The Hydrological Environment of Moreton Bay, Queensland, 1967-68

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By B. S. NEWELL*

Summary

Moreton Bay lies between latitudes 27°00′S. and 27°42′S. and longitudes 153°03′E. and 153°26′E. It has a surface area of 1.38×10^9 m^2 and a volume of 1.17×10^{10} m^3. The annual temperature range found was 13 degC at the surface and 9 degC at 21 m. The annual chlorinity range was 9.1‰ at the surface and 2.1‰ at 21 m. Maximum temperature (29°C) was in January and minimum (16°C) in August. Maximum tidal currents decrease from *c.* 2 kt in the east to *c.* 1 kt in the centre and *c.* 0.5 kt in the west. Time–series observations showed an irregular distribution of chlorinity and temperature unrelated to tidal phase.

I. INTRODUCTION

This report describes the results obtained from five hydrological surveys of Moreton Bay, carried out to provide environmental information for the East Coast Prawn Project of the Queensland Fisheries Research Institute and the Commonwealth Scientific and Industrial Research Organization.

II. MORETON BAY GENERAL DESCRIPTION

Moreton Bay (Fig. 1) is 40 miles long from north to south and has a maximum width of 20 miles. The southern portion narrows to a complex of islands forming the delta of the Logan R. The Bay is bordered in the west by the coastal plain and in the east by Moreton I. and North Stradbroke I.

The bottom topography is irregular, especially near the northern and eastern tidal deltas, but, in general, the Bay has a shallow western and southern portion shelving to a deep basin in the eastern central area. The maximum depth recorded was 42 m.

The total area of the Bay south of an east–west line through Cape Moreton is 1.38×10^9 m^2. The total water volume under this area is 1.17×10^{10} m^3. Estimates of the latter were made by planimetry of depth contours checked by summing the products of grid rectangle area and mean depth in each rectangle.

The hydrological boundaries of the Bay on the east and west are the coast and the barrier islands. In the south, a functional boundary lies at the meeting of co-tidal lines from the Bay and from the outside ocean. This boundary is near the southern end of Russell I. (Fig. 1). In the north, the boundary was taken to be the east–west line through Cape Moreton, which was the approximate northern limit of all surveys, and close to the narrowest part of the Bay's northern exit, though not the cross-section of least area. The latter was on a line running 284° true for 10 miles from the promontory south of Tangalooma, and thence to South Point, and had a

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cross-sectional area of 1.4 × 10^5 m^2 (Fig. 1). The narrowest section across the northern Bay, along a line due east from Skirmish Point, had a cross-sectional area of 1.84 × 10^5 m^2.

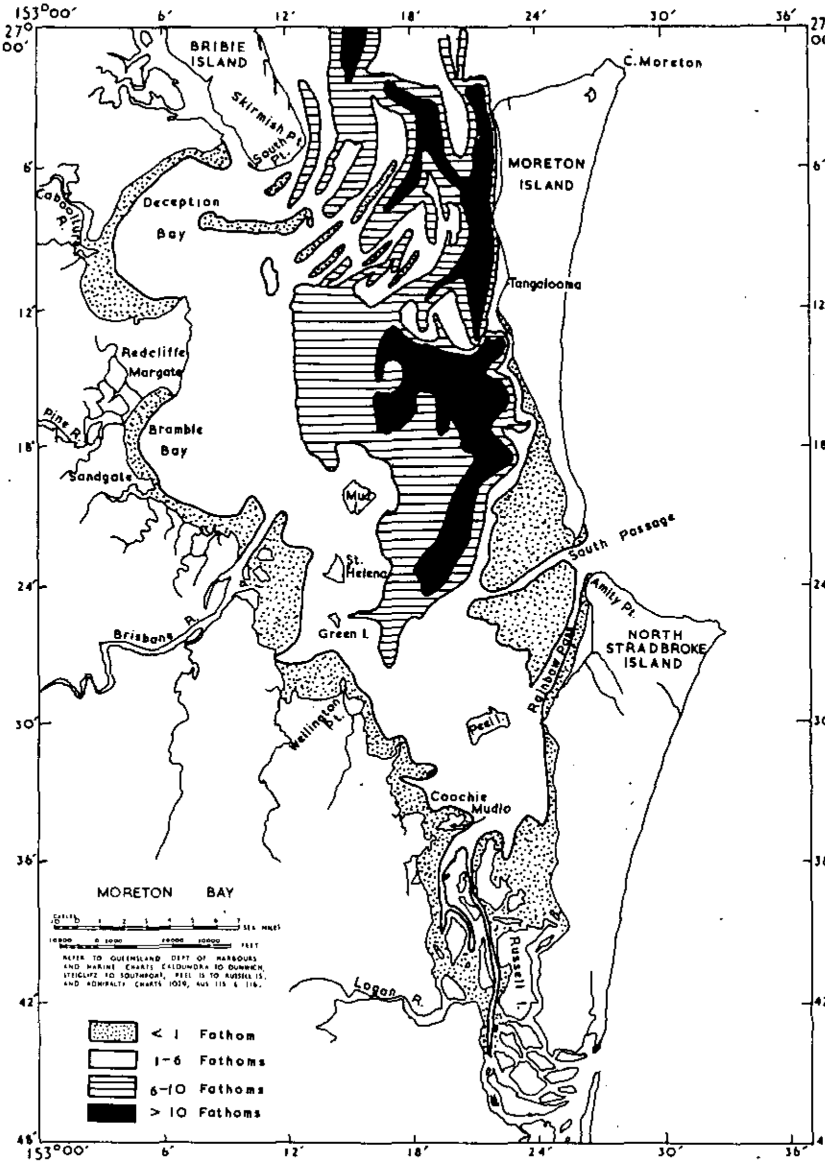


Fig. 1.–Moreton Bay depth contours.

The geological history and present sediment distribution of the Bay have been described by Maxwell (unpublished data). Briefly, the Bay is a result of subsidence in the Maryborough basin during Palaeozoic times, followed by igneous changes and sedimentation up to a climax in the Cretaceous. Spasmodic upheavals and further sedimentation have occurred since. The Bay contains several relict coral reefs and communities, whilst the three largest islands (Mud, St. Helena, and Green) in the central portion lie on a tongue of volcanic lava extending north from Wellington Point. The two large eastern barrier islands (Moreton and North Stradbroke) are dunes formed from wind-blown sand, and are still subject to wind- and stream-erosion and undercutting. The dominant sedimentary material in present times is sand, which forms the bottom along the eastern fringe of the Bay and forms the tidal deltas in the north and between the two barrier islands. Mud is contributed by the rivers entering the Bay, and dominates the sediments in the lower reaches of the river and the deep basin. The shallow western flow of the Bay is formed of a mixture of mud and sand.

The tidal deltas are still growing. That in the north consists of a series of banks orientated roughly NE. to SW., with four deep channels between. The delta between Moreton and North Stradbroke Is. is fan-shaped, and contains two tide-scoured channels, South Passage and Rainbow Passage.

The rivers entering the Bay from the coastal plain along the western fringe are, from north to south, the Caboolture, the North and South Pine, the Brisbane, and the Logan. The flow in these rivers fluctuates markedly, showing no clear seasonal pattern (Queensland Irrigation and Water Supply Commission, Water Resources Branch, private communication).

The Commonwealth Bureau of Meteorology maintains two stations on the Bay, at Sandgate and at Cape Moreton (Fig. 1). Winds recorded at these stations over the period January 1967 to December 1968 are depicted graphically in Figures 2 and 3 (Bureau of Meteorology, Brisbane, private communication). For each month are shown the number of times on which any wind was recorded from each of 16 compass points. A seasonal pattern emerges, with winds from north to east predominating between December and April, and from south to south-west between May and August. From September to November, winds are variable in direction. At the right hand margin of the histogram for each month is shown the frequency of occurrence of winds in three categories of velocity: less than 5 m/s, 5–9.5 m/s, and greater than 9.5 m/s. Winds are generally stronger at Cape Moreton than at Sandgate. At Cape Moreton gusts of up to 30 m/s were recorded on some occasions, whilst at Sandgate winds seldom exceeded 10 m/s. There is no obvious seasonal pattern in the occurrence of strong or light winds. However, when the (arithmetic) mean wind was calculated for each month (Table 1), some seasonal pattern did emerge, namely that the overall wind is least in the months July to October. The mean winds are always higher at Cape Moreton than at Sandgate, and reach a maximum in March. There is no clear maximum at Sandgate.

At both Sandgate and Cape Moreton the maximum air temperature occurs in January, and the minimum in July (Table 1). However, whilst summer air temperatures are similar at both stations, winter air temperatures are generally lower at Sandgate than at Cape Moreton (Bureau of Meteorology 1956).

In Figure 4 are shown some of the tidal characteristics of Moreton Bay. Co-tidal lines and amplitude ratios were obtained from the Department of Harbours and Marine, Queensland, Chart Brisbane 1.62. In all cases, the flood tide takes a southerly direction, and the ebb tide a northerly. The mean range of tide in the Bay is

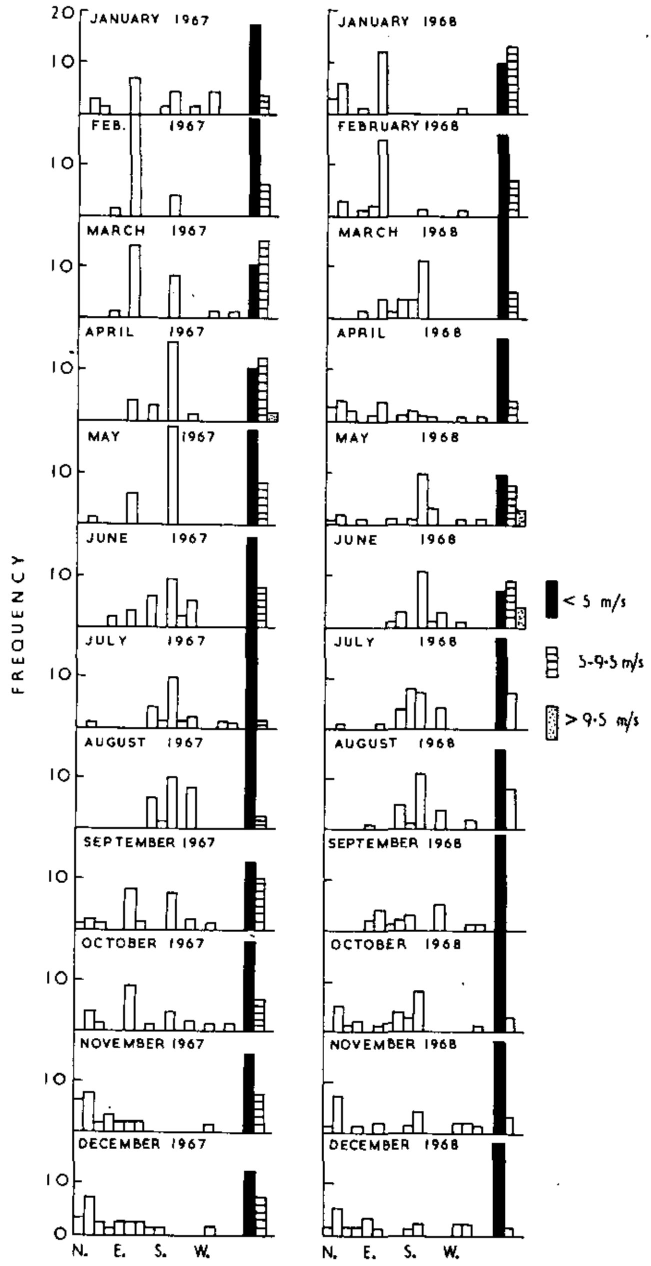


Fig. 2.–Frequency of winds from the 16 points of the compass, and in three velocity ranges, at Sandgate, January 1967 to December 1968.

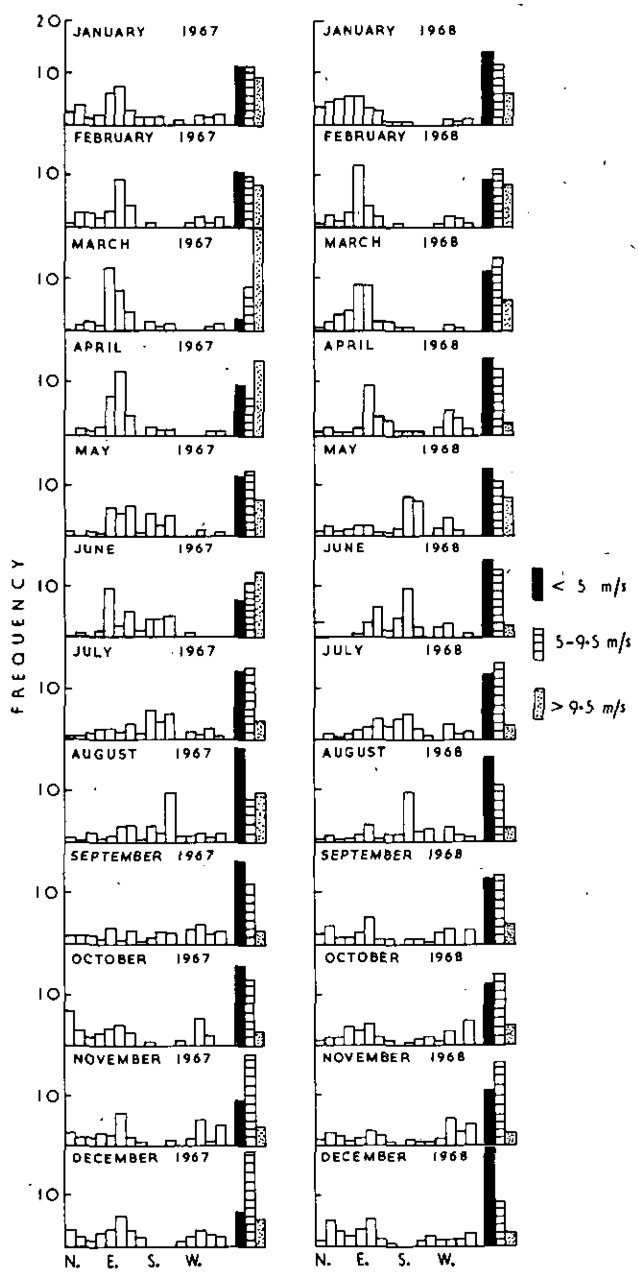


Fig. 3.–Frequency of winds from the 16 points of the compass, and in three velocity ranges, at Cape Moreton, January 1967 to December 1968.

TABLE 1

MEAN AIR TEMPERATURE (T_a), SEA SURFACE TEMPERATURE (T_W), WIND VELOCITY ($\overline{V}$), RAINFALL (R), AND EVAPORATION (E) FOR EACH MONTH OF THE YEAR AT SANDGATE OR CAPE MORETON

Number of years' observations from which mean was calculated is also given

Parameter	No. of Years' Observations	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
						Sandgate							
T_a (°C)	26	24.4	24.0	22.9	20.4	17.6	15.1	14.0	14.7	17.0	19.6	21.7	23.5
T_W (°C)	1	28.0	27.4	26.3	24.5	21.9	18.5	17.6	17.0	19.3	23.0	25.2	26.9
$\overline{V}$ (m/s)	2	3.4	3.2	3.1	3.9	3.9	4.2	2.2	2.1	2.7	2.6	3.2	3.3
R (in.)	30	5.9	5.9	5.5	4.2	2.6	3.0	2.2	1.2	1.8	2.5	4.3	4.8
E (in.)	1	5.8	4.8	4.4	5.7	5.6	4.4	2.1	1.7	2.4	3.5	4.5	5.6
$(R-E)$		+0.1	+1.1	+1.1	−1.5	−3.0	−1.4	+0.1	−0.5	−0.6	−1.0	−0.2	−0.8
						Cape Moreton							
T_a (°C)	30	24.3	24.2	23.5	21.4	18.8	16.6	15.9	16.5	18.5	20.3	22.0	23.5
T_W (°C)	1	25.5	25.5	25.5	25.5	22.5	19.5	18.8	18.5	19.8	21.5	23.1	24.6
$\overline{V}$ (m/s)	2	6.6	6.9	8.2	7.1	5.9	7.5	5.2	5.3	5.2	5.2	6.0	5.9
R (in.)	30	6.0	6.1	7.3	6.5	7.5	6.0	4.9	2.9	2.8	2.7	3.5	4.7
E (in.)	1	6.5	6.2	9.3	10.4	7.4	7.6	5.4	5.0	4.4	4.3	4.8	5.3
$(R-E)$		−0.5	−0.1	−2.0	−3.9	+0.1	−1.6	−0.5	−2.1	−1.6	−1.6	−1.3	−0.6

about 6 ft at springs and 3 ft at neaps. There is no evidence of seiche movements or amphidromic points.

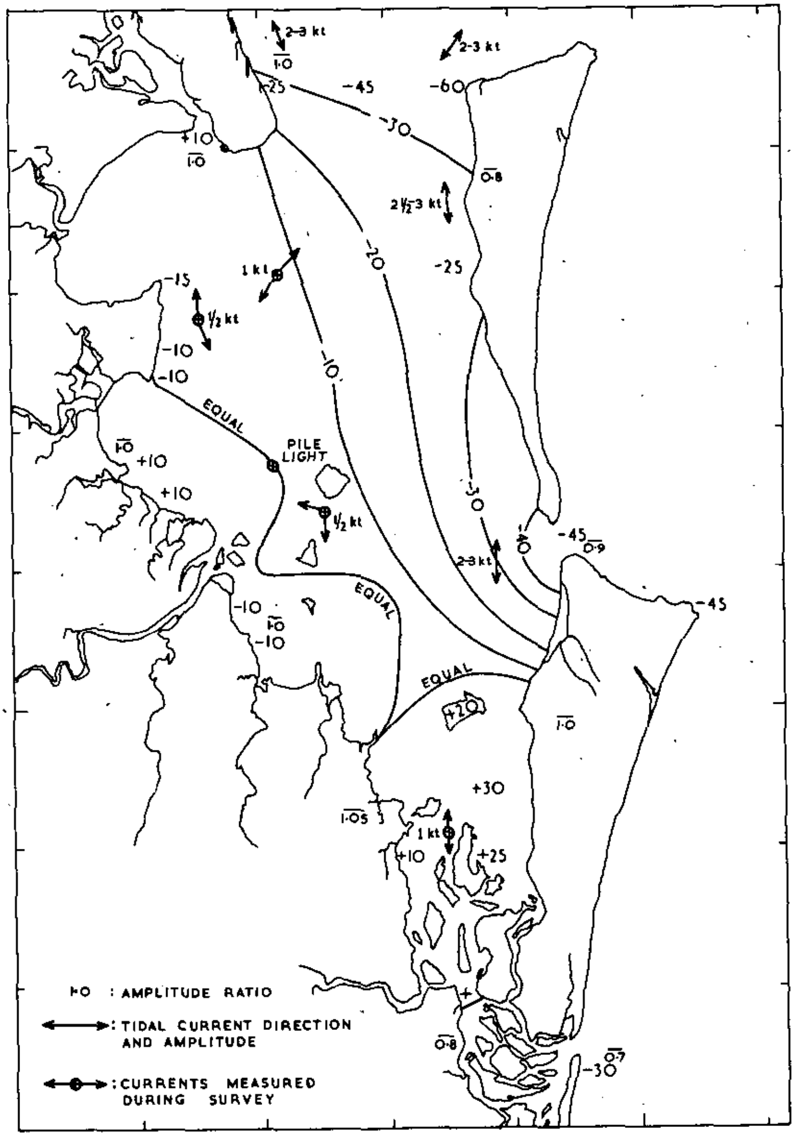


Fig. 4.—*Chart of Moreton Bay showing co-tidal lines and amplitude ratios relative to Pile Light. Numerals on co-tidal lines indicate minutes. Also showing tidal current direction and maximum magnitude [from "Australia Pilot" (British Admiralty 1950)].*

III. METHODS

For the survey, the Bay was divided by a grid (Fig. 5) into rectangles of side 2′ longitude (10,880 ft) by 2′ latitude (12,200 ft). Any measurement within a grid rectangle was identified by the number of that rectangle.

All measurements of chlorinity and temperature were made with CSIRO meters (Hamon 1956).

All current measurements were made with a metal vane of the type described by Pritchard and Burt (1951).

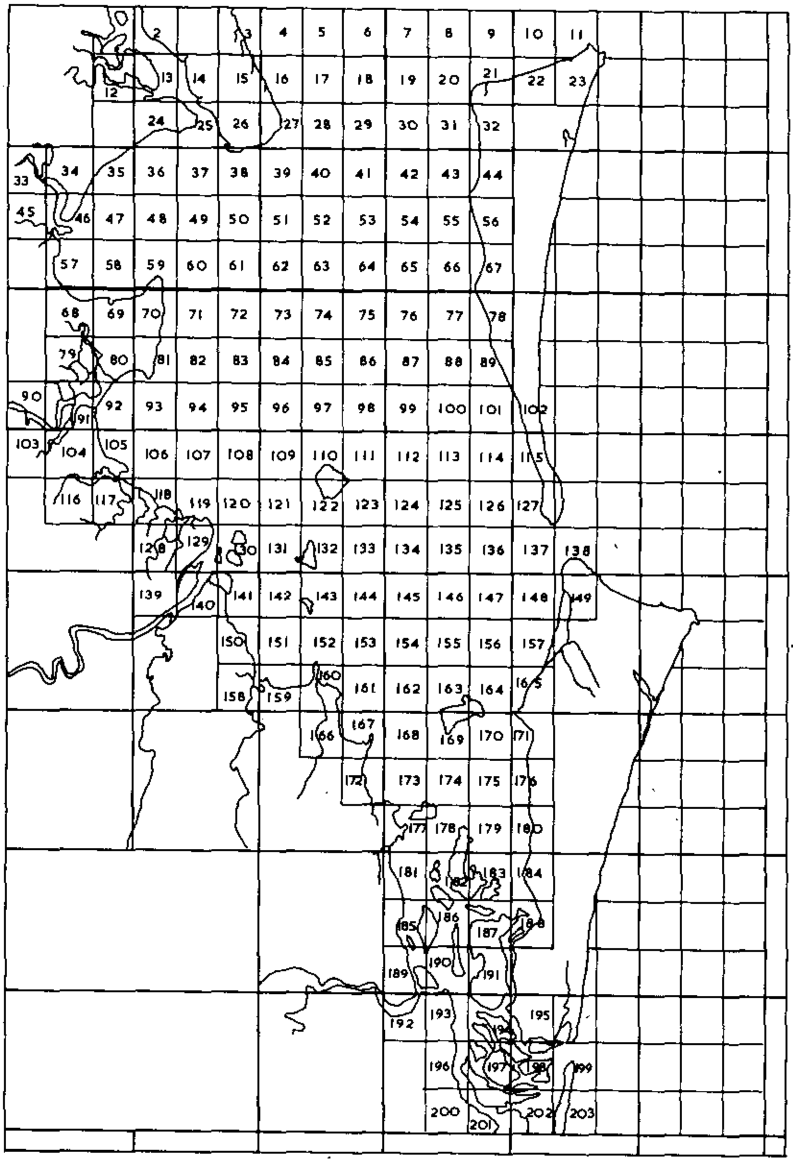


Fig. 5.–Grid station system.

The surveys were conducted by personnel from CSIRO, the Queensland Department of Harbours and Marine, and the Zoology Department, University of Queensland. The vessels employed were – M. V. *Marelda* (CSIRO), M. V. *Kooya* and *Peter Pan* (Department of Harbours and Marine), M. V. *Wanderer* (University of Queensland), and M. V. *Stradbroke* (private charter).

IV. Chlorinity

The coverage of grid stations varied between surveys, and tidal changes were rapid compared to the time taken to complete each survey (2–5 days). In an attempt to minimize these difficulties and give an overall picture of chlorinity distribution, histograms were drawn of the frequency of occurrence of chlorinities in convenient class intervals at each depth. These are shown in Figure 6. (Horizontal and vertical distribution of chlorinity will be further discussed under temperature–chlorinity relationships and the distribution of fresh water in the Bay.)

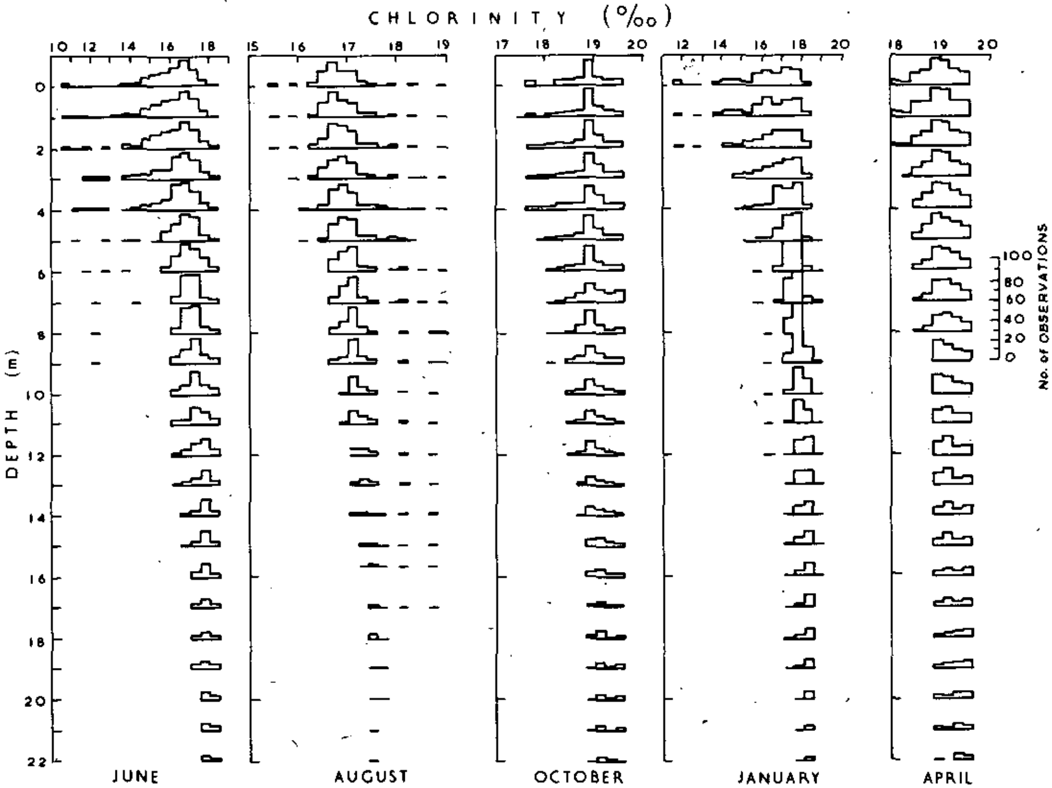


Fig. 6.—Frequency of occurrence of chlorinity values in various class intervals, at 1-m intervals of depth. From all stations sampled in June, August, and October 1967 and January and April 1968.

In each month a pattern of distribution could be observed. All the lowest chlorinities found occurred in the western and southern shallow portions of the Bay. All the highest chlorinities occurred along the eastern fringe. The modal values were all found in a central zone orientated NNW. to SSE. The dimensions of each zone, the horizontal and vertical chlorinity gradients, and the actual chlorinities observed varied from one survey to another, mainly as a result of varying river flow into the Bay. In each month except April the modal chlorinity increased with depth, especially in the western areas, suggesting that horizontal transport of river water was more rapid than its vertical mixing (Fig. 6).

The total annual range of chlorinity observed at each depth, regardless of position, is shown in Figure 7. The range was greatest in the uppermost 9 m of the

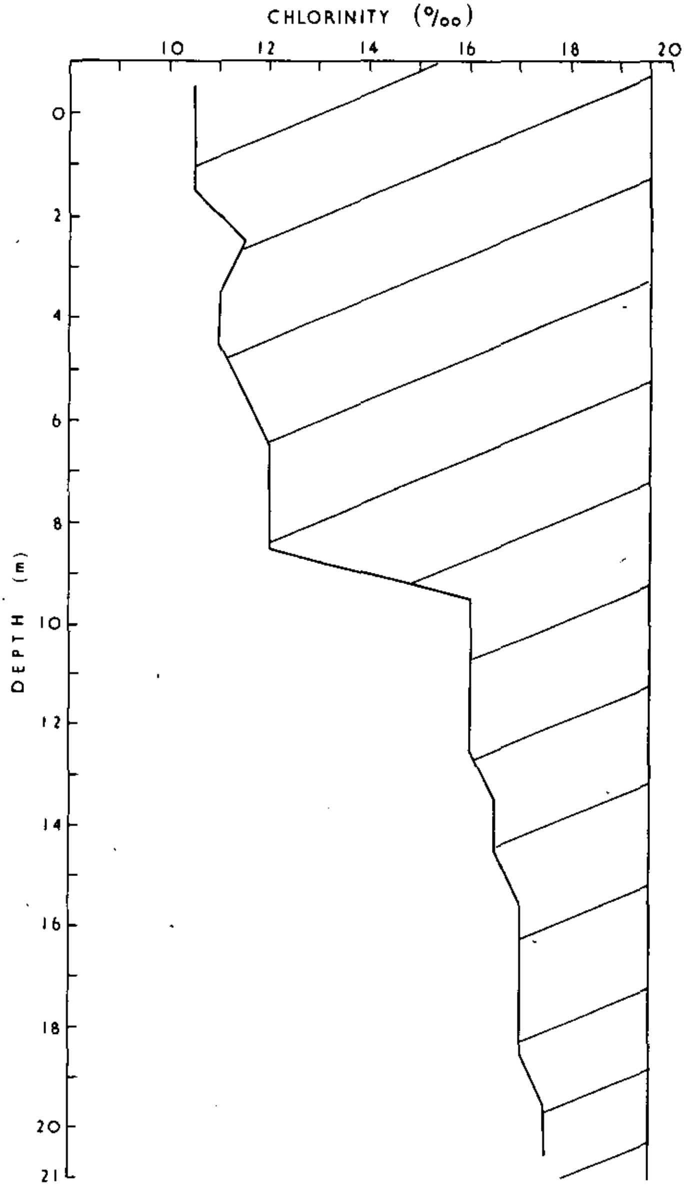


Fig. 7.–Chlorinity (‰) in Moreton Bay, at 1-m intervals of depth to 21 m.

water column (9.1–7.6‰) decreasing rapidly below 9 m to a range of only 2.1‰ at 21 m. This confirms the suggestion that vertical transport of fresh water is relatively slow, especially in the portions of the Bay deeper than 9 m.

V. TEMPERATURE

The temperature data were plotted in the same fashion as for chlorinity (Fig. 8), except that a constant class interval (1 degC) was used. However, the distribution of

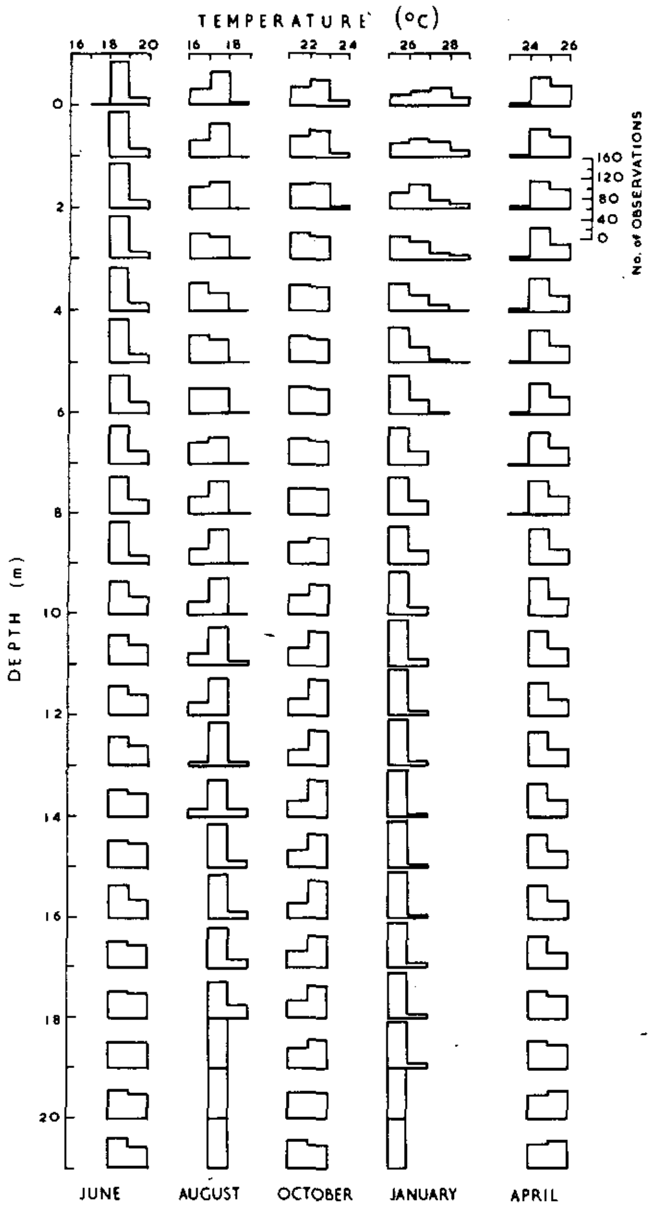


Fig. 8.–Frequency of occurrence of temperature values, at 1-m intervals of depth and 1 degC intervals of temperature, in June, August, and October 1967 and January and April 1968.

temperature within the Bay was not so clear-cut as chlorinity. A general pattern was apparent, in that, during June, August, and April, measurements in the north-eastern portion of the Bay and adjacent to the gap between the barrier islands provided the highest temperatures, whilst in October and January these areas provided the lowest temperatures. These are the areas most influenced by the outside ocean, where the heat reservoir available to counter-balance the annual cycle of winter heat loss and summer heat gain is greater than in the shallow Bay. However, within this pattern there were small local variations. In October a large area of water as cold as the outside ocean (21–22°C) filled the southern portion of the Bay, whilst a large patch of warm water (23–24°C) occurred in the area between the Brisbane R., Margate, and Mud I. In January isolated high temperatures (28–29°C) occurred in the centre of the Bay, whilst in April a patch of cold water (23–24°C) lay off the mouth of the Brisbane R.

The annual range of temperature over the whole Bay is shown in Figure 9.

The modal surface temperatures in the vicinity of Sandgate and Cape Moreton were plotted for the five surveys and a smooth curve drawn through each set of five points. From these curves, the monthly values were interpolated, and are given in lines 2 and 8 of Table 1. The annual range at Cape Moreton (7°C) was less than at Sandgate (11°C). The annual minimum occurs in August at both localities, one month later than the annual minimum air temperature. The month of maximum temperature is almost certainly January at Sandgate, but lack of data for February and March may conceal a maximum later than January at Cape Moreton.

VI. TEMPERATURE–CHLORINITY RELATIONSHIPS

The vertical and horizontal distribution of temperature and chlorinity was examined by means of temperature–chlorinity diagrams (Figs. 10–14). The distributions observed showed only one common feature throughout the year, namely, a tendency for the north-east and east portions of the Bay to contain water of high chlorinity, and for the west portions of the Bay, water of low chlorinity. Otherwise the distribution pattern was different in each survey. However, the individual temperature–chlorinity plots at any one station showed in general a continuous change with depth, no inflexions being observed. The temperature–chlorinity diagrams could therefore be simplified to the extent of showing only surface and bottom values, the degree of separation of these values on the diagrams indicating the degree of stratification at the station. Where only a surface value is shown in Figures 10–14 then surface and bottom values were identical. The bottom values represent a large depth range (approx. 2–30 m) but this disadvantage is overcome to a great extent by the tendency for the deeper stations to occur in the eastern areas where vertical mixing is most effective, and vertical gradients in temperature and chlorinity are least. In January, when surface values indicated pronounced diurnal heating effects, values at 1 m were used. In April 1968 the vertical structure was so uniform at each station that only mid-depth values were plotted to avoid crowding of the diagram. Location of individual values was indicated in each diagram by grid rectangle number (cf. Fig. 5) except for January

1968. The large vertical gradients of temperature and chlorinity, and overlapping in the diagram for that month made the comparison of grid numbers difficult and

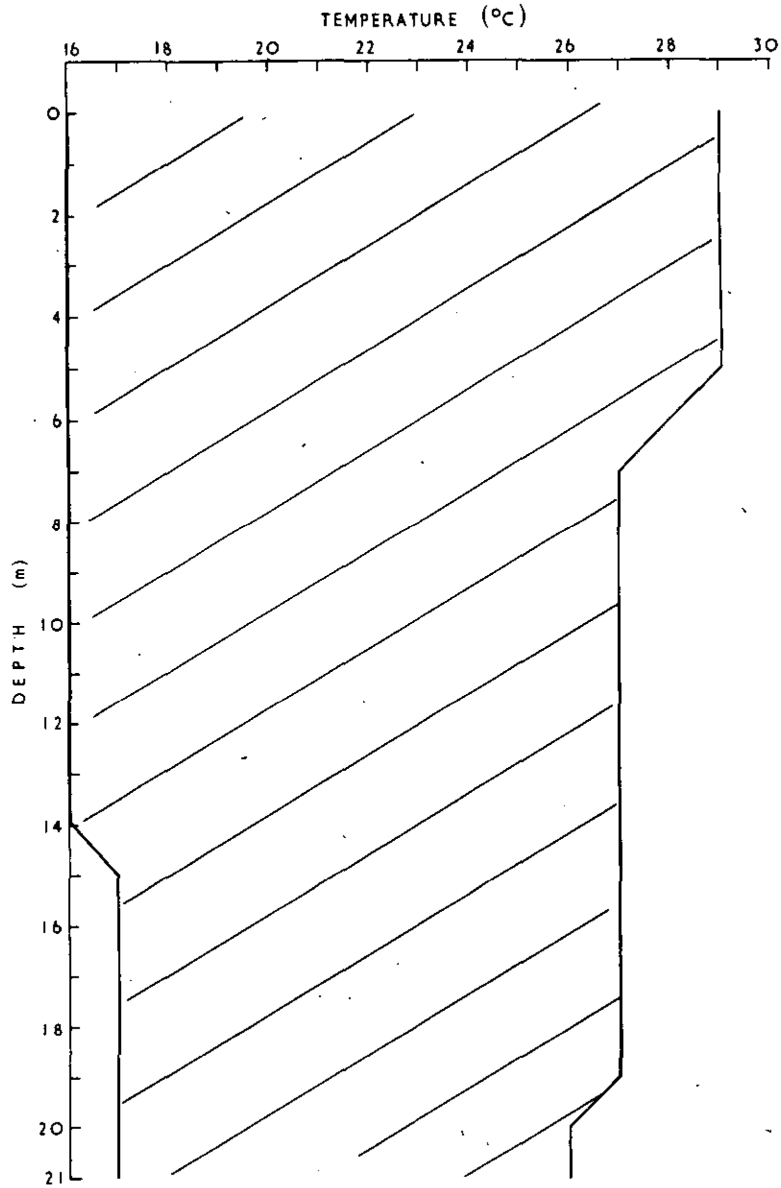


Fig. 9.–Temperature (degC) in Moreton Bay, at 1-m intervals to 21 *m depth*.

symbols were used instead. The situation in each of the five surveys will be discussed in sequence.

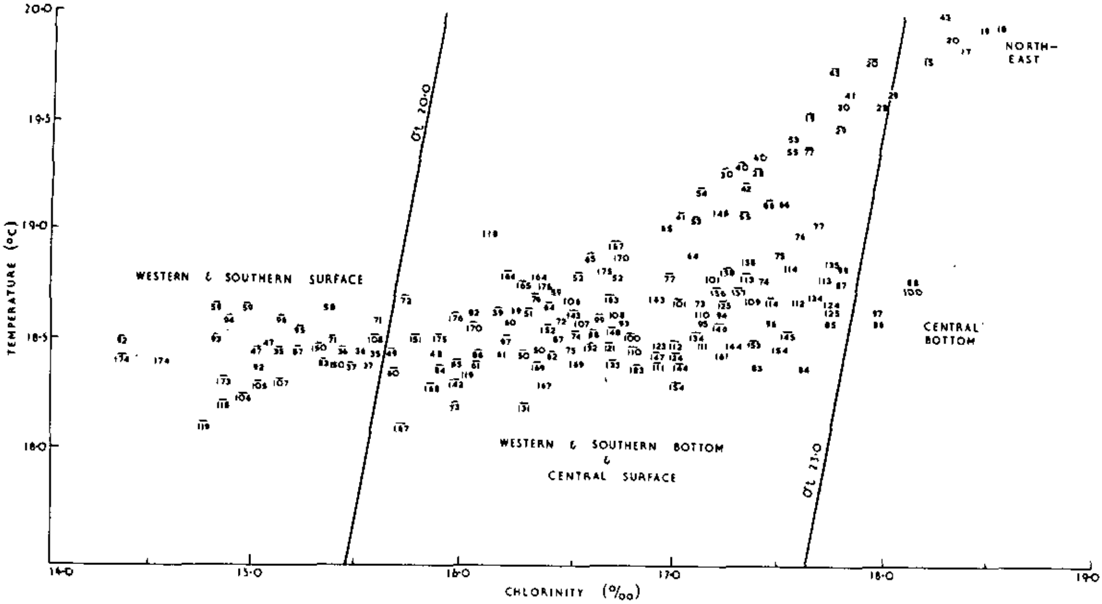


Fig. 10.–Temperature-chlorinity characteristics at surface and bottom in Moreton Bay, June 1967. Numbers refer to grid stations. Surface characteristics barred, bottom characteristics unbarred. Names indicate geographic location of stations.

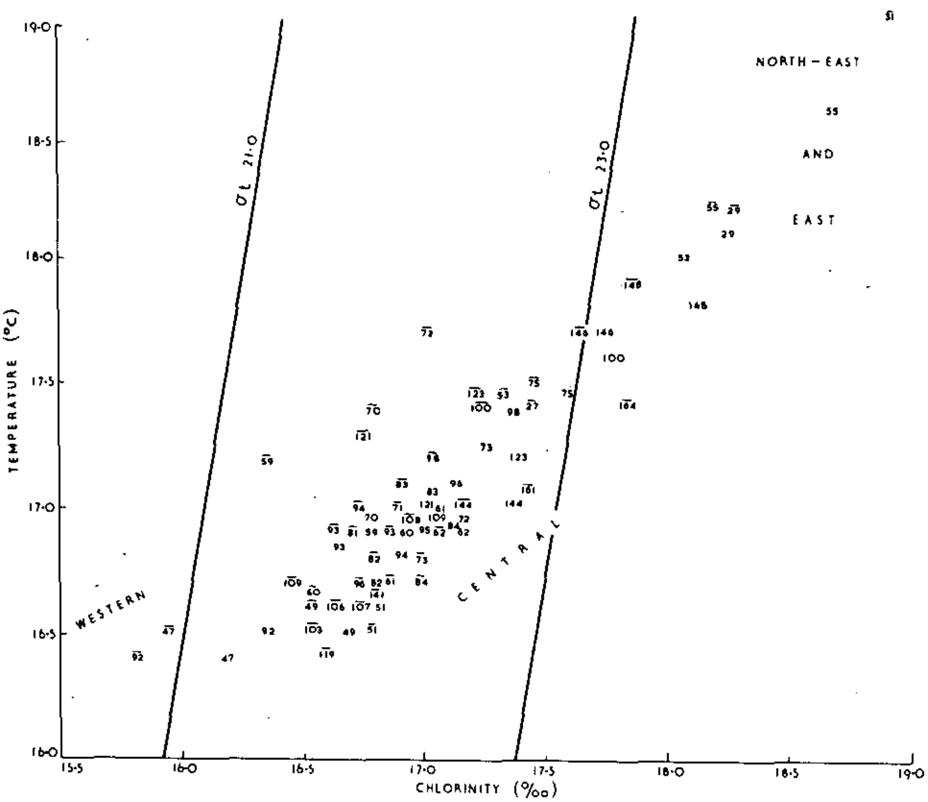


Fig. 11.–As for Figure 10. August 1967.

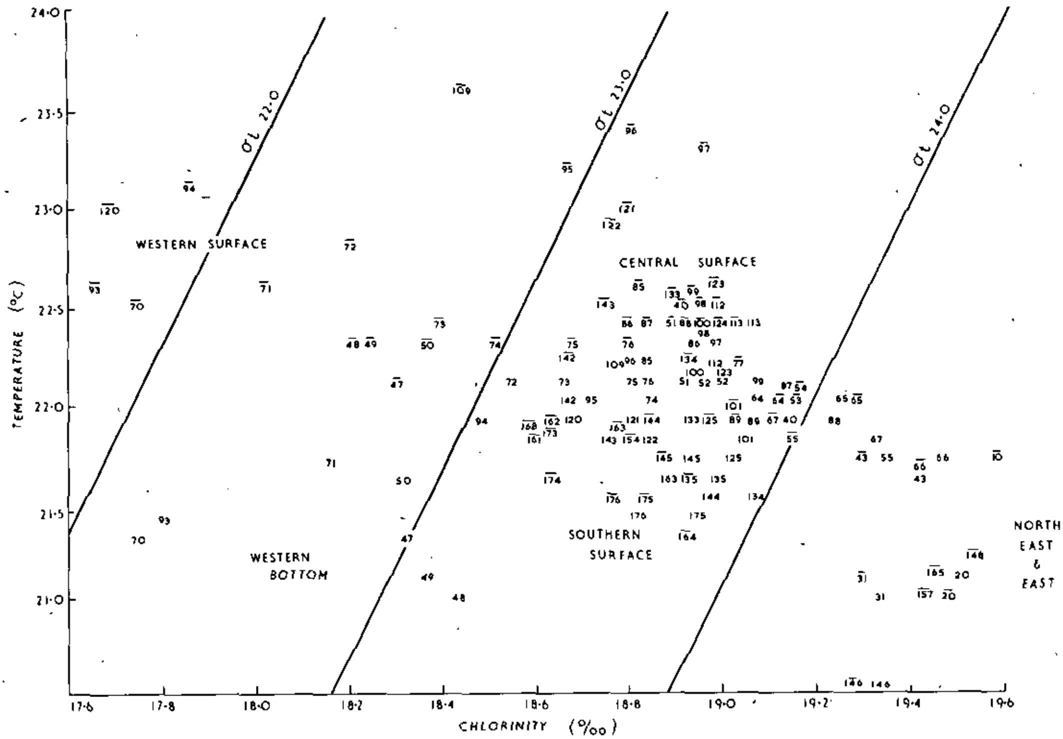


Fig. 12.–As for Figure 10. October 1967.

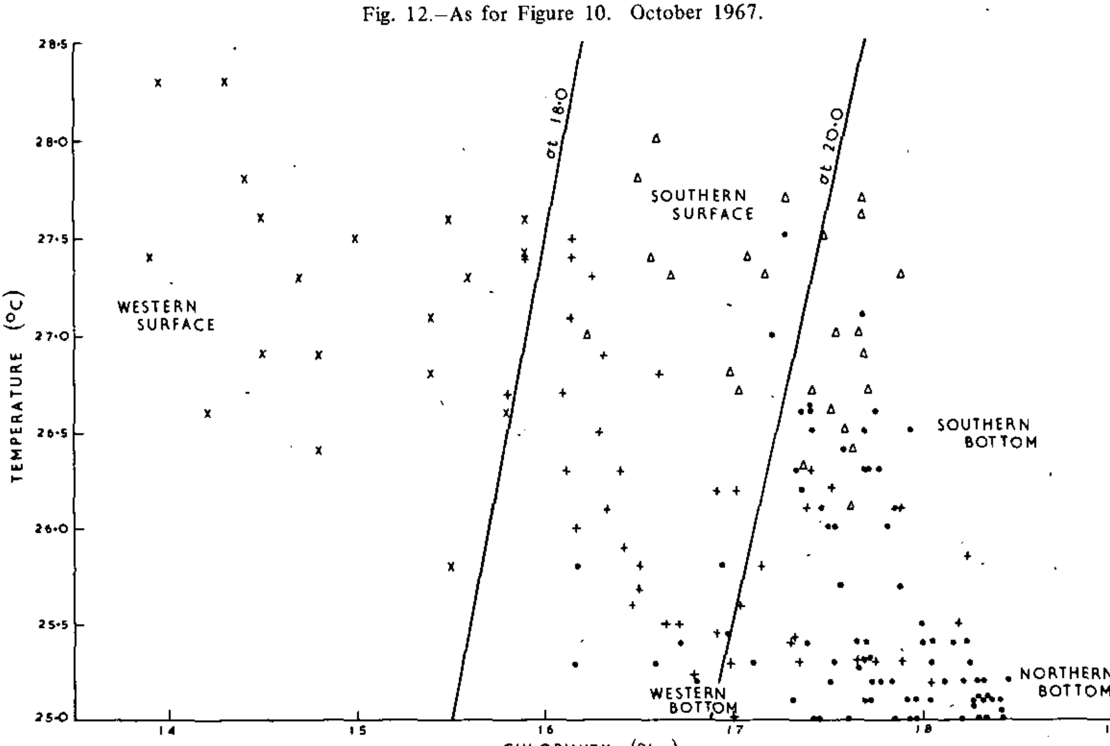


Fig. 13.–Temperature-chlorinity characteristics at 1 m depth and bottom in Moreton Bay, January 1968. X 1-m values west of line from South Point to Green I. △ 1-m values south of line from Green I. to Amity Point. + 1-m values east and north of these lines. ● All bottom values. Names indicate geographic location of stations.

In June 1967 (Fig. 10) the high-chlorinity water entering the north-east portion of the Bay was more than 1 degC warmer than the remaining Bay water, and tended to be slightly colder and less saline at the surface than at the bottom. This may presumably be explained by more rapid mixing with Bay water at the surface. There was a clear mixing path between this externally influenced water and the main mass of surface water in the centre zone of the Bay. This mixing appeared to continue into the deeper water of the south and west. A quite separate mixing path occurred

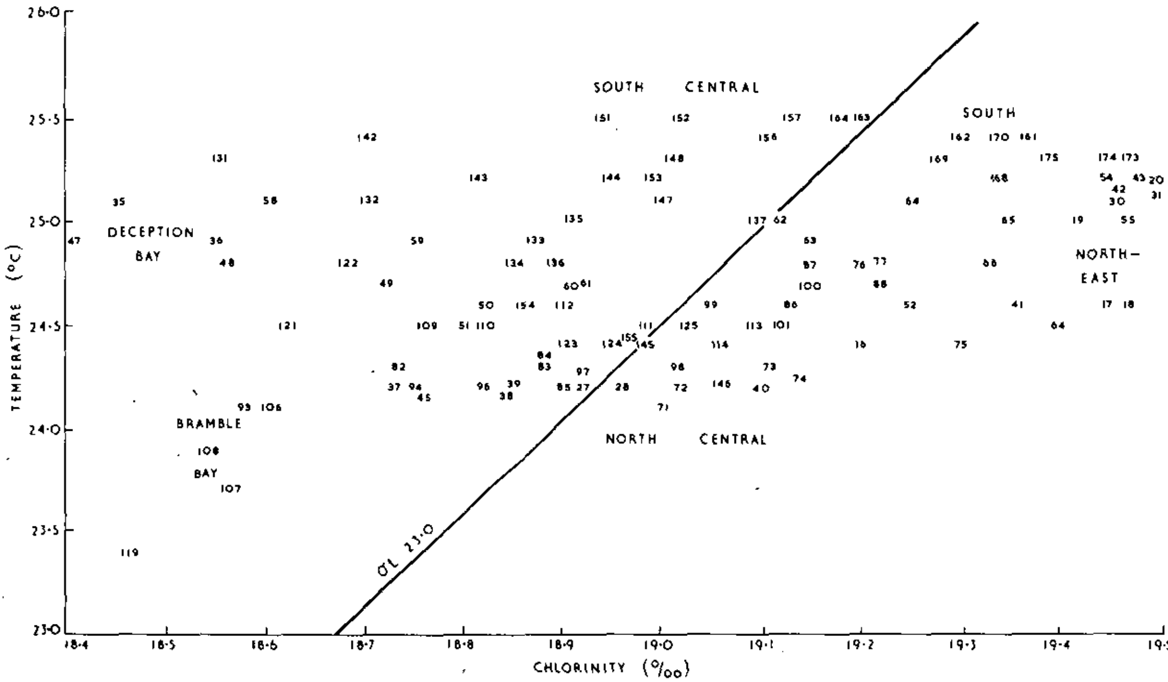


Fig. 14.–Temperature–chlorinity characteristics at mid-depth in Moreton Bay, April 1968. Numbers refer to grid stations. Names indicate geographic location of stations.

between central surface water and the western and southern surface water. This was across a steeper density gradient. The central bottom water (the deepest water in the Bay) was isolated from these previous mixing patterns, having high chlorinity and low temperature and hence high density. The situation was characterized by very small temperature but very high chlorinity gradients both vertically and horizontally throughout the main area of the Bay.

In August 1967 (Fig. 11) the situation was much simpler than in June. A broad mixing path formed between the incoming warm and saline water in the north-east and east, and the cold brackish water in the west. Vertical gradients in either temperature or chlorinity were small, and whilst the total horizontal gradients in temperature (2 degC) and chlorinity (2.5‰) were large, most values were grouped over a small range. There was no evidence of isolated bottom water.

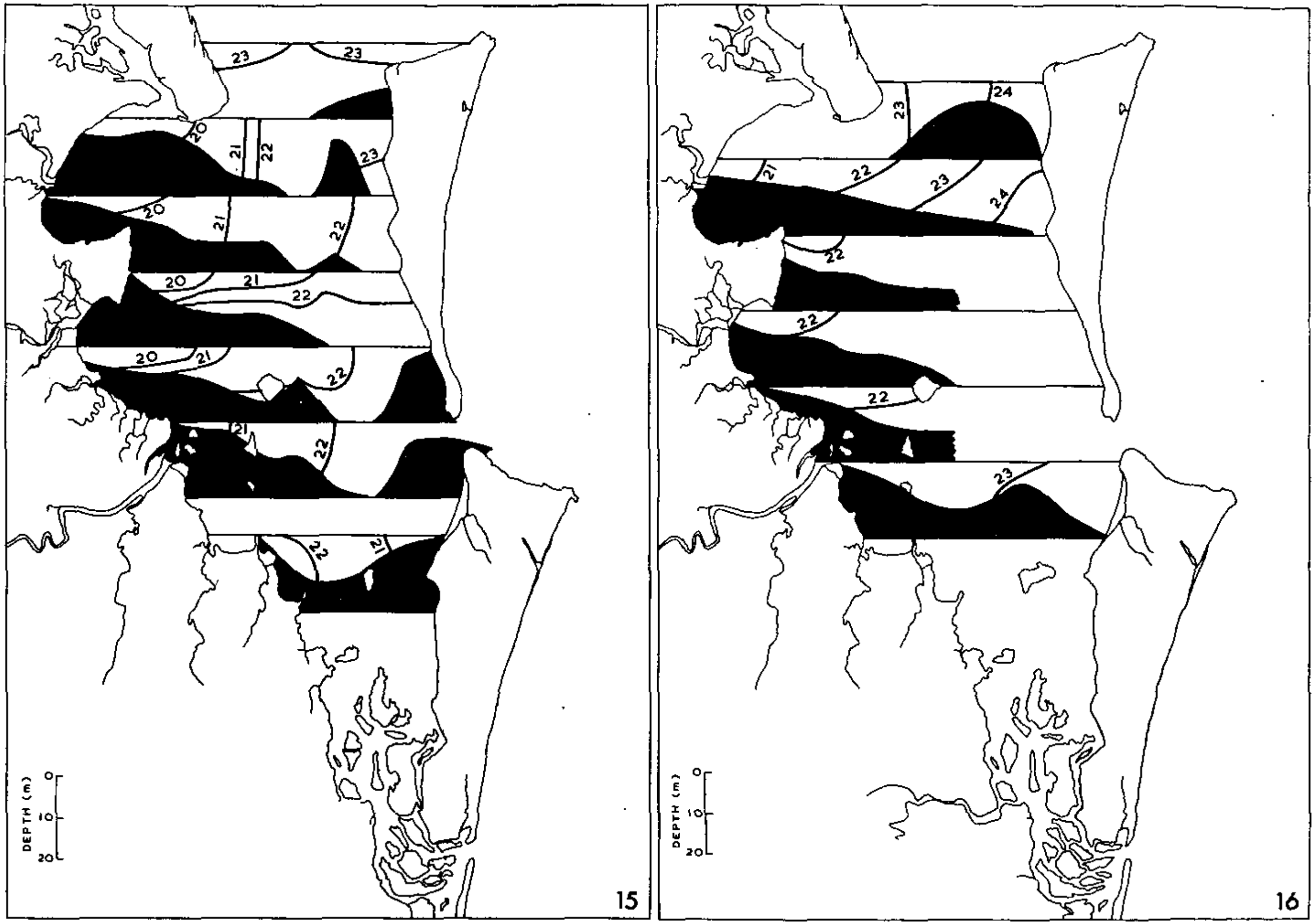
In October 1967 (Fig. 12) vernal heating had raised temperatures throughout the Bay, so that the incoming oceanic water in the north-east and east was colder than Bay water by 1–2 degC. However, there was again a clear mixing gradient between incoming water and water at all depths in the central zone, and thence on to the western surface water. Vertical gradients of temperature and chlorinity were slight at stations in the north-east, east, and centre, but a large temperature gradient (*c.* 1.5 degC) existed between surface and bottom in the west and at a group of stations around Mud I. (95, 96, 97, 109, 121, 122). Surface temperatures were generally lower (by about 0.5 degC) in the south than in the centre, the central zone being very obviously influenced by warm brackish water from the western margins of the Bay.

In January 1968 (Fig. 13) the solar heating of the Bay observed in October had increased still further until a temperature gradient of nearly 3 degC existed between incoming water in the north-east and the surface waters in the west and south of the Bay. However, river influx was obviously greater from the northern rivers, since southern surface chlorinity values were high. Two mixing gradients along the surface could be observed, one between the north-east and west, and the other between north-east and south. Vertical gradients in chlorinity were high (up to 3‰) in the western zone of the Bay, but negligible in the south and north-east, whilst vertical temperature gradients were high throughout the Bay, ranging from *c.* 1–2 degC in the north-east and south to as much as 3 degC in the west. Since high surface temperatures (*c.* 27–28°C) were observed in both west and south, despite the differences in chlorinity (*c.* 3‰) it is apparent that solar heating was a more important factor than influx of river water in warming the shallower areas of the Bay.

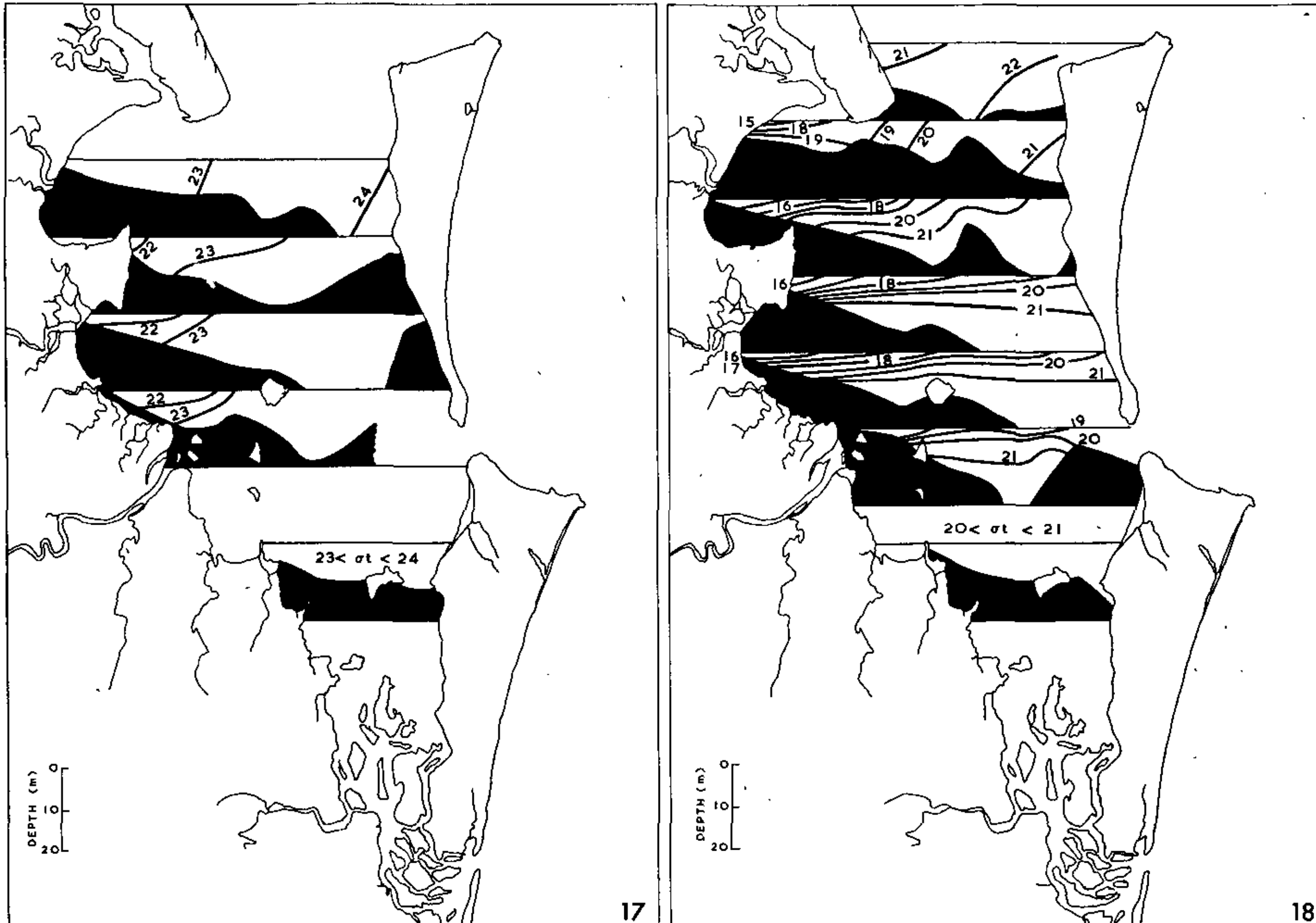
In April 1968 (Fig. 14) whilst temperatures remained high (24.0–25.5°C) throughout the Bay, there was an absence of the large vertical and horizontal gradients observed in the other four surveys. Vertical gradients in both temperature and chlorinity were so slight that most surface and bottom values were almost identical. Horizontal variation in temperature was confined to a difference of *c.* 1.5 degC between the north-central and the south and south-central areas. The effect of this is seen in the range of density throughout the Bay. Whereas in the other surveys density ranged over several units of σ_t, in April the total density range was less than 2 units. The most prominent feature in April was the even horizontal chlorinity gradient between incoming water in the north-east and water along the western margin. Water in the south tended to be of much higher chlorinity, approaching that of the incoming oceanic water.

VII. Density

The distribution of density on each of the five surveys is shown diagrammatically in Figures 15–19. The bottom profile and isopycnals are shown in a series of east–west sections. These sections are the same for June 1967 and January and April 1968, but the scarcity of data for August and October 1967 necessitated the use of other and fewer east–west sections. Even then two sections in August are incomplete (Fig. 16). Discrepancies in depths result from the rapid changes in depth within any grid rectangle, each station being identified only by the grid number. The isopycnals were drawn by hand through each section, ignoring small scale irregularities. In this



Figs. 15 and 16.–Distribution of isopycnals along selected east-west sections in Moreton Bay. Values on contours are whole units of sigma-*t*. Shaded areas delineate bottom profile. 15, June 1967; 16, August 1967.



Figs. 17 and 18.–As for Figure 15. 17, October 1967; 18, January 1968.

way tidal changes were minimized. However, since the observations along each section often covered several hours and between sections several days, the distributions shown in Figures 15–19 represent only a generalized situation.

Each figure shows a gradient of density, rising from west to east, except for the southern portion of the Bay, which may have an east to west gradient or none at all. The west to east gradient arises from the lowering of chlorinity along the western

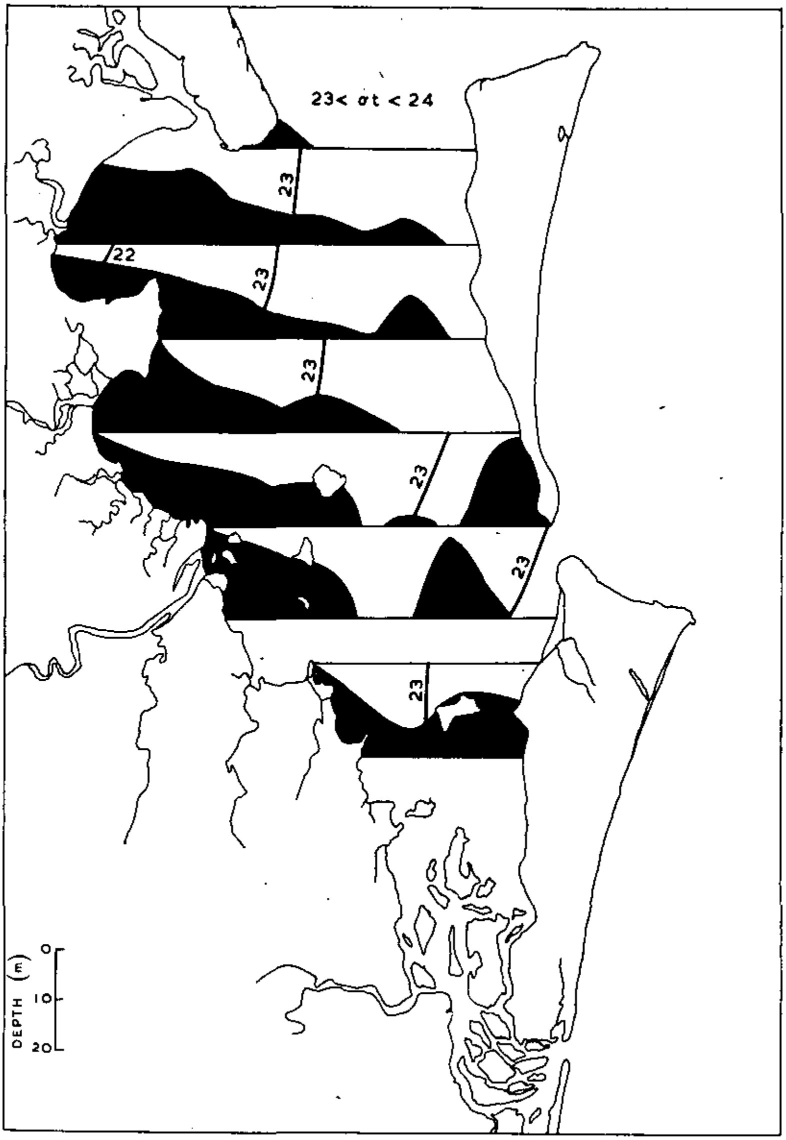


Fig. 19.–As for Figure 15. April 1968.

fringe by river inflow. However, the gradient is profoundly affected by the annual temperature cycle of the Bay. It may be seen that in June 1967 (Fig. 15) the east–west density range is only a little more than 2 units of σ_t, whilst in January 1968 (Fig. 18) the gradient covers over 6 units of σ_t. This occurs in spite of the fact that chlorinity gradients were in general similar in January and in June (Fig. 6). An explanation may be found in the tendency for Bay temperatures to be colder than the outside ocean in winter, and warmer in summer (Figs. 10–14).

The summer increase and winter decrease of Bay temperatures by heat gain from or heat loss to the atmosphere is most profound in the shallower western and southern areas. The reduction of density by freshwater influx is therefore minimized by cooling in winter and augmented by heating in summer.

Vertical density gradients in the Bay tend to be steeper in the west, despite the shallower depths, in fact in all months except January 1968 the deeper eastern portions of the Bay have almost uniform vertical density. Since mixing results mainly from wind and tidal currents this is perhaps not surprising. Tidal currents (Fig. 4) are generally stronger in the east, as are the winds (Table 1; Figs. 2, 3).

VIII. FRESHWATER EXCHANGE

The total catchment area for the five rivers entering Moreton Bay amounts to 1.816×10^{10} m^2 (Queensland Irrigation and Water Supply Commission, Water Resources Branch, private communication). This is a little over 13 times the area of the Bay, so that direct contribution of fresh water to the Bay by precipitation over the Bay itself, even neglecting evaporation, would be negligible compared to river contribution. In fact, there is a slight excess of evaporation over precipitation in the Bay. Evaporation rates at Sandgate and Cape Moreton were calculated from the mean values of air temperature, water surface temperature, and wind (Table 1) and the mean monthly values of relative humidity for each location (Bureau of Meteorology 1956). It was assumed that the air at the water surface was saturated with moisture. The formula used was:

$$E = 0.133\ V\,(e_w - e_a)\ ,$$

where E = evaporation rate (in/day), V = wind speed (m/s), e_w = water vapour pressure at sea surface (inHg), and e_a = water vapour pressure of air over sea (inHg). The evaporation constant (0.1) recommended by Wyrtki (1961) was used in developing this expression. The resulting mean monthly rates of evaporation, in inches, are given in lines 5 and 11 of Table 1. Mean monthly rainfall (Bureau of Meteorology 1956) is given in lines 4 and 10.

Both evaporation and rainfall are generally higher at Cape Moreton than at Sandgate. At Cape Moreton, rainfall is maximal from March to May, and minimal from August to November, whilst at Sandgate rainfall is maximal from January to March and minimal from July to October. There is therefore some difference in the timing as well as the magnitude of rainfall at the two locations. There is no clear annual maximum of evaporation at Sandgate, but the lowest rates obtained from July to October. These lower rates are the product of both low wind velocities and small values of $(e_w - e_a)$. Conversely, at Cape Moreton, there is little change in the values of $(e_w - e_a)$ throughout the year. The highest evaporation rates occur in March and April at the time of strongest winds, and the slightly lower evaporation rates prevailing from July to December coincide with, in general, weaker winds.

The differences between precipitation and evaporation at each location for each month (lines 6 and 12, Table 1) show an excess of evaporation over precipitation for the whole year except January, February, March, and July at Sandgate, and May at

Cape Moreton. The total annual excess for Sandgate is 6.6 in. and for Cape Moreton, 15.7 in. The mean of these rates would result in a loss of approximately 3.86×10^8 m^3 of water per year from the surface of the Bay.

The monthly total river discharges into the Bay from June 1967 to May 1968 are given in Table 2 (Queensland Irrigation and Water Supply Commission, Water Resources Branch, private communication). For this period, the total freshwater influx was 4.665×10^9 m^3, compared with which evaporation losses were small. In a drought year evaporation losses would represent about 3.5% of the total volume of the Bay. However, the shallower depths in the western and southern fringes of the Bay would produce unequal distribution of the evaporative effects, and high chlorinities could be expected along the western shore.

TABLE 2

TOTAL RIVER DISCHARGE FROM JUNE 1967 TO MAY 1968 AND ACTUAL FRESHWATER CONTENT FOR THOSE DAYS OF THE MONTH ON WHICH SURVEYS WERE CONDUCTED

Month*	$10^{-6} \times$ River Discharge (m^3)	Freshwater Content, F (%)	Month*	$10^{-6} \times$ River Discharge (m^3)	Freshwater Content, F (%)
June (20–22)	2180	16.00	December	15	
July	252		January (23–25)	1770	12.30
August (8–9)	92	8.1	February	120	
September	22		March	101	
October (24–26)	53	3.00	April (22–24)	18	2.90
November	18		May	24	

*Dates of survey of freshwater content given in parentheses.

Calculation of the rate of dispersal of the river discharge through and out of the Bay presents a difficulty in that the Bay is an estuary with its axis turned through a right-angle. River flow is in general eastwards into the Bay whilst the major contribution of salt water occurs as a north–south tidal flux along the eastern fringe, with a slight incursion of oceanic water between the barrier islands (Fig. 4). The fresh water is transferred eastwards as a density current only in times of high river discharge in summer (Fig. 18). At other times, transfer appears to depend on lateral mixing presumably by shearing effects along the east–west tidal velocity gradient. Eastward mixing is most pronounced in the central region of the Bay (Figs. 15, 18, and 19).

However, a knowledge of the freshwater distribution within the Bay seemed a prerequisite to any study of flushing rate, and the actual freshwater content of the Bay at the time of each survey was computed from the distribution of chlorinity. In each grid rectangle in which a station was occupied in any month, the water column was treated as a stack of water layers 1 m thick. The chlorinity within each layer was taken as the means of the chlorinities at the top and bottom surface of each layer. The freshwater content, F, of each layer was then calculated from the expression:

$$F = (C_1 - C_2)/C_1 ,$$

where C_1 is the chlorinity of oceanic water entering the Bay each flood tide, and C_2 the mean chlorinity in the layer.

In order to obtain a value of C_1, an examination was made of all chlorinity values available for the ocean area immediately adjacent to Moreton Bay, viz. within the limit of 22°34′ and 28°01′ latitude, and from the coast to 154°41′ longitude. (Data from CSIRO Oceanographical Station Lists Volume Nos. 36, 39, 43, 50, and 73, and CSIRO Oceanographical Cruise Reports Nos. 6 and 13.) Some 39 observations were available, taken in every month except December. Monthly means ranged from 19.53 to 19.75‰, with an overall mean of 19.65‰. Since the total range was small compared to that found within the Bay (Fig. 6) the overall mean was taken for C_1.

The values of F were converted into volumes of fresh water present in each 1-m layer, and summed for all the grid rectangles covered in each survey. The total was then divided into the total water volume under all grid rectangles covered in each survey. The resulting ratios (the overall proportions of fresh water in the Bay) are given in Table 2 as percentages.

In the absence of evidence to the contrary it was assumed that tidal flushing of the Bay in the long term took the form of an exchange of a roughly constant volume of Bay water with an equal volume of outside oceanic water each tidal cycle. In this, the usual estuarine situation, a constant proportion of the freshwater content would be removed each cycle, the absolute amount removed varying with the freshwater content. This may be expressed:

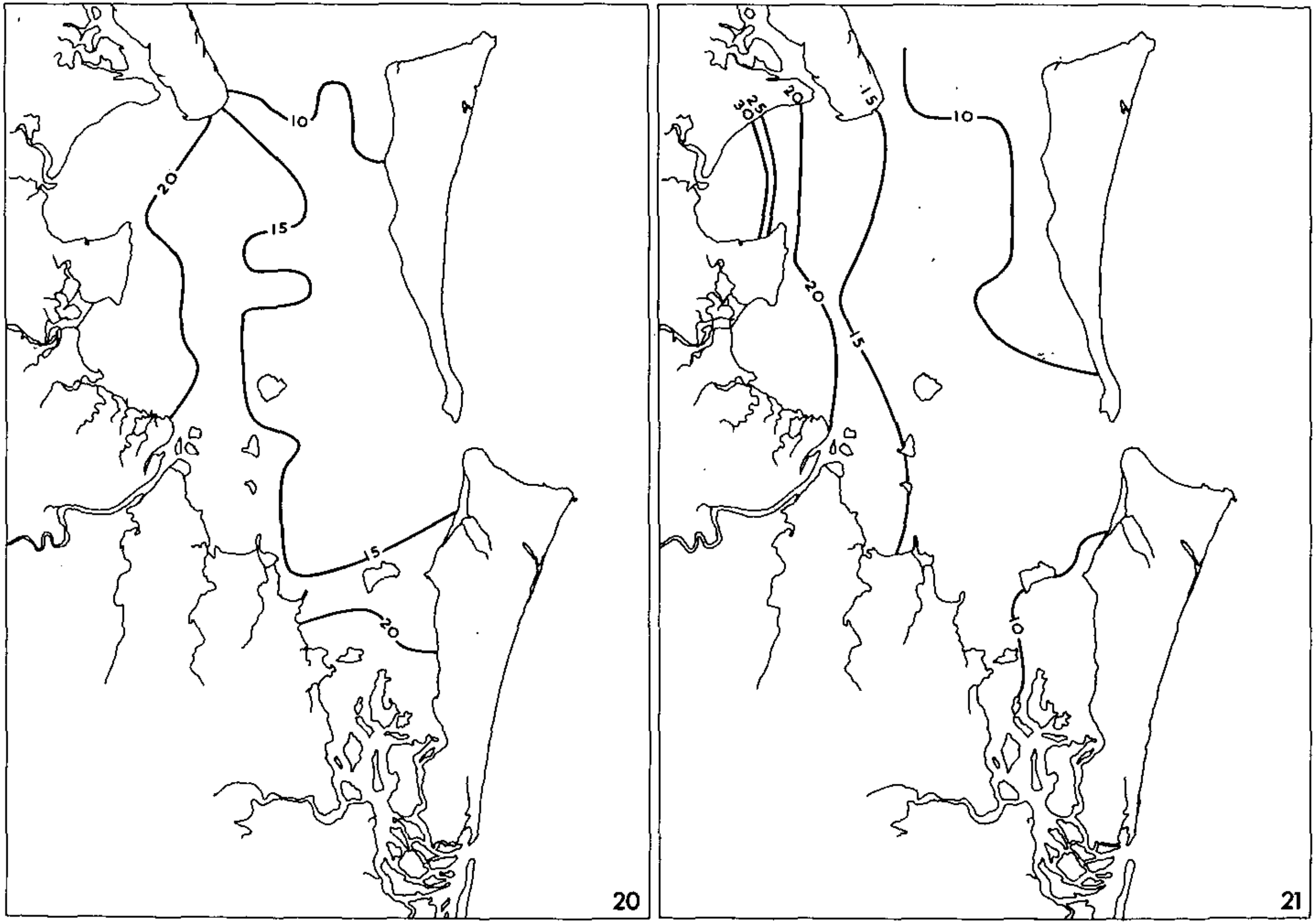
$$\mathrm{d}F/\mathrm{d}t = KF + R \ ,$$

where F is the freshwater content of the Bay, R the rate of flow of river water into the Bay, and K the coefficient of loss of fresh water per unit time. This expression may be integrated to the more convenient form:

$$K = \frac{R_{(t,t_0)} + (F_t - F_0)}{\frac{1}{2}(t - t_0)(F_t + F_0)} \ ,$$

where $R_{(t,t_0)}$ is the volume of river flow in the time interval $(t - t_0)$.

Four solutions for K could be obtained, using the information in Table 2 for the periods June to August, August to October, October to January, and January to April. The values of K for the four periods were, respectively, −0.80, −0.43, −0.16, and −0.61 (mean −0.50/month). The poor agreement seemed probably due to apportioning river flow between survey dates as though it were uniformly distributed in each month. To overcome this problem a graphical solution to allow monthly divisions was undertaken. The freshwater contents found in June, August, and October 1967 were plotted against time, and a curve drawn through the three points, extrapolating to December. This was taken as an approximation to the rate of change of freshwater content, and the intercepts at the beginning and end of each month were used to calculate both the mean freshwater content for that month and the volume difference. The latter added to the river flow for that month gave the total fresh water voided from the Bay. When this was expressed as a ratio of the mean freshwater content for each month, far better agreement was obtained. The values of K thus calculated were: July −0.63, August −0.50, September −0.40, October −0.50, and November −0.56 (mean −0.52/month). No curve could be drawn for the period January to April 1968, since only two points were available. However, if a loss



Figs. 20 and 21.–Distribution of freshwater content (%) in Moreton Bay. 20, June 1967; 21, January 1968.

coefficient of −0.50 was applied for that period it could be calculated that the freshwater content of 1.440×10^9 m^3 found in January should have declined to 3.4×10^8 m^3 in 2.9 months. This is extremely close to the 3-month interval which actually occurred between the two surveys of January and April 1968. It would therefore seem that a loss coefficient of about −0.50/month is admissible.

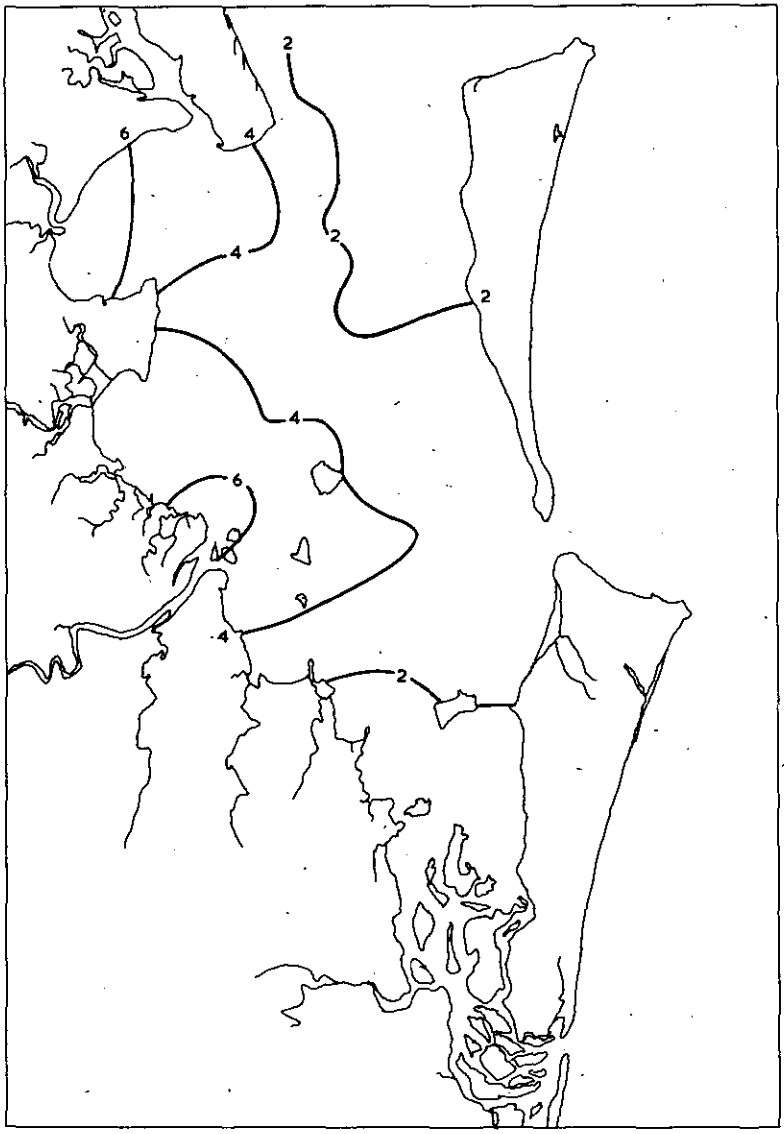


Fig. 22.–Distribution of freshwater content (%) in Moreton Bay in April 1968.

Since there are about 60 tidal cycles in each month (one unit of time) the proportion of fresh water removed from the Bay each tidal cycle will be given by:

$$1 - (F_t/F_0) = 1 - e^{-0.0083} = 0.0083 \ ,$$

where F_0 is the fresh water present initially, and F_t the fresh water present after one tidal cycle. It therefore appears that only about 0.83% of the freshwater content of the Bay is exchanged through the northern boundary each tidal cycle. The intertidal volume varies from 1.38 to 2.76×10^9 m^3 with a mean of 2.07×10^9 m^3, which represents about 15% of the total Bay volume at high water. From this we may deduce that only about 5–6% of the intertidal volume is in fact exchanged.

The distribution of fresh water in the Bay by area for June 1967 and January and April 1968 is shown in Figures 20, 21, and 22. (No such diagrams could be presented for August and October 1967. The area of coverage was inadequate for contouring.) In June and January, both months of high river discharge (Table 2), the contours are orientated north–south over most of the Bay, emphasizing the east–west chlorinity gradient mentioned earlier (Section IV). Even in April, a month of low river discharge (Table 2) when freshwater content was generally low and the Bay almost uniformly mixed vertically (Section V; Fig. 14), this gradient still persists, with the main influx of oceanic water clearly isolated to the north-east. From Figures 21 and 22 it may be deduced that there is some escape of brackish water from Deception Bay northwards round Bribie I.

VIII. TIME–SERIES OBSERVATIONS

Measurements of chlorinity and temperature at half-hour intervals in time and from surface to bottom at 1-m intervals in depth over at least 24 hr were made at fixed locations on nine occasions. In June 1967 observations were made from M. V. *Stradbroke* anchored at Grid Stations 63, 132, and 178. The same vessel was used in January 1968, anchored at Grid Stations 63, 122, and 178. In August 1967 measurements were taken at Redcliffe jetty (Grid Station 70) and from M. V. *Marelda* anchored in Grid Station 71. In October 1967 a series of observations were made at Tangalooma jetty (Grid Station 67).

The pattern of results obtained was in all cases very complicated. No clear tidal reversal from low to high chlorinity (or temperature) was apparent. Instead, a very heterogeneous distribution of temperature–chlorinity characteristics with time was found. Some indication of this complexity is illustrated in Figure 23, which shows the density profiles for each hour of the ebb and flood over 13 hr, starting from the fourth hour of the ebb (double-barred line) at 0840 on 24th January 1968 at Grid Station 122. There is no return of the density profiles to their starting point over one tidal cycle, nor are the changes with time in phase at the various depths.

The temperature–chlorinity characteristics at each hour of the tide over two tidal cycles are shown for the same station at 1 m and 7 m depth in Figures 24 and 25. Some of the irregularity of tidal changes in temperature may be explained by diurnal heating. This effect appeared to some extent at all depths in the shallower stations (67, 70, 71, 122, 132, and 178) and at the surface at the deeper stations (62, 63). However, any observable diurnal trend was small compared to the total range in temperature over a tidal cycle, and often masked by advective changes.

This complexity of tidal changes in chlorinity and temperature at a fixed point could be explained in two ways. Either an erratic pattern of tidal currents was operating on a system of uniform temperature and chlorinity gradients, or a simple tidal current ellipse was advecting a system of great heterogeneity past the observation point. From the current measurements made, it is believed that the latter was the case. This will be discussed in the next section.

Since the area surveys of the Bay were made concurrently with the time–series observations, it was possible to compare the distribution of chlorinity and temperature with time and area.

Any observation at a grid station having temperature–chlorinity characteristics within the co-ordinates containing the 24-hr observations was entered on the

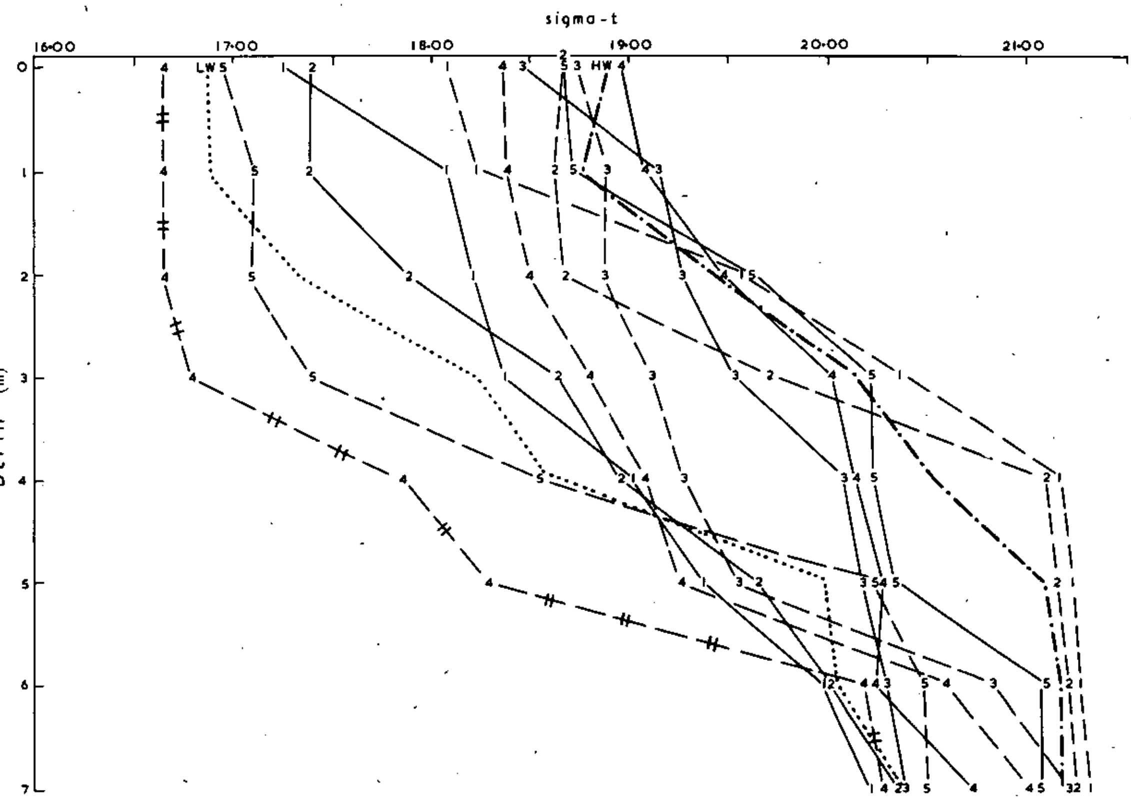


Fig. 23.—Depth of profiles of sigma-*t* at Station 122 (January 1968). One-hourly intervals of tide (– – – – – ebb; ———— flood) from fourth hour of ebb (double-barred) at 0840 to fourth hour of ebb at 2030, 24.i.68. . . . . . Low water. _. _. _. _. High water. Numerals indicate hour of ebb or flood.

temperature–chlorinity diagram for the latter at the same depth. Figures 24 and 25 show this for 1 m depth and 7 m depth (bottom) at Grid Station 122. Not all stations are represented on both diagrams, so that there is some difference in water movement with depth. However, if any grid station entered on Figures 24 and 25 is considered to be a possible site of origin for water of characteristics observed at the fixed Station 122, an area may be delineated which gives the maximum likely excursion of water past the fixed station over two tidal cycles. Such areas of excursion were surprisingly similar for most depths at any one of the nine fixed stations, and showed little difference with times of year for the

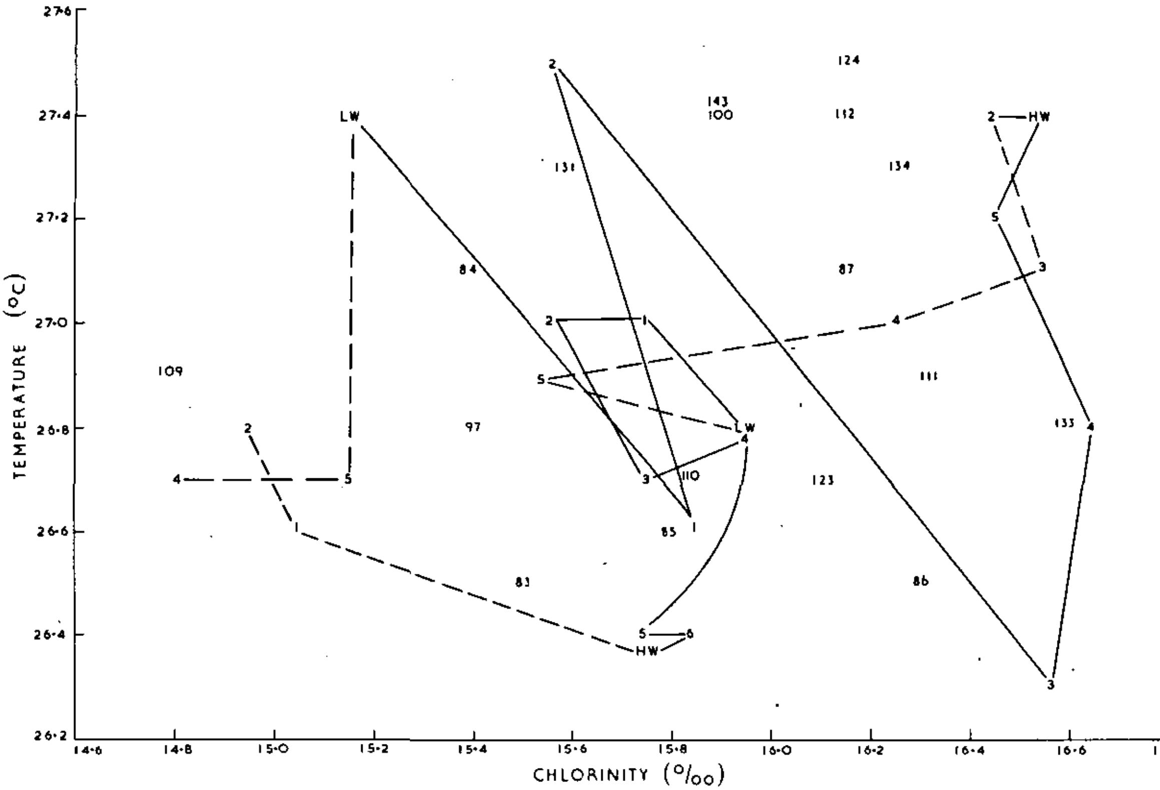


Fig. 24.–Temperature-chlorinity characteristics at 1 m depth at Station 122, 24.i.68. Hourly values (––––– ebb; ——— flood). Temperature-chlorinity characteristics at adjoining stations over the same period are indicated by grid station numbers (83–143).

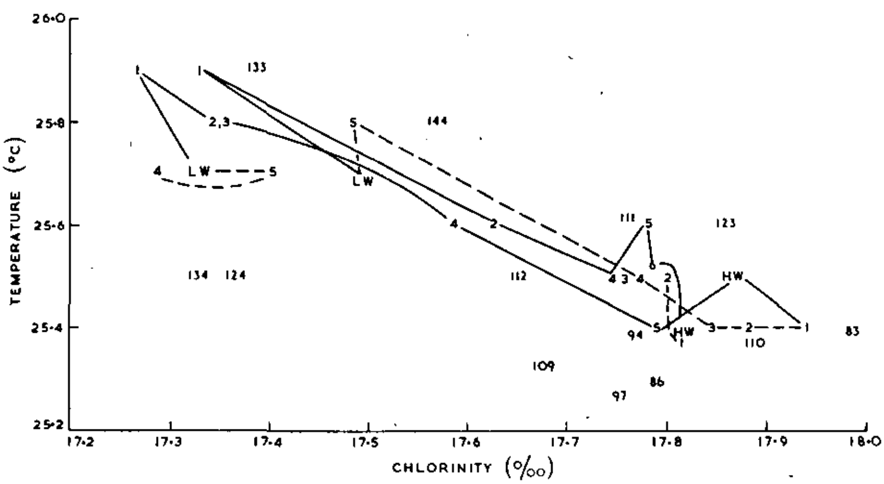


Fig. 25.–Temperature-chlorinity characteristics at 7 m depth at Station 122, 24.i.68. Hourly values (––––– ebb; ——— flood). Temperature-chlorinity characteristics at adjoining stations over the same period are indicated by grid station numbers (83–144).

Stations 62/63, 122/132, and 178. The tidal excursions as determined in this way are shown in Figure 26, and the limited overlap is remarkable.

The clearest features of Figure 26 are the isolation of the southern end of the Bay, and the general north–south orientation of the tidal influence areas. This

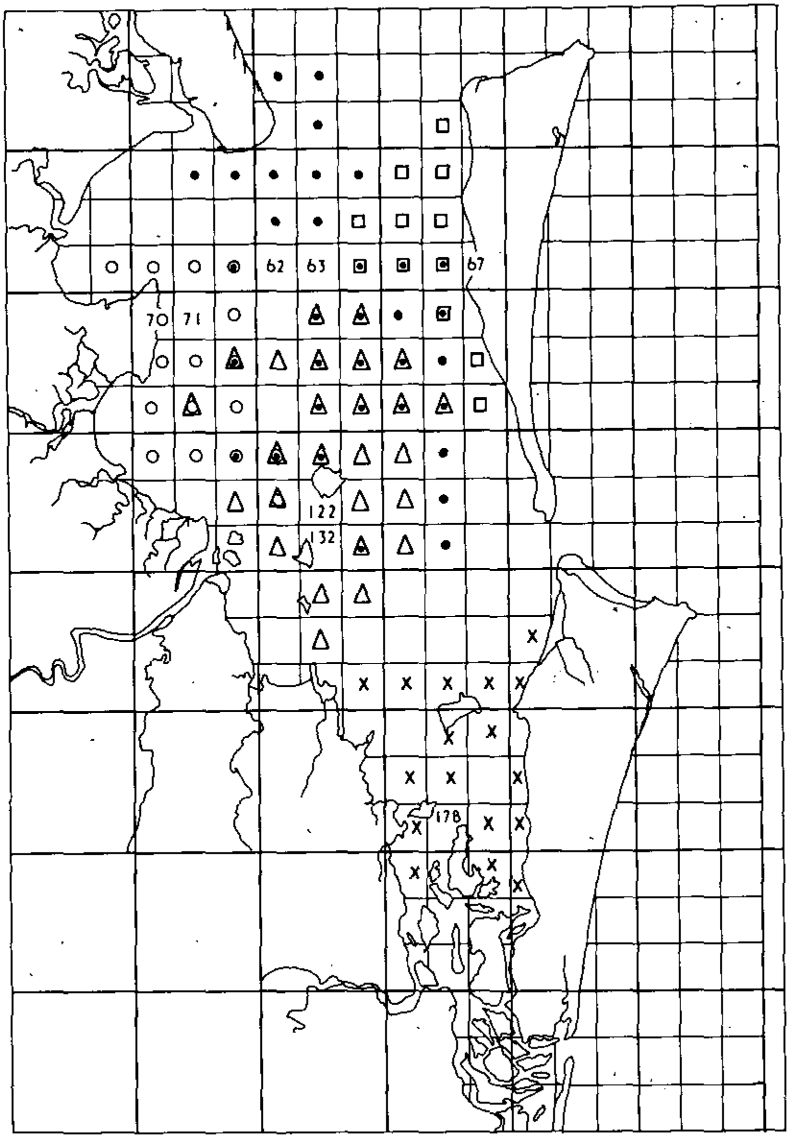


Fig. 26.–Areas around time-series stations within which similar temperature-chlorinity characteristics were found to those at the fixed stations over at least two tidal cycles. Stations 63, 132, 178, June 1967; Stations 70, 71, August 1967; Station 67, October 1967; Stations 62, 122, 178, January 1968. □ 67. ● 62/63. ○ 70/71. △ 122/132. X 178.

figure also emphasizes a point made earlier that the Bay water is divided into an eastern fringe, a western and southern fringe, and a central zone. The greatest overlap (six grid rectangles) occurs between the centrally situated Stations 62/63 and 122/132.

The great variability of chlorinity and temperature at a fixed site over short periods of time emphasizes another point made earlier, viz., the dubiety of simple diagrams of isohaline distribution based on area surveys lasting several days.

IX. CURRENT MEASUREMENTS

Measurements of current velocity and direction from surface to bottom were made with the Pritchard vane on four occasions. The first of these was in August 1967, when the vane was used from M. V. *Marelda* anchored in grid rectangle 71. The other three were in January 1968 when measurements were made from M. V. *Stradbroke* anchored in grid rectangles 62, 122, and 178. All series of measurements were carried out at half-hour intervals over at least 24 hr. The tidal ellipses were extremely narrow, in fact the currents were unidirectional for most of the time, tending southerly on the flood and northerly on the ebb (Fig. 4). Presentation of the data could therefore be simplified to an amplitude–time curve (Fig. 27). However, calculation of current velocity required measurement of the angle subtended with the vertical by the line supporting the vane, using a bubble clinometer. This proved unsatisfactory with the flexible nylon line used when working from a pitching and rolling ship. Not only did the line flex at the clinometer, but the clinometer was not always in the plane of the subtended angle. Because of this uncertainty, and also because no systematic trend of current velocity with depth could be discerned, the results were plotted as single points and a smooth curve of best fit drawn by hand through them. Furthermore, because there were periods of nil velocity at slack water and the amplitude curves were not symmetrical, it was not considered valid to calculate the mean velocity by simply multiplying maximum observed velocity by $\pi/2$. Instead, the mean velocity was taken as the area under each curve divided by the time span from one slack water to the next, whilst the area itself was used as an approximation to the half-tidal excursion. The mean half-tide velocities (V) in ft s^{-1} and half-tide excursions (L) in feet are given in Figure 27.

The first use made of the current measurements was to check the areas of tidal excursion plotted by means of temperature–chlorinity distribution (Fig. 26). Taking Grid Station 62, the tidal excursion by current measurement varied over four half-cycles from 26,900 to 42,000 ft, i.e. a range of 2½–4 grid rectangles in a north–south direction. Since, as we have seen earlier, the tidal movement does not involve simply the to and fro passage of the same water, we must consider twice this range to be the limiting distance from which water may reach a fixed station. Figure 26 shows a possible north–south range of 11 grid rectangles through Station 62, whereas current measurements indicated a probable maximum of eight grid rectangles. The two independent approaches therefore give a similar result but confirm that the range based on temperature–chlorinity distribution is the maximum possible.

For Station 71 the tidal excursion from current measurements varied from 11,500 to 24,500 ft, i.e. from 1–2 grid rectangles. Figure 26 shows a total range based on temperature–chlorinity distribution of six grid rectangles, biased to the south. The mean velocities for the flood tides at Station 71 (0.92 and 1.05 ft s^{-1}) were higher than those recorded for the ebb tides (0.58, 0.80, and 0.83 ft s^{-1}) so that the bias to the south is probably valid. However, once again, the temperature–chlorinity distribution gives an overestimate of range.

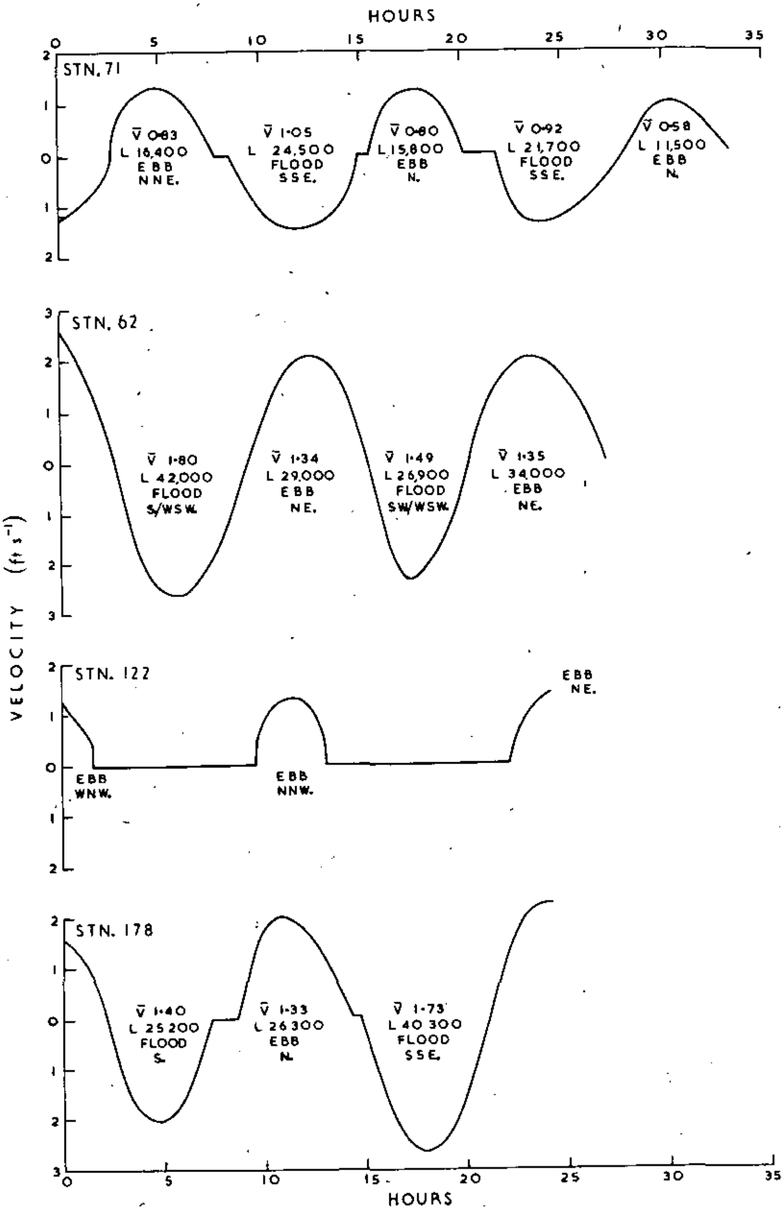


Fig. 27.–Magnitude and direction of currents measured at Stations 71 (August 1967), 62 (January 1968), 122 (January 1968), and 178 (January 1968). *V*, mean velocity in ft s^{-1}; *L*, half-tidal excursion (ebb or flood) in feet.

At Station 178 the current measurements gave a tidal excursion from 25,200 to 40,300 ft, i.e. 2½–3½ grid rectangles. This is in close agreement with the total north–south range of six grid rectangles found from temperature–chlorinity distribution (Fig. 26).

The results from Station 122 are anomalous. Only one clear tidal excursion, and then only of 3 hr duration, was recorded. Most of the time, current readings were zero, even though the depth fluctuated by 1 m over each of the three half-cycles. Such ebb movements as were observed tended to WNW. on two half-cycles out of three rather than N. or NE. as at the other stations.

The current measurements at Station 178 were also used to verify the chosen southern hydrological boundary of the Bay. The east–west cross-section of the Bay at the level of Station 178, from Coochiemudloe I. to North Stradbroke I., was found to have an area of approximately 19.5×10^3 m^2. For the three half-tidal cycles observed, with excursions of 25,200, 26,300, and 40,300 ft respectively (Fig. 27), the volumes of water entering (or leaving) this cross-section were 150×10^6 m^3, 156×10^6 m^3, and 240×10^6 m^3. The tidal changes in depth observed were 2 m, 2 m, and 3 m respectively. All these were about twice the predicted tide range for Pile light (Queensland Department of Harbours and Marine) so that the southern end of the Bay would seem to form an antinode or terminal point for the Bay tides. The volumes of water entering or leaving the Coochiemudloe–North Stradbroke cross-section could have produced the observed rise and fall over an area of 75×10^6 m^2, 78×10^6 m^2, or 80×10^6 m^2 respectively. The mean of these three (77.6×10^6 m^2) covers the area from Grid Station 177 to approximately Grid Station 190, i.e. up to about the region where the co-tidal lines change from plus to minus relative to the Pile light (Fig. 4). All the tidal flux in the southern end of the Bay north of grid rectangles 193 and 194 can therefore be accounted for in incursion of water from the north, i.e. the Bay proper. The amount of oceanic water entering the Bay from the south must be negligible.

X. CONCLUSIONS

Moreton Bay may be considered as an estuary in which tidal influx occurs along an axis (N.–S.) at right angles to the direction of river inflow (W.–E.). The tidal flux occurs along the deep eastern side of the Bay, whilst the rivers flow onto the shallow western and southern fringe. A velocity gradient of tidal currents diminishing from east to west sets up shear forces which produce lateral mixing of fresh water eastwards. The mixing causes a heterogeneous distribution of chlorinity and temperature, but the eastern deeper portion of the Bay is more profoundly mixed than the shallow western and southern portions, probably because of stronger winds and tidal currents. The southern portion of the Bay depends upon tidal mixing from the north for water exchange.

Distribution of temperature and chlorinity are affected by river discharge, seasonal cooling or heating, and tidal mixing. Given the fluctuations to be expected, both in magnitude and timing, in the first two of these influencing factors, it is unlikely that the Bay ever exhibits the same hydrological structure twice. It would seem unprofitable to make further surveys involving scanty measurements over large areas, without relation to tidal state. Rather should future work either make use of synoptic surveys (e.g. aerial photography) or time–series observations at several points in limited areas.

Viewed as an environment for prawns, Moreton Bay presents some disadvantages. Given that most prawn species complete a life cycle of migration between marine (or near-marine) conditions at spawning through brackish littoral nursery grounds to marine conditions again, the Bay would seem to offer the range of conditions required. In fact one could expect that some species of prawn might become totally adapted to a life cycle within the Bay, even though the annual range of temperature and chlorinity is greater than in the outside sea. Such species, however, would be subjected to severe stress during occasional flood or drought years. On the other hand, species still maintaining a spawning migration to the continental shelf have the double handicap of maintaining a migration of juveniles out of the Bay and a movement of larvae into the Bay, through a relatively restricted entrance, by means of a small (5–6%) exchange of water each tidal cycle. Flood conditions, producing a resultant flux of water out of the Bay, would presumably assist the outward migration of juveniles, whilst drought conditions, with evaporation producing a resultant flux of water into the Bay, might assist passive transport of larvae into the Bay.

In general, Moreton Bay would seem to offer a site for investigating theoretical models of the interdependence of prawn numbers and behaviour with environmental factors. It affords easily measured short-term changes in such factors, is easily accessible, and is a semi-enclosed system where input and output may be monitored.

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