

Empirical Stability Relationships for Estuarine Waterways and Equations for Stable Channel Design

Terry M. Hume

Water Quality Centre
DSIR—Marine and Freshwater
Department of Scientific and Industrial Research
P.O. Box 11-115
Hamilton, New Zealand

ABSTRACT

HUME, T.M., 1991. Empirical stability relationships for estuarine waterways and equations for stable channel design. *Journal of Coastal Research*, 7(4), 1097-1111. Fort Lauderdale (Florida). ISSN 0749-0208.



Empirical relationships between channel morphology and hydraulic parameters, similar to those for open coast tidal inlets, are derived for eleven estuarine waterways in the Auckland region, New Zealand. The waterways are tidal channels and creeks located in harbors where there is low littoral drift and stream inflow. They are mesotidal (tidal prism ranges from about 1.3×10^6 to 29×10^6 m³) and the sediments are muddy fine sands. Causeway-modified waterways have generally smaller throat areas compared to natural waterways of similar tidal prism because the causeway constriction increases current velocity and therefore flow through the channel and bed scour results in a relatively deep channel (*i.e.* a lower width/depth ratio and more efficient channel). At one waterway adjustment in channel geometry after causeway construction resulted in considerable bed scour and it took some 15 to 20 years for the channel to develop a new equilibrium profile. The empirical relationships can be used to calculate the design cross-section of estuary channels prior to modification by engineering works such as causeways, or where new canal waterways are to be dredged. The Auckland waterways data were used to test some common stable channel design formulae. The Lacey (1958) and the Simons and Albertson (1960) formulae underestimate throat area, whereas the Maza and Echarvarria (1973) and Bruun (1978) formulae can be successfully used to predict waterway scour depth and throat area.

ADDITIONAL INDEX WORDS: *Tidal inlet stability, tidal hydraulics, inlet morphology, estuary, Auckland, New Zealand, causeways, empirical model.*

INTRODUCTION

Engineering works in estuaries, such as causeways and reclamations, which restrict channel width can significantly reduce the tidal prism and disturb the channel stability. They can also cause substantial bed scour, threatening bridge piles and abutments and buried pipelines. The works can modify the tidal circulation, flushing and sediment deposition within the bays affecting the water quality and biology.

Predicting the effects of engineering works can be difficult because of the problems of coupling tidal flows with short period wind waves, river inflow and sediment transport equations. In the first instance the coastal engineer makes the predictions of waterway area and scour depth using empirical methods that relate

channel geometry and flow parameters, before embarking on more sophisticated (and expensive) numerical and physical model studies.

Empirical relationships between the shape of a tidal inlet throat and tidal flow have been used to characterize the inlet morphological (cross sectional area) stability, predict inlet response to dredging and structural works, and even natural changes (*e.g.* O'BRIEN, 1931, 1969; HEATH, 1975; JARRETT, 1976; VINCENT and CORSON, 1981). The relationship between tidal inlet throat cross-sectional area (A) versus tidal prism (Ω) is one of the most widely reported. Most studies have been applied to inlets on exposed sandy coasts where waves cause littoral drift. A small number of studies have described similar, but less well correlated, A - Ω relationships for tidal waterways inside estuaries (PILLSBURY, 1956; NELSON, 1977; VAN DER KREEKE and HARING, 1979; BYRNE *et al.*,

1980). In New Zealand formulae developed for river channel design (e.g. LACEY, 1929; BLENCH, 1957; SIMONS and ALBERTSON, 1960 and MAZA and ECHAVARRIA, 1973), have been applied to tidal channels to estimate the stable design cross-section and scour depth for causeways (e.g. MINISTRY OF WORKS AND DEVELOPMENT, 1979) and tidal inlets (KINGSTON REYNOLDS THOM and ALLARDICE, 1986). However the relevance of these formulae to tidal situations is untested.

This study examines the morphological stability of natural and causeway modified estuarine waterways (tidal channels and creeks located inside harbors) of the Auckland region, New Zealand (Figure 1), where the surficial sediments are fine grained and where there is low littoral drift and stream inflow. Empirical relationships for natural and causeway-modified estuarine waterways are developed for these situations and compared to those relationships for New Zealand's open coast inlets. Simple empirical models for estimating hydraulic parameters from morphology data are derived and commonly used stable channel design formulae are tested against the field data.

PHYSICAL SETTING

The eleven estuarine waterways are "subestuaries" in the Tamaki River and the Waitemata, Manukau and Kaipara Harbors of the Auckland region (Figure 1), and are locations where data are available from detailed flow gaugings. The waterways range in area from 90 to 1520 ha (Table 1). They are shallow, and low tide exposes narrow incised channels flanked by extensive areas of low gradient intertidal flats. Surficial sediments on the tidal flats are largely muddy fine sands but the channel floors can be coarser where lag deposits and bedrock outcrops occur. The waterways are characterized by mesotidal (spring tide range is 2.7 to 3.5 m), semi-diurnal tides, with spring tidal prisms ranging from c. 1.3×10^6 to 29×10^6 m³ (Table 1). Freshwater input is generally small except during floods. Five of the waterways are in their 'natural' state, the other six are 'modified' by causeways for road and rail (Table 1).

METHODS

The Data

At each site the following data were available: (1) datums and levels in terms of mean tide level, (2) channel cross-section profiles measured by echo sounder or lead line soundings at the time of the tidal flow gaugings, (3) water level, depth and velocity measured by current meter flow gauging techniques. The current meter measurements were made on a number of verticals across the waterway, at several depths on each vertical and at 30 minute intervals throughout a half or full tidal cycle.

The field measurements were made at natural or artificial (causeway) constrictions (the throat) in the waterways following periods of stable stream inflows (when stream inputs were small) and generally on spring tides. Hence the channel cross-section profiles are considered to be characteristic of spring tidal flow conditions and not of weaker tide flow situations or floods.

Data Analysis

The parameters used to quantify waterway shape were computed from the channel cross-section profiles. They included throat width measured at mean tide level (W_{mtl}), maximum and mean depths (D_{max} and D_{mn}), throat area measured below mean tide level (A_{mtl}), and throat area measured below the level of peak discharge (A_p). An estimate of the waterway surface area at high tide above the throat (E) was made by planimeter from the NZMS 260 1:50,000 scale topographic maps.

The waterway hydraulic parameters, spring tidal prism (Ω_s), peak discharge in section (Q_p) and mean maximum velocity in section (V_{mm}), were calculated from the flow gauging data. The mean discharges were calculated from the product of flow cross-sectional area and mean velocity in section. The mean discharges versus time curves were then numerically integrated to determine the tidal prism.

The main driving force in Auckland estuaries is the semi-diurnal tides. There are substantial differences between the spring and neap tide ranges at each waterway (Manukau and Kaipara sites: mean spring range 3.4 m, mean neap range 2.0 m; Tamaki and Waitemata sites:

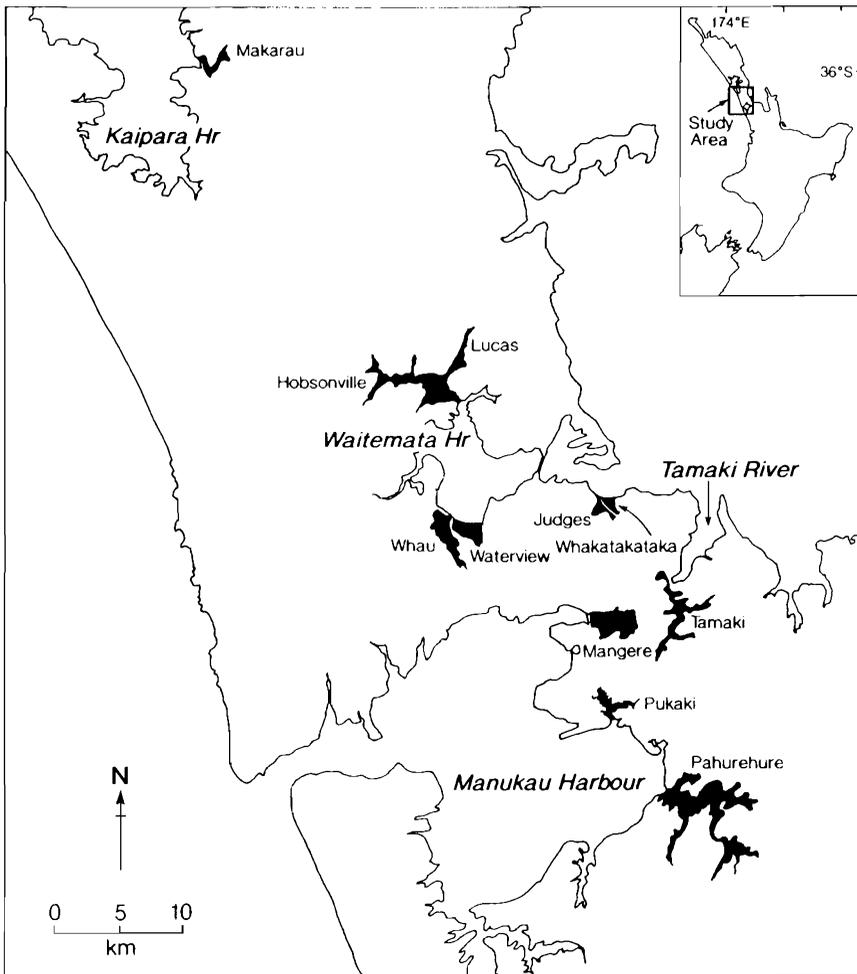


Figure 1. Location of Auckland tidal waterways referred to in this paper.

mean spring range 2.7 m, mean neap range 2.0 m), and therefore the strength of tidal flows. Hence, to facilitate comparisons between sites, the hydraulic data were 'normalized' to the mean spring tide situation, because it is under high discharge (spring tide) conditions that channel cross-sections tend to scour and equilibrate with flows. Therefore, the mean spring tidal prism (Ω_s) at a site was computed from the measured tidal prism (Ω) by:

$$\Omega_s = \Omega \cdot \frac{R_s}{R} \quad (1)$$

where R_s is the mean spring tide range at the

Standard Port and R is the tide range measured at the site at the time of the gauging. The calculation is based on the assumption that the tidal prism is proportional to the tidal range. In fact, because most field measurements were made on spring tides, the data required little adjustment, thus minimizing errors in the 'normalization' calculation.

All possible relationships between the morphological and hydraulic parameters were tested by sketch plotting and by regression analysis. Where necessary logarithmic transformations of the data were used to distribute the data more evenly and to produce a random

Table 1. Physical characteristics of the selected Auckland waterways. (Pre-refers to dimension before causeway construction, post- to dimension after causeway construction).

Site	Estuary area at high tide (E) ($m^2 \times 10^4$)	Catchment area ($m^3 \times 10^4$)	Year causeway constructed	Waterway width at high tide (m)		Throat depth max (D_{max}) (m)	Throat width (W_{mtl}) (m)	Throat area (A_{mtl}) (m^2)	Mean maximum velocity (V_{mm}) (m/s)	Tidal prism spring (Ω_s) ($m^3 \times 10^3$)
				pre-	post-					
Makarau	148	9,516	-	120	-	2.8	70	145	0.95	1,288
Judges	89	350	1928	1,000	46	3.0	41	96	1.41	1,330
Lucas	132	3,500	-	200	-	3.3	155	341	0.73	2,427
Waterview	204	1,600	1952	1,400	60	5.6	44	180	1.84	2,790
Pukaki	212	1,722	1964	370	90	6.8	75	340	1.12	3,000
Whakatakataka	187	1,600	1928	800	85	6.3	80	323	1.12	3,643
Whau	356	2,764	1948	500	166	6.7	146	625	0.87	6,206
Tamaki	586	7,935	-	160	-	10.5	148	1,060	0.71	8,437
Mangere	660	3,446	1915	800	240	8.6	234	1,469	0.70	14,137
Hobsonville	741	20,000	-	377	-	10.5	343	2,342	0.68	19,708
Pahurehure	1,520	14,074	-	520	-	13.8	372	2,382	1.01	29,032

distribution in the residuals. This initial analysis showed that both linear and power functions provided the best fits on the data. More detailed analysis was undertaken on promising relationships.

RESULTS AND DISCUSSION

The key morphological and hydraulic data for the estuaries are presented in Table 1.

Empirical Formulae

The parameters between which significant relationships were determined are illustrated by bivariate plots in Figure 2. Acceptance of significant relationships was based on consideration of the residual and normal probability plots, r^2 , F- and t-ratio statistics. For a relationship to be accepted with a 1% level of significance on the basis of 11 sites, the analysis must produce an F-ratio greater than 10.56 with 1° and 9° of freedom. Table 2 shows the regression equations, type of curve fitted, the r^2 and F-values for the relationships determined in this paper. The larger the r^2 and F-ratio values, the better the curve fits the data.

From the analysis the following conclusions are evident (Figure 2 and Table 2):

- (1) There are good relationships between waterway hydraulic parameters Ω_s and Q_p and throat morphological parameters A_{mtl} and D_{max} . The relationships between Ω_s and Q_p and throat area are best, showing the least scatter. The relationships between the hydraulic parameters and throat area/depth measured below mean tide level are more significant than those for throat area/depth measured at peak flow.
- (2) There is no significant relationship ($r^2 < 5\%$) between throat area A_{mtl} and mean maximum velocity (V_{mm}).
- (3) There is only a weak relationship between maximum throat depth (D_{max}) and width (W_{mtl}).
- (4) There is a strong relationship between estuary surface area as measured above the throat at high tide (E) and throat depth (D_{max}), throat area (A_{mtl}), peak discharge (Q_p) and tidal prism (Ω_s).

The scatter in the data is due in part to inaccuracies involved in field measurement of the parameters and also the fact that the processes

may not truly reflect simple relationships. Factors controlling the relationships are discussed below.

The good relationships between the waterway hydraulic and morphological parameters are consistent with findings of other workers (e.g. O'BRIEN, 1969; HEATH, 1975). The data show that the flow geometry is best parameterized by throat cross-sectional area and that the oscillating tidal flow in the waterway, as defined by the tidal peak discharge and prism, is a major factor controlling tidal waterway dimensions. The poor relationship between the morphological parameters and mean maximum velocity ($r^2 < 5\%$) is contrary to the findings of DE JONG and GERRITSEN (1985) who report a good relationship for the Western Scheldt Estuary.

Inspection of the width/depth ratios for the waterways (Table 1) shows that the W/D_{max} ranges from 8 to 47 and that the causeway sites generally have the narrower and deeper throats ($W/D_{max} = 8$ to 27). This wide range of values can perhaps be explained by the fact that at some sites (e.g. Judges and Waterview) currents have scoured the unconsolidated sediments from the central channel floor to expose the sandstone bedrock. In these situations scour cannot cut an equilibrium profile by simply deepening the central channel, instead the current scours the more readily erodible unconsolidated sediments on the channel flanks. In this way the throat attains an equilibrium profile, and therefore a good relationship between the throat area and the hydraulic parameters. However poorer relationships hold between throat width/depth and the hydraulic parameters (Figure 2) because throat scour is depth limited in some parts of the channel.

Parameters such as peak discharge and tidal prism are important in studies of flushing of pollutants in estuaries and in the design of engineering works such as causeways and navigation channels. In New Zealand small tidal waterways outside the major ports are generally uncharted, therefore estimates from bathymetric data are not possible. Often an estimate is quite adequate for some jobs. The good relationships between the tidal waterway hydraulic and morphologic parameters and estuary surface area suggest a rapid and inexpensive method of estimating these parameters. For the Auckland waterways at least the

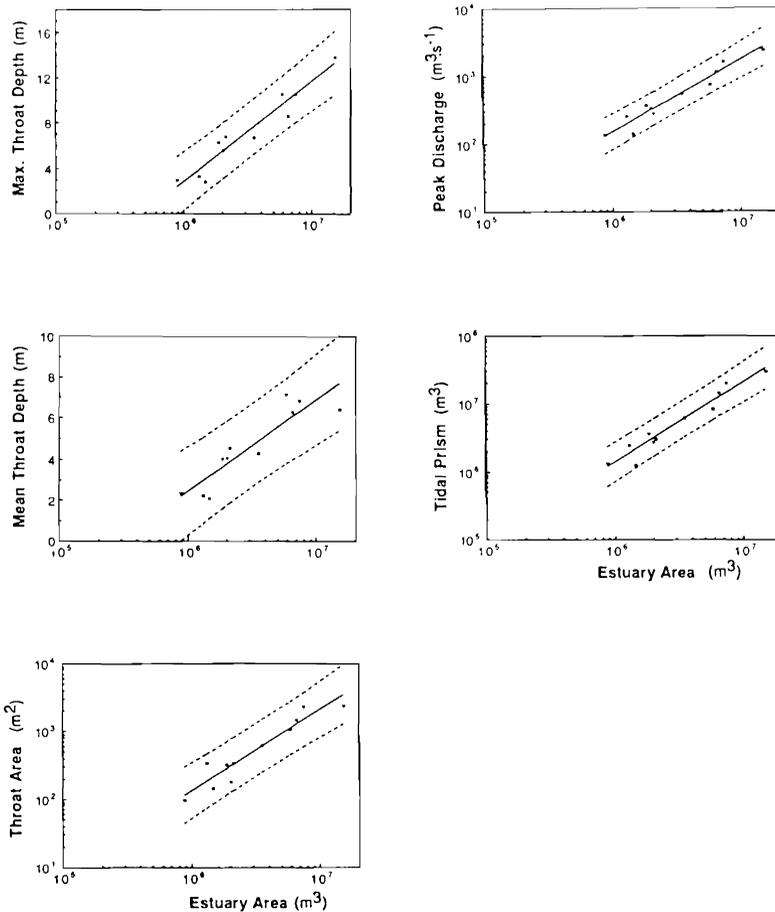


Figure 2. Plots of selected morphometric and hydraulic parameters. Throat width (W_{mt}), maximum and mean depths (D_{max} and D_{mn}) and area (A_{mt}) are all measured below mean tide level. Estuary area measured at high tide above the inlet throat (E). Tidal prism (Ω_p) and peak discharge in section (Q_p) scaled to mean spring tide. Regression lines are shown (see Table 2 for equations). Dashed lines represent the 95% confidence limits for individual values of y predicted from x .

tidal discharge and prism may be estimated from the equations presented in Table 2, once the channel cross-section profile has been measured in the field (or from bathymetric data if it is available). Alternatively simple and inexpensive measurements of estuary area made off a topographic map may give adequate estimates of estuary morphometric and hydraulic parameters. Similar methods may be applicable to other estuaries.

Throat area-tidal prism relationships are generally applied to tidal inlets situated on exposed sandy coasts where waves cause long-shore drift and where there is low average river

discharge to tidal discharge (*e.g.* O'BRIEN, 1931, 1969; HEATH, 1975; JARRETT, 1976; KRISHNAMURTHY, 1977; VINCENT and CORSON, 1981; COSTA, 1982). They characterize the throat cross-sectional area stability of inlets, provide a means of calculating a stable inlet gorge cross-sectional area for engineering design purposes (*e.g.* BRUUN, 1978) or alternatively provide a simple method of estimating the tidal prism from throat profile data. A small number of studies have described similar, but less well correlated, A - Ω relationships for waterways inside estuaries (*e.g.* PILLSBURY, 1956; NELSON, 1977; VAN DER KREEKE and HARING, 1979;

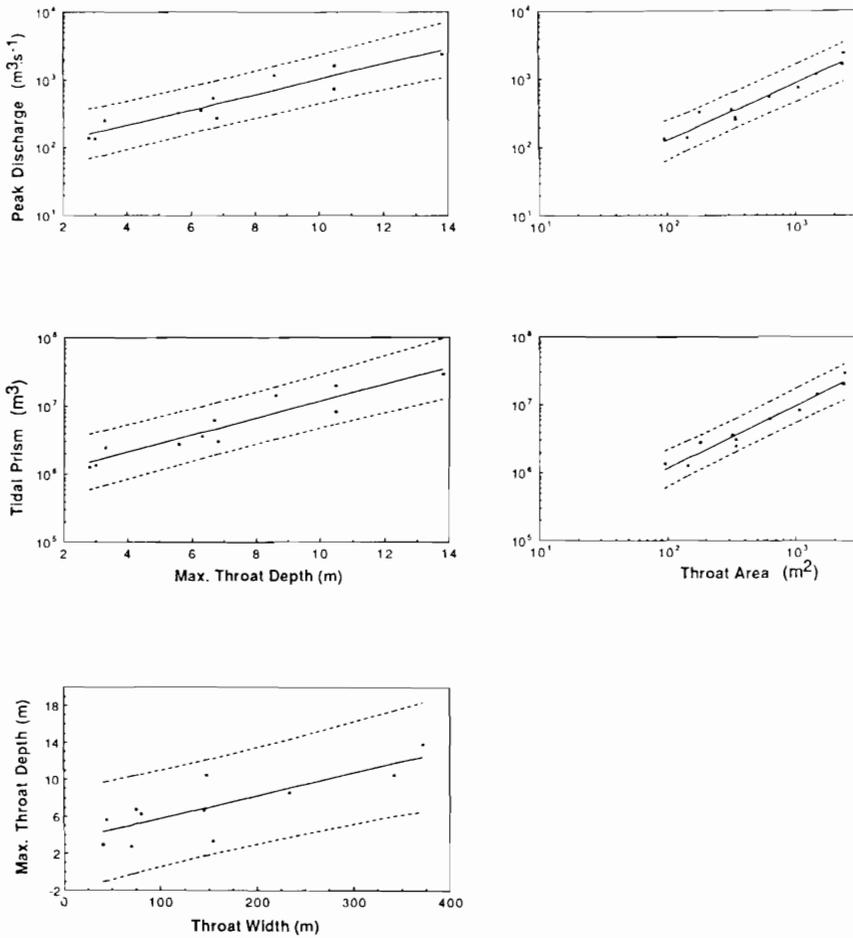


Figure 2. (Cont.)

BYRNE *et al.*, 1980; DE JONG and GERRITSEN, 1985).

The relationship between throat area (A_{mtl}) versus tidal prism (Ω_a) for the eleven Auckland tidal waterways (Figure 3, Table 2) shows that:

- (1) There appears to be a difference in the A - Ω relationships for the natural and causeway-modified situations.
- (2) For the same tidal prism, causeway-modified waterways have smaller throat areas than natural waterways, particularly for the smaller waterways.
- (3) The throat area and tidal prism of Auckland tidal waterways are related by the following equations:

All waterways $A_{mtl} = 6.54 \times 10^{-5} \cdot \Omega_a^{1.027}$

($r^2 = 0.954$, $n = 11$) (2)

No-causeways $A_{mtl} = 4.37 \times 10^{-4} \cdot \Omega_a^{0.915}$
($r^2 = 0.982$, $n = 5$) (3)

Causeways $A_{mtl} = 7.39 \times 10^{-6} \cdot \Omega_a^{1.164}$
($r^2 = 0.965$, $n = 6$) (4)

- (4) Equations for causeway-modified waterways have larger exponents than do equations for natural waterways.

There is a good physical reason why waterways with causeways can have smaller throat areas compared to natural waterways of similar tidal prism. When a channel is constricted by a causeway the current velocity and therefore the flow through the channel increases and also bed scour results in a relatively deep channel (*i.e.* a lower width/depth ratio and more efficient

Table 2. Regression results for the 11 Auckland estuaries. Equations represent linear and power curves. Throat width (W_{mtl}), maximum and mean depths (D_{max} and D_{mn}) and area (A_{mtl}) are measured below mean tide level. Estuary area (E) was measured at high tide. Tidal prism (Ω_s) and peak discharge in throat section (Q_p) have been scaled to mean spring tide.

Dependent variable	Independent variable	Curve fitted	r ² %	F-ratio
log Ω_s	log A_{mtl}	$\log \Omega_s = 1.547 \times 10^4 \cdot A_{mtl}^{0.928}$	95	186.0
Log A_{mtl}	log Ω_s	$A_{mtl} = 6.536 \times 10^{-5} \cdot \Omega_s^{1.027}$	95	186.0
log Ω_s	log E	$\Omega_s = 1.261 \times 10^{-1} \cdot E^{1.172}$	94	151.0
log Q_p	log E	$Q_p = 6.083 \times 10^5 \cdot E^{1.062}$	94	149.0
log Q_p	log A_{mtl}	$Q_p = 2.668 \cdot A_{mtl}^{0.833}$	93	127.0
D_{max}	log E	$D_{max} = 8.847 \log E - 50.295$	92	106.0
log Q_p	D_{max}	$\log Q_p = 1.119 \times 10^{-1} \cdot D_{max} + 1.883$	90	72.1
log A_{mtl}	log E	$A_{mtl} = 7.938 \times 10^{-6} \cdot E^{1.203}$	90	79.6
log Ω_s	D_{max}	$\log \Omega_s = 1.234 \times 10^{-1} \cdot D_{max} + 5.829$	89	71.7
D_{mn}	log E	$D_{mn} = 4.099 \log E - 21.932$	76	28.8
D_{max}	W_{mtl}	$D_{max} = 2.456 \times 10^2 \cdot W_{mtl} + 3.269$	65	16.9

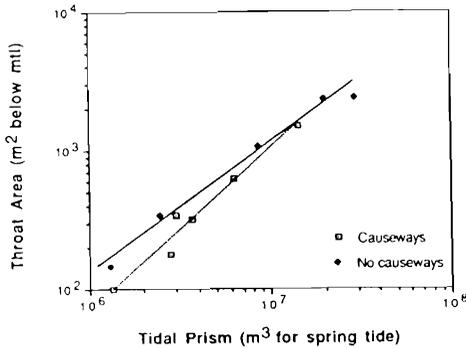


Figure 3. Relationships between the throat areas at mean tide level (A_{mtl}) and mean spring tidal prism (Ω_s) for the natural and causeway modified tidal waterways in the Auckland area.

channel). Hence a smaller flow area is required for any given tidal prism. The smaller causeway modified waterways (*i.e.* Judges, Water-view, Pukaki and Whakatakataka) had their waterway width substantially reduced (76 to 96%) by causeway construction and today they generally have the relatively deeper channels with the greater current velocities (Table 1).

To test if there was a significant difference in the A - Ω relationships for the natural and causeway-modified waterways the regression lines (3) and (4) were compared, using the method described by SNEDECOR and COCHRAN (1980, p. 385). The slopes and elevations of the lines differed significantly only at the 90% confidence level. On a statistical basis alone it would appear that until more data are available to analyze the A versus Ω relationships for

Auckland waterways, the general equation (2) is adequate to estimate A for channel design purposes. However when the physical situation is taken into account it would seem more appropriate to use equations (3) and (4) for design purposes, particularly for waterways with smaller tidal prisms (say $< 10^7 \text{ m}^3$).

Figure 3 and regression analysis demonstrate that A - Ω relationships analogous to those derived for open coast sandy inlets hold for waterways in the interior of harbors in the Auckland area, where sediments are fine grained and where there is negligible littoral transport. The relationships are not directly comparable to those derived by BYRNE *et al.* for small 'inlets' in the upper reaches of Chesapeake Bay which are much smaller (tidal prism ranges from about 10^3 to 10^5 m^3) and extrapolations of this type are undesirable (HUME and HERDENDORF 1988a). Similarly the relationships are not directly comparable to those derived by HEATH (1975) for New Zealand open coast inlets because the estuaries described by Heath were generally far larger (tidal prism ranges from about 14×10^6 to $1990 \times 10^6 \text{ m}^3$) than those for Auckland waterways. Nonetheless the relationships are fairly similar to those reported by HUME and HERDENDORF (1988b) for New Zealand barrier enclosed tidal inlets on sandy open coasts (Figure 4). The slightly larger throats for the Auckland waterways perhaps reflect the more cohesive nature of the sediments and the lack of littoral drift.

Waterway and Inlet Stability

Tidal inlet stability has two important aspects, namely cross-sectional area (morphol-

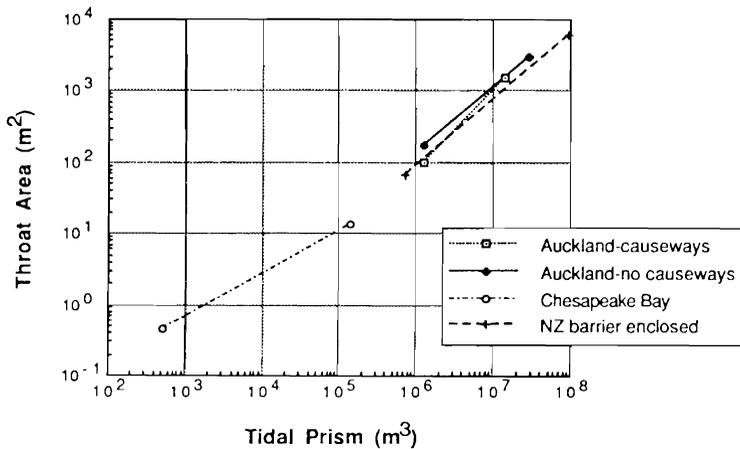


Figure 4. Regression lines for Auckland tidal waterways with and without causeways, and for the New Zealand barrier enclosed (open coast) tidal inlets described by Hume and Herdendorf (1988b) and the Chesapeake Bay inlets of Byrne *et al.*, 1980.

ogical) stability and location stability. The A- Ω relationship has been used to characterize the morphological stability of barrier enclosed inlets on sandy coasts, as it indicates that the size of the tidal gorge is one of the main factors determining the ability of flow to transport sediment through the entrance (BRUN and GERITSEN, 1960). Inlet gorges that are stable conform to the relationship, *i.e.* there is a balance between inlet geometry and tidal flow through the gorge. Those lying 'off-the-line' are out of equilibrium and demonstrate a tendency for either scour or deposition.

The Auckland estuarine waterways conform to an A- Ω relationship suggesting they are morphologically stable (Figure 3). At some sites there is direct physical evidence that this is the case and that the waterway cross-section has adjusted to the new hydraulic regime since causeway construction. At Waterview Inlet (Figure 1) for example there was a substantial reduction in throat width (a 96% reduction from 1400 m to 60 m) when a causeway and bridge were constructed for a motorway in 1952. The channel was deepened by dredging a new waterway throat (Figure 5) and additional, but very limited, tidal exchange was achieved by directing flow through several small culverts in the embankment west of the bridge. Low tide inspection of the main channel site shows deep scour holes at both the upstream and down-

stream bridge channel approaches suggesting the dredged design channel was too small in cross-section. This is confirmed by survey data which shows that since the throat was dredged in 1952 the channel bed has scoured more than 5 meters (Figure 5). A plot of maximum channel depth and area versus time shows rapid adjustment in the first 5–10 years followed by slower change thereafter (Figure 6). After about 20 years the entrance appears to have reached geometric stability. The 10–20 years for the Waterview channel cross-sectional area adjustment is large compared with the more rapid (about a few months to a year) cross-section adjustment exhibited by tidal inlets on sandy open coasts (*e.g.* BURTON and HEALY, 1985; HEALY, 1985). The difference is probably due to the fact that in upper harbor areas there is little sediment transport (due to low sediment availability), the sediments are more cohesive (have a higher proportion of mud in the sand) and there is little wave energy to suspend sediment (*cf.* open coast inlets where wave action is present). Furthermore in the estuarine waterways the currents scour the waterway gorge to bedrock in places which apparently results in a longer time to erode the entire cross-section to an equilibrium profile. Historical bed profile surveys of the Whau and Pukaki Creek channels suggest they too have now reached equilibrium after causeway construction resulted in adjustment

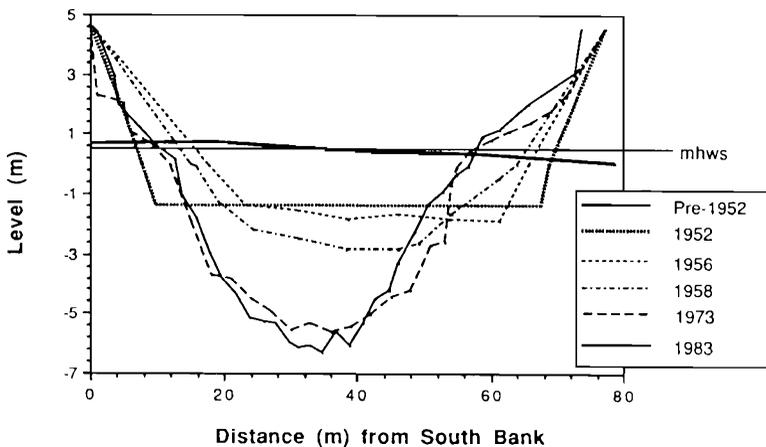


Figure 5. Changes in channel cross-section profiles at the Waterview Inlet between 1952 and 1983. The 1952 profile is the dredged design channel.

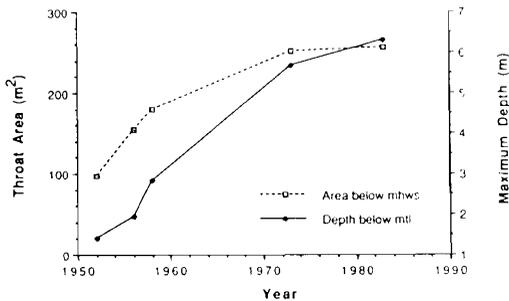


Figure 6. Plots of channel throat area and depth versus time at Waterview Inlet 1952-1983.

by scour. Given that about 20 years or more have passed since causeway construction at the other Auckland sites (Table 1), it is probable that they too are now morphologically stable.

The relatively long time taken by the Auckland waterways to reach equilibrium has important environmental significance because the morphometry of coastal embayments has a strong influence on coastal water exchange (BOON and BYRNE, 1981). Immediately following causeway construction the reduced throat area reduces the volume of water entering and leaving the estuary (*i.e.* the tidal prism). This results in reduced flushing and sedimentation upstream of the causeway until such time as

bed scour returns the throat dimensions to equilibrium.

Empirical Formulae for Stable Channel Design

This section examines empirical relationships commonly used for stable channel design and tests their applicability to the design of causeways.

Lacey

Lacey, in a series of papers (1929, 1933, 1946, 1958), presented equations for designing stable bed channels in alluvium based on field data. Converting one of Lacey's equations to the metric form shows that the wetted cross-sectional area, A , (m^2) of a stable channel at peak discharge is given by:

$$A = \frac{1.26(1.81)Q^{5/6}}{f^{1/3}} \tag{5}$$

where Q is the maximum (or peak) discharge (m^3/s) and the coefficient f is a silt factor (which accounts for the cohesion associated with fine sediment) expressed as:

$$f = 1.59\sqrt{d_{50}} \tag{6}$$

where d_{50} is the mean grain size (millimeters).

The writer computed throat area by the Lacey

formula for the Auckland waterways using Q = peak discharge for a mean spring tide and d_{50} of 0.088 mm (very fine sand). Comparing the computed Lacey A with throat cross-sectional areas measured below a water level corresponding with peak tidal discharge demonstrates that the Lacey formula underestimates stable channel dimensions in most situations (Table 3).

Simons and Albertson

SIMONS and ALBERTSON (1960) remedied some of the deficiencies in the Lacey method by using a more comprehensive range of field data to derive terms to account for the strength of channel bed and banks (when they happen to be different materials). Converting their formulae to the metric form shows that the wetted area, A , (m^2) of a stable channel is given by:

$$A = 1.995 \cdot (K_1 \cdot Q^{0.5})(K_2 \cdot Q^{0.36}) \quad (7)$$

where Q is the peak discharge (m^3/s) and K_1 and K_2 are coefficients to account for the types of channel bed and banks.

The writer computed A for the Auckland waterways using Q = peak discharge for a mean spring tide and K values as recommended by Henderson (1966, Table 10.3) for a situation of sand bed and cohesive sediment banks (*i.e.* $K_1 = 2.6$ and $K_2 = 0.44$). Comparing computed A with throat cross-sectional areas measured in the field demonstrates that the Simons and Albertson formula generally underestimates the channel dimensions and offers no improvement over the Lacey formula.

The underestimates of throat cross-section by both the Lacey and the Simons and Albertson formulae (equations 5 and 7) may reflect their development for river cross-sections of a more regular shape. In Auckland waterways the channel cross-section is irregular due to the sinusoidal and reversing nature of the tidal flow, tidal flats and bed rock exposure in some places. Perhaps the Auckland waterways are less hydraulically efficient and offer more resistance to flow and are therefore larger in cross-section. Interestingly in the 3 situations where the Lacey and Simons and Albertson formulae overestimate channel area, namely Judges, Waterview and Whakatakataka, the waterways have undergone the greatest constriction due to causeways (Table 1) and scour has cut a deeper throat profile. It is probable

that the Lacey and Simons and Albertson formulae are suited best for use in small tidal channels dredged and maintained to a regular cross-section.

Maza and Echavarria (1973)

This formula was developed from field studies and is recommended as a means to evaluate general scour in river beds formed of sand and gravel. In a straight reach the maximum depth from design water level to scoured bed level, $D_s(m)$ is given by:

$$D_s = 0.365 \frac{D_o}{D_{mo}} \cdot \frac{Q^{0.784}}{B^{0.784} \cdot d_{50}^{0.157}} \quad (8)$$

where D_o is the depth from design water level (WL = water level at peak discharge, m) to the lowest point in cross-section, D_{mo} is the depth from WL to mean bed level (m), Q is the peak discharge (m^3/s) in the tidal cycle, B is the channel width at peak discharge (m), and d_{50} the sediment mean grain size (m).

In New Zealand the method is recommended for use in estimating scour depth for bridge and causeway waterway design (MINISTRY OF WORKS AND DEVELOPMENT, 1979).

Applying the Maza and Echavarria formula to the causeway-modified Waterview, Pukaki and Whau tidal waterways, and using the historical pre-causeway bed profile data and $d_{50} = 0.088$ mm (very fine sand) to calculate post-constriction bed scour, shows that the formula estimates the existing bed scour depth to within +8 to -28% of the existing depth (Table 3). The Waterview and Whau values are in close agreement with the depths existing today. However, at Pukaki Creek there is a large (-28%) underestimate of scour depth. This may be accounted for by the following factors. Firstly the discharge measurements at Pukaki Creek were made on the flood tide. Ebb tide peak discharges are commonly 10-20% greater than those on the flood. Increasing the flood tide Q by say 15% gives a D_s (calculated) of 5.4 m thus reducing the error. Secondly, because the scour section is on a channel curve, where flows have cut a parabolic-shaped cross-section, we can apply a correction factor of 1.2 for a moderate bend (MINISTRY OF WORKS AND DEVELOPMENT, 1979) which then gives a scour depth prediction of 6.48 m. These changes bring the predicted scour

Table 3. Comparison of field measurements and calculated values of throat area and scour depth (determined below level corresponding to peak discharge). The % difference indicates whether the calculated value A is smaller (-ve) or larger (+ve) than the value of A determined by field measurement.

Inlet	Tidal prism (mean spring) (Ω_1)	Lacey throat area		Simons and Albertson throat area		Bed survey date	Maza and Echavarría scour depth		Bruun c
		calc.	diff.	calc.	diff.		meas.	calc.	
	($\text{m}^3 \times 10^3$)	(m^2)	(%)	(m^2)	(%)		(m)	(m)	(%)
Makarau	1,288	177	- 29	157	- 37				1.52
Judges	1,330	175	+ 52	170	+ 48				1.44
Lucas	2,427	291	- 29	262	- 36				1.51
Waterview	2,790	270	+ 17	335	+ 46	1952	5.6	6.06	+ 8
Pukaki	3,000	314	- 25	283	- 32	1964	6.76	4.84	- 28
Whakatakataka	3,643	397	+ 16	361	+ 6				1.40
Whau	6,206	558	- 26	513	- 32	1948	6.33	6.08	- 4
Tamaki	8,437	721	- 27	669	- 32				1.26
Mangere	14,137	1,054	- 33	989	- 31				1.17
Hobsonville	19,708	1,370	- 45	1,296	- 48				1.15
Fahurehure	29,032	1,931	- 17	1,848	- 21				1.18

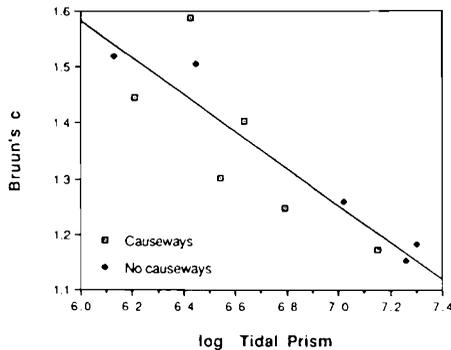


Figure 7. Bruun c (see equation 9) versus spring tidal prism for Auckland tidal waterways. Note that the value of Bruun c is smaller for the waterways of larger tidal prism.

depth to within 4% of the depth measured in the field.

These findings suggest that for Auckland waterways the Maza and Echavarría method estimates scour depth with an error of $\pm 10\%$, which is adequate for most engineering design purposes.

Bruun

BRUUN (1978) presented a formula for making a first approximation of inlet gorge cross-section area for design purposes as:

$$A = \frac{c \cdot \Omega \cdot \pi}{V_{mm} \cdot T} \quad (9)$$

where A is the throat area at mid tide (m^2) coinciding with peak flow, Ω is the spring tide prism (m^3), V_{mm} is the mean maximum (spring tide) velocity (m/s) over the cross-section (calculated as Q/A), T is the measured tidal period (sec) and c is a coefficient (dimensionless) which accounts for the non-sinusoidal nature of the current in the inlet and has been shown to depend on the inlet bay geometry, friction and ocean tidal characteristics (KEULEGAN, 1967). KEULEGAN and HALL (1950) observed that $c = 0.86$ gave good agreement with most measurements while BRUUN (1978) suggested 0.8–1.0 for inlets on sandy open coasts. Obviously correct selection of c is important in estimating A . Using equation (9) and the field data the writer calculated c for Auckland waterways as being 1.15 to 1.59 (averaging 1.34), being smaller for the larger waterways (Table 3 and Figure 7).

The Bruun formula can be used to estimate stable channel cross-sectional area for engineering works in Auckland waterways using a value of c ranging between 1.2 and 1.6 and scaled according to the size of the tidal prism using the equation:

$$c = 3.571 - 0.331 \log \Omega \quad (10)$$

$$(r^2 = 0.79, n = 11)$$

This Study

Figure 4 and equations (3) and (4) can be used to calculate a stable cross-sectional area for Auckland waterways. The equations suggest that for any given tidal prism the throat area of the natural channels is greater than that for causeway-modified waterways (for the smaller waterways at least), which reflects the higher current velocities and greater flow capacity of the channels and the relatively deeper channels (decrease in the width/depth ratio and therefore channel capacity) which accompany channel constriction by the causeway. This suggests that a natural waterway described by equation (3) can be constricted by a causeway to the degree predicted by equation (4) without significantly affecting the flow and sediment transport characteristics, thereby minimizing environmental impact and scour.

CONCLUSIONS

The strong coherence between waterway shape and tidal flow parameters indicates that tidal flow is the principal mechanism controlling the shape, although wave action, river flow and bottom sediment type and littoral transport also play a role.

A - Ω relationships, similar to those commonly used to characterize the stability of tidal inlets on sandy exposed coasts, have been derived for tidal waterways in the interior of Auckland harbors where muddy sediments predominate and sediment transport is small. The relationships are similar to those reported by HUME and HERDENDORF (1988b) for New Zealand barrier enclosed tidal inlets on sandy open coasts (Figure 4), although the Auckland waterways have larger throats and/or smaller tidal prisms than those of open coast inlets. The natural and causeway modified waterways are best characterized by separate A - Ω relationships.

Adjustments to waterway throat dimensions in the interior of harbors following constriction by engineering works are very slow (c. 10 to 15 years), compared to those for inlets on sandy open coasts (several months to a year).

Using the data from Auckland tidal waterways to test the formulae commonly employed in stable channel design shows that:

(1) Both the Lacey and the SIMONS and ALBERTSON (1960) formulae underestimate throat area and are not suitable for use in these tidal situations, except perhaps for small channels dredged (and maintained) to regular cross-section.

(2) The MAZA and ECHAVARRIA (1973) formula estimates maximum scour depth with an accuracy of about $\pm 10\%$.

(3) The BRUUN (1978) formula can be used if it is scaled for tidal prism.

(4) The $A-\Omega$ relationships derived in this paper

$$A = 4.37 \times 10^{-4} \cdot \Omega_s^{0.915} \text{ (equation 3, no causeway)}$$

$A = 7.39 \times 10^{-6} \cdot \Omega_s^{1.164}$ (equation 4, causeway) can be used to estimate A in natural and causeway modified situations.

Applying the above findings to Auckland (and perhaps other) tidal waterways to estimate causeway channel dimensions and bed scour will minimize the impact on the tidal flow regime and sediment transport patterns.

ACKNOWLEDGEMENTS

The author thanks Prof. T.R. Healy of the University of Waikato and colleagues R. Bell, and B. Vant for their review comments on the manuscript.

LITERATURE CITED

- BLENCH, T., 1957. *Regime Behaviour of Canals and Rivers*. London: Butterworths Scientific Publications, 138p.
- BOON, J.D., III and BYRNE, R.J., 1981. On basin hypsometry and the morphodynamic response of coastal inlet systems. *Marine Geology*, 40, 27-28.
- BRUUN, P., 1978. *Stability of Coastal Inlets—Theory and Engineering*. Amsterdam: Elsevier, 510p.
- BRUUN, P. and GERRITSEN, F., 1960. *Stability of Coastal Inlets*. Amsterdam: North Holland, 123p.
- BURTON, J.H. and HEALY, T.R., 1985. Tidal hydraulics and stability of the Maketu Inlet, Bay of Plenty. *Proceedings 1985 Australasian Conference on Coastal and Ocean Engineering*, pp. 139-150.
- BYRNE, R.J.; GAMMISH, R.A., and THOMAS, G.R., 1980. Tidal prism-inlet area relationships for small tidal inlets. *Proceedings, 17th International Conference on Coastal Engineering*, ASCE, pp. 2517-2533.
- COSTA, S.L., 1982. On the geometric stability of tidal inlets. *Proceedings, 18th International Conference on Coastal Engineering*, ASCE, pp. 126-127.
- DEJONG, H. and GERRITSEN, F., 1985. Stability parameters of Western Scheldt Estuary. *Proceedings, 19th International Conference on Coastal Engineering*, ASCE, pp. 3078-3093.
- HEALY, T.R., 1985. Assessment of stability and natural hazard risk of the Whakatane Spit and inlet in relation to proposed marina development. *Proceedings 1985 Australasian Conference on Coastal and Ocean Engineering*, pp. 295-308.
- HEATH, R.A., 1975. Stability of some New Zealand coastal inlets. *New Zealand Journal of Marine and Freshwater Research*, 9, 449-457.
- HENDERSON, F.M., 1966. *Open Channel Flow*. New York: Macmillan, 522p.
- HUME, T.M. and HERDENDORF, C.E., 1988a. The Furt-Heath relationship for tidal inlet stability reviewed. *New Zealand Journal of Marine and Freshwater Research*, 22, 129-134.
- HUME, T.M. and HERDENDORF, C.E., 1988b. A geomorphic classification of estuaries and its application to coastal resource management. A New Zealand example. *Ocean and Shoreline Management*, 11, 249-274.
- JARRETT, J.T., 1976. Tidal prism-inlet area relationships. US Army Corps of Engineers, Coastal Engineering Research Center and Waterways Experimental Station, Vicksburg, MS., *GITI Report No. 3*, 32p.
- KEULEGAN, G.H., 1967. Tidal flows in entrances. Water level fluctuations of basins in communications with seas. *Technical Bulletin No. 14*, Committee on Tidal Hydraulics, U.S. Army Engineers Waterways Experimental Station, Vicksburg, Mississippi, 89p.
- KEULEGAN, G.H. and HALL, J.V., 1950. A formula for the calculation of tidal discharge through an inlet. *Bulletin of the Beach Erosion Board*, 4, 15-29.
- KRISHNAMURTHY, M., 1977. Tidal prism of equilibrium inlets. *Journal of the Waterway Port Coastal and Ocean Division*, ASCE 103, No. WW4, 423-432.
- KINGSTON, REYNOLDS, THOM and ALLARDICE, 1986. Maketu Estuary Study: Stage I Report. KRTA Auckland, 128p.
- LACEY, G., 1929. Stable channels in alluvium. *Minutes of Proceedings of the Institution of Civil Engineers*, 229, 259-252.
- LACEY, G., 1933. Uniform flow in alluvial rivers and channels. *Proceedings of the Institution of Civil Engineers*, 237, 421-453.
- LACEY, G., 1946. A general theory of flow in alluvium. *Journal of the Institution of Civil Engineers*, 27, 16-47.
- LACEY, G., 1958. Flow in alluvial channels with sandy mobile beds. *Proceedings of the Institution of Civil Engineers*, 9, 145-164.
- MAZA, J.A. and ECHAVARRIA, F.J., 1973. Contribution to the study of general scour. *Proceedings, International Symposium on River Mechanics*, Interna-

- tional Association for Hydraulic Research, pp. 795–803.
- MINISTRY OF WORKS AND DEVELOPMENT, 1979. Code of practice for the design of bridge waterways. *Civil Division Publication 705/C*, 72p.
- NELSON, R.C., 1977. The relative sensitivity of estuaries and coastal inlets to engineering works. *Proceedings, 3rd Australian Conference on Coastal and Ocean Engineering*, Institution of Engineers Australian National Conference Publication 77/2, pp. 137–142.
- O'BRIEN, M.P., 1931. Estuary tidal prisms related to entrance areas. *Civil Engineer*, 1, 738–739.
- O'BRIEN, M.P., 1969. Dynamics of tidal inlets. *Proceedings, Symposium on Coastal Lagoons*, Mem. Simp. International Lagunas Costeras, UNAM-UNESCO, Mexico 1967, 397–406.
- PILLSBURY, G.B., 1956. *Tidal Hydraulics*. U.S. Corps of Engineers, Vicksburg, USA, 247p.
- SIMONS, D.B. and ALBERTSON, M.L., 1960. Uniform Water Conveyance Channels in Alluvial Material. *Journal of the Hydraulics Division*, ASCE, 86, No. HY5, 73–99.
- SNEDECOR, G.W. and COCHRAN, W.G., 1980. *Statistical Methods*, 7th edition. Ames, Iowa: Iowa State University Press, 507p.
- VAN DER KREEKE, J., and HARING, J.A.C., 1979. Equilibrium flow areas in the Rhine-Meuse delta. *Coastal Engineering*, 3, 97–111.
- VINCENT, C.L., and CORSON, W.D., 1981. Geometry of tidal inlets: empirical equations. *Journal of Waterway, Port, Coastal and Ocean Division*, ASCE, 107, No. WW1, 1–9.

□ ZUSAMMENFASSUNG □

Empirische Zusammenhänge zwischen der Morphologie einer Strömungsrinne und hydraulischen Parametern, die denjenigen von Gezeitenrielen an einer offenen Meeresküste ähnlich sind, werden für elf ästuarine Wasserstraßen im Gebiet von Auckland, Neuseeland, hergeleitet. Die Wasserstraßen sind Wattrinnen und -bäche, die in Häfen mit schwacher Küstenströmung und geringem Zufluß liegen. Sie sind mesotidal mit Gezeitenvolumina von $1,3 \times 10^6$ bis $29 \times 10^6 \text{ m}^3$ und haben als Sedimente schlammige Feinsande. Durch Dämme veränderte Wasserstraßen haben im allgemeinen engere Öffnungsgebiete im Vergleich zu natürlichen Wasserstraßen mit einem ähnlichen Gezeitenvolumen. Der Bau von Dämmen erhöht nämlich die Strömungsgeschwindigkeit, weshalb der Durchfluß durch die Rinne und die Erosion an ihrem Boden zu einer relativ tiefen Rinne führt (d.h. zu einer Abnahme des Verhältnisses von Breite zu Tiefe und zu einer verbesserten Rinnenbildung). Bei einer Wasserstraße führte die Korrektur bezüglich der Gestalt der Rinne nach dem Dammbau zu einer beträchtlichen Vertiefung des Bettes, und es dauerte 15 bis 20 Jahre, bis sich ein neues Gleichgewichtsprofil einstellte. Die empirisch gewonnenen Beziehungen können zur Berechnung von zukünftigen Querschnitten ästuariner Strömungsrinnen vor deren Veränderung durch Ingenieurmaßnahmen, wie etwa den Bau von Dämmen oder das Ausbaggern neuer Kanäle, verwandt werden. Die mittels der Wasserstraßen von Auckland gewonnenen Daten wurden benutzt, um einige der geläufigen Berechnungsformeln für stabile Strömungsrinnen zu testen. Die Formeln von LACEY (1958) und SIMONS & Albertson (1960) unterschätzen die Werte im Öffnungsgebiet der Rinnen, während die Formeln von MAZA & ECHAVARRIA (1973) und BRUUN (1978) mit Erfolg angeandt werden können, um die Erosionstiefe der Wasserstraßen und die Entwicklung in ihren Öffnungsgebieten vorherzusagen.—*Helmut Brückner, Geographisches Institut, Universität Düsseldorf, Universitätsstr. 1, D-4000 Dusseldorf 1, F.R.G.*