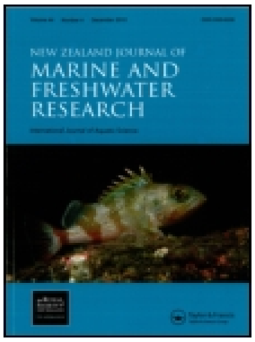

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BROAD CLASSIFICATION OF NEW ZEALAND INLETS WITH EMPHASIS ON RESIDENCE TIMES

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ABSTRACT

Thirty-two New Zealand coastal inlets are tentatively classified into seven groups with probable similar circulation patterns, based on ratios of their physical parameters: volume, tidal compartment, entrance width, surface area, length, and average width. Eighteen of these have a predominant tidal flow, shown from their small ratio ($\beta < 4$) of tidal compartment to total volume, and the cross-sectional areas of their entrances are controlled by the tidal flow: Moutere, Waimea, Aotea, Whanganui, Avon-Heathcote, Tauranga, Parengarenga, Porirua-Pauatahanui, Kawhia, Nelson, Rangaunu, Raglan, Whangarei, Bluff, Otago, Hokianga, Manukau, and Whangaruru. The other fourteen range from long narrow sounds with probable strong vertical circulation (e.g., Pelorus Sound) to large bays with strong mean horizontal circulations (e.g., Tasman and Hawke Bays).

Examples of residence time calculated in inlets with $\beta > 4$ are given for Tasman Bay, a bay with a mean horizontal circulation, which has a residence time of 1–3 months, and Pelorus Sound, an inlet with a vertically complex circulation, which has a residence time of about 20 d.

INTRODUCTION

To date there have been only a few detailed studies of the circulation in New Zealand coastal inlets and most of these have been subsidiary to other programmes (e.g., Booth 1974, 1975). With the current interest in man's effect on his environment, there is a growing need for knowledge of the physical oceanographic aspects of various inlets with the immediate aim of answering questions such as "What is the rate of dispersion of material discharged at a particular site?". Each question has to be answered individually because each inlet, or even each site within an inlet, has unique features. Rates of dispersion, however, depend not only on the specific local circumstance but also on the overall residence time of water in the inlet which, in turn, is governed by the broad-scale circulation. The overall residence time within inlets in considered here.

The quantitative details of the circulation in inlets have been successfully modelled numerically in simplified outlines of specific estuaries and detailed physical scale models of some estuaries have been developed (e.g., Hydraulics Research 1973). The development of such models is expensive, time consuming, and requires verification against detailed observations. Although it is not immediately possible to study all the New Zealand coastal inlets, if the inlets are classified into groups with similar physical properties, later detailed studies in specific inlets

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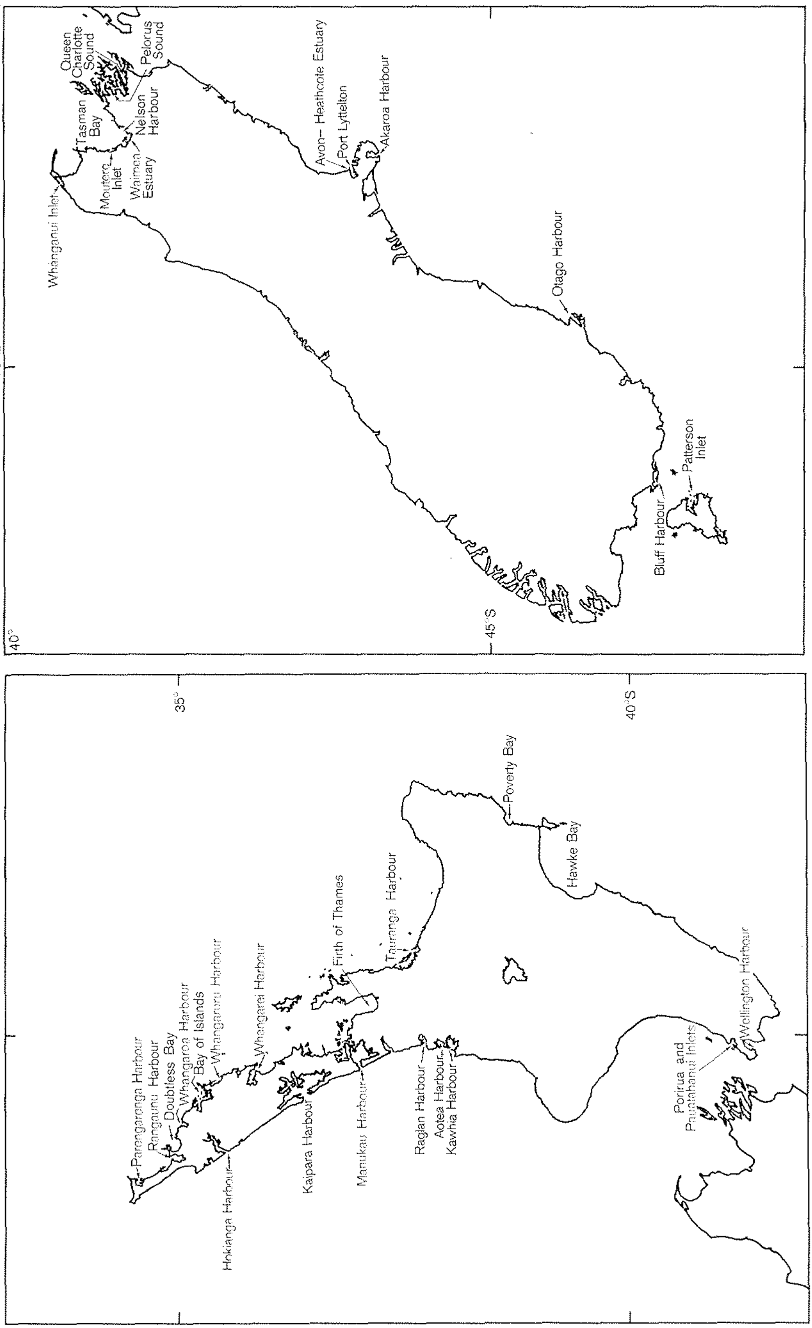


FIG. 1—Location maps of the coastal inlets considered.

will indicate, for example, the type of circulation to be expected in other inlets in the same group. In this paper, then, 32 New Zealand coastal inlets (Fig. 1) have been tentatively classified into groups in terms of factors such as their tidal compartment, bathymetry, freshwater inflow, etc. Obviously this cannot be definitive, for it is essentially a collation of the relevant physical parameters.

The 32 inlets include a range of types from small shallow inlets with extensive mudflats, such as the Moutere Inlet, to large open-mouthed bays, such as Hawke Bay. The list is not all embracing, however, and specifically bays, such as Pegasus Bay, which appear as indentations in the coastline with no defined mouth, and the fiord-type inlets found on the south-west coast of the South Island have not been considered. To demonstrate the complexity that can be present in the circulation, the present knowledge of the circulation in two inlets, one a large open-mouthed bay (Tasman Bay) and the other a long narrow inlet (Pelorus Sound) is discussed with particular reference to the residence time of their waters.

PHYSICAL FACTORS INFLUENCING THE CIRCULATION

The main factors governing the broad mean circulation within an inlet with a small entrance (as opposed to an open bay) are generally thought to be the amount of freshwater runoff, the energy available to mix different water types (tidal, wind mixing, bottom friction, breaking interfacial waves), the bathymetry, and the predominant wind field. In large, open-mouthed bays the circulation also depends on the open boundary conditions. Superimposed on this circulation, and in some cases dominating it, will be the tidal flow and the variable wind-induced or atmospheric pressure-induced motions. The parameters by which these factors can best be classified without detailed observational knowledge have been collected together in Table 1. These are the surface area at high tide, area of mudflats at low tide, entrance cross-sectional area, tidal range, tidal compartment, volume of water at low tide, catchment area, inlet perimeter, entrance width, and maximum length of the inlet.

Surface areas were calculated from either Navy Hydrographic Charts or Lands and Survey Maps using a planimeter. Brief references to these charts are given in Table 1, the full references are given in the literature cited. Cross-sectional areas were calculated from the depths shown on hydrographic charts. The tidal compartment is taken as the product of the tidal range with the sum of the water surface area at low spring tide and half the area of the mudflat. The volumes of water at low tide were estimated from average depths for different fractional areas of the inlet concerned. All these parameters are thus more or less inexact.

Other physical characteristics derived mainly from the values shown in Table 1 are given in Table 2. These include the freshwater inflow and ratios of the physical dimensions and volumes to tidal compartments of the inlets. The availability of river discharge data for these inlets as a

TABLE 1—Physical characteristics of 32 New Zealand inlets. (Parameters for Porirua-Pauatahanui Inlet should read: surface area 8; tidal compartment at springs 10, at neaps 8; volume at low water springs 9.)

Inlet Name	Surface Area at High Tide ϕ	Mudflat Area at Low Tide	Cross-sectional Area Entrance Low Tide Spring	Cross-sectional Area Entrance Mid Tide Spring	Tidal Range (m) Spring Tides	Tidal Range (m) Neap Tides	Tidal Compartment Spring Tides	Tidal Compartment Neap Tides	Volume at low Water Spring	Catchment Area Including Surface Area	Perimeter	Width at Entrance W	Maximum Length L	Source of Data
	($10^6 m^2$)	($10^6 m^2$)	($10^3 m^2$)	($10^3 m^2$)	(m)	(m)	($10^6 m^3$)	($10^6 m^3$)	($10^6 m^3$)	(10^3 km^2)	(km)	(km)	(km)	
Moutere	7	7	0.4	0.9	4.2	2.4	15	9	0	0.2	22	0.5	7	H61
Avon-Heathcote	8	8	-	-	2.1	1.3	11	6	0	0.2	12	0.2	4	Knox *et al.* 1973
Aotea	36	32	2.2	3.6	2.9	1.7	59	35	8	0.2	38	1	11	H2535
Waimea	29	24	2.3	5.8	3.4	1.8	58	31	13	1.0	69	2.6	13	H61, L Sheet S20
Whanganui	24	19	2.3	3.9	2.9	1.5	42	22	7	0.1	40	1.3	13	L Sheet S3, H61
Parengarenga	63	57	6.2	7	2.13	1.4	73	48	24	0.3	106	0.5	19	H5111, L Sh. N1-4
Nelson	14.3	11.4	2	2.6	3.4	2.6	30	23	13	0.1	26	1	9	H6142
Tauranga	224	208	7.3	7.8	1.62	1.24	178	136	96	1.4	230	1.2	37	H541
Kawhia	67	51	8	11	2.9	1.7	121	71	80	0.6	123	1	13	H73
Porirua-Pauatahanui	15	3.1	1.4	1.8	1.6	1.3	22	17	22	0.2	20	0.2	8	Irwin, in press
Rangaunu	97	62	7.1	8.8	2.0	1.5	134	101	140	0.3	50	2	14	H5113
Raglan	24	15	2.9	3.6	2.8	1.8	46	29	50	0.5	76	0.5	11	H4421
Whangarei	95	56	13	14	2.46	1.74	164	116	200	0.5	110	0.8	18	H5213
Bluff	55	22	3.8	4.5	2.2	1.5	97	66	198	0.1	54	2	17	H6721, L Sheets S181, S182
Otago	46	13	4.7	5.1	1.74	1.28	69	51	145	0.2	60	1.5	21	H6612
Hokianga	115	65	11	13	2.77	1.78	228	147	500	1.5	207	1	33	H4212
Manukau	344	145	42	46	3.38	1.95	918	530	2000	1.1	280	2.5	30	H4314
Whangaruru	15	2	21	23	2	1.5	28	21	78	0.07	40	2.4	6	H5111
Lyttelton	43	11	28	30	1.92	1.64	72	61	230	0.02	55	2	15	H6321
Firth of Thames	735	81	400	440	3.72	2.68	2580	1860	9200	4.5	126	22	39	H533
Kaipara	947	409	73	82	2.68	1.52	1990	1130	8070	6.4	612	7.5	61	H43
Whangaroa	19	5	4.3	4.7	1.95	1.34	33	23	136	0.3	48	0.5	6	H1092
Akaroa	44	2	45	47	1.89	1.52	81	65	500	0.2	51	2	16	H6324
Doubtless Bay	185	6	642	652	1.9	1.4	346	255	3700	0.7	192	12	18	H2525
Paterson Inlet	89	9	55	59	2.0	1.4	168	120	1920	0.3	188	0.5	18	H52
Tasman Bay	4621	69	2450	2560	3.44	1.8	16000	8300	2.2×10^5	10.1	536	76	75	H61
Poverty Bay	58	-	140	146	1.4	1.2	81	70	1160	2.3	37	9	11	H65
Pelorus Sound	290	20	117	121	2.37	1.46	660	410	10940	1.7	386	4	50	H615
Bay of Islands	179	8	1034	1050	1.95	1.46	340	260	6000	1.8	200	20	19	H5122
Wellington Harbour	87	-	38	39	1.01	0.94	88	82	1740	0.8	51	2.5	14	H4633
Queen Charlotte Sound	70	-	880	890	1.4	0.5	98	35	2800	0.2 to West Head	229	1.8	22	NZ615
Hawke Bay	2950	-	5250	5300	1.34	1.22	3950	3600	1.8×10^5	17.2	260	80	90	H56

TABLE 2—Freshwater runoff and ratios of physical characteristics of 32 New Zealand inlets. (Parameters for Porirua-Pauatahanui Inlet should read: perimeter ÷ surface area 2.5; surface area ÷ maximum length 1; total volume ÷ spring tidal compartment 1.9; volume at low water ÷ average runoff 26.)

Inlet Name	Average Annual Runoff	Average Runoff January	Average Runoff July	Perimeter ÷ Surface Area	Surface Area ÷ Maximum Length	RESIDENCE TIME: Total Volume ÷ Spring Tidal Compartment β	Volume at Low Water ÷ Average Runoff	Total Volume ÷ Spring Tidal Compartment + Average Runoff
	m^3s^{-1}	m^3s^{-1}		km^{-1}	km	Tidal periods	days	days
Moutere	2	1	7	3.1	1	1	0	0.5
Avon-Heathcote	1.3	0	7	1.5	2	1	0	0.5
Aotea	10	2	8	1.1	3.3	1.1	9.3	0.6
Waimea	13	4	36	2.4	2.2	1.2	11.6	0.6
Whanganui	4	2	4	1.7	1.8	1.2	20	0.6
Parengarenga	7	2	10	1.7	3.3	1.3	40	0.7
Nelson	2	1	5	1.8	1.6	1.4	75	0.7
Tauranga	37	13	52	1	6.1	1.5	30	0.8
Kawhia	30	9	21	1.8	5.2	1.7	31	0.9
Porirua - Pauatahanui	4	1	5	1.3	1.9	2	64	1.0
Ranganunu	8	3	12	0.5	6.9	2	202	1.1
Raglan	18	3	17	3.2	2.2	2.1	32	1.1
Whangarei	12	2	17	1.2	5.3	2.2	193	1.1
Bluff	3	1	2	1.0	3.2	3	764	1.6
Otago	1	1	2	1.3	2.2	3.1	1678	1.6
Hokianga	38	5	53	1.8	3.5	3.2	152	1.6
Manukau	28	4	40	0.8	11.5	3.2	826	1.6
Whangaruru	0.2	0.1	0.3	2.7	2.5	3.8	4512	2.0
Lyttelton	1	0	5	1.3	2.9	4.2	2661	2.2
Firth of Thames	115	16	163	0.2	19	4.6	926	2.4
Kaipara	16	2	23	0.6	16	5.0	5836	2.6
Whangaroa	7	2	10	2.5	3.2	5.1	225	2.6
Akaroa	2	-	6	1.2	2.8	7.2	2892	3.7
Doubtless Bay	2	0.5	3	1.0	10.3	11	21405	6.1
Paterson Inlet	7	2	7	2.1	4.9	12	3173	6.4
Tasman Bay	256	90	361	0.1	62	15	9943	7.6
Poverty Bay	58	8	81	0.6	5.3	18	231	8.8
Pelorus Sound	44	6	62	1.3	5.8	18	2877	9.1
Bay of Islands	46	7	65	1.1	9.4	19	1509	9.6
Wellington Harbour	20	7	29	0.6	6.2	21	1007	10.7
Queen Charlotte Sound	3	0.8	6	3.3	3.2	30	10799	15.3
Hawke Bay	438	154	618	0.1	3.3	47	4755	24.0

whole are very limited, and therefore an indirect method for calculating the freshwater discharge has been used. This consisted of taking the product of the catchment area with the surplus rainfall as presented in broad contours by Couter (1973). The surplus rainfall is that in excess of the rainfall needed to maintain a soil moisture capacity (0.075 m was adopted by Coulter 1973) in conjunction with an average rate of potential evapotranspiration. To check the validity of the method the river discharge data kindly provided by Mr R. J. Curry of the Ministry of Works and Development, Wellington (pers. comm., 1975) for the inlets in central New Zealand are presented in Table 3, along with the appropriate surplus rainfall estimates. The agreement is very good, especially when the possible errors in both methods, such as the spatial changes in the rainfall pattern, are considered.

The ratio of the perimeter to surface area of the inlets (Table 2) gives a measure of the degree of indentation or asymmetry; this ratio is

TABLE 3—Freshwater inflows ($m^3.s^{-1}$) from river gauging (R. J. Curry, Ministry of Works and Development, pers. comm.) and from rainfall surplus derived from Coulter (1973) (– = not considered separately.)

		OBSERVED INFLOW				INFLOW FROM RAINFALL SURPLUS		
Inlet	River	Low Flow	Mean Flow	Annual Flood	Maximum Flood	January	Average	July
Wellington Harbour	Hutt	4.2	34	370	1 980	25	7	29 30
Porirua-Pauatahanui	Porirua	0.1	0.7	28	140	–	–	
	Kenepuru	0.04	0.1	7.1	40	–	–	
	Kahao	0.02	0.18	3.5	30	–	–	
	Horokiwi	0.08	0.45	18	110	–	–	
	Pauatahanui	0.09	0.5	17	95	–	–	
	Duck	0.02	0.09	4.2	35	–	–	
	Total	0.35	2.02	77.8	450	4	1	5
Tasman Bay	–	22	115	1 100	7 500	256	90	361
Pelorus Sound	–	5.8	53	230	5 600	44	6	62
Queen Charlotte Sound	–	0.8	10.3	36	1 100	3	0.8	6
Whanganui Inlet	–	0.3	2.9	49	160	4	2	4

large for an inlet with many indentations or a long narrow inlet, and small for a smooth circular inlet. The mean annual percentage frequency of wind direction over New Zealand has been presented by Garnier (1958).

CLASSIFICATION

The inlets considered have been listed in Tables 1 and 2 in increasing order of the ratio of total volume to the spring tidal compartment. As will be discussed later, this ratio is often used as a measure of tidal flushing.

Furkert (1947) showed that in many inlets around New Zealand the entrance cross-sectional area (E) is linearly related to the tidal compartment (α). Further analysis (Heath 1975) indicates that for 16 inlets (Whangaroa, Whangarei, Bluff, Raglan, Kaipara, Manukau, Hokianga, Kawhia, Tauranga, Rangaunu, Parengarenga, Otago, Nelson, and Aotea Harbours, Whanganui and Moutere Inlets) the relationship found by least squares is

$$\alpha = 16224\ E^{.97}$$

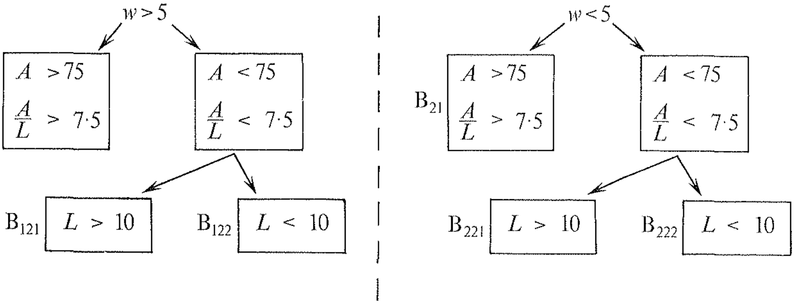
with a correlation coefficient (r) of 0.95. (The Waimea Inlet, the Avon-Heathcote Estuary, and Porirua-Pauatahanui Inlets, though not considered by Heath (1975), also fit closely to this relationship.) The correlation coefficient for 2 × 16 random numbers is less than 0.29 for 90% of the estimates (Fisher & Yates 1963). The overall cross-sectional area at the inlet entrance is controlled by the ability of the tidal flow to transport sediment, there being no net erosion or deposition of sediment at the entrances. Further, the tidal flow must dominate any other flow;

this is clearly seen from the small ratio (β) of the total volume to the spring tidal compartment (Table 2). The inlets can be separated into two groups, those in which the tidal flow dominates (Group A) and those in which other motion might be of importance (Group B). Based on the inlets considered by Heath (1975) all those inlets with $\beta < 4$ belong to group A, whereas most of those inlets with $\beta > 4$ belong to group B (Table 2).

This latter group includes Kaipara and Whangaroa Harbours which did not fit as closely to the linear cross-sectional area : tidal compartment relationship as the other inlets considered by Heath (1975). Inlets in group B can be further subdivided in terms of their physical dimensions. This subdivision is rather arbitrary, but serves to separate such diverse inlets as Hawke Bay and Whangarei Harbour. The criteria used are to group those inlets in which there is likely to be a non-tidal circulation induced by forcing from the mouth, or a horizontal two-dimensional wind induced circulation, etc. In terms of the entrance width w, surface area A, length L, and average width A/L, we can arbitrarily classify the inlets in group B by the following criteria:

1. $w > 5$ km (boundary forcing),
2. $w < 5$ km (no boundary forcing),
3. $A > 75$ km^2 (horizontal two-dimensional circulation by wind),
4. $A < 75$ km^2 (no horizontal two-dimensional circulation),
5. $L > 10$ km (vertical two-dimensional circulation by wind), and
6. $L < 10$ km (no vertical two-dimensional circulation).

In terms of inlet classifications these criteria give:



B_{11} : boundary forcing and both vertical and horizontal two-dimensional wind derived motion.
B_{121} : boundary forcing and vertical two-dimensional wind derived motion.
B_{122} : boundary forcing.
B_{21} : vertical and horizontal two-dimensional wind derived motion.
B_{221} : vertical two-dimensional wind derived motion.
B_{222} : mainly tidal motion.

The inlets in group B could then be allocated:

B_{11} : Tasman Bay, Hawke Bay, Firth of Thames, Doubtless Bay, Bay of Islands.

B_{121} : Poverty Bay.
B_{122} : none of the inlets studied.
B_{21} : Kaipara, Wellington (the value of A/L is misleading as Wellington Harbour has a long entrance channel).
B_{221} : Lyttelton, Akaroa, Paterson Inlet, Pelorus Sound, Queen Charlotte Sound.
B_{222} : Whangarei.

RESIDENCE TIME

The residence time of water in an inlet is the time from its initial entrance to its final exit and will be different for different parcels of water, depending on their initial relative densities and from where they enter. Because the density of a water parcel will change with time, the residence time is difficult to measure directly. There are, however, a number of indirect methods available, the one most often quoted being the tidal prism method (see, e.g., Bowden 1967, Dyer 1973).

Assuming that the water entering the inlet on an incoming tide (α) completely mixed with that in the inlet (of total volume V), then an estimate of the residence time is given by $V/\alpha \times T$, where T is the tidal period; around New Zealand the dominant tide is lunar semi-diurnal, and therefore $T = 12.42$ h. This assumption of complete mixing is probably seldom justified, and therefore the estimates by this method given in Table 2 (β column) are at best lower limits for tidal flushing. A less stringent assumption is that the water entering the inlet on a flood tide mixes completely with water immediately inside the inlet. This mixed water (50/50) then leaves on the ebb tide, during which time complete mixing of the remaining water takes place. The estimate of the residence time would then be 2β for those inlets with values of $\beta > 2$. Further consideration of the freshwater inflow does not alter the residence times significantly in the inlets considered (Table 2).

In many of the inlets considered (Group A, $\beta < 4$, Table 2), the flushing will be dominated by the tides. In other inlets (Group B, $\beta > 4$), other indirect estimates of the residence time can sometimes be made using knowledge of whether there is any appreciable two-dimensional flow, whether the flow is tidal, etc. Examples of the type of estimates that can be made will be discussed for an inlet with a two-dimensional mean circulation (Tasman Bay) and for a long narrow inlet (Pelorus Sound).

RESIDENCE TIME IN TASMAN BAY

Drift card observations indicate that the surface flow in Tasman Bay is highly wind dependent (Heath 1973). The mean flow, however, appears to consist of a clockwise circulation in Golden Bay, and anti-clockwise circulation in the main part of Tasman Bay, with an additional southwards flow on the eastern side of Tasman Bay. Results of a numerical model of the circulation in this bay resulting from specification of the flow outside the bay and a wind of 25 knots from the west (Heath 1976) and other direct current measurements (Ridgway in press) support this circulation pattern. In a large open-mouthed bay such as Tasman Bay we can estimate the residence time associated with both the mean circulation and the tides.

RESIDENCE TIME ASSOCIATED WITH MEAN CIRCULATION: Using a depth average outflow of 0.02 $m{\cdot}s^{-1}$ (based on measurements presented on the chart, Hydrographic Branch 1973b) across half the entrance to the bay (1.35×10^6 m^2) gives a residence time of

$$\frac{2.2 \times 10^{11}}{0.02 \times 1.35 \times 10^6} \text{ s} = 94 \text{ d}$$

where the volume of water in Tasman Bay is estimated as 2.2×10^{11} m^3. Increasing the outflow speed to the surface flow velocity from drift card experiments (Heath 1973), 0.07 $m{\cdot}s^{-1}$, gives a residence time of

$$\frac{0.02}{0.07} \times 94 = 27 \text{ d}$$

Heath (1973) gave an alternative estimate based on the drift card investigations. Using the surface speeds given by the release to recovery time of the drift cards, he estimated the associated Ekman Transport (see, e.g., Neumann & Pierson 1966) and hence the residence time of 67 d associated with a surface speed of 0.07 $m{\cdot}s^{-1}$ which would be associated with a wind speed of 8 $m{\cdot}s^{-1}$. Doubling the wind speed decreases the residence time to a quarter of its previous value (i.e., 16 d). Heath (1973) pointed out that although a wind with a speed of 16 $m{\cdot}s^{-1}$ (31 knots) blowing continuously for 16 d across the entrance to Tasman Bay would be unlikely, the funnelling effect of Cook Strait (Garnier 1958) will often produce a strong wind in the required direction.

RESIDENCE TIME ASSOCIATED WITH TIDES: The tidal prism method may not be appropriate to a bay with a wide entrance, such as Tasman Bay, even if there was no mean circulation within the bay, because most of the water near the entrance would enter and leave the bay several times while passing across the entrance in the mean flow (assuming the offshore mixing is small). In inlets with small width, most of the outgoing tidal water moves along the coast in the mean flow, and therefore new water enters on the next flood tide. In a wide bay, only that water leaving the entrance near the end towards which the mean flow along the coast is directed will not re-enter the bay on the next tide. A more appropriate estimate then is given by considering the amount of *new* water entering the bay each tidal cycle. If the mean flow along the coast near the entrance is v_D (and we assume this mean flow is directed across the mouth), then the amount of new water entering the bay over a tidal cycle (period T) is

$$nw = \frac{v_D \times T \times \alpha}{w}$$

(w the entrance width, α the tidal compartment). Values of v_D = 0.05 m.s^{-1} (Hydrographic Branch 1973b) and T = 12.4 h give a residence time

$$\frac{w \times \phi}{0.05 \times T \times \alpha} \times T = 317\ \mathrm{d}$$

(ϕ the volume). This residence time is separate from that associated with the mean circulation in the bay.

In summary, the residence time of water in Tasman Bay is mainly governed by the mean circulation with enhancement by the tides and fluctuating winds. The residence time would appear to be between 1–3 months.

RESIDENCE TIME IN PELORUS SOUND

The modified tidal prism method of Ketchum (1951) rather than the direct tidal prism method for calculating the residence time is probably more appropriate for use in Pelorus Sound, where the ratio (β) of the volume to tidal compartment is large. In the modified tidal prism method the inlet is subdivided into sections; the volume at low tide of each (V_n) being equal to the volume at high tide of the adjacent landward section ($V_{n-1} + P_{n-1}$), P_{n-1} being the tidal compartment of section $n-1$. The section next to the river at the head of the inlet has limits such that its tidal compartment P_0 is equal to the total freshwater inflow over a tidal cycle R, i.e.,

$$\begin{aligned} P_0 &= R \\ V_1 &= P_0 + V_0 = V_0 + R \\ V_2 &= V_1 + P_1 = V_0 + R + P_1 \\ V_n &= V_0 + R + \sum_{m=1}^{n-1} P_m \end{aligned}$$

An amount of freshwater R must flow through each section over a tidal cycle. The exchange of water with that in the adjacent landward section (r_n) is given by the ratio of the tidal compartment to the high tidal volume, i.e.,

$$r_n = \frac{P_n}{P_n + V_n}$$

The amount of freshwater leaving a section that arrived on the previous tidal cycles is given by

$$r_nR,\ r_n(1 - r_n)R,\ r_n(1 - r_n)^2R,\ r_n(1 - r_n)^{m-1}R$$

and the amount remaining is $(1 - r_n)R$, $(1 - r_n)^2R$, $(1 - r_n)^mR$. The total amount of freshwater in each section (Q_n) is then

$$Q_n = R\{1 + (1 - r_n) + (1 - r_n)^2 + (1 - r_n)^m\}$$

$$Q_n = \frac{R}{r_n}$$

TABLE 4—Value of the tidal compartment (P_n), volume of water at low tide (V_n), exchange coefficients ($r_n = \frac{P_n}{P_n + V_n}$) ($r_n^1 = r_n \frac{D_n}{H_n}$) for each section ($n$) in Pelorus Sound, the limits of the sections being determined by Ketchum's (1951) modified tidal prism method as discussed in the text; H_n is in the depth of the mixed layer and D_n the average depth in section n

n	P_n ($10^6 m^3$)	V_n ($10^6 m^3$)	r_n	r_n^1
0	2.3	1.15	0.66	0.74
1	2.6	3.4	0.43	0.75
2	6.7	5.9	0.53	0.74
3	4.7	12.6	0.27	0.74
4	6.4	17.3	0.27	0.74
5	3.0	23.7	0.11	0.74
6	38.1	26.7	0.59	4.60
7	3.5	64.8	0.05	0.74
8	3.6	68.3	0.05	0.74
9	5.1	71.9	0.07	0.75
10	11.5	77.0	0.13	0.75
11	4.8	88.5	0.05	0.74
12	3.9	93.3	0.04	0.75
13	7.2	97.2	0.07	0.75
14	4.1	104.4	0.04	0.79
15	4.3	108.5	0.04	0.79
16	3.8	112.8	0.03	0.70

Consequently, the salinity in each section S_n is related to that of the seawater outside the inlet S_E by

$$(P_n + V_n)\ S_n = \phi_n S_E$$
$$P_n + V_n = \phi_n + Q_n$$
$$\text{i.e., } S_n = S_E\ (1 - \frac{R}{P_n})$$

This method would not appear to work when $P_n < P_{n-1}$, for then the salinity increases towards the head of the inlet.

In many inlets the fresh water is mainly confined to an upper mixed layer, and then r_n^1 is given by $r_n^1 = \frac{P_n}{(V_n + P_n)} \frac{D}{H}$ (H the depth of the mixed layer, and D the average depth in section n).

This modified tidal prism method has been applied to Pelorus Sound for comparison with observations obtained in June–July 1973 (Fig. 2) by Heath (1974). The values of P_n, V_n, r_n, r_n^1 (for $H = 2$ m) are given in Table 4, and the observed and calculated salinities are shown in Fig. 3. The value of P_n near the confluence of the Kenepuru Arm with Pelorus Sound includes the tidal compartment of the Kenepuru Arm, into which there is relatively little freshwater inflow compared with that flowing

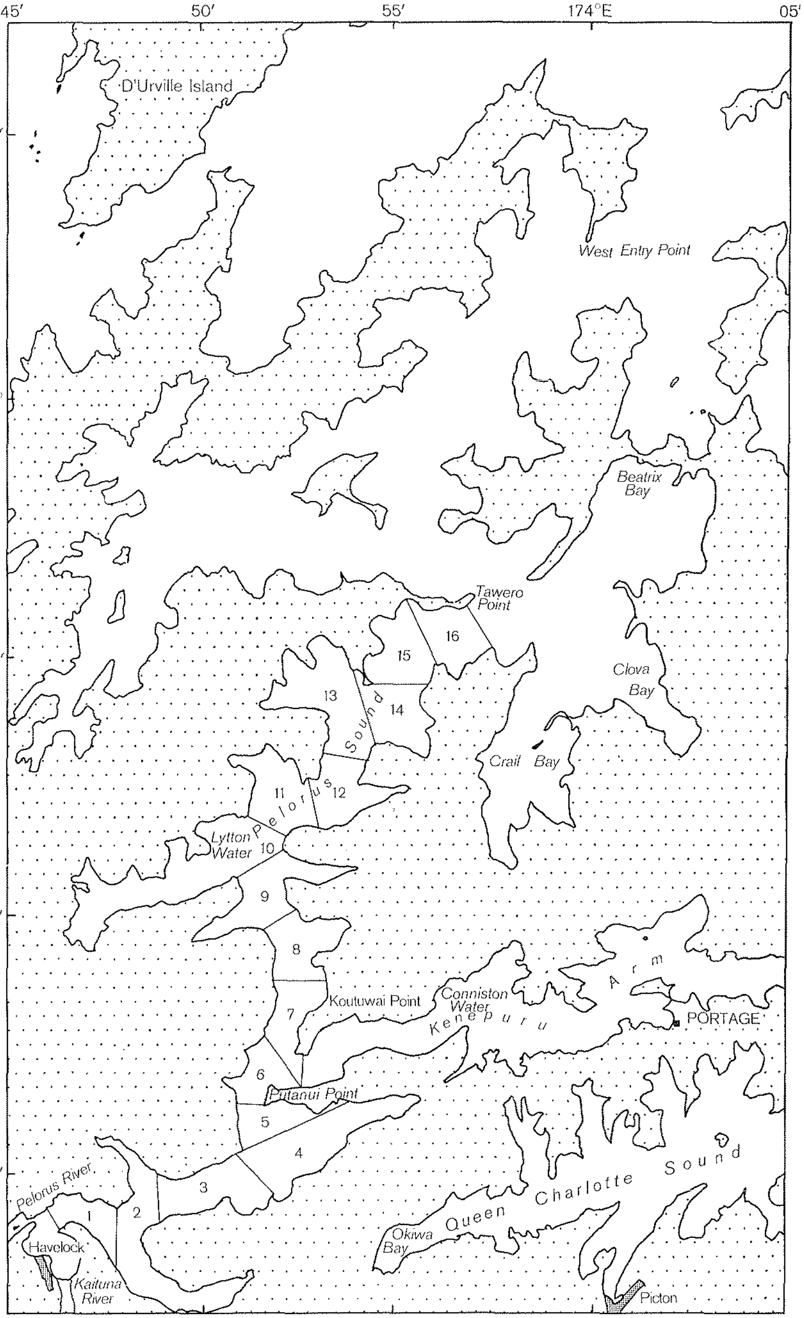


FIG. 2—Positions of sections in Pelorus Sound used in Ketchum's (1951) modified tidal prism method of calculating the residence time of water.

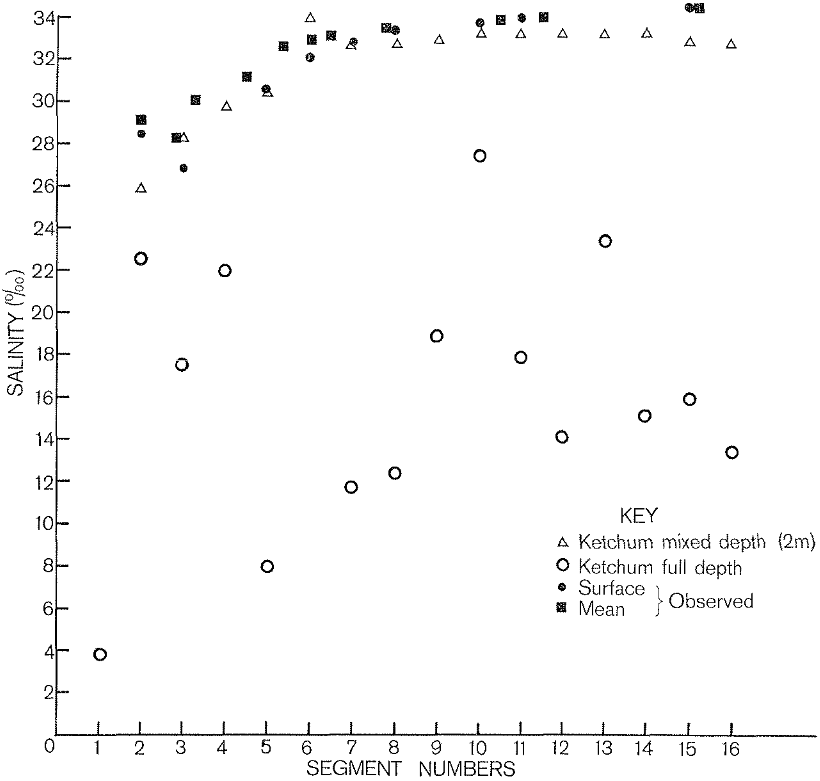


FIG. 3—Depth mean, and surface salinities observed in Pelorus Sound on 29 & 30 June 1973 and the salinities calculated by Ketchum's (1951) modified tidal prism method under the assumption of complete vertical mixing and with a mixed layer depth of 2 m. The external salinity near Tawero Point (Fig. 3) was taken as 34.34‰ and the freshwater inflow as 50 $m^3.s^{-1}$. The segment positions are shown in Fig. 2.

into the head of Pelorus Sound from the Pelorus and Kaituna Rivers. This method is inappropriate if we assume each section has homogeneous water at high tide, but is appropriate for an assumed upper mixed layer of 2 m depth. In this situation, however, this method does not solve our original question of predicting the residence time from tidal and freshwater inflow data alone, for the process is obviously quite complex.

The values of Q_n, the amount of freshwater, calculated by Ketchum's (1951) modified 'tidal prism' method are greater than observed (Fig. 3), indicating that the exchange ratios r_n are under-estimates, and therefore that the mixing and flushing is quicker than that due solely to barotropic tidal mixing alone. During flood conditions, the freshwater moves rapidly down the sound in a thin upper layer (L. Carter, NZOI, pers. comm.), and there is an internal tide in the sound (Heath 1976) which would enhance the mixing and essentially increase the tidal compartments. Clearly, Ketchum's modified tidal prism method cannot be applied at random.

The overall residence time of water in Pelorus Sound has been calculated by dividing the total amount of freshwater in the sound by the freshwater inflow (Heath 1973). The value of 21 d is remarkably close to the tidal prism flushing time of $2 \times 9.1 = 18.2$ d, but this could be only a coincidence for, as indicated above, the tidal flushing is enhanced by the presence of an internal tide.

CONCLUSION

The broad classification, according to their physical parameters, of the 32 inlets considered conveniently subdivides them into two major groups. In one group, tidal flow is dominant, in the other different types of driving forces may also be important. Further subdivision in the latter group gives rise to six subgroups.

Obviously, detailed observations are required to allow the circulation pattern in each inlet to be defined with any confidence, as is illustrated by the two examples considered, Tasman Bay and Pelorus Sound. However, the broad classification provides an indication of the type of circulation expected in each group, and the results of definitive studies in one group member can then be used at least in planning of studies of other members within the group.

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