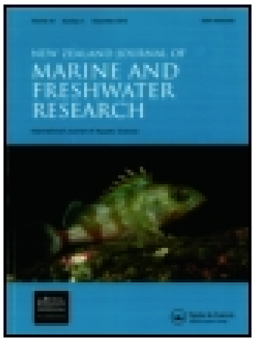

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STABILITY OF SOME NEW ZEALAND COASTAL INLETS

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ABSTRACT

The relation of tidal compartments to entrance cross-sectional areas is examined for 20 coastal inlets. Sixteen inlets conform to a linear relationship, which is consistent with stable entrances the sizes of which are determined by the ability of the tidal flow to transport sediment. Based on this criterion deposition should be taking place at the entrances of the other four inlets: Wellington, Lyttelton, and Akaroa harbours, and Paterson Inlet. Available data confirm this for Wellington and Lyttelton Harbours.

INTRODUCTION

The interesting observation that the tidal compartment (the volume of water entering the harbour on an incoming tide) and the entrance cross-sectional area of many New Zealand inlets are simply related was made by Furkert (1947). He found that, on a logarithmic plot of these parameters for many inlets, the points lie approximately in a straight line. This relationship has been observed in many inlets throughout the world and indicates that one of the main factors determining the size of the entrance is the ability of the flow through the entrance to transport sediment (see e.g., Bruun & Gerritsen 1960).

In this paper the relationship between the cross-sectional area and tidal compartments of 20 New Zealand coastal inlets is examined. The calculations were made from more recent observations than those available to Furkert (1947). The inlets which do not follow the simple relationship are also examined in terms of their entrance stability.

OBSERVATIONS

Tidal compartments for both spring and neap tides and cross-sectional areas at the entrance at mid and low tides under spring tidal conditions are given in Table 1. The values for spring tides with the cross-sectional area at mid tide are plotted in Fig. 3. The locations of the inlets are shown in Figs 1 and 2. Brief references to the source of data are also given in Table 1, with the full references provided under the literature cited. Surface areas of the inlets were calculated from published charts using a planimeter. The area used in calculating the tidal compartments was the mean of the area at high water and at low water.

TABLE 1—Surface area, cross-sectional area at the entrance, tidal compartment, and tidal range for 20 New Zealand coastal inlets.

INLET	SURFACE AREA (high spring tides, $m^2 \times 10^6$)	AREA MUDFLATS (low spring tides, $m^2 \times 10^6$)	CROSS-SECTIONAL AREA AT ENTRANCE (spring tides, $m^2 \times 10^3$)		TIDAL COMPARTMENT ($m^3 \times 10^6$)		TIDAL RANGE (m)		CHART OR MAP USED (NZ = Hydrographic Charts; NZMS1 = Lands & Survey Maps)
			Mid tide	Low tide	Spring tide	Neap tide	Spring tide	Neap tide	
Kaipara Harbour	947	409	82	73	1990	1130	2.68	1.52	NZ43
Manukau Harbour	344	192	46	42	838	483	3.38	1.95	NZ4314
Hokianga Harbour	115	65	13	11	228	147	2.77	1.78	NZ4212
Whangarei Harbour	95	56	14	13	164	116	2.46	1.74	NZ5213
Kawhia Harbour	67	51	11	8	121	71	2.90	1.70	NZ73
Tauranga Harbour	224	208	7.8	7.3	178	136	1.62	1.24	NZ541
Rangaunu Harbour	97	62	8.8	7.1	134	101	2.01	1.52	NZ5113
Parengarenga Harbour	63	57	7	6.2	73	48	2.13	1.40	NZMS1 N1–4; NZ5111
Otago Harbour	46	13	5.1	4.7	69	51	1.74	1.28	NZ6612
Whangaroa Harbour	19	5	4.7	4.3	33	23	1.95	1.34	NZ1092
Whanganui Inlet	24	19	3.9	2.3	42	22	2.90	1.50	NZMS1 S3; NZ61
Bluff Harbour	55	22	4.5	3.8	97	66	2.20	1.50	NZMS1 S181, 182; NZ6721
Raglan Harbour	24	15	3.6	2.9	46	29	2.81	1.80	NZ4421
Moutere Inlet	7	Nearly all	0.9	0.4	15	9	4.20	2.40	NZ61
Nelson Harbour	14.3	11.4	2.6	2.0	30	23	3.40	2.60	NZ6142
Aotea Harbour	36	32	3.6	2.2	59	35	2.90	1.70	NZ2535
Wellington Harbour	87	Hardly any	39	38	88	82	1.01	0.94	NZ4633
Akaroa Harbour	44	3	47	45	81	65	1.89	1.52	NZ6324
Paterson Inlet	89	9	59	55	168	120	2.00	1.40	NZ52
Lyttelton Harbour	43	12	30	28	72	61	1.92	1.64	NZ6321

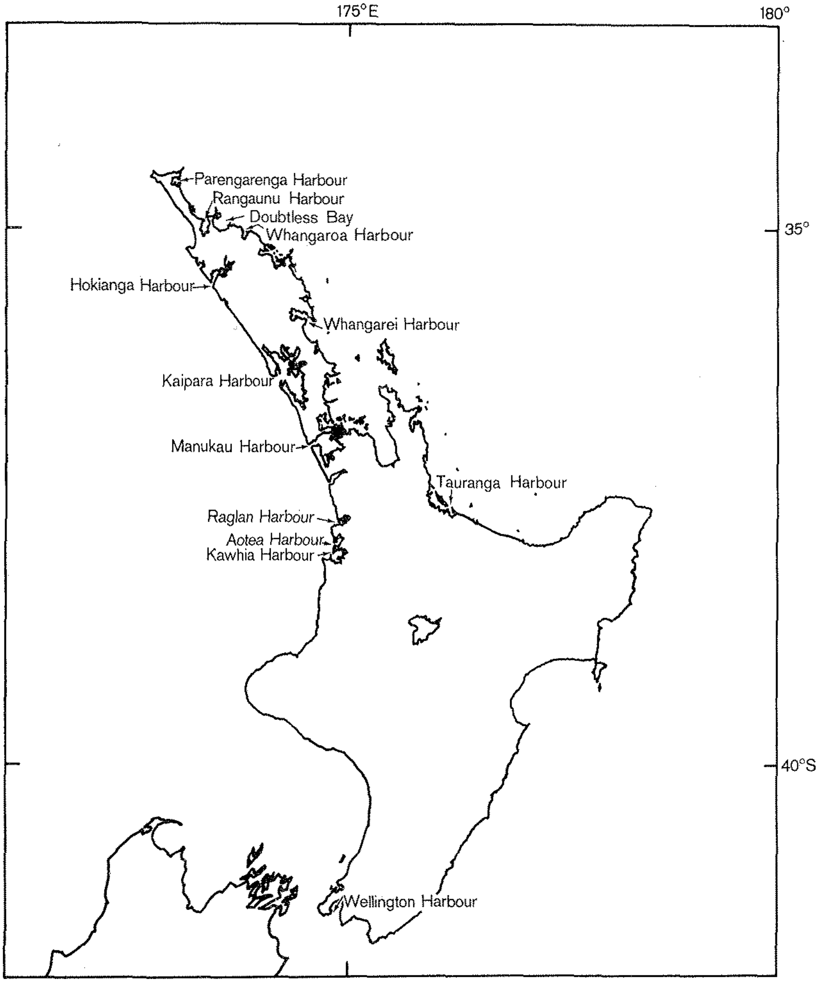

FIG. 1—Location map of the coastal inlets considered in the North Island.

RESULTS

The dependence of the entrance cross-sectional area (A) on the tidal compartments (α) for 16 inlets conforms to a simple relationship. Fitting a straight line by least squares to the $\log_{10}$ of these parameters for these inlets gives (Table 2):

$$\log \alpha = 0.98 \log A + 4.21$$

or $$\alpha = A^{0.98}\, 10^{4.21}$$

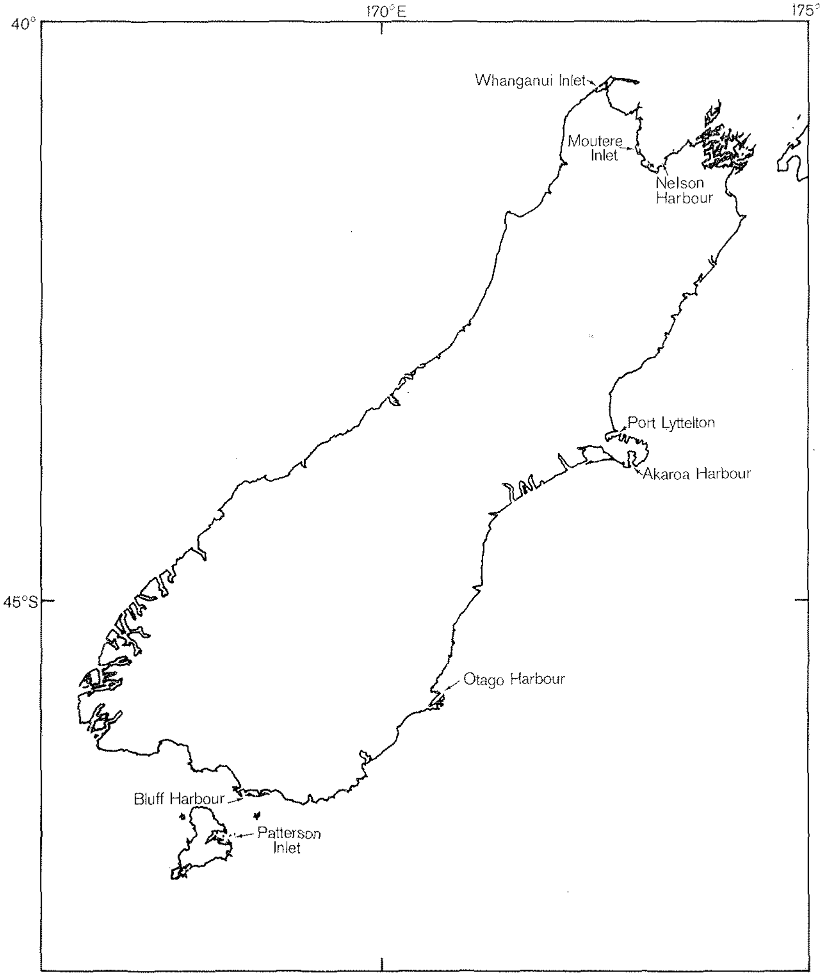

FIG. 2—Location map of the coastal inlets considered in the South Island.

The correlation coefficient is 0.95, whereas that for 2 × 16 random numbers where 90% of the estimates of the correlation coefficient (r) are less than r_s is only 0.29 (Fisher & Yates 1963), indicating extremely high correlation.

Peak flow conditions were chosen for plotting, as this would be the period of maximum erosion and therefore would be expected to have the greatest influence on entrance size. In general, the fit for other conditions was only marginally less than that for peak conditions. This

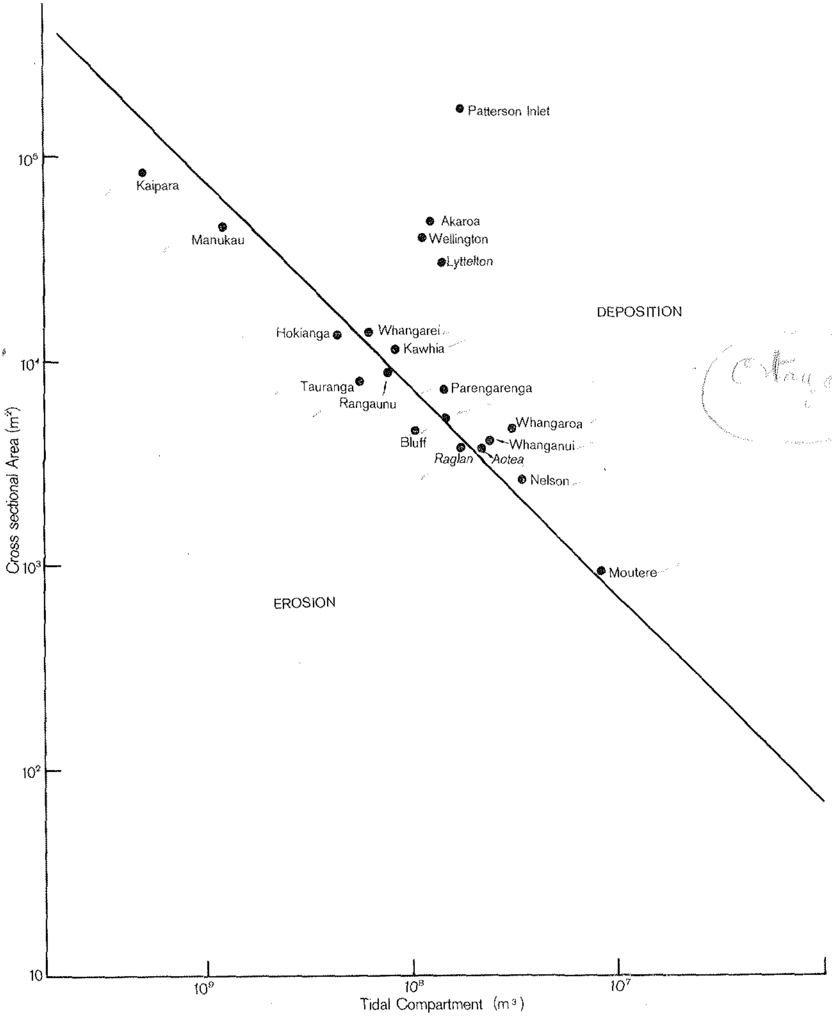

FIG. 3—Logarithmic plot of tidal compartment (m^3) versus entrance cross-sectional area (m^2) for several New Zealand coastal inlets for spring tidal conditions, the cross-sectional area being at mid tide. The line represents the best linear fit for the first 16 inlets listed in Table 1, as calculated by least squares.

TABLE 2—Values of m (gradient) and r (correlation coefficient) for linear correlation between $\log_{10}$ (cross-sectional area at the entrance) and $\log_{10}$ (tidal compartment) for different tidal conditions [i.e., $\log_{10}$ (tidal compartment) $= m \log_{10}$ (cross-sectional area) $+ c$] for 16 inlets.

CROSS-SECTIONAL AREA AT	TIDAL COMPARTMENT UNDER	m	r
Mid spring tide	Spring tides	0.98	0.95
Mid spring tide	Neap tides	0.96	0.96
Low spring tide	Spring tides	0.82	0.91
Low spring tide	Neap tides	0.90	1.00

probably indicates the broad nature of the dependence, because the size of the cross-sectional area also depends on other factors such as bathymetry, wave field, sediment grain size, and rate of supply.

DISCUSSION

In a stable entrance with a supply of sediment, the bottom stress must be such that no nett erosion or deposition takes place. The critical stress (τ_c) can be related to the speed v by

$$\tau_c = \rho g \frac{v^2}{C^2}$$

where ρ is the water density, g the acceleration of gravity, and C Chezy's coefficient (see Ippen 1966). Consider an inlet with tidal compartment α into which a sinusoidally varying tidal velocity $v_o \sin \omega t$ flows through an entrance of cross-sectional area $A_0 + A_1 \cos \omega t$. Then integration over half a tidal cycle of period T gives:

$$\frac{v_0 A_0 T}{\pi} = \alpha = \sqrt{\frac{\tau_c C^2}{\rho g}} \left(\frac{A_0 T}{\pi}\right)$$

which, within the limits of the observations, has the same functional dependence as the observed correlation equation. This indicates that, in a broad sense, the maximum bottom stress averaged across the entrance in these inlets is the same.

For the inlets considered, the scatter about the linear fit is so small that it is not possible to suggest which of the factors mentioned above might be important in determining the exact entrance size.

The value of v_0 the maximum tidal speed averaged across the entrance is then

$$v_0 = \frac{\pi}{T} 10^{4.21} = 1.14 \text{ m.s}^{-1}$$

For a typical value of Chezy's coefficient (C) of 50 $m^{\frac{1}{2}} \cdot s^{-1}$, with this speed of 1.14 $m \cdot s^{-1}$, the critical bottom stress is about 5.1 $N \cdot m^{-2}$. According to studies of existing data on tidal inlets (e.g., table 7, Bruun & Gerritsen 1960), this is the critical shear stress at the entrance of a stable inlet under heavier littoral drift and sediment load. We conclude, then, that the 16 inlets, the cross-sectional areas of which depend nearly linearly on the tidal compartment, have stable entrances whose size is governed mainly by the maximum flow.

Published competency curves (e.g., Sundborg 1956) relating the water speed needed to initiate sediment movement on a *level bottom* indicate that a speed of 1.14 $m \cdot s^{-1}$ would be capable of moving all sediment grain sizes up to a diameter of 10 mm (i.e., gravel). Although the sloping sides of the entrances will decrease the critical stress, the presence of a moving sediment load increases it (e.g., table 3, Bruun & Gerritsen 1960). In the inlets considered, the cross-sectional area is generally smallest at the entrance, and therefore tidal speeds will be greatest there. Consequently, sediment that enters the entrance on a flood tide is likely to be deposited inside the inlet, where the stress decreases below that necessary to initiate sediment movement for the particle sizes involved. There is likely to be a large area just inside the entrance in which the sediment is deposited, for the critical stress decreases both with decreasing sediment size and decreasing sediment load. Tidal speeds inside the harbour will in general be less than those at the entrance, but still might be large enough to transport smaller grain size bedload material, most probably in association with wave-induced longshore currents. Finer sediment that reaches the entrance from inside will be quickly swept away by the quicker flow there.

The entrances of some inlets which are used as ports have been altered by dredging. At Nelson before dredging the cross-sectional area was about 1700 m^2 (Hydrographic Branch 1957a, NZ60), but after the dredging shown in the chart published in 1969 (Hydrographic Branch 1969, NZ6142) the cross-sectional area was 2500 m^2. This change is enough to shift the point for Nelson in Fig. 2 from below the stable line (i.e., on the erosion side) to slightly above the stable line (or the deposition side) although the change is very small in terms of the scatter about the stable line.

INLETS NOT CONFORMING TO THE SIMPLE RELATIONSHIP

Of the inlets considered, Akaroa, Wellington, and Lyttelton harbours, and Paterson Inlet, do not conform to the simple relationship. All four lie on the deposition side of the distribution (Fig. 3). Brodie (1955) showed through comparison of bathymetric maps surveyed at different periods that there was deposition at the entrance to Lyttelton Harbour. Based on similar evidence, after taking into account the uplift by the 1855 earthquake, J. W. Brodie (NZO1, pers. comm.) has found that there is also nett deposition at the Wellington Harbour entrance. However, in both of these harbours there is evidence (Brodie 1955, 1958; Garner & Ridgway 1955) that the flow at the entrances is not a simple flow in and out of the harbour at the corresponding stages of the tide, but that there is considerable difference in the direction of flow at different parts of the entrance at any one time.

Further evidence for this situation is given by direct current measurements at the entrance. Based on a sinusoidal flow uniform across the entrance, the maximum speed in Lyttelton and Wellington Harbours would be 0.17 and 0.16 $m.s^{-1}$ respectively. However, maximum speeds of 0.3 $m.s^{-1}$ in the entrance to Lyttelton Harbour (Garner & Ridgway 1955) and 0.46 $m.s^{-1}$ in the entrance to Wellington Harbour (Hydrographic Branch 1969, NZ4633) have been observed. The increased speeds accompanying the complicated tidal patterns would lead to a larger stable entrance cross-sectional area than that suggested by the stable line shown in Fig. 2, and indeed the entrances to these inlets might be more stable than at first suggested by Fig. 2.

It is clear, then, that in many New Zealand coastal inlets the size of the cross-sectional area is governed by the tidal flow resulting from the size of the tidal compartment, and that in these inlets the flow is dominated by the tidal flow.

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