0.46	0.45	0.41	0.40	0.45
Silicate	4.5	6.6	11.6	12.5	9.6	11.9	17.1	13.9	11.8	9.0	10.4	8.1

Nutrients as μg–at./l.

Table II.—Comparison of air temperatures (Albert Park) and sea surface temperatures (Calliope Dock), 1959–64 inclusive.

	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
A	19.8	20.1	18.6	16.4	13.9	12.0	11.3	11.5	13.0	15.0	16.2	18.3
B		0.72			0.84			0.44			0.74	
C	20.9	21.9	20.8	18.8	15.9	13.9	12.6	12.6	13.8	16.0	17.6	18.6
D		0.79			0.96			0.67			0.91	
E		0.55			0.81			0.67			0.65	

A. Grand monthly means of air temperature (°C).
B. Standard deviation of monthly anomalies of air temperature.
C. Grand monthly means of sea surface temperature (°C).
D. Standard deviation of monthly anomalies of sea surface temperature.
E. Correlation coefficient between monthly anomalies of sea surface temperatures and of air temperatures.

Results and Discussion

Data from Prince's Wharf are presented as monthly means in Table I. Weekly oxygen and nutrient figures are plotted in Fig. 3.

There appears to be relatively little regular information on sea temperatures in Auckland Harbour, but it may be worthwhile to calculate grand monthly means from such data as are available. This was done using the monthly means reported by Hounsell (1935), Skerman (1958) and the 1963 data from Prince's Wharf together with unpublished information collected (by R.N.Z.N. Dockyard personnel using an alcohol thermometer) from the vicinity of Calliope Dock during 1959–64 inclusive. With data irregularly collected over a long period of time only the broadest interpretation is possible, particularly as slightly different localities are involved.

If the grand monthly means so calculated are plotted against time and a smooth curve drawn through the points, then the mean maximum and minimum temperatures (and hence the mean annual range) may be deduced together with the approximate dates on which they occur. At Auckland the maximum sea surface temperature of about 21.8° C occurs around mid-February, the minimum temperature (about 11.9° C) at the beginning of August, and the mean annual range is thus about 9.9° C. Hounsell (1935) gives figures for the average yearly range of sea surface temperature over the years 1929–32 at various localities in the vicinity of Auckland and, as might be expected, the range in the open sea is less than in estuarine waters.

TABLE III.—Rainfall (inches) at four stations in the Auckland area during 1963, compared with monthly averages at Auckland over the period 1921–50 (latter data from N.Z. Official Yearbook, 1964).

Recording Station	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Year
Albert Park	2.65	2.54	3.94	3.54	3.03	5.17	4.51	4.08	2.78	0.83	2.92	1.88	37.87
Whenuapai	3.08	3.58	4.26	3.86	2.95	6.35	5.85	3.08	4.85	1.20	5.15	2.94	47.15
Nihotupu	4.42	5.95	7.68	5.81	6.22	9.12	7.98	5.05	6.90	4.90	6.41	5.52	75.96
Dairy Flat	2.31	2.30	5.20	4.12	3.10	7.44	6.64	3.84	3.66	1.00	5.53	2.43	47.57
Auckland 1921-50	3.3	4.1	2.8	4.3	4.8	5.5	5.5	4.3	3.8	4.2	3.2	3.1	48.9

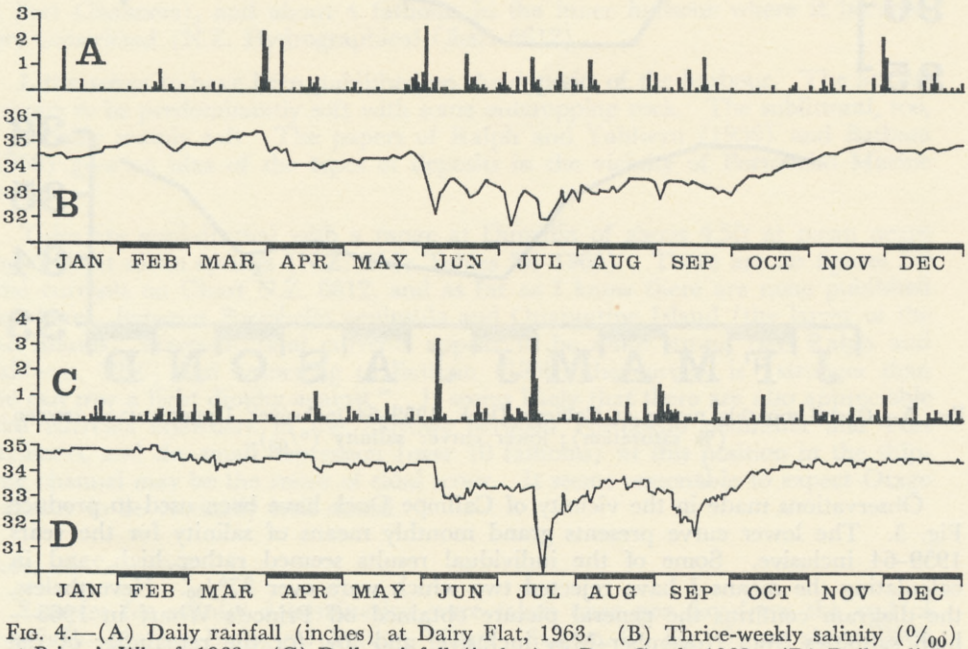

FIG. 4.—(A) Daily rainfall (inches) at Dairy Flat, 1963. (B) Thrice-weekly salinity ($^0/_{00}$) at Prince's Wharf, 1963. (C) Daily rainfall (inches) at Ross Creek, 1963. (D) Daily salinity ($^0/_{00}$) at Portobello, 1963.

The data from Calliope Dock have been examined further. Although these observations are infrequent, between 3 and 4 times per month on average, they have been continued for a number of years (1959–64). In Table II, grand monthly means of sea surface temperature are compared with air temperature data recorded over the same period of time at Albert Park (central Auckland, less than 1 mile from Prince's Wharf). The data have been grouped into 3–monthly periods for calculation of standard deviations of anomalies and correlation coefficients. It will be seen that there is a moderately high correlation between sea and air temperatures. Furthermore, sea temperatures are appreciably higher than air temperatures at all times of the year.

Rainfall, as run-off, is probably the most important factor affecting the variations of salinity in the estuary. Table III gives the monthly rainfall during 1963 for three localities (Albert Park, Whenuapai, and Dairy Flat) within the harbour catchment area, and one (Nihotupu Auxiliary Reservoir) just outside it. As might be expected, the Waitakere Ranges (exemplified by Nihotupu Auxiliary Reservoir) have a higher rainfall than other localities in the Auckland area, and Henderson Creek derives most of its run-off from the eastern slopes. On average, the Auckland area has a rather uneven rainfall over the year but with a definite maximum in the winter months (Table III); 1963 was not exceptional in this respect. In Fig. 4 the daily rainfall at Dairy Flat (in the catchment area of the Riverhead stream) has been compared with the thrice-weekly salinity figures for Prince's Wharf. It is apparent that the salinity at Prince's Wharf falls soon after heavy rainfall, the effect being much more pronounced in winter than in summer.

Fig. 5.—Grand monthly means at Calliope Dock, 1959–64 inclusive: Upper curve: oxygen (% saturation); lower curve: salinity ($^0/_{00}$).

Observations made in the vicinity of Calliope Dock have been used to produce Fig. 5. The lower curve presents grand monthly means of salinity for the years 1959–64 inclusive. Some of the individual results seemed rather high, and in calculating the means I have rejected two which were over $37^0/_{00}$. Nevertheless, the diagram confirms the general picture obtained off Prince's Wharf in 1963—high salinities from November–May inclusive, and low for the remainder of the year.

TABLE IV.—Results of Boat Transects in Auckland Harbour.

	Station		A	F	H	I	J	K
	Depth (Metres)		>10	9	4½	5	3½	3
Winter	Time		10.40	12.15	13.50	14.30	15.15	15.55
	Temperature (°C)	Surface	13.4	13.0	12.7	12.3	12.2	12.1
		Bottom	13.4	13.2	12.7	12.6	12.2	12.1
	Salinity (°/oo)	Surface	34.3	33.5	32.0	29.7	27.4	22.2
		Bottom	34.4	33.9	32.6	30.9	28.0	23.7
	Oxygen (ml/l and % sat.)	Surface	5.81 (103)	5.81 (102)	5.94 (105)	5.93 (106)	6.08 (110)	6.30 (118)
		Bottom	5.78 (102)	5.72 (101)	5.85 (103)	6.03 (107)	5.99 (108)	5.68 (105)
Summer	Time		10.30	12.00	13.15	14.15	15.10	15.45
	Temperature (°C)	Surface	19.5	20.0	20.4	20.6	20.8	21.0
		Bottom	19.7	20.0	20.4	20.7	20.8	21.0
	Salinity (°/oo)	Surface	34.9	34.7	34.5	33.9	33.7	32.4
		Bottom	35.0	34.9	34.4	34.0	33.7	32.8
	Oxygen (ml/l and % sat.)	Surface	5.33 (105)	5.21 (104)	5.10 (102)	4.92 (100)	4.83 (98)	4.96 (103)
		Bottom	4.96 (98)	4.96 (99)	4.99 (100)	4.96 (101)	4.88 (99)	4.65 (96)

Upper: 25 June 1963 (H.W. 10.28 hrs, 10.9′ ; L.W. 16.17 hrs, 1.3′).
Lower: 19 December 1963 (H.W. 09.50 hrs, 9.9′ ; L.W. 15.34 hrs, 2.1′).

Dissolved oxygen (in terms of ml/l) was at a minimum in February and a maximum in August. Physical factors affecting the solubility of oxygen in sea water include temperature and, to a lesser extent, salinity. Expressing the results as percentage saturation may therefore give a better idea of biological activity. This has been done using the data of Truesdale and Gameson (1957) and a somewhat different picture emerges. The minimum (about 96–98%) occurred from April–June and the maximum (> 102%) from August–November, with a peak in the latter month.

TABLE V.—Surface Data collected in Auckland Harbour on 12 June 1963 (H.W., 11.01hrs, 9.7′).

Station	Time	Temperature (°C)	Salinity (°/oo)	Oxygen (ml/l)	Oxygen (% sat.)
B	11.40	14.5	33.9	5.48	99
C	11.50	14.5	33.7	5.60	101
D	11.58	14.4	33.6	5.53	100
G	12.40	14.8	33.6	5.40	98
F	12.46	14.6	33.2	5.44	99
E	12.51	14.7	33.4	5.57	102

The grand monthly means of oxygen saturation in the vicinity of Calliope Dock during 1959–63 inclusive are presented in Fig. 5 (upper curve). The original data were derived according to the procedure outlined in the American Public Health Association (1955) publication (Bell, pers. comm.). The general picture is similar to that off Prince's Wharf, although the actual saturation values are lower. However, surface samples collected from a boat in this part of the harbour (see Table V) did not reveal any great variation in oxygen saturation, so it is possible that the difference may be due to the somewhat different procedure and calculation. It should be noted that the position regarding the accuracy of published figures of oxygen saturation in natural waters is at present uncertain (Montgomery *et al*, 1964).

Nutrients were, in general, low in summer and high in winter. All showed a rise in autumn. Phosphate and nitrite, however, declined after an April peak to a minimum in November. Silicate, although showing an autumnal peak, did not reach maximum values until July. It is possible that some high silicate values may be related to fresh water run-off (*cf*. Fig. 3 F with Fig. 4 A and B). Nitrate also reached a peak in April, remained high in May and June (although maximum values were not as high as in Otago Harbour, see below), and fell off in July, minimum values were recorded in November.

Turning now to data collected in other localities, Table IV presents surface and bottom temperature, salinity and oxygen at stations in the harbour between Bean Rock and Herald Island. Two series of results were obtained, one in winter (June 25, 1963) and the other in summer (December 19, 1963). On these particular days the salinity recorded at Princes Wharf was close to the monthly mean, so the picture provided by the transects is probably typical for the time of year. In summer there was virtually no vertical stratification throughout the greater part of the harbour, and only at the station furthest upstream (off Herald Island) was there a slight difference (about $0.4^0/_{00}$) between surface and bottom salinity. In winter, however, rather more vertical stratification was apparent. The outermost station (Bean Rock) was still well mixed, but progressively increasing vertical stratification was found upstream; off Herald Island the difference between surface and bottom salinity amounted to $1.5^0/_{00}$. It will be noted that on both transects sampling proceeded up-harbour against the ebb stream, the outermost station being worked at approximately high water and the innermost at low water.

As one might expect, there are horizontal differences in temperature and salinity. Temperatures tend to fall up-harbour in winter and rise in summer, consistent with the cooling and warming brought about by intertidal flats. The fall in salinity as one proceeds up-harbour is much greater in winter than in summer, a reflection of the much greater run-off at that time of the year. Rainfall in the Auckland area is, on average, heavier during the winter months (Table III). Furthermore, such processes as evaporation and plant transpiration are at a minimum in the winter, thus tending to increase the proportion of rainfall which appears as run-off. These processes are collectively summarised by the term potential evapotranspiration (see Garnier, 1958, who gives monthly values for Auckland and Dunedin).

Small differences in salinity exist across the outer part of the harbour (see Table V), but the means of several series of such observations are needed to reveal any definite pattern.

From the results of the harbour transects it is clear that much of Auckland Harbour is vertically well mixed. There is little doubt that this is due to the strong tidal currents, 2 knots (*ca* 100cm/sec) or more at springs, which are found throughout its length. Tidal currents of 2 knots in parts of the English Channel, for example, maintain sufficient turbulence to make the water column vertically homogeneous and prevent the formation of a thermocline in summer (Dietrich, 1950). It may be noted that Wallace *et al* (1958) suggested that tidal mixing had brought about the fairly even vertical distribution of bacteria which they found in the outer part of Auckland Harbour.

The bacterial surveys of Auckland Harbour by Wallace and Newman (1953) produced evidence of pollution by domestic sewage. At the present time, however, the city sewage is treated at the Mangare sewage farm before discharge into the Manakau Harbour, and there seemed to be little chemical indication of serious pollution during the present survey. Neither phosphate nor nitrite showed unduly high values. Furthermore, the water was well oxygenated throughout the year, although saturation values were not quite as high as might be expected in the open sea; it is possible that this may have been brought about by the oxygen demand of suspended matter.

Table VI.—Auckland Harbour: data from station M (fresh water above Riverhead) in 1963.

Date	Temperature (°C)	Oxygen (ml/l)	Oxygen (% sat.)	Nutrients (all μg–at./l) PO_4	SiO_3	NO_3	NO_2
27 February	18.9	3.15	50	1.7	98	–	1.3
7 April	15.3	5.96	88	1.8	69	1.9	3.0
3 July	11.7	6.65	90	1.3	172	4.4	0.9
22 October	15.1	5.08	74	1.6	75	3.3	2.0

Phosphate and silicate seem always to be relatively abundant. Silicate is certainly provided in large amount by the fresh water entering the harbour (see Table VI). Phosphate is also contributed by fresh water, but some may be released from estuarine muds (see, e.g., Rochford, 1952). Nitrate in conjunction with oxygen (as % saturation) seems to provide the best indicator of biological activity, which was apparently at a minimum during April–June and high from August–January. November seemed to be the peak month, with oxygen saturation often over 105% and nitrate sometimes barely detectable. Phosphate, too, was at its lowest in November although it did not approach a limiting value.

Table VII.—Tidal variations in surface temperature and salinity at three localities in Auckland Harbour during 1963.

Locality	Tide	19th Feb. T°C	S°/₀₀	3rd April T°C	S°/₀₀	17th June T°C	S°/₀₀	21st Oct. T°C	S°/₀₀
Prince's Wharf	H.W.	23.2	34.96	19.7	34.87	12.3	33.48	16.2	34.11
	L.W.	22.9	34.92	19.3	34.76	12.3	33.01	16.4	34.04
Herald 1	H.W.	20.9	34.0	18.2	32.4	11.8	30.3	16.9	33.4
	L.W.	22.8	32.9	18.2	29.9	11.7	24.5	17.7	32.4
Riverhead	H.W.	21.2	30.7	18.9	18.1	11.9	5.0	18.0	25.5
	L.W.	23.2	23.2	17.9	3.5	11.7	2.0	17.1	18.0

The nutrient cycle thus seems to be similar to that of coastal waters with high values in the winter followed by a spring decline as the phytoplankton outburst gets under way. Autumn regeneration followed low summer values. Superimposed upon the pattern is the contribution by fresh water run-off in the form of abundant silicate with a lesser amount of phosphate and nitrite. It may be noted in passing that the fresh water entering at Riverhead appears to be rather low in oxygen, particularly in summer (Table VI).

In an estuary such as this, tidal differences in temperature and salinity might be expected at any particular locality. Table VII presents data on surface samples collected at high and low water (on the same day) from "land" stations in the harbour. It is clear that tidal fluctuations do occur; in the case of salinity these tend to be greater in the upper part of the harbour than in the lower, and in general greater in winter than in summer. Temperature and salinity data from Prince's Wharf for the four-monthly periods December, 1962–March, 1963, and June–September, 1963, were examined according to the procedure outlined in Proudman (1943). No regular tidal oscillation was demonstrated, although there were indications that differences of about 1° C may be expected during a tidal cycle in the summer months. It is clear, however, that many more data are required to demonstrate tidal variations on a statistical basis.

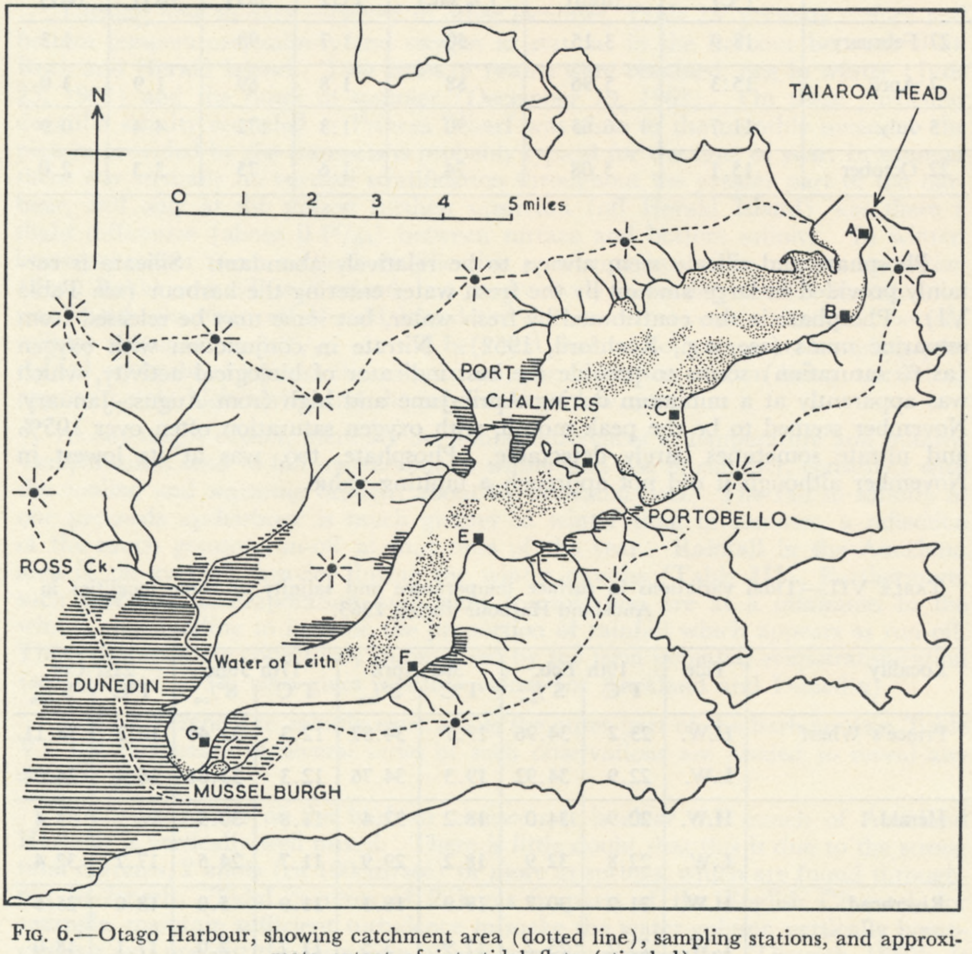

Fig. 6.—Otago Harbour, showing catchment area (dotted line), sampling stations, and approximate extent of intertidal flats (stippled).

TABLE VIII.—Comparison of air temperature (Musselburgh) and sea surface temperatures (Portobello), 1952–63 inclusive.

	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
A	15.3	15.1	13.7	11.6	9.1	7.0	6.2	7.2	9.3	11.4	12.7	14.0
B		0.89			0.94			0.56			0.85	
C	16.2	15.7	14.2	12.0	9.4	7.5	6.3	7.3	9.4	11.9	13.6	15.0
D		0.77			0.83			0.49			0.90	
E		0.81			0.77			0.62			0.74	

A. Grand monthly means of air temperature (°C).
B. Standard deviation of monthly anomalies of air temperature.
C. Grand monthly means of sea surface temperature (°C).
D. Standard deviation of monthly anomalies of sea surface temperature.
E. Correlation coefficient between monthly anomalies of air temperatures and of sea surface temperatures.

OTAGO HARBOUR

General Description

Otago Harbour (Fig. 6) is long and narrow, lying approximately NE–SW, with the city of Dunedin at the inner end and a relatively constricted outlet to the Pacific Ocean at the other. Numerous small creeks drain the hills surrounding the harbour (approximate catchment area outlined in Fig. 6), but the only stream of any consequence is the Water of Leith which enters via the northern part of Dunedin.

Apart from the narrow and tortuous shipping channel, the harbour is very shallow (1 fathom or less) with large areas exposed at low water. The depth of the shipping channel is some 5–10 fathoms in the outer harbour (i.e., downstream of Port Chalmers), and about 4 fathoms in the inner harbour where it becomes very constricted (N.Z. Hydrographical Chart 6612).

Little seems to have been published on the deposits of the harbour. The littoral appears to be predominantly soft with some outcropping rock. The sublittoral, too, is probably mainly soft. The papers of Ralph and Yaldwyn (1956) and Batham (1956) give an idea of the types of deposits in the vicinity of Portobello Marine Station.

Tides are semi-diurnal with a range at Dunedin of about 4.5ft at mean neaps and 5.6ft at mean springs (N.Z. Tide Tables for 1964) . There are no figures for tidal currents on Chart N.Z. 6612, and as far as I know there are none published elsewhere. Between Portobello peninsula and Quarantine Island (the larger of the two islands), however, tidal currents appear to be quite strong (see Ralph and Yaldwyn, 1956) and according to Batham (1956) the current is "stronger than one can row a light dinghy against". It seems likely that there are also appreciable tidal currents elsewhere in the narrows between Portobello peninsula and Port Chalmers, and the small depression (over 10 fathoms) at this position in the shipping channel may be the result of tidal scour. It seems reasonable to expect Otago Harbour to be vertically well mixed.

Notes on Sampling

Samples for salinity determination were taken once per day from the end of Portobello Marine Biological Station Wharf (Station D, Fig. 6) at about 0900 hours (the same time as the daily temperature readings). Batches of samples were rail-freighted to Auckland for analysis. Samples for oxygen and nutrient analysis were also taken from the same locality, approximately once per month, and as far as possible at high water. All were taken in duplicate and air-freighted to Auckland. Treatment and preservation were as already described, but the nitrate–nitrite samples were not centrifuged until reaching Auckland.

Analysis of oxygen and nutrient samples was performed as soon as possible after receipt; in one case, however (June 20), the samples were delayed in transit for almost a week (transit time was usually one day), and an extra batch of samples was therefore collected early in July. No oxygen or nutrient samples were collected in January, 1963, but to provide information over a complete year, samples were taken in January, 1964.

Table IX.—Monthly Means of Salinity ($^{0}/_{00}$) at Portobello during 1963 compared with monthly means of rainfall (inches) at four stations in the Otago catchment area and monthly averages of rainfall at Musselburgh over the period 1921–50 (latter data from N.Z. Official Yearbook for 1964). Rainfall figures for Portobello by courtesy of Dr E. J. Batham.

	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Year
Salinity at Portobello	34.82	34.75	34.40	34.43	34.29	33.50	32.71	33.44	32.81	34.10	34.45	34.55	
Rainfall at: Ross Creek	2.42	3.58	2.86	2.81	2.61	7.26	8.68	3.65	6.20	2.35	3.19	3.95	49.56
Musselburgh	1.94	2.90	2.68	1.61	2.02	4.05	4.85	3.03	3.33	1.34	2.00	2.84	32.59
Portobello	3.20	3.41	3.17	2.55	1.79	4.61	5.66	3.77	4.58	1.38	3.21	3.48	40.81
Taiaroa Head	1.55	2.43	2.54	1.89	1.40	2.77	3.06	2.73	3.35	0.99	2.08	1.86	26.65
Musselburgh (1921-50)	2.8	2.5	2.5	2.5	2.6	2.9	2.5	2.3	2.2	2.5	2.8	2.9	31.0

Results and Discussion

Daily sea surface temperatures have been taken from Portobello Marine Biological Station Wharf since July, 1952, and the Director (Dr E. J. Batham) has kindly made the monthly means available to me. From them the grand monthly means for the period 1952–63, inclusive, have been calculated and are given in Table VIII where they are compared with air temperatures recorded at Musselburgh. The data have been grouped into 3–monthly periods for calculation of standard deviation of anomalies and correlation coefficients. It is seen that there is a high correlation between sea and air temperatures, particularly in the period January–June. As at Auckland, sea temperatures are higher than air temperatures, although the difference is small during the winter months.

From a smooth curve drawn through the grand monthly means of sea surface temperature plotted against time it may be deduced that the mean maximum temperature (about 16.3° C) at Portobello occurs in the latter half of January, and the mean minimum temperature (about 6.2° C) about the third week in July. The mean annual range is thus about 10.1° C. Compared with Auckland, the mean annual range at Portobello is slightly greater, the mean maximum and minimum temperatures are lower by about 6° C and occur about three weeks earlier. As might be expected, the annual range at Portobello is greater than on the adjacent exposed coast (Batham, 1958).

Tidal variations in temperature have been investigated by Skerman (1958), who used data over the 4–monthly period December, 1953–March, 1954, and demonstrated that temperatures at Portobello during this period were, on average, rather more than 1° C higher just after low water than in the hour after high water.

Monthly means of salinity at Portobello during 1963 are given in Table IX. This table also gives the monthly rainfall during 1963 at four localities in the harbour catchment area. During 1963 rainfall was somewhat atypical in that it was heavier during winter and spring than during the rest of the year (the average rainfall seems to be spread fairly evenly over the whole year, see Table IX). Even so, we may still expect salinities to be low in winter months with an average rainfall as potential evapotranspiration is then much reduced, and a higher proportion of rainfall will appear as run-off.

Salinity anomalies over the period December, 1962–March, 1963, and June–September, 1963, were examined, but no regular tidal oscillation was found.

Table X.—Oxygen (ml/l) and Nutrients (μg–at./l) in Otago Harbour.

Date	Oxygen	Phosphate	Silicate	Nitrate	Nitrite
19 Feb. 1963	5.68 5.68	0.54 0.57	3.1 3.0	1.3 –	0.12 0.12
19 March	6.19 6.23	0.47 0.51	3.6 2.8	0.4 0.6	0.11 0.13
17 April	6.23 6.23	0.51 0.57	1.4 1.7	1.0 0.9	0.18 0.18
15 May	6.60 6.55	0.30 0.32	1.2 1.1	0.5 0.5	0.06 0.07
20 June	6.76 6.79	0.51 0.49	5.0 4.8	3.3 1.7	0.30 0.36
3 July	7.76 7.76	0.51 0.35	4.6 5.0	3.1 3.3	0.37 0.30
28 July	7.50 7.54	0.47 0.45	17.7 17.0	8.7 7.8	0.36 0.36
21 August	7.28 7.30	0.36 0.33	17.1 15.2	3.8 3.6	0.31 0.30
24 September	6.76 6.68	0.37 0.37	3.3 4.0	0.5 0.5	0.14 0.12
22 October	6.73 6.71	0.33 0.33	3.7 5.1	0.1 0.2	0.02 0.03
20 November	6.44 6.46	0.39 0.43	4.6 4.4	0.5 –	0.11 0.07
18 December	6.22 –	0.57 0.58	2.4 2.4	0.4 0.5	0.12 0.13
26 Jan. 1964	6.32 6.35	0.41 0.37	3.8 4.7	<0.1 <0.1	0.08 0.09

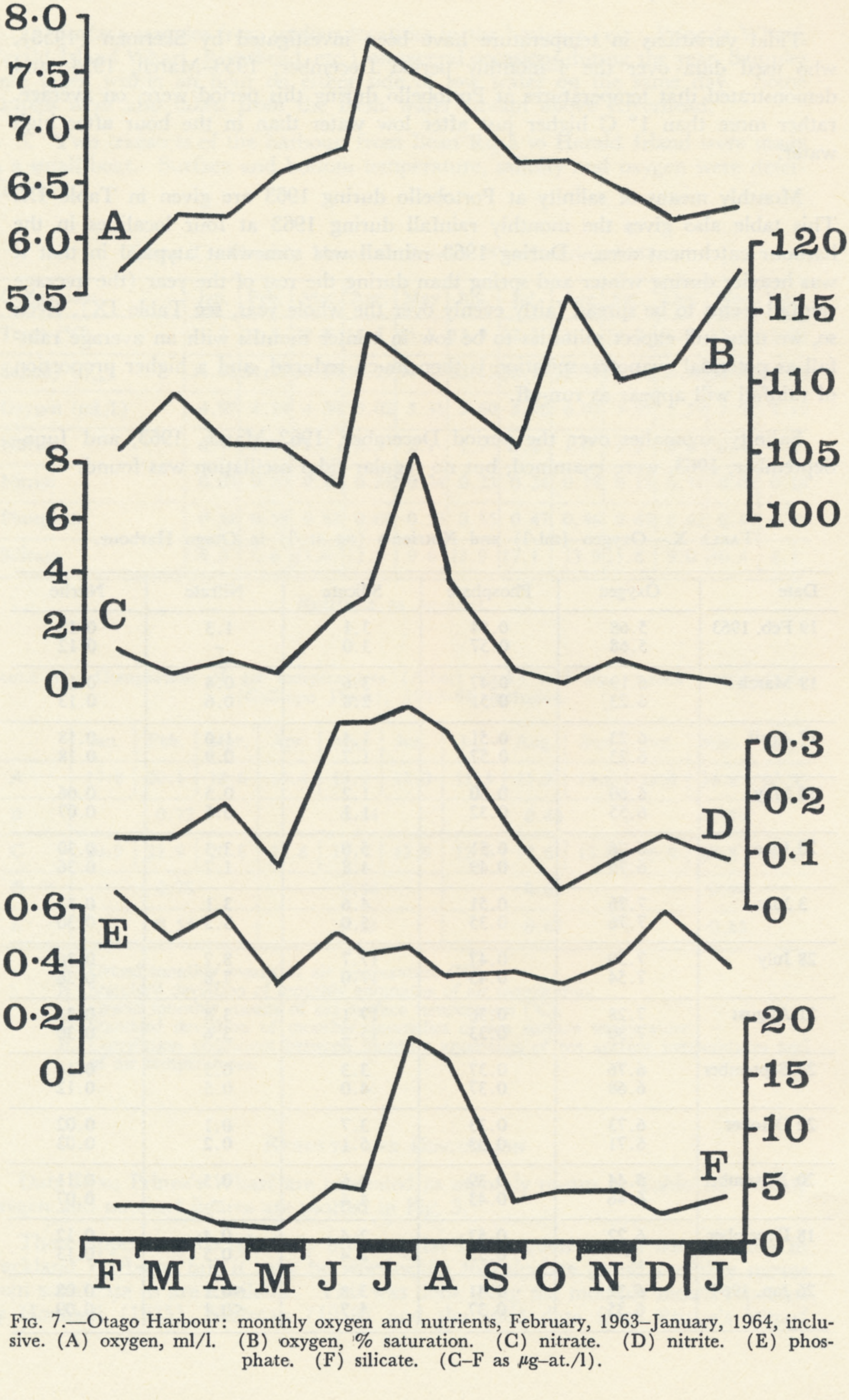

Fig. 7.—Otago Harbour: monthly oxygen and nutrients, February, 1963–January, 1964, inclusive. (A) oxygen, ml/l. (B) oxygen, % saturation. (C) nitrate. (D) nitrite. (E) phosphate. (F) silicate. (C–F as μg–at./l).

Figures for oxygen and nutrients are given in Table X, and means of duplicate estimations plotted in Fig. 7. With samples at monthly intervals, only very general conclusions may be drawn from the results. There does not seem to be any marked pattern in the distribution of phosphate. On the other hand nitrate, nitrite and silicate all show well-defined maxima in July and August (nitrite in June as well) but are low for the remainder of the year.

There is little evidence of organic pollution. Phosphate and nitrite were not unduly high, and the water was over 100% saturated with oxygen throughout the year (as in the open sea). Compared with Auckland Harbour there seemed to be much less suspended matter in the water (noted when centrifuging nutrient samples).

Oxygen (expressed as % saturation) declined during the autumn to a minimum in June. The high saturations recorded in July and August were unexpected as nitrate (as well as silicate and nitrite) were then at maximum values. The peaks of oxygen saturation in October and January, however, probably are indicative of high biological activity particularly as nitrate was very low at the time.

A series of samples were taken (on August 24, 1962) in Otago Harbour by wading out from the shore at various localities (see Fig. 6) between Taiaroa Head and Dunedin. Results of temperature and salinity estimations are given in Table XI. It will be seen that the horizontal salinity gradient is not great, there being only about $2^0/_{00}$ difference between outer and inner stations. The salinity recorded at Portobello on this particular day was close to the monthly mean for August, 1963. The results may thus be indicative of average conditions during the winter when the horizontal salinity gradient will be greater than in summer. It seems likely that Otago Harbour is even more of a " tidal " harbour than is Auckland.

Table XI. Temperature and salinity at "shore" stations in Otago Harbour, 24 August 1962.

Station	Time	Temperature (°C)	Salinity ($^0/_{00}$)
A	13.00	9.8	34.4
B	14.00	10.3	34.2
C	14.20	10.6	33.6
D	16.40	9.1	33.8
E	15.00	10.0	33.4
F	15.25	9.6	32.7
G	15.50	9.4	32.6

ACKNOWLEDGMENTS

This work was carried out while in receipt of N.Z. University Grant No. 62/245, which is gratefully acknowledged.

Sincere thanks are offered to: Professor J. E. Morton (in whose department most of the work was carried out) for his encouragement and advice, Mr J. W. Brodie for the loan of a reversing water bottle, Professor D. R. Llewellyn for permission to use the spectrophotometer in his department, and Mr J. Webb for the loan of a Knudsen burette.

Dr E. Batham and Mr S. Rainer calculated the monthly means of sea surface temperatures at Portobello. My thanks are additionally due to Dr Batham for her encouragement and help in organising other aspects of this work. Mr J. A. Bell, deputy constructive manager of H.M.N.Z.N. Dockyard, Auckland, kindly provided the basic data collected from the vicinity of Calliope Dock, and F/O A. J. Tiller (R.N.Z.A.F.) the information on tidal currents in the upper part of Auckland Harbour. The Director of the N.Z. Meteorological Service provided air temperature and rainfall data for the Auckland and Dunedin areas. Text-figs. 1, 2 and 6 are based on official publications, and are reproduced by permission of the Department of Lands and Survey, New Zealand, and of the Hydrographer of the Royal New Zealand Navy.

Mr J. S. Colman and Dr E. J. Batham read and commented on the manuscript. I should also like to thank the following for their help at various times: Mr J. B. Jillett, Mr A. D. Michael, Dr J. Harris and Miss A. Justice.

Literature Cited

American Public Health Association, 1955. *Standard Methods for the Examination of Water, Sewage and Industrial Wastes,* 10th Edn. New York.

Armstrong, F. A. J., 1949. A source of error in the absorbtiometric determination of inorganic and total phosphorus in sea water. *J. Mar. biol. Ass. U.K.* 28: 701–705.

Bartrum, J. A., 1917. Concretions in the Recent sediments of Auckland Harbour. *Trans. N.Z. Inst.* 49: 425–428.

Batham, E. J., 1956. Ecology of southern New Zealand sheltered rocky shore. *Trans. roy. Soc. N.Z.* 84: 447–465.

——— 1958. Ecology of southern New Zealand exposed rocky shore at Little Papanui, Otago Peninsula. *Trans. roy. Soc. N.Z.* 85: 647–658.

Brodie, J. W., 1958. A note on tidal circulation in Port Nicholson, New Zealand. *N.Z. J. Geol. Geophys.* 1: 684–702.

Cassie, R. M., 1960. Hydrology of Hauraki Gulf. *Proc. N.Z. ecol. Soc.* 7: 40–43.

Dietrich, G., 1950. Die anomale Jahresschwankung des Wärmeinhalts im Englischen Kanal, ihre Ursachen und Auswirkungen. *Deutsche hydrog. Zeits.* 3: 184–201.

Garner, D. M., 1961. Hydrology of New Zealand coastal waters, 1955. *N.Z. Dep. sci. industr. Res. Bull.* 138.

——— 1962. Analysis of hydrological observations in the New Zealand region, 1874–1955. *N.Z. Dep. sci. industr. Res. Bull.* 144.

Garnier, B. J., 1958. *The Climate of New Zealand.* London: Edward Arnold.

Harvey, H. W., 1948. The estimation of phosphate and of total phosphate in sea waters. *J. Mar. biol. Ass. U.K.* 27: 337–359.

——— 1955. *The Chemistry and Fertility of Sea Waters.* Cambridge University Press.

Hounsell, W. K., 1935. Hydrographical observations in Auckland Harbour. *Trans. roy. Soc. N.Z.* 64: 257–271.

Jacobsen, J. P.; Robinson, R. J.; Thompson, T. G., 1950. A review of the determination of dissolved oxygen in sea water by the Winkler method. *Pub. sci. Ass. Océanogr. phys.* No. 11.

Linzey, J. T., 1944. A short study of the hydrography of the estuary of the Avon and Heathcote Rivers, near Christchurch. *Trans. roy. Soc. N.Z.* 73: 365–376.

Maxwell, B. E., 1956. Hydrobiological observations for Wellington Harbour. *Trans. roy. Soc. N.Z.* 83: 493–503.

Montgomery, H. A. C.; Thom, N. S.; Cockburn, A., 1964. Determination of dissolved oxygen by the Winkler method and the solubility of oxygen in pure water and sea water. *J. appl. Chem.* 14: 280–296.

MULLIN, J. B.; RILEY, J. P., 1955a. Storage of sea water samples for the determination of silicate. *Analyst* 80: 73–74.

——— 1955b. The colorimetric determination of silicate with special reference to sea and natural waters. *Analyt. chim. acta* 12: 162–176.

——— 1955c. The spectrophotometric determination of nitrate in natural waters, with particular reference to sea water. *Analyt. chim. acta* 12: 464–480.

OXNER, M.; KNUDSEN, M., 1920. Chloruration par la méthode de Knudsen. *Bull. Comm. Int. Explor. Méditer.* No. 3.

POWELL, A. W. B., 1937. Animal communities of the sea-bottom in Auckland and Manukau Harbours. *Trans. roy. Soc. N.Z.* 66: 354–401.

PROUDMAN, J., 1943. Note on the variations of salinity of the surface waters of the Irish Sea. *Mon. Not. roy. astr. soc. Geophys. Suppl.* 5: 67–70.

RALPH, P. M.; YALDWYN, J. C., 1956. Sea-floor animals from the region of Portobello Marine Biological Station, Otago Harbour. *Tuatara* 6: 57–85.

ROCHFORD, D. J., 1952. The application of studies on estuarine hydrology to certain problems in Australian oyster biology. *Cons. Perm. Int. Explor. Mer, Rapp. et Proc.-Verb.* 131: 35–37.

SKERMAN, T. M., 1958. Seasonal variations in sea water surface temperatures within New Zealand harbours. *N.Z. J. Geol. Geophys.* 1: 197–218.

SLINN, D. J., 1956. Phosphate and oxygen in sea water off the Isle of Man during the years 1952–54. *Ann. Rep. Port Erin mar. biol. Sta.* 68: 30–38.

STRICKLAND, J. D. H.; PARSONS, T. R., 1960. A manual of sea water analysis. *Fish. Res. Bd. Can., Bull.* No. 125.

TRUESDALE, G. A.; GAMESON, A. L. H., 1957. The solubility of oxygen in saline water. *J. du Cons.* 22: 163–166.

WALLACE, G. M.; NEWMAN, L. E., 1953. Bacteriological survey of Auckland Harbours; Part I, Extent of sewage fields in Waitemata Harbour. *N.Z. J. Sci. Tech.* B34: 515–522.

WALLACE, G. M.; NEWMAN, L. E.; JERROME, J. L., 1958. Bacteriological survey of Auckland Harbours; Part V, Vertical distribution of sewage in Waitemata Harbour. *N.Z J. Sci.* 1: 23–34.

D. J. SLINN,
Department of Zoology,
University of Auckland;
and
Marine Biological Station,
Port Erin,
Isle of Man,
U.K.