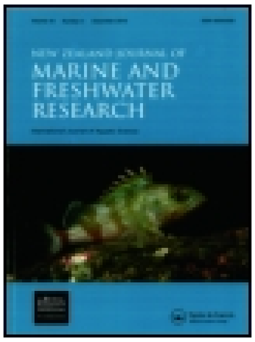

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CIRCULATION AND HYDROLOGY OF MANUKAU HARBOUR

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ABSTRACT

Current meter and current drogue measurements made over tidal periods show that the circulation in Manukau Harbour is mainly tidal, with strongest flows within the inner harbour in the four main channels. In the entrance channel, peak tidal speeds reach $2.25\ m.s^{-1}$ at the surface, and $0.6\ m.s^{-1}$ near the bottom. Salinity and temperature observations show that the water is nearly homogeneous with depth in summer. A residence time of 22 d is calculated, assuming the small horizontal salinity contrast is maintained by freshwater inflow and evaporation.

INTRODUCTION

Many of New Zealand's coastal inlets have recently been classified into groups of similar circulation types based on their physical properties (Heath 1976). One main reason for this classification is to enable the analysis of the circulation and hydrology in one inlet to be used as a guide in studies of other inlets in the same group.

To obtain a better understanding of their circulation and hydrology, it is intended to study at least one inlet within each of the classified groups. Towards this end, a study of the Manukau Harbour is presented here. Within the classification, Manukau Harbour is a large, tidally controlled inlet, and was chosen specifically because pressure being imposed on it by shoreline developments and effluent discharge is creating a need to estimate the residence time of its waters.

Manukau Harbour is one of the several shallow, drowned river valleys located on the west coast of the North Island. It opens to the sea via a narrow (2.2 km wide) deep (30 m) channel (Fig. 1) with a bar approximately 5 km offshore at its shallowest point. The position of the channel through the bar varies in that it swings towards the north over a period of 30–40 y before breaking out again in the south (Auckland Harbour Board unpublished 1964).

In the inner harbour proper, four main channels subdivide extensive shallow banks (Fig. 1). The surface area at high tide is 340 km², of which 145 km² is exposed mudflat at low spring tides.

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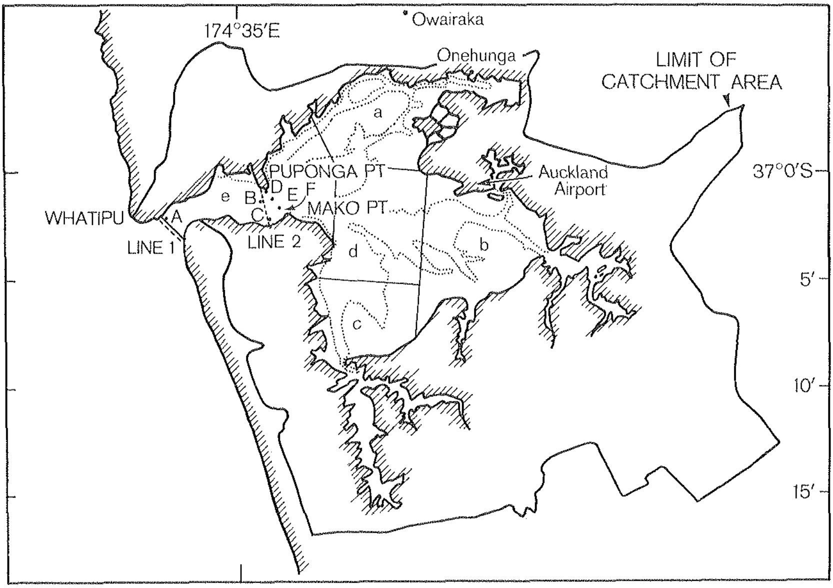

FIG. 1—Manukau Harbour and catchment showing the extent of the mudflats at low spring tide (dotted); a–e = zones through the boundaries of which the mean speeds were calculated from the changes in tidal volume; Lines 1 and 2 = the cross-sections across which volume transports were calculated; and A–F = the positions where the current measurements were made.

FRESHWATER RUN-OFF

The total catchment area which drains into the harbour (including the harbour surface area) is 1.1×10^9 m^2. The freshwater run-off into the harbour can be estimated from the product of catchment area with surplus rainfall. Surplus rainfall is that in excess of rainfall needed to maintain a soil moisture capacity in conjunction with an average rate of potential evapotranspiration: 0.075 m was adopted by Coulter (1973) as the soil moisture capacity. Contours of surplus rainfall have been presented for New Zealand by Coulter (1973) and a detailed set of contours covering Northland, including Manukau Harbour, for mean rainfall data between 1941 and 1970 have been drawn by the Ministry of Works and Development (J. R. Waugh, MOWD, Whangarei, pers. comm.). The latter chart (Fig. 2) clearly indicates at least two distinct catchment areas draining into Manukau Harbour, the catchment on the north-west shore near the entrance having a distinctly higher runoff than that east and south of the harbour. The area of the north-west catchment is about 7.5×10^7 m^2 which, with a mean annual run-off of 0.035 m^3·s^{-1}·km^{-2}, gives a run-off of 2.6 m^3·s^{-1}. Most of this run-off is collected in water supply reservoirs and eventually reaches the Mangere Treatment Plant, which discharges almost constantly throughout the year at an average

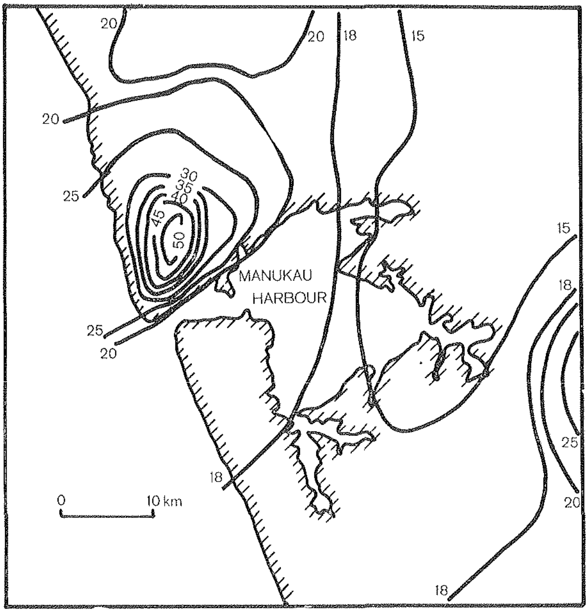

FIG. 2 — Potential mean annual runoff ($1 \cdot s^{-1} \cdot km^{-2}$) in the vicinity of Manukau Harbour, (1941–70) (data from J. R. Waugh, Ministry of Works and Development, Whangarei, pers. comm.).

rate of 2.3 $m^3 \cdot s^{-1}$. For the rest of the catchment area of 6.85×10^8 m^2, the run-off rate is about 0.018 $m^3 \cdot s^{-1} \cdot km^{-2}$ giving a freshwater inflow of 12.3 $m^3 \cdot s^{-1}$. The annual rainfall in this area is about 1.2 m which, over the surface area of the harbour, gives an inflow of 12.9 $m^3 \cdot s^{-1}$. The total run-off is then 28 $m^3 \cdot s^{-1}$. Coulter (1973) gives average runoff figures for the months of January (8 mm) and July (115 mm) near Manukau Harbour which clearly indicate a strong tendency for the major runoff to occur in winter (see also Fig. 3). From these figures then we might expect a freshwater inflow into the Manukau Harbour of about 47 $m^3 \cdot s^{-1}$ in winter and 3.3 $m^3 \cdot s^{-1}$ in summer.

TEMPERATURE AND SALINITY

Temperature salinity (T/S) surveys of Manukau Harbour were made near high tide in the northern half of the harbour on 2 February 1976 (Stns 4–14) and in the southern half on 4 February 1976 (Stns 16–29). A further T/S survey over the complete harbour at low tide was made on 8 February 1976 (Stns 31–41). Data from these surveys are given in Appendix 1, station positions are shown in Fig. 4, and station times in Fig. 5.

Salinity increased seawards with a change of only about 3‰ between the heads and the innermost shore away from rivers (Fig. 4). The change in salinity between high and low tide at the same position was

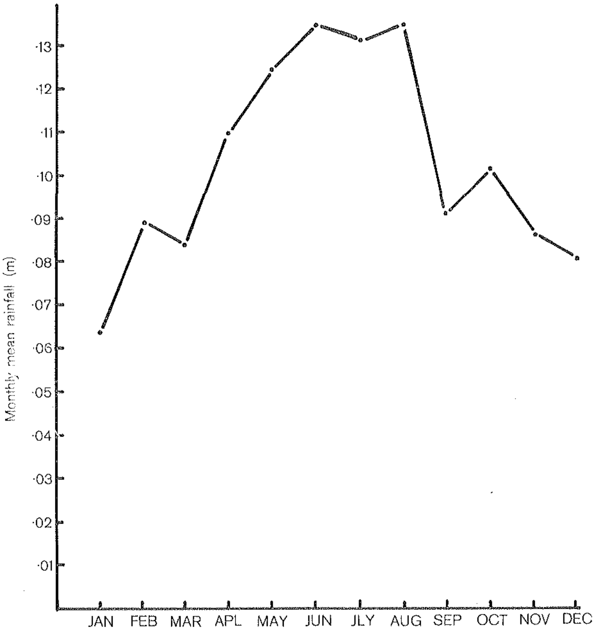

FIG. 3 — Monthly mean rainfall at Mangere, Auckland, averaged over the years 1941–70 (N.Z. Meterological Service 1973).

about 0.5‰ (Fig. 4) and salinity changed little with depth (Fig. 6). Water temperature changed very little horizontally or vertically, with values in the range 19–21°C. The harbour appeared, then, to be well-mixed vertically, with only small evidence of freshwater runoff decreasing the salinity.

CIRCULATION

At spring tides the tidal compartment in the harbour proper, excluding entrance channel, is 6.9×10^8 m^3 and the low tidal volume is 4.5×10^8 m^3; at neaps the values are 4.5×10^8 m^3 and 5.6×10^8 m^3 respectively (Table 1). The amount of freshwater run-off over half a tidal cycle (6.2 h) even in winter is small by comparison, being only 1.2×10^6 m^3. Clearly, then, with between 45% and 60% of the water leaving the harbour proper on an outgoing tide, and comparatively little freshwater inflow, the flow must be dominated by the tides.

FLOW WITHIN THE HARBOUR

Within the harbour proper the flow is mainly tidal and aligned along the channels (Fig. 7). Mean flow in the clearly defined channels can thus be estimated from the change in upstream volume with time. The inner harbour has therefore been subdivided into five zones (Fig. 1). Tidal prisms and cross-sectional areas at midtide for these are given (Table 2)

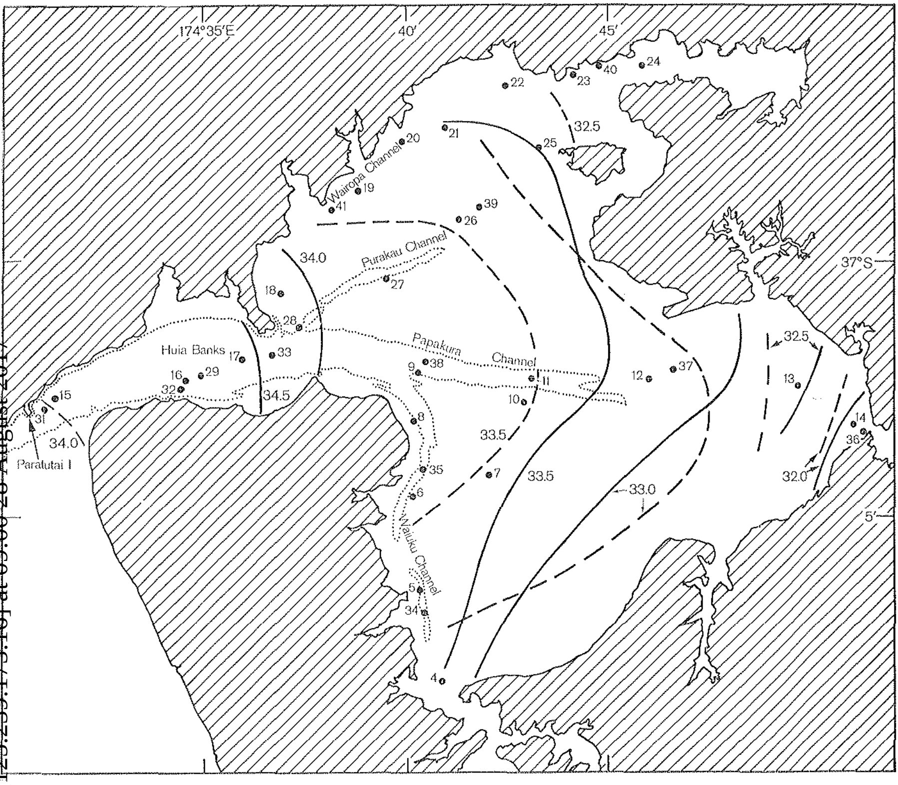

FIG. 4—Isohalines (‰) at the sea surface near high (solid lines) and low tide (dashed lines); dotted line is 10 m isobath. Station positions are also shown; in the Appendix, all station numbers are prefixed by the letter O.

along with the peak sinusoidal tidal flows averaged across the cross-sectional area at midtide needed to satisfy continuity. Current drogues were tracked in each of the main channels in February 1976 (Fig. 7) and from these observations peak tidal speeds under neap and spring tides have been estimated (Table 2) for comparison with those calculated from continuity requirements.

FLOW IN THE ENTRANCE CHANNEL

The volume of water at low tide in the deep main channel is approximately equal to the tidal compartment of the inner harbour, inshore from Puponga Point (Fig. 1, Table 1). If there was no diffusion and the flow in the entrance channel was uniform across the channel, the water in the inner harbour would just move back and forth between the entrance channel and the inner harbour. Current measurements in the entrance channel are therefore of special interest.

TABLE 1—Volumes of water within the zones of Manukau Harbour shown in Fig. 1 calculated by Mr D. Mortimer, Engineer (Reconstruction), Auckland Regional Authority

Zone	Tide	Volume at Low water (10^6 m^3)	Volume at High water (10^6 m^3)	Difference HW−LW (10^6 m^3)
a	Spring	66.5	225.5	159.0
	Neap	88.5	193.5	105.0
b	Spring	78.5	275.0	196.5
	Neap	106.0	231.0	125.0
c	Spring	64.5	206.5	142.0
	Neap	86.0	180.0	94.0
d	Spring	244.0	442.0	198.0
	Neap	277.0	403.0	126.0
Inner Harbour	Springs	453.5	1149.0	695.5
= (a+b+c+d)	Neaps	557.5	1007.5	450.0
Heads only	Springs	610.0	767.0	157.0
e	Neaps	638.0	727.0	89.0
Harbour	Springs	1063.5	1916.0	852.5
+ Heads	Neaps	1195.5	1734.5	539.0

Furkert (1947) demonstrated that the entrance cross-sectional area in many New Zealand inlets, including Manukau Harbour, is simply related to the tidal compartment. This has subsequently been interpreted in an examination of 20 New Zealand coastal inlets as indicating that the entrance cross-sectional area is controlled by the tidal flow, which in turn is related to the tidal compartment (Heath 1975); it also shows again that the main flow through the entrance is tidal.

Several sets of current measurements, each over a tidal cycle, have been made by the Royal New Zealand Navy (Hydrographic Branch

TABLE 2—Tidal compartments of the zones in Manukau Harbour shown in Fig. 1, cross-sectional areas of water on their seaward boundaries, and the resulting cross-sectionally averaged amplitude of the assumed sinusoidal flow through their seaward boundaries (– = no data)

	TIDAL COMPARTMENT (10^6 m^3)		CROSS-SECTIONAL AREA AT MID TIDES (m^2)	PEAK FLOW (cm.s^{-1})	
ZONE	Spring	Neap		Sinusoidal Spring tides	Observed
a	159	105	14.1×10^3 (W section)	17.0	138
b	196	125	2.7×10^5	5.5	–
c	142	94	1.8×10^5 (N section)	5.3	–
d	536	345	4.9×10^4 (W section)	75.0	–
e	853	539	5.8×10^4	135.0	–

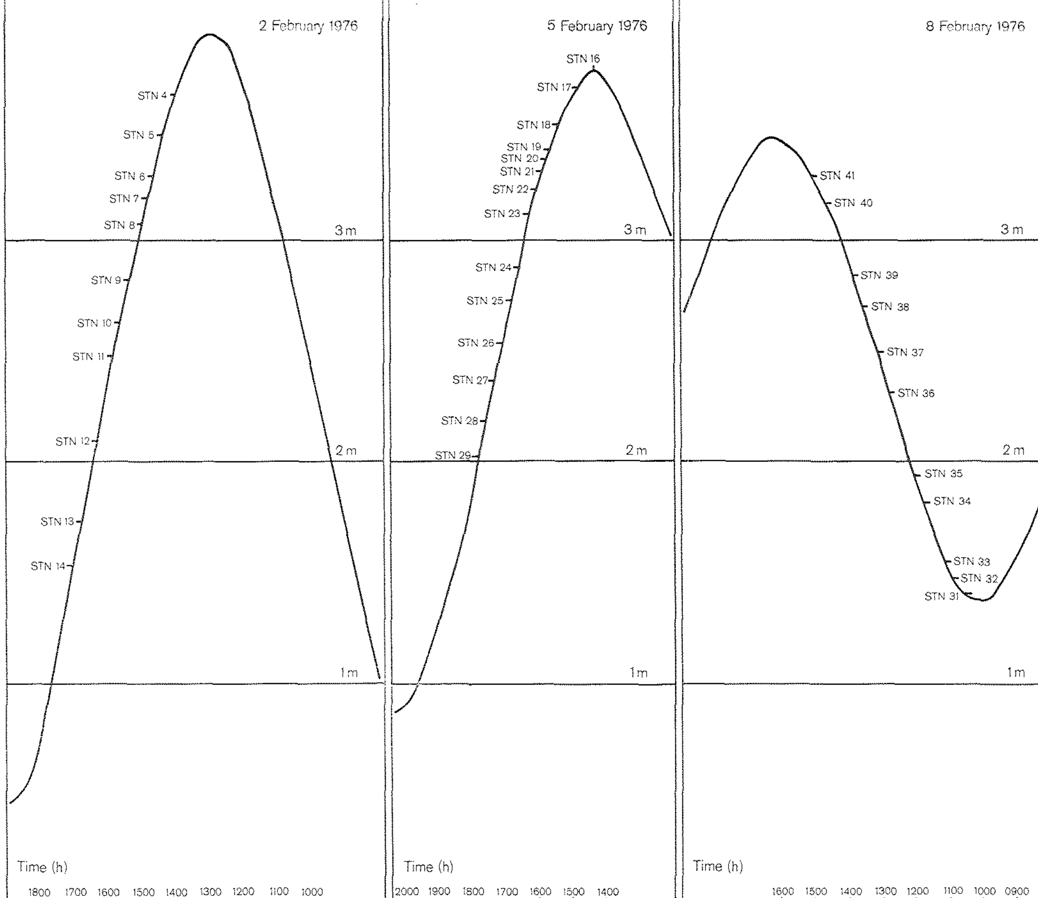

FIG. 5—Tidal elevation at Onehunga plotted against time. The times when the temperature/salinity/depth stations were occupied are also shown. Daylight saving time (= NZST + 1 h) is used.

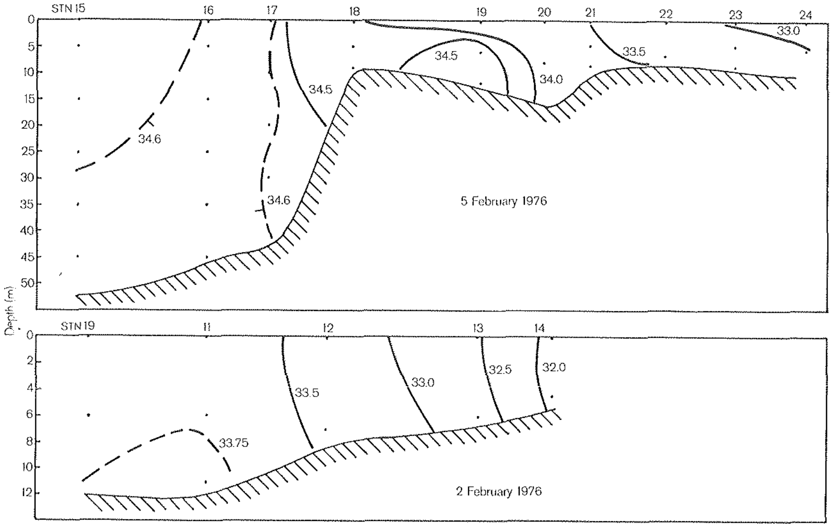

FIG. 6—Sectional plots of salinity (‰) along the entrance and Wairopa Channel (*upper*) and the Papakura Channel (*lower*) (see Fig. 4, where station positions are given; stages of the tide when the stations were occupied are shown in Fig. 5).

1973) (Figs 8, 9), by the Auckland Regional Authority in the entrance channel (Figs 9, 10) and by the New Zealand Oceanographic Institute (Fig. 11). These Eulerian measurements have been collected together in Table 3 as volume transports, calculated as the product of the cross-sectional area with the flow along the channel, integrated over a tidal cycle. For those measurements not extending over a tidal cycle the volume transport has been calculated using a sinusoidal current speed fitted to the available measurements.

The RNZN current observations right at the entrance (position A, Fig. 1) when multiplied by the cross-sectional area of the main channel (neglecting the shallow fringes which comprise only 25% of the area) and integrated over the incoming tide under spring (or neap) tides gave volumes of 6.9×10^8 (4.3×10^8) m^3 (Table 3). However, the values for the outgoing tide are less by about 30% (Fig. 8) indicating there must be appreciable spatial variabilities in the flows. The values, however, are remarkably close to the tidal compartments of 8.5×10^8 (5.4×10^8) m^3 (Table 3).

Using the same calculations at the inner end of the entrance where the harbour starts to open out (line 2, Table 3) indicates that the flow is not as uniform as at the entrance, being larger at position B (Fig. 1) at the surface than in the cross-sectionally averaged mean. There is significant variation with depth here (Figs 10, 11) although the flow near the bottom is still appreciable. Also there is no appreciable phase

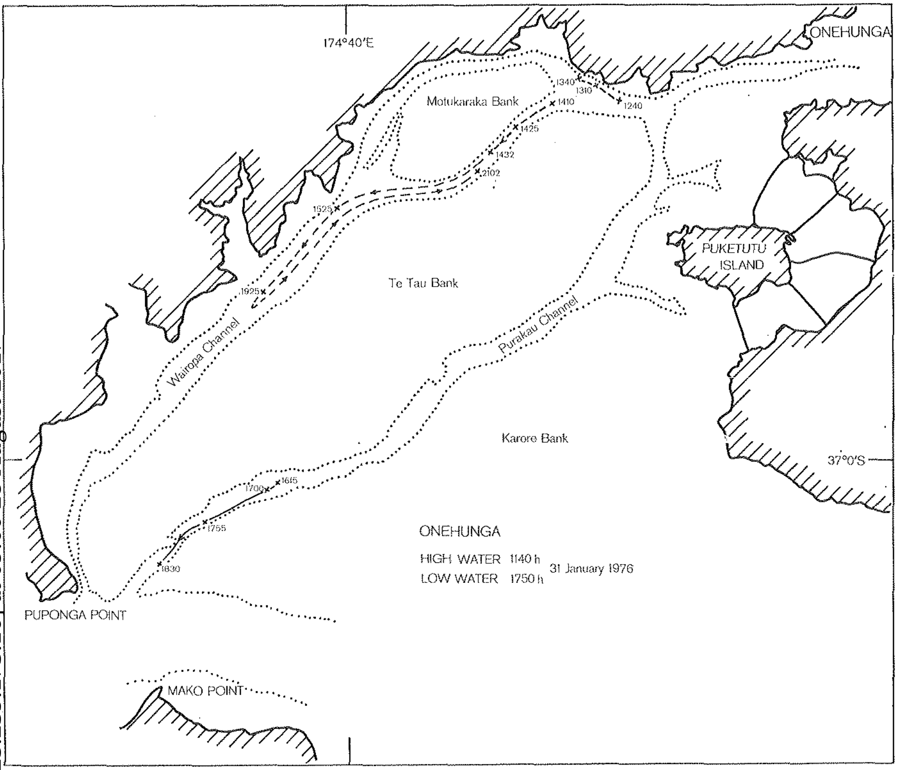

FIG. 7—Trajectories of parachute drogues at 2 m depth tracked in the Wairopa Channel on 31 January 1976 (dashed) and in the Purakau Channel on 9 February 1976 (solid). Daylight saving time (= NZST + 1 h) is used for all times quoted; dotted line is approximate position of channel.

difference with depth. The variability within the flow is important in considering the residence time of water within the harbour.

RESIDENCE TIME OF WATER IN MANUKAU HARBOUR

The residence time of water in an inlet is difficult to measure directly, for it differs for different parcels of water depending on their initial relative densities and their point of entrance. One simple indirect method for calculating the residence time is the tidal prism method (see, e.g., Bowden 1967) in which the water entering the inlet on an incoming tide (α) is assumed to be completely mixed with that in the inlet (of tidal volume V). The residence time is then $V/\alpha T$, where T is the tidal period, which for Manukau gives 1.2 d and 1.7 d for spring and neap tides respectively. In general, the assumption of complete mixing is seldom

TABLE 3—Summary of tidal compartments (m^3) in two sections of Manukau Harbour as calculated by either integrating the direct current measurements with time over an incoming or outgoing tide, or from the product of the tidal range and surface area

A. Tidal compartment of whole Manukau Harbour, i.e., inland of line 1, Fig. 1

(1) Hydrographic Branch (1973) current measurements at the surface at point A, Fig. 1

4.6×10^8 spring tide – outgoing
6.9×10^8 spring tide – incoming
3.0×10^8 neap tide – outgoing
4.3×10^8 neap tide – incoming

(2) Auckland Regional Authority current measurements 18 April 1974 at Whatipu, from six depths at each point

7.8×10^8 neap tide – outgoing
7.0×10^8 neap tide – incoming

(3) Tidal range and surface area at mid-tide

8.5×10^8 spring tide
5.4×10^8 neap tide

B. Tidal compartment of Manukau Harbour less the entrance channel, i.e., inland of line 2, Fig. 1

(1) Hydrographic Branch (1973) current measurements at the surface at point B, Fig. 1

15.0×10^8 spring tide – outgoing
10.1×10^8 spring tide – incoming
6.7×10^8 neap tide – outgoing
5.1×10^8 neap tide – incoming

(2) Auckland Regional Authority current measurements 18 April 1974 at two stations near Puponga and Mako Points, Fig. 1.

8.1×10^8 neap tide – outgoing
6.9×10^8 neap tide – incoming

(3) New Zealand Oceanographic Institute current measurements 10 February 1976 at three stations and three depths at each, Fig. 9

2.8×10^8 neap tide

(4) Tidal range and surface area at mid-tide

6.9×10^8 spring tide
4.5×10^8 neap tide

justified, and therefore these estimates are at best lower limits. Further, the tidal compartment of the inner Manukau Harbour is approximately the same as the volume at low water of the deep entrance channel. If, then, there were no diffusion and the flow in the entrance channel were uniform across the channel, the water in the inner harbour would just move back and forth between the channel and the inner harbour. Limited current measurements in the entrance indicate, however, that the flow is not uniform, for the volume leaving the harbour as given by current measurements is not the same as the tidal compartment of the inner harbour. Some measure of the residence time due to the tides is given by

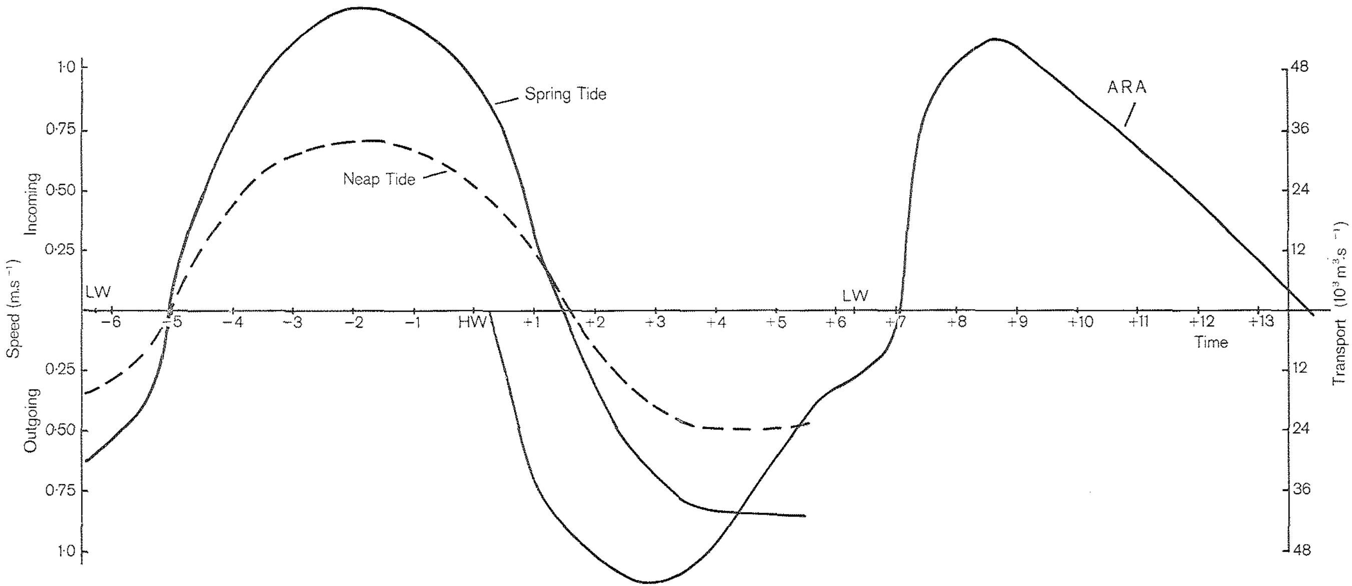

FIG. 8—Current speeds perpendicular to Line 1 at Position A (Fig. 1) calculated from the velocity data for spring and neap tides on Chart NZ4314 (Hydrographic Branch 1973). The time scale (h) refers to high water at Paratutai Island, and the shift of the time of zero flow to after high water is probably caused by inaccuracies in the tidal predictions on the days of measurement; the original measurements are referred to Westport as the standard port. The volume of water transferred near Whatipu Point on 18 April 1974 as measured by the Auckland Regional Authority is shown on the trace labelled ARA.

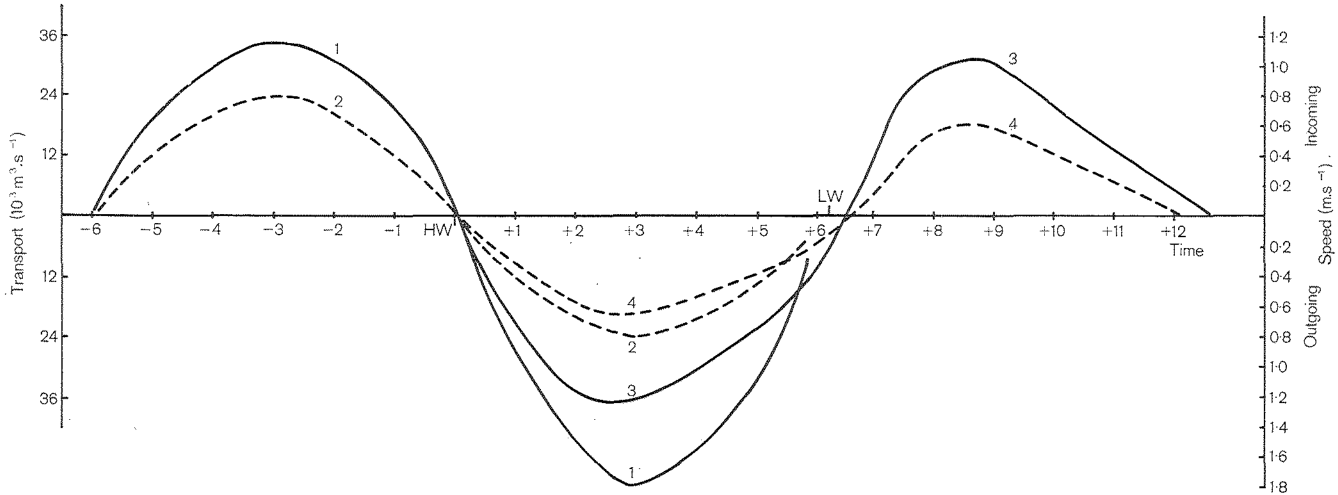

FIG. 9—Current speed (trace 3 at spring tide, trace 4 at neap tide) perpendicular to Line 2 at Position B (Fig. 1) calculated from the velocity data on Chart NZ4314 (Hydrographic Branch 1973). The volumes of water transferred near Puponga (trace 1) and Mako Points (trace 2) on 18 April 1974 as measured by the Auckland Regional Authority are also shown. The time scale (h) refers to high water at Paratutai Island.

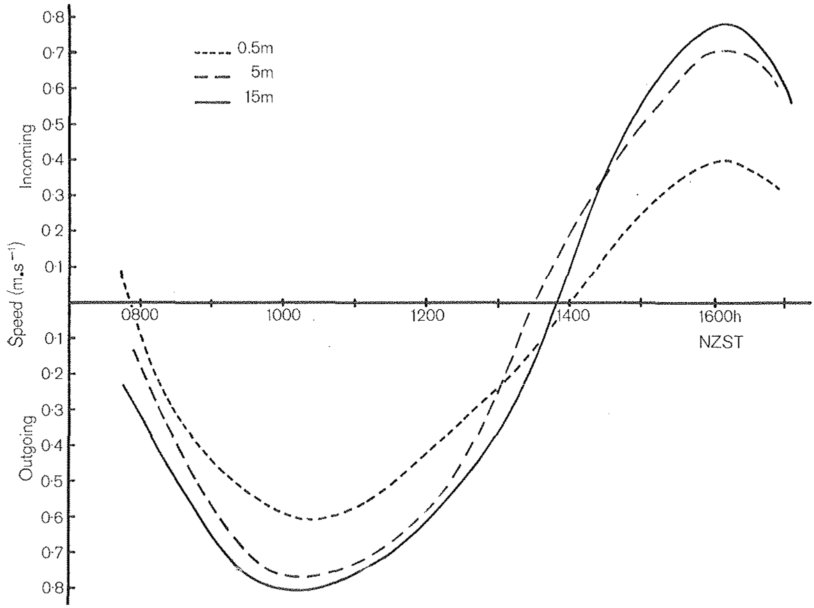

FIG. 10 Longitudinal component of flow near the inner entrance to Manukau Harbour (Position C on Line 2, Fig. 1) at three depths measured by the Auckland Regional Authority on 18 April 1974.

$$\gamma = \left(\frac{V}{\int_0^A \int_0^{T/2} \{v(t) \frac{V_0 \pi}{T\phi} \sin \omega t\} \, dA \, dt} \right) T$$

where $v(t)$ is the observed velocity on line 2 (Fig. 1) of cross-sectional area ϕ; V_0 is the low water volume in the entrance channel; $\omega = 2\pi/T$ is the angular frequency of the tide, and the integration is carried out only for

$$v(t) > \frac{V_0 \pi}{T\phi} \sin \omega t$$

The excess speed

$$\{v(t) - \frac{V_0 \pi}{T\phi} \sin \omega t > 0\}$$

cannot occur throughout the entire cross-sectional area, for V_0 is approximately equal to the tidal compartment. Here the excess speed has been assumed to occur through quarter the cross-sectional area. Estimates

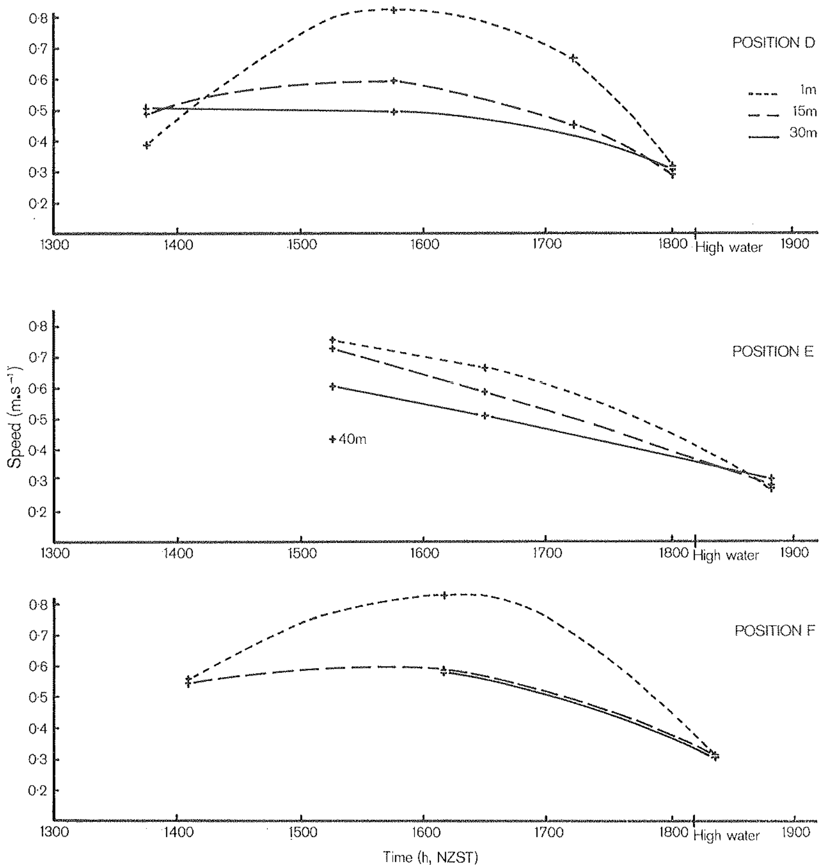

FIG. 11— Longitudinal component of flow at three positions near the inner entrance to Manukau Harbour (positions D, E, F on Line 2, Fig. 1) measured with a Watts current meter by N.Z. Oceanographic Institute, 10 February 1976.

of the residence time based on the volume transports (Table 3) are 6–9 d for neap tides and 3 d for spring tides.

The above estimate is only a slight modification of the tidal prism method and is not very satisfactory because it is based on Eulerian measurements, whereas there might be large spatial changes in the flow downstream. Current drogue measurements were therefore made in the entrance channel on an outgoing tide on 1 February 1976 at depths of 2 m, 5 m and 20 m (Fig. 12) and an incoming tide at depths of 2 m and 20 m on 6 February 1976. These measurements clearly show that the water does not simply move back and forth between the entrance channel and the inner harbour, but that there is also considerable exchange of water between the open ocean and inner Manukau Harbour over a tidal cycle. In both cases the drogues at all depths traversed the length of the entrance channel in about 2 h or about approximately a third of the time between tidal elevation extremes. This then gives an estimate of

$$\frac{V}{\frac{2}{3} \times \alpha \times \frac{1}{4}} \times 12.42\,\mathrm{h}$$

for the residence time. The factor ¼ is again the assumed proportion of the cross-sectional area through which the flow is much larger than that cross-sectional uniform flow needed to satisfy continuity. The overall residence times calculated in this way are 5.2 d and 7 d for spring and neap tides respectively.

These estimates, of the order of 5–10 d, are probably more appropriate to water in the outer reaches of the inner harbour near the entrance channel. To obtain an indication of the average residence time, the amount of freshwater within the harbour, the freshwater input, and evaporation rates have all been estimated. During the period of the salinity survey on 2 and 4 February 1976, the average salinity within the harbour was about 33.5‰ whereas the salinity at the entrance (which is also diluted by the Waikato River outflow situated 38 km south of the Manukau Harbour entrance) was about 34.5‰. The amount of freshwater in the harbour is then

$$\Phi\ (1 - \frac{33.5}{34.5})$$

where Φ is the total volume of water at high tide. Freshwater inflow R can be calculated from the mean surplus runoff for January ($3.3\ m^3 \cdot s^{-1}$) plus the direct rainfall on to the harbour over the previous month of $27.8\ m^3 \cdot s^{-1}$, the average rainfall at Auckland airport and Owairaka (Fig 1) for January 1976 (rainfall figures were kindly provided by the N.Z. Meteorological Service). The average water lost through evaporation over the harbour is $11.5\ m^3 \cdot s^{-1}$ (the mean evaporation at Mangere for the months January and February from 1959 to 1970 is 124 mm and 99 mm respectively; at Otara from 1958 to 1970 it is 122 mm and 94 mm). The residence time in seconds is then given by

$$\Phi\ (1 - \frac{33.5}{34.5}) / (27.8 - 11.5) = 22\,\mathrm{d}$$

assuming the salinity is not changing with time. This is an estimate of the mean residence time for all the water in the harbour. The residence time decreases as the water moves seawards.

A summary of these residence times is given in Table 4.

CONCLUSION

The main flow in Manukau Harbour is tidal. Current speeds in the main channels are greater than required by continuity alone, indicating there is a significant difference in the speed at different points across the

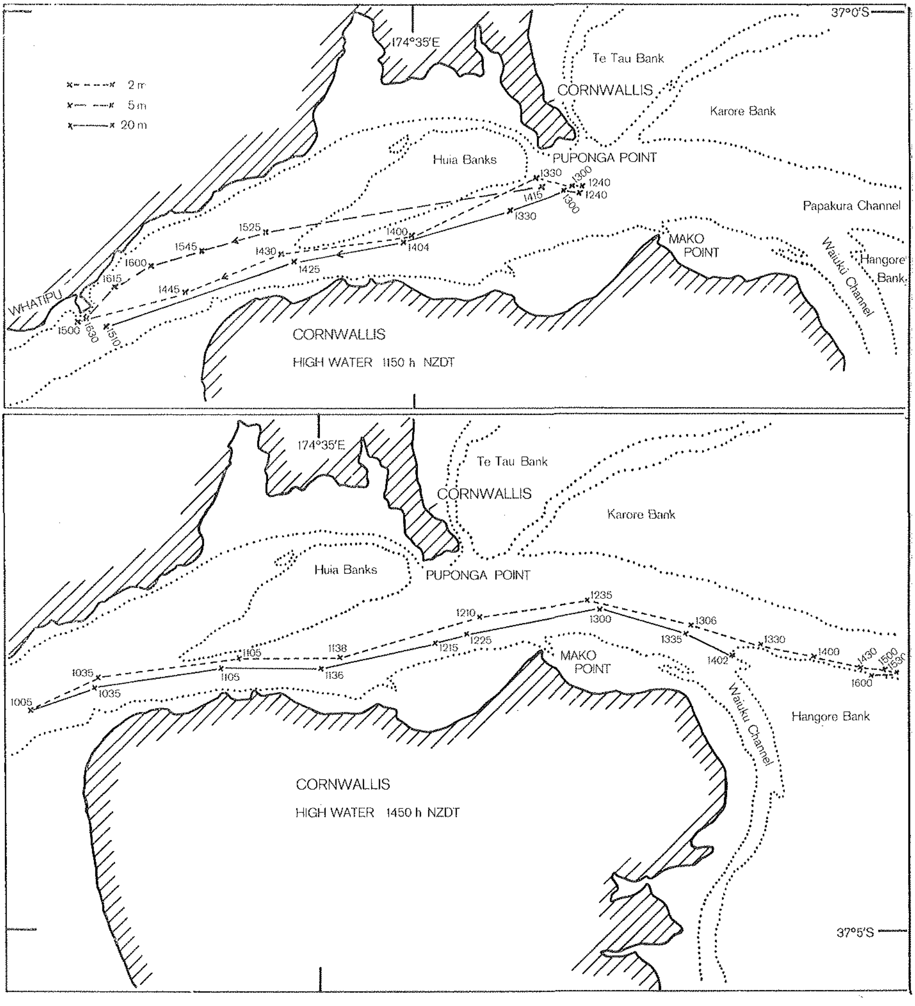

FIG. 12—Trajectories of parachute drogues tracked by N.Z. Oceanographic Institute in the Manukau Harbour entrance channel on an outgoing tide (*upper*) and incoming tide (*lower*) on 1 January and 6 February 1976 respectively; dotted lines indicate approximate positions of channels.

channels. The non-uniformity in the tidal flow probably enhances the flushing of the inlet and maintains the near vertically homogeneous nature of the water.

Residence times estimated for the inner harbour from the direct current measurements near the entrance channel are 5–10 d. The actual mean residence time is probably near the 22 d estimated from the salinity contrast between the water inside and outside the harbour.

TABLE 4—Summary of estimates of the residence time of water within Manukau Harbour calculated from independent sets of observations

(1) From the salinity deficit using the salinity distribution and freshwater inflow in February 1976
22 d

(2) From the tidal prism method
1.2–1.7 d

(3) From Eulerian current measurements for water inshore of line 2, Fig. 1
(a) Measurements by Hydrographic Branch (1973)
spring tide 3 d
neap tide 9.4 d
(b) Measurements by Auckland Regional Authority 18 April 1974
neap tide 5.8 d

(4) From Lagrangian measurements made by N.Z. Oceanographic Institute, February 1976
spring tide 5.2 d
neap tide 7 d

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APPENDIX 1—Station data from Manukau Harbour; station positions are shown in Fig. 4 and station times in Fig. 5 (Z = observation depth (m); T = temperature (°C); S = salinity (‰))

Z	T	S
Stn 04		
0	20.85	33.64
7	20.50	33.64
Stn 05		
0	20.62	33.61
8	20.30	33.70
Stn 06		
0	20.40	33.74
2	20.40	33.74
Stn 07		
0	20.30	33.72
3	20.10	33.72
Stn 08		
0	20.30	33.81
7	20.12	33.83
Stn 09		
0	20.30	33.71
6	20.00	33.72
11	19.93	33.75
Stn 010		
0	20.10	33.59
3	20.04	33.58
Stn 011		
0	20.20	33.72
6	19.90	33.70
11	20.05	33.80
Stn 012		
0	20.42	33.42
7	20.20	33.46
Stn 013		
0	20.35	32.51
6	20.30	32.81
Stn 014		
0	20.40	31.96
4.5	20.45	31.91
Stn 016		
0	19.75	34.61
5	19.50	34.68
15	19.48	34.68
25	19.48	34.68
35	19.50	34.68
45	19.45	34.69
Stn 017		
0	19.80	34.62
10	19.65	34.60
20	19.63	34.61
30	19.65	34.59
40	19.68	34.60
Stn 018		
0	20.60	34.01
5	20.30	34.18
9	20.35	34.21
Stn 019		
0	21.39	33.74
6	20.83	33.70
12	20.45	33.97

Z	T	S
Stn 020		
0	21.98	33.57
8	20.74	33.75
16	20.51	33.66
Stn 021		
0	21.55	33.50
4.5	21.15	33.50
8.5	20.99	33.56
Stn 022		
0	21.50	33.43
7	20.90	33.43
Stn 023		
0	21.90	32.96
5	21.30	33.24
9	21.05	33.34
Stn 024		
0	21.80	32.81
5	21.40	33.00
Stn 025		
0	21.40	33.44
6	21.20	33.72
Stn 026		
0	21.20	33.84
7	20.75	33.90
Stn 027		
0	21.45	33.78
6	21.25	–
12	20.70	33.82
Stn 028		
0	20.72	34.03
8	20.60	34.04
15	20.53	34.06
Stn 029		
0	20.52	34.18
5	20.31	34.20
15	20.15	34.31
25	20.17	34.30
35	20.03	34.24
Stn 031		
0	19.65	34.01
5	–	–
10	19.51	34.11
20	19.36	34.24
30	19.31	34.25
40	19.40	34.26
Stn 032		
0	20.00	33.91
10	19.87	34.35
20	19.85	34.02
30	19.84	34.01
40	19.72	34.01
Stn 033		
0	20.45	33.80
10	19.96	33.83
20	19.90	33.89
30	20.01	33.91
40	19.95	33.96

APPENDIX 1—(*Continued*)

Z	T	S	Z	T	S
Stn 034			Stn 039		
0	20.35	33.08	0	19.80	33.46
8	19.80	33.55	6	19.43	33.42
Stn 035			12	19.30	33.45
0	20.30	33.81	Stn 040		
8	20.00	33.79	0	19.00	32.05
16	19.95	33.79	6	19.82	31.97
Stn 037			Stn 041		
0	20.40	33.32	0	20.00	33.44
5	19.61	33.50	5	19.91	33.63
10	19.94	33.57	11	19.98	33.64
Stn 038					
0	20.53	33.84			
9	20.09	33.90			
18	19.95	33.90			