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On the Use of Empirical Stability Relationships for Characterising Estuaries

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ABSTRACT

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Data from New Zealand and overseas studies are used to support the hypothesis that area-prism (A-Ω) relationships, like those used to characterise the entrance throat stability of barrier enclosed tidal inlets on exposed sandy coasts, hold for a wide variety of estuary types ranging from lagoon to river mouth situations to large coastal embayments. The relationships indicate that both the bay size and the amount of littoral drift are important in determining the geometry of estuary mouths. The empirical relationships can be used to characterise and classify estuaries.

ADDITIONAL INDEX WORDS: *Estuaries, inlets, coastal geomorphology, models, New Zealand.*

INTRODUCTION

Empirical stability relationships have been used to characterise the stability of the entrances of estuaries on sandy coasts (tidal inlets) and to predict changes in channel size and shape (morphometry) and tidal flows resulting from entrance training works and dredging. The relationship between the tidal inlet throat cross-sectional area (A) versus tidal prism (Ω):

$$A = C\Omega^n \text{ (where C and n are constants)}$$

has been used to describe the cross-sectional area (morphological) stability of the throat or gorge (the narrowest and deepest section of the tidal inlet) and is one of the most widely reported models. A-Ω relationships have mostly been applied to tidal inlets situated on exposed sandy coasts that have wave-built barrier spits and with low average river discharge compared to tidal flux (*e.g.* O'Brien, 1931; Heath, 1975; Jarrett, 1976; Krishnamurthy, 1977; Vincent and Corson, 1981; Hume and Herdendorf, 1987, 1988a). In a similar way Shigemura (1980) described A-Ω relationships for tidal bays located on rocky coasts of Japan, and Nelson (1977), Byrne *et al.* (1980), Riedel and Gourlay (1980), and Hume (1991) have described similar relationships for small sheltered waterways in the interior of estuaries.

The above examples raise the possibility that A-Ω relationships hold for a wide range of estuary types. New Zealand is a good situation to test this hypothesis because its varied geology and wave climate mean that a great variety of estuaries occur along its 10,000 km of open coastline (Hume and Herdendorf, 1988b). Also most estuaries are in their natural state and unaltered by protective structures such as jetties.

New Zealand's estuaries have been classified by Hume and Herdendorf (1988b) into five broad categories (Table 1) that reflect the primary processes that shaped the depositional basin, namely: (1) fluvial erosion, (2) marine/fluvial erosion, (3) tectonic, (4) volcanic, and (5) glacial. These categories are further subdivided on the basis of geomorphologic and oceanographic characteristics, in particular entrance (inlet) shape and size (morphometry) and river input, into 16 types which reflect the dominant fluvial and coastal processes operative in each estuary. Funnel-shaped estuaries (Type 1) are funnel-shaped and branched drowned valley systems with wide unrestricted entrances; they receive little fluvial input and are situated on sheltered, low littoral drift shores. Headland enclosed estuaries (Type 2) are drowned valley systems with little fluvial input, and the entrance throat is constricted by rocky headlands

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Table 1. *Classification of New Zealand estuaries (after Hume and Herdendorf, 1988b).*

Primary Mode of Origin of Depositional Basin	Estuary Type	
Fluvial erosion	Funnel-shaped (Type 1)	
	Headland enclosed (Type 2)	
	Barrier enclosed	Double-spit (Type 3)
		Single-spit (Type 4)
		Tombolo (Type 5)
		Island (Type 6)
		Beach (Type 7)
	River mouth	Straight-banked (Type 8)
		Spit-lagoon (Type 9)
		Spit-lagoon (Type 10)
		Deltaic (Type 11)
Marine/fluvial	Coastal embayment (Type 12)	
Tectonism	Fault defined embayment (Type 13)	
Volcanism	Diastrophic embayment (Type 14)	
	Volcanic embayment (Type 15)	
Glaciation	Glacial embayment (Type 16)	

situated on low littoral drift shores. Barrier enclosed estuaries (Types 3–7), which occur commonly on the northeast coast of the North Island, have small freshwater input and are generally formed on exposed coastlines when littoral drift builds double-spit (Type 3) or single-spit (Type 4), tombolo (Type 5), barrier island (Type 6), or bay-head beach (Type 7) barriers that restrict exchange between the estuary and the sea. River mouth estuaries (Types 8–11) are characterised by high freshwater inflow from large catchments and are subdivided into straight-banked (Type 8), spit-lagoon (Types 9 and 10) and deltaic (Type 11) estuaries, reflecting varying degrees of fluvial and littoral sediment input to the systems. Coastal embayments (Type 12) are characterised by small catchments, little fluvial input, and wide rock headland entrances. Estuaries of tectonic origin are fault-defined embayments (Type 13) whose shorelines are controlled by faults (inlet widths <2 km) and large diastrophic embayments (Type 14) of more complex origin (inlet widths >5 km). Volcanic embayments (Type 15) include small explosion craters with narrow openings to the sea. Glacial embayments (Type 16) occur only in the southwest of the South Island and are fiords which have deep stable entrances with depositional sills. In this study examples of these various types plus tidal creeks in the interior of harbours are examined.

The 82 estuaries examined in this study (Figure 1) range in surface area from about 1 to 4,600 km^2, and in tidal prism from 5×10^5 to 5×10^9 m^3. They are micro- and meso-tidal (tidal range 1.2 to 4.2 m) estuaries characterised by semi-diurnal tides.

The purpose of this paper is to: (1) examine the data from New Zealand estuaries to determine whether empirical relationships may in fact apply to a wide range of estuary types, (2) compare the relationships for New Zealand estuaries to those reported elsewhere and (3) determine whether empirical stability relationships have utility in characterising and classifying estuaries.

METHODS

For each estuary the entrance cross sectional area A (m^2) (measured below mean tide level) and the tidal prism Ω (m^3) (mean spring tide) were taken from the literature (most of which are reported in HUME and HERDENDORF, 1987) and computed from hydrographic charts (Appendix 1). Because current velocity data were unavailable at most sites, a "mean" velocity V_m (m/sec) through the entrance (over a ½ tidal cycle, *i.e.* T = 6 hours) was computed as:

$$V_m = \Omega/[(21{,}600)(A)]$$

Most data were available for barrier enclosed estuaries because these types are common type and the most extensively studied. For the barrier enclosed and the tidal creek estuaries the current flows and the tidal prism were measured largely by current meter flow gaugings over half or full tidal cycles (*e.g.* HUME, 1991; HUME and HERDENDORF, 1992). For the river mouth (Types 8–10) estuaries, the type where river input contributes significantly to the flow, the "tidal prism"

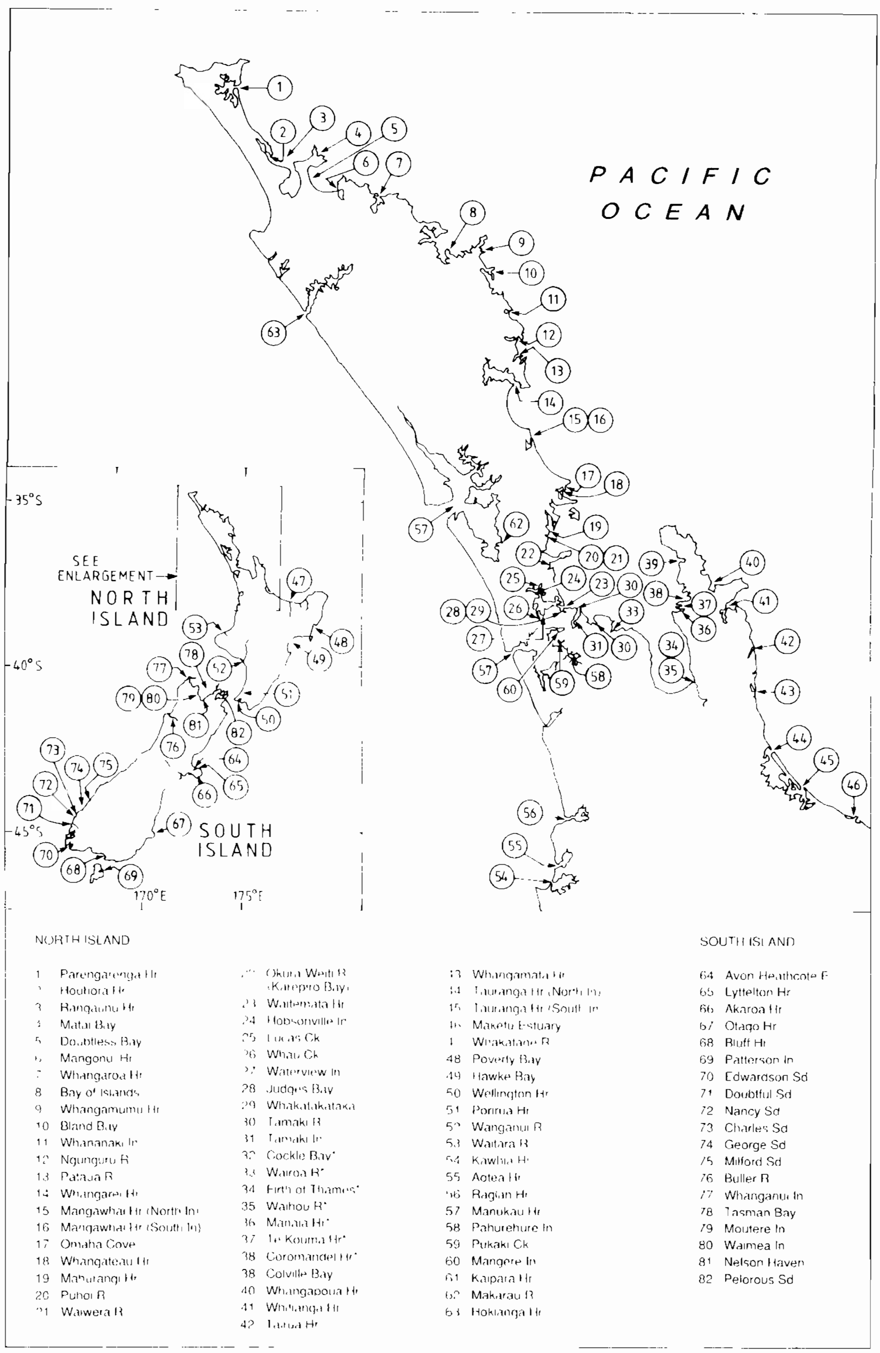

Figure 1. Location of New Zealand estuaries referred to in this paper. Hr = harbour, In = inlet, R = river, Ck = creek, E = estuary, Sd = sound.

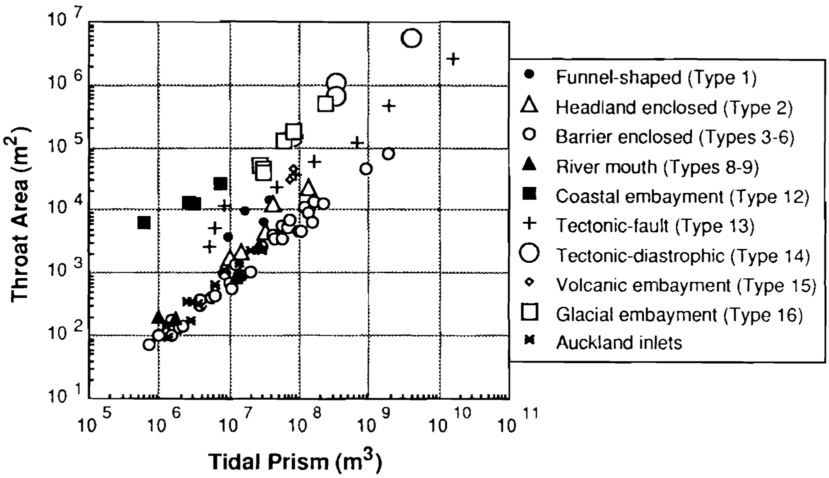

Figure 2. Scatterplot between estuary entrance throat cross-sectional area (A) at mid tide and mean spring tidal prism (Ω) for the various types of estuaries found on the New Zealand coast.

was crudely estimated as being the sum of the spring flood tide prism (determined by field measurement) plus the mean river outflow over a 6 hour period. There were only 2 volcanic (Type 15) estuaries in the data set. Therefore while regression analysis was not possible, the volcanic sites were plotted on the scatter plots for comparison.

We tested the relationships between estuary throat cross-sectional area and tidal prism, by sketch plotting and regression analysis. The plots showed that logarithmic transformations of the data distributed the data more evenly and produced random distribution in the residuals. Aceptance of significant relationships was based on consideration of the residual and normal probability plots, r^2, F- and t-ratio statistics (SNEDECOR and COCHRAN, 1980).

RESULTS

The estuary throat cross-sectional area versus tidal prism analysis show the following features:

(1) Plotting the whole data set shows a broad band of roughly linear trend (Figure 2).

(2) When the estuaries are grouped by type the distribution suggests that the major estuary types are best represented by individual A-Ω relationships. There are good relationships ($r^2 > 0.92$) between entrance area (A) and tidal prism (Ω) for the major classes of estuary, except for the funnel-shaped estuaries ($r^2 = 0.57$) (Table 2).

(3) Regression analysis (Table 2 and Figure 3) of the log transformed data shows that the values of the exponent (n) in the relationships (the slope of the lines) is similar, ranging from about 0.53 to 1.17. The value of C (the intercept), is markedly different for some of the estuary types. The barrier enclosed estuaries have small entrances compared to estuaries of tectonic-fault and tectonic-diastrophic origins which have entrances of 1 and 2 orders of magnitude larger, respectively, for any given tidal prism.

(4) Statistical testing confirmed that at the 95% confidence level the A-Ω regression lines for each of the estuary type was significant, except in the case of the funnel-shaped (Type 1)/headland enclosed (Type 2) estuaries where the small data set and the scatter of data meant that the relationships were significant only at about the 75% confidence level. Of course discrimination between the different estuary types is easily possible on the basis of other criteria (such as estuary size, inlet shape and river input). For instance, the funnel-shaped (Type 1) estuaries with flared entrances are readily distinguishable from the headland enclosed (Type 2) estuaries which have constricted rock headland bounded inlets.

Our Figure 3 differs from a preliminary version reported by HUME and HERDENDORF (1988b) because the 3 outliers representing fiords with complex throats (multiple entrances, islands/reefs at the entrance) have been omitted from the data set. Also Figure 3 suggests a greater similarity of

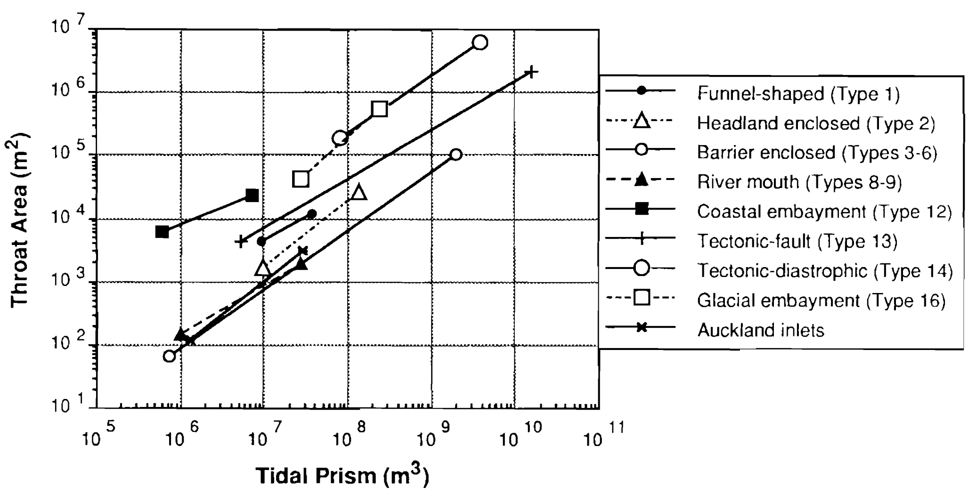

Figure 3. Regression lines for entrance cross-sectional area (A) at mid tide versus mean spring tidal prism (Ω) for New Zealand estuaries.

the A-Ω relationships for Types 12, 14 and 16 estuaries than reported by HUME and HERDENDORF (1988b).

Figure 4 shows how the "mean" current through the estuary entrance varies with estuary type. It appears that the stronger "mean" current flows (>0.2 m/sec) characterise those estuaries with constricted entrances (*i.e.* the tidal creek, river mouth, barrier enclosed and headland enclosed types).

DISCUSSION

The scatter of the data for each of the estuary types (Figures 2 and 3) is in part related to inaccuracies inherent in the determination of the throat area and tidal prism. For instance, in the case of the funnel-shaped estuaries the data set is small and we had very limited bathymetric data for situations where, because of the extensive intertidal areas in these estuaries, good bathymetric data is necessary to get a reasonable estimate of tidal prism. Therefore further data is needed to check if an A-Ω relationship characterises funnel-shaped estuaries. For some estuary types the scatter in the data is due to large natural variability in throat cross-section. This is most pronounced for the river mouth estuaries where changing river flows alter the scour regime producing large variations in throat cross-sectional area. Hence river mouth stability is perhaps not well described by A-Ω relationships, although the mean throat area data appears to give a fairly good relationship for our small data set. We have little data for estuaries of volcanic origin (Type 15), but our 2 data points plot with tectonic-fault (Type 13) estuaries

Table 2. *Results of regression analysis on the major estuary types.*

	Estuary Type	Power Regression A-Ω relationship	Determination Coefficient (r^2)	n
1	Funnel-shaped	$A = 4.21 \times 10^{2} \cdot \Omega^{0.[illegible]19}$	0.57	4
2	Headland enclosed	$A = 7.02 \times 10^{5} \cdot \Omega^{1.054}$	0.92	5
3–7	Barrier enclosed	$A = 2.46 \times 10^{4} \cdot \Omega^{0.927}$	0.98	32
8–10	River mouth	$A = 4.39 \times 10^{3} \cdot \Omega^{0.75[illegible]}$	0.94	5
12	Coastal embayment	$A = 5.46 \cdot \Omega^{0.529}$	0.96	4
13	Tectonic-fault	$A = 2.54 \times 10^{2} \cdot \Omega^{0.[illegible]8}$	0.98	9
14	Tectonic-diastrophic	$A = 1.48 \times 10^{2} \cdot \Omega^{0.898}$	0.96	4
16	Fiord	$A = 9.50 \times 10^{5} \cdot \Omega^{1.165}$	0.98	6
	Auckland inlets	$A = 6.54 \times 10^{5} \cdot \Omega^{1.027}$	0.95	11

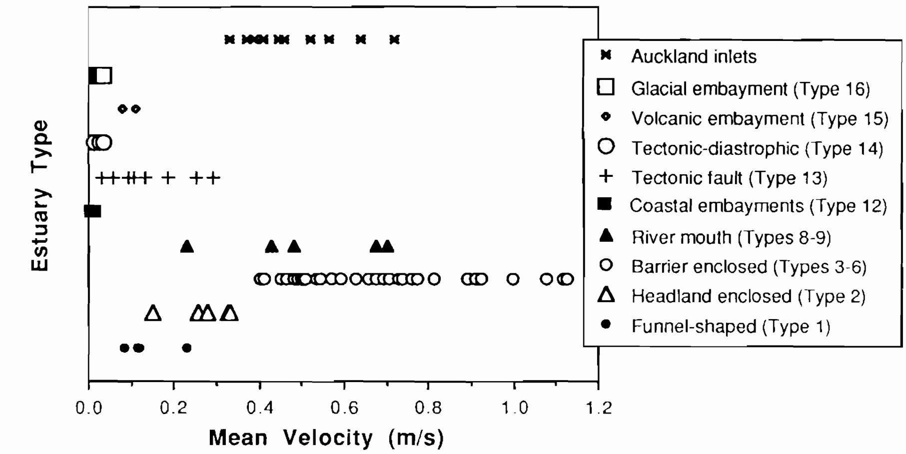

Figure 4. Plot showing the mean (in section) velocity through the estuary entrance (averaged over a half spring tidal cycle) for different types of estuaries.

(Figure 2) suggesting that volcanic estuaries are not characterised by a unique A-Ω relationship.

Figure 3 shows that A-Ω relationships similar to those commonly reported for barrier enclosed estuaries hold for a wide variety of estuary types. At first glance this finding is rather surprising, particularly for estuary types such as coastal embayments where tidal currents are very weak (Figure 4) and where one would not expect tides to be an important factor in controlling entrance dimensions, sedimentation and scour.

A-Ω relationships for tidal inlets on sandy littoral drift shores show that the size of the tidal throat is one of the main factors determining the ability of flow to transport sediment through the entrance (Bruun and Gerritsen, 1960). Inlet gorges that are morphologically stable (*i.e.* have the ability to return to their initial configuration after a disturbance) conform to the relationship because there is a balance between tidal flow (as defined by the tidal prism) and littoral drift to the gorge and so the inlet remains open. The tidal

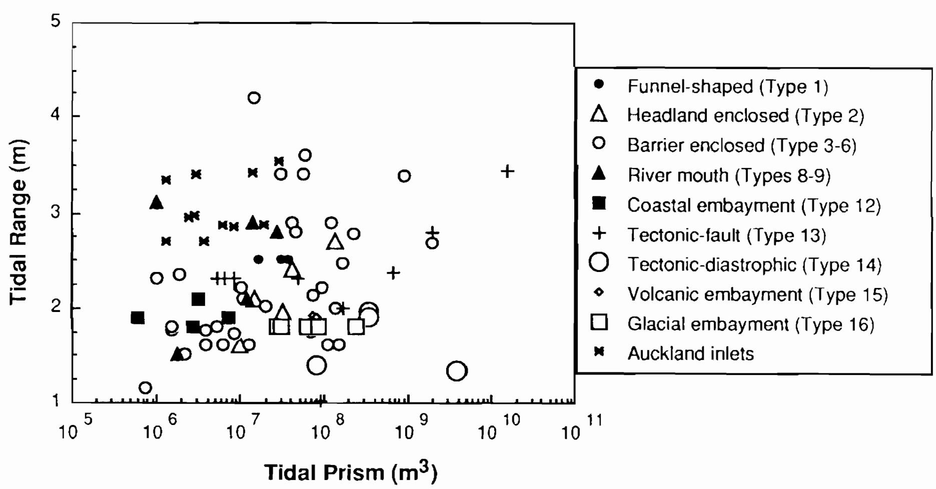

Figure 5. Tidal prism (Ω) versus tidal range (R) for New Zealand estuaries.

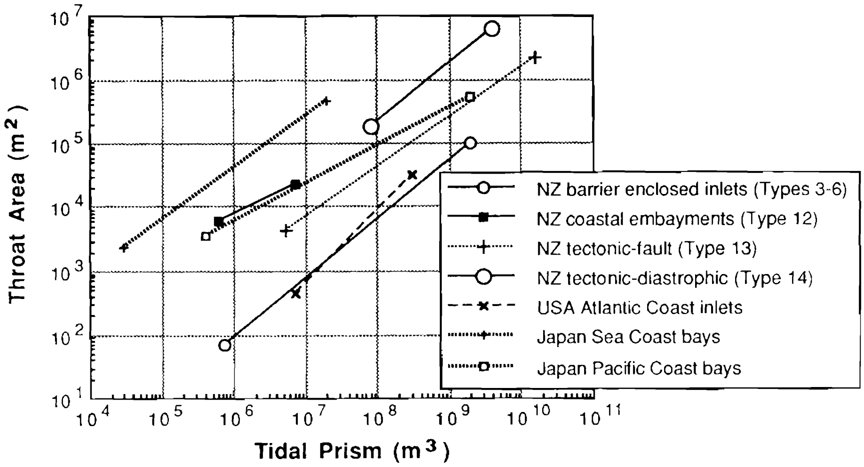

Figure 6. Comparison of A-Ω regression lines for various types of estuary found on the New Zealand coast with barrier enclosed estuaries on the Atlantic coast of the USA (JARRETT, 1976) and tidal bays located on rocky coasts of Japan (SHIGEMURA, 1980).

prism of course is a function of tide range and bay size and shape. A plot of tide range versus tidal prism for the New Zealand estuaries (Figure 5) shows no apparent relationship between these parameters suggesting that the size of the tidal prism is primarily a function of bay morphometry. This is consistent with the findings of other workers who have shown that the coastal morphometry has a strong impact on water exchange both on coasts dominated by the tides (BOON and BYRNE, 1981) even in places where the tidal range is small (HARKANSON *et al.*, 1986). Bay morphometry is determined partly by the geological processes that shaped the bay. The estuary classification of HUME and HERDENDORF (1988b) is based in part on the nature of the depositional processes that shaped the basin and on bay morphometry. Hence estuaries with fundamentally different bay morphometry would be expected to have characteristic A-Ω regression lines.

A comparison of Figures 3 and 4 shows that the estuaries with small inlet throats and large tidal prisms have the strongest currents. They also represent the estuary types that lie on the shores with greatest amounts of littoral drift. It is apparent therefore that such entrances have to maintain high current velocities to prevent their entrances being blocked by littoral drift, a situation that happens from time to time at river mouth and barrier enclosed entrances. At the top of Figure 3 lie the marine erosion and coastal embayments with wide and deep entrances. In these situations there is little sediment transport through the entrance and weak currents (Figure 4) combined with wave stirring are adequate to effect sediment transport and adjustments in entrance dimensions to maintain a stable entrance.

Data from other New Zealand and overseas studies supports the hypothesis that A-Ω relationships exist for a variety of estuary types. HEATH (1975) reported an A-Ω relationship for 20 New Zealand estuaries. Fifteen of these were of the barrier enclosed type. In a subsequent reviewing of his findings HEATH (1976) pointed out that 4 of the outliers in his data set were inlets on rocky shores (or Type 2 headland enclosed estuaries) where factors such as the hydraulic regime and rate of sediment supply influence the size of the entrance. Interestingly another of his data points (Whangaroa Harbour), the one that plotted furthest off the line (*i.e.* had the largest residual), is also a headland enclosed (Type 2) estuary. The A-Ω relationships for 14 small tidal creeks in Chesapeake Bay described by BYRNE *et al.* (1980) and for tidal creeks in the Auckland area reported in this study (Figure 3) are similar, but they differ from those reported for barrier enclosed inlets on sandy coasts (*e.g.* JARRETT, 1976 and this study, Figure 3). Figure 6 shows that the barrier enclosed inlets of the Atlantic coast of the U.S.A. (34 inlets without jetties, JARRETT, 1976) plot close to the line for their New Zealand barrier enclosed (Types 3–7) inlet counterparts. The New Zealand coastal embayments (Type 12) and tectonic-diastrophic embayments (Type 14) plot close to the the lines for similar tidal bays located on rocky, low littoral drift shores of the Pacific Coast (51 sites) and Japan Sea Coast (15 sites) of Japan (SHIGEMURA, 1980, Table 5). In summary, data from overseas studies appears to support the findings of this study that A-Ω relationships characterise different estuary types.

CONCLUSIONS

(1) A-Ω relationships similar to those widely used to characterise and model tidal inlet stability on sandy exposed coasts hold for a wide variety of estuaries.

(2) Although estuary entrance shape is influenced by a variety of factors including tidal flow, wave action, river flow, and littoral transport, the strong coherence between entrance shape and tidal flow (prism) indicates that the balance of tidal flow (as determined by the bay size) and littoral drift determine entrance dimensions for many types of estuary.

(3) At a generic level A-Ω relationships can be used to characterise and classify estuaries.

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Appendix 1. *Morphometric and hydrologic data for New Zealand estuaries. Hr = harbour, In = inlet, R = river, Ck = creek, E = estuary, Sd = sound.*

Estuary	Reference No.	Estuary Type	Surface Area at High Tide ($\times 10^6$ m^2)	Throat Area at Mid Tide ($\times 10^3$ m^2)	Tide Range (m)	"Mean" Throat Velocity (m/sec)	Tidal Prism ($\times 10^6$ m^3)
			North Island				
Parengarenga Hr	1	4	63	7	2.13	0.48	73
Houhora Hr	2	4	13.4	10.5	2.01	0.89	20.2
Rangaunu Hr	3	4	97	8.8	2.0	0.7	134
Matai Bay	4	12	1.6	12.9	2.1	0.01	3.2
Doubtless Bay	5	14	185	652	1.9	0.03	346
Mangonui Hr	6	2	10.3	2.1	2.1	0.33	15.1
Whangaroa Hr	7	2	19	4.7	1.95	0.33	33
Bay of Islands	8	14	179	1,050	1.95	0.02	340
Whangamumu Hr	9	12	1.6	13.5	1.8	0.01	2.7
Bland Bay	10	12	4.2	26.2	1.9	0.01	7.3
Whananaki In	11	4	2.8	0.17	1.77	0.41	1.5
Ngunguru R	12	4	4.6	0.31	1.76	0.57	3.8
Pataua R	13	4	2.8	0.14	1.51	0.73	2.2
Whangarei Hr	14	4	95	14	2.46	0.54	164
Mangawhai Hr (North In)	15	6	1.2	0.1	1.8	0.69	1.5
Mangawhai Hr (South In)	16	6	4.7	0.4	1.8	0.63	5.4
Omaha Cove	17	12	0.3	6.6	1.9	0.01	0.6
Whangateau Hr	18	4	9.2	0.66	2.2	0.74	10.5
Mahurangi Hr	19	2	24.1	12.8	2.4	0.15	42
Puhoi R	20	4	2	0.13	2.34	0.68	1.9
Waiwera R	21	4	0.9	0.1	2.3	0.46	1
Okura-Weiti R	22	1	6.3	3.75	2.2	0.12	9.5
Waitemata Hr	23	2	66.6	22.9	2.69	0.28	136.9
Hobsonville In	24	17	7.41	2.34	2.87	0.39	19.71
Lucas Ck	25	17	1.32	0.341	2.96	0.33	2.43
Whau Ck	26	17	3.56	0.63	2.88	0.46	6.21
Waterview In	27	17	2.04	0.18	2.97	0.72	2.79
Judges Bay	28	17	0.89	0.096	2.69	0.64	1.33
Whakatataka In	29	17	1.87	0.32	2.69	0.52	3.64
Tamaki R	30	1	11.5	6.27	2.5	0.23	30.8
Tamaki In	31	17	5.86	1.06	2.85	0.37	8.44
Cockle Bay	32	1	10.9	9.45	2.5	0.08	16.8
Wairoa R	33	1	19	15	2.5	0.11	37
Firth of Thames	34	13	741	482	2.8	0.19	1,951
Waihou R	35	8	12.7	2.7	2.8	0.48	28
Manaia Hr	36	13	4.4	5.2	2.3	0.06	6.4
Te Kouma Hr	37	13	2.7	2.6	2.3	0.09	5.3
Coromandel Hr	38	13	23.6	23.6	2.3	0.09	47.8
Colville Bay	39	13	4.5	12.1	2.3	0.03	8.3
Whangapoua Hr	40	4	13.1	0.98	1.72	0.40	8.5
Whitianga Hr	41	4	15.6	1.3	1.6	0.45	12.6
Tairua Hr	42	5	6.12	0.43	1.6	0.66	6.1
Whangamata Hr	43	4	4.3	0.36	1.6	0.50	3.9
Tauranga Hr (North In)	44	6	80.4	4.68	1.6	1.27	95.8
Tauranga Hr (South In)	45	6	115.6	6.26	1.6	1.37	130.8
Maketu E	46	4	2.15	0.07	1.15	0.49	0.74
Whakatane R	47	9	1.9	0.19	1.5	0.43	1.75
Poverty Bay	48	14	58	146	1.4	0.03	81
Hawke Bay	49	14	2,950	5,300	1.34	0.04	3,950
Wellington Hr	50	13	87	39	1.01	0.10	88
Porirua Hr	51	2	8	1.8	1.6	0.26	10
Wanganui R	52	9	4	0.848	2.1	0.68	12.4
Waitara R	53	8	0.6	0.2	3.1	0.23	1.0
Kawhia Hr	54	4	67	11	2.9	0.51	121
Aotea Hr	55	4	36	3.6	3.6	0.76	59

Appendix 1. *Continued.*

Estuary	Reference No.	Estuary Type	Surface Area at High Tide ($\times 10^6$ m^2)	Throat Area at Mid Tide ($\times 10^3$ m^2)	Tide Range (m)	"Mean" Throat Velocity (m/sec)	Tidal Prism ($\times 10^6$ m^3)
Raglan Hr	56	4	24	3.6	2.8	0.59	46
Manukau Hr	57	4	344	46	3.38	0.92	918
Pahurehure In	58	17	15.2	2.38	3.54	0.56	29.0
Pukaki Ck	59	17	2.12	0.34	3.4	0.41	3
Mangere In	60	17	6.6	1.47	3.4	0.45	14.14
Kaipara Hr	61	4	947	82	2.68	1.12	1,990
Makarau R	62	17	1.48	0.15	3.35	0.41	1.29
Hokianga Hr	63	4	115	13	2.77	0.81	228
			South Island				
Avon-Heathcote	64	4	8	0.56	2.1	0.91	11
Lyttelton Hr	65	15	43	30	1.92	0.11	72
Akaroa Hr	66	15	44	47	1.89	0.81	81
Otago Hr	67	4	46	5.1	1.74	0.63	69
Bluff Hr	68	4	55	4.5	2.2	1.00	97
Patterson In	69	13	89	59	2.0	0.13	168
Edwardson In	70	16	47.7	183.3	1.8	0.02	84.8
Doubtful Sd	71	16	134	504.2	1.8	0.02	239
Nancy Sd	72	16	15.3	51.7	1.8	0.03	27.4
Charles Sd	73	16	17.2	44.9	1.8	0.03	30.4
George Sd	74	16	34.7	128.3	1.8	0.02	61.9
Milford Sd	75	16	17.6	41.7	1.8	0.04	31.3
Buller R	76	9	3	0.92	2.9	0.70	14.01
Whanganui In	77	4	24	3.9	2.9	0.50	42
Tasman Bay	78	13	4,621	2,560	3.44	0.29	16,000
Moutere In	79	6	7	0.9	4.2	0.77	15
Waimea In	80	6	29	5.8	3.4	0.46	58
Nelson Haven	81	4	14.3	2.6	3.4	0.53	30
Pelorous Sd	82	13	290	121	2.37	0.25	660