WATER & SOIL MISCELLANEOUS PUBLICATION NUMBER 108

TIDAL INLET STABILITY:

Proceedings of a Seminar, Christchurch
4 December 1985

National Water and Soil
Conservation Authority

ISSN 0110–4705

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WATER & SOIL MISCELLANEOUS PUBLICATION 108

TIDAL INLET STABILITY:

Proceedings of a Workshop, Christchurch
4 December 1985

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WELLINGTON 1987

TIDAL INLET STABILITY: Proceedings of a Workshop, Christchurch 4 December 1985

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Water & Soil Miscellaneous Publication No. 108, 1987, 82p.
ISSN 0110-4705

This document summarises the proceedings of a workshop on tidal inlet stability, convened by the Water Quality Centre as part of the Australasian Conference on Coastal and Ocean Engineering held in Christchurch, New Zealand. It includes a background paper, a summary of open discussion, and a bibliography of tidal inlet stability.

National Library of New Zealand
Cataloguing-in-Publication data

HUME, T. M. (Terry Martyn), 1948-
Tidal inlet stability : proceedings of a workshop, Christchurch, 4 December 1985 / T.M. Hume and C.E. Herdendorf. - Wellington, N.Z. : Published for the National Water and Soil Conservation Authority by the Water and Soil Directorate, Ministry of Works and Development, 1987. - 1 v. - (Water & soil miscellaneous publication, 0110-4705 ; no.108)
551.45
1. Inlets--Congresses. 2. Hydrodynamics--Congresses. 3. Coast changes--Congresses. 4. Coastal zone management--Congresses. I. Herdendorf, Charles E. II. National Water and Soil Conservation Authority (N.Z.). III. New Zealand. Water and Soil Directorate. IV. Australasian Conference on Coastal and Ocean Engineering (1985 : Christchurch, N.Z.). V. Title. VI. Series: Water & soil miscellaneous publication ; no. 108.

Front Cover — *Colour enhanced image of Whangateau tidal inlet on Auckland's east coast, New Zealand. Image shows an elongate bar of sand deposited by ebb tide jet transport of sand out of Whangateau Harbour into Omaha Bay. The tip of Omaha sand spit is stabilised by rock groynes.*
Photo: Air Logistics, Auckland. 23 August 1980.

Published for the National Water and Soil Conservation Authority
by the Water and Soil Directorate, Ministry of Works and Development,
P.O. Box 12-041, Wellington, New Zealand.

CONTENTS

Figures

Tables

ACKNOWLEDGEMENTS

The authors wish to thank colleagues including K. Smith, J. Dahm, B. Williams and N. Burns who reviewed the background paper. We are particularly grateful to those vocal workshop participants for their contribution at the workshop and for their reviews of the proceedings. Julie Burton acted as recorder and provided an excellent transcript of the proceedings from the tapes and notes.

WORKSHOP ORGANISATION

A workshop held as part of the 1985 Australasian Conference on Coastal and Ocean Engineering, at Canterbury University, Christchurch, New Zealand, on 4 December 1985.

SPONSORED BY: Institution of Engineers, Australia
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Water Quality Centre
Ministry of Works and Development
Hamilton, New Zealand

WORKSHOP CONVENORS: T M Hume and C E Herdendorf
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PREFACE

A half-day workshop on tidal inlet stability was convened by the Water Quality Centre, Ministry of Works and Development, Hamilton, as part of the 1985 Australasian Conference on Coastal and Ocean Engineering, at Canterbury University, Christchurch, New Zealand on 4 December 1985. The workshop was attended by a wide range of people including scientists, engineers and planners from government departments, consulting firms, local authorities, universities, harbour boards and industry from New Zealand and overseas (Appendix I).

The objectives of the tidal inlet stability workshop were to: (1) review New Zealand and overseas research, (2) discuss the techniques available for assessing tidal inlet stability, and (3) identify research needs.

A background paper written by the authors and presented by T M Hume, is reproduced in this publication. It outlines management problems in inlets and reviews recent overseas and New Zealand research on tidal inlet stability (1975-1985). To supplement the review the bibliography of tidal inlet stability (Appendix II) lists: (1) a selection of 31 pre-1975 publications on tidal inlets, considered "classics" on this subject by the compilers of this bibliography and, (2) important 1975-85 overseas publications, including a more exhaustive list of New Zealand works on this and related topics. The background paper also describes the application of research to management problems, examines the use and abuse of existing knowledge and tools, and identifies areas for future research. This document is particularly focussed on management problems in New Zealand inlets.

The background paper and related topics were then open for general discussion. The proceedings are reported here under subheadings, not necessarily in the order they were raised at the workshop, largely because some of them were mentioned more than once. Professor F Gerritsen made closing remarks.

Appendix III lists technical papers presented at the conference relating to the subject of tidal inlet stability which are presented in the conference preprints.

The purpose of this publication is to report the proceedings of the tidal inlet stability workshop, create an awareness of tidal inlet stability problems, and collate and disseminate up-to-date information on the topic in a form useful to resource managers and planners.

TIDAL INLET STABILITY:
A WORKSHOP BACKGROUND PAPER

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Hamilton

This paper outlines management problems in inlets, reviews recent overseas and New Zealand research on tidal inlet stability (1975-1985), describes the application of research to management problems, examines the use and abuse of existing knowledge and tools, and identifies areas for future research. This document is particularly focussed on management problems in New Zealand inlets.

INLET MANAGEMENT PROBLEMS

Tidal inlets occupy a unique position on the coast because they form the link between open coastal waters and sheltered inland waterways. Commercial and residential development at inlets and in adjacent areas has generated the need for technical information to facilitate planning, and for impact assessment to achieve a balance between commercial, recreational, and environmental interests (Table 1).

Planning for and reporting on the impact of these developments requires a knowledge of natural changes of inlet stability, together with a means of predicting the way inlets will respond to man-made changes which affect water and sediment transfers in the system.

Ideally, managers need to have at their disposal reliable and effective hydraulic and sediment models to enable such predictions. In the case of the larger inlets and commercial ports there is often available the considerable sums of money needed to fund such studies. When these resources are unavailable predictions must be based on (1) semi-quantitative conceptual models which rely on an understanding of the processes in natural systems that affect sedimentation and coastal stability, (2) case studies of similar situations from which the likely consequence of change can be inferred, or (3) simple empirical

Table 1. Information requirements associated with various inlet uses

	Action	Information Gap	Risk
1	Industrial facility siting	Erosion rate and adequate buffer frontage	Erosion of site
2	Commercial and residential development	Erosion rate and adequate buffer frontage	Erosion of site
3	Installation of power cables and water supply pipelines	Bed level fluctuation and adequate burial depth	Exposure and collapse of utility line
4	Reclamations associated with port and other work	Tidal flow and sediment transport response, collective effect	Impairment of navigation
5	Construction of entrance training works	Tidal flow and sediment transport response	Impairment of navigation
6	Dredging for channel maintenance and sand mining (e.g. aggregate, minerals, beach nourishment)	Location, quantities, tailings disposal, and tidal flow and sediment transport response	Estuary infilling, channel instability
7	Catchment works (e.g. river diversion, stop-banking, drainage)	Tidal flow and sediment transport response, back-water effects, ecological response	Shoreline erosion and channel instability, flooding, change in ecology
8	Beach erosion defence	Effect on littoral drift	Down-drift erosion, channel instability
9	Causeways	Effect on tidal compart-ment and flow patterns, ecological response (e.g. changes in shelter)	Siltation, change in ecology

models. The latter approach is applicable to numerous small New Zealand inlets. These typically have small permanent populations but a high influx of persons in the summer. Local authorities have a small rating base but amenities must be designed to cope with the high transient populations during vacation periods. Because the authorities have little money to investigate problems in each inlet, it is most efficient and cost effective to systems and to utilise existing, and develop new, simple predictive models that are of general application to coastal management problems.

Although this workshop focuses on tidal inlet stability we should always be aware that inlet stability problems and their solutions need to be considered along with a host of social, biological and other physical issues. A New Zealand case that exemplifies this, Maketu Estuary, has been described by Burton and Healy (1985) and Tortell (1985) (Appendix III). Prior to 1956, Maketu was a small (2 km^2) barrier spit enclosed river mouth estuary with a catchment of 1178 km^2 receiving a mean annual river input of about 50 $m^3.sec^{-1}$. In 1956, as part of a drainage and river control scheme, the Kaituna River was diverted directly to sea at the Te Tumu cut. This reduced the estuary's catchment area to 28 km^2 and freshwater input to a very small amount converting the Maketu estuary to a microtidal barrier enclosed lagoon. Since this diversion there has been reported marked shoaling of the inlet, changes in inlet width and in the shape of the sandspit and changes in the distribution and abundance of fish and shellfish in the estuary. The ramifications of these changes are considerable, including loss of navigable waterways and mooring areas, shoreline erosion inside the inlet, and loss of traditional fishing grounds and food sources for the local Maori people. Thus, there has been impact on commerce, recreation, and human values.

Today there is considerable pressure from the local people to divert the river back into the estuary to return things to their pre-diversion state. Of course the solution is not that simple because since 1956: (1) the river water quality has deteriorated due to runoff from livestock farms and agricultural land, sewage from the Te Puke Borough treatment plant, waste from the Rangiruru Freezing Works and fruit processing plant discharges, (2) the river flow characteristics have been altered by land use changes and catchment works and (3) the estuary has changed, the tidal prism has been reduced, the bathymetry has changed and the textural characteristics of the sediments have altered. Simply diverting a different river back into a different estuary will not reinstate the pre-diversion situation. In fact, it could have a marked detrimental effect on present shellfish quality and flood protection works around the estuary.

The situation is complex, the answers need to be multidisciplinary.

OVERSEAS AND NEW ZEALAND RESEARCH

There is a wealth of information on tidal inlet stability in the literature. The bibliography presented at the end of this paper lists: (1) a small selection of pre-1975 "classic" publications on tidal inlet stability and (2) the more important 1975-1985 overseas publications and New Zealand works on the topic.

In New Zealand the bulk of research on tidal inlet stability has been undertaken as part of university research, notably by the Earth Sciences Department of Waikato University. Until recently the work has primarily been done as part of broader estuarine research and undertaken on an estuary-by-estuary basis (e.g., Hohoura, Rangaunu, Ngunguru, Whangarei, Mangawhai, Mahurangi, Auckland, Tauranga, Ohiwa, Wellington, Pauatahanui, Waitara, Kawhia, Manukau, Pelorous Sound, Avon-Heathcote, Delaware and the sounds of Fiordland). Most of these works are largely descriptive in nature.

Recently, detailed process and modelling studies, as part of port development investigations, on estuary and tidal inlet hydraulics and sediment transport have been published on Whangarei Harbour (works by Black, 1983; Danish Hydraulics Institute, 1982; Healy, 1981) and Tauranga Harbour (works by Barnett, 1985; Black, 1985 and Healy, 1985).

The only regional studies are works by Furkert (1947) and Heath (1975). Integration of data from more recent studies into a regional framework is being undertaken by the authors of this paper.

Studies in progress include those for north-east coast North Island inlets (Hume and Herdendorf), Rangaunu (Pickrill), Auckland estuaries (Hume), Whangapoua Harbour (Colby), Maketu (Burton; Kingston Reynolds Thom & Allardice), Nelson (Barnett) and Lyttelton Harbour (Curtis).

APPLICATION OF RESEARCH TO MANAGEMENT PROBLEMS

A number of techniques are available to assess inlet stability and design improvements. To facilitate discussion of these it is first important to briefly review inlet types and clarify relevant terminology.

Terminology

Tidal inlets are defined here as all connections between the open ocean and a bay, fiord, lagoon, or "lake", and through which reversing tidal flows are concentrated.

1. Inlet types

Although estuarine basins have a variety of origins, from a geological standpoint most have formed since the last glacial maximum (Otiran) when sea-level stood about 130 m below the present level (18000-20000 yr B.P.). With eustatic sea-level rise to the present level, about 6500 yr B.P., the sea flooded river valleys and coastal embayments. Since this event some of these features have undergone modification by infilling in the headwaters, particularly when catchments are small. Conversely, where fluvial input is large and coastal wave energy and currents are low, sediments are transported through an infilled basin and build delta complexes on a prograding coast. The entrances to submerged valleys and embayments on some deeply indented coasts have been constricted and partly infilled by the development of barrier features. The size and orientation of these features reflect quantities and direction of littoral drift, and the direction of wave approach.

Hume and Herdendorf (1985) have grouped New Zealand estuaries into five broad categories that reflect mode of origin namely: (1) fluvial erosion, (2) marine erosion, (3) tectonic, (4) volcanic, and (5) glacial. These origin categories are subdivided morphometrically, particularly on their inlet characteristics, into 8 classes and 15 types which reflect catchment and coastal hydraulic and sedimentologic processes (Fig. 1). Type examples are illustrated in Fig. 2.

Those of fluvial erosion origin divide into 4 classes and 10 types. Unrestricted inlets (Type 1) are funnel-shaped and branched drowned valley systems with little fluvial input and have unrestricted entrances situated on sheltered, low littoral drift shores. Headland enclosed inlets (Type 2), are drowned valley systems with little fluvial input, and the inlet throat is constricted by rocky headlands situated on low littoral drift shores. Barrier enclosed lagoons which occur commonly on the north-eastern coast, of the North Island, have small freshwater input and are generally formed on exposed coastlines when littoral drift builds a double-spit (Type 3) or single-spit

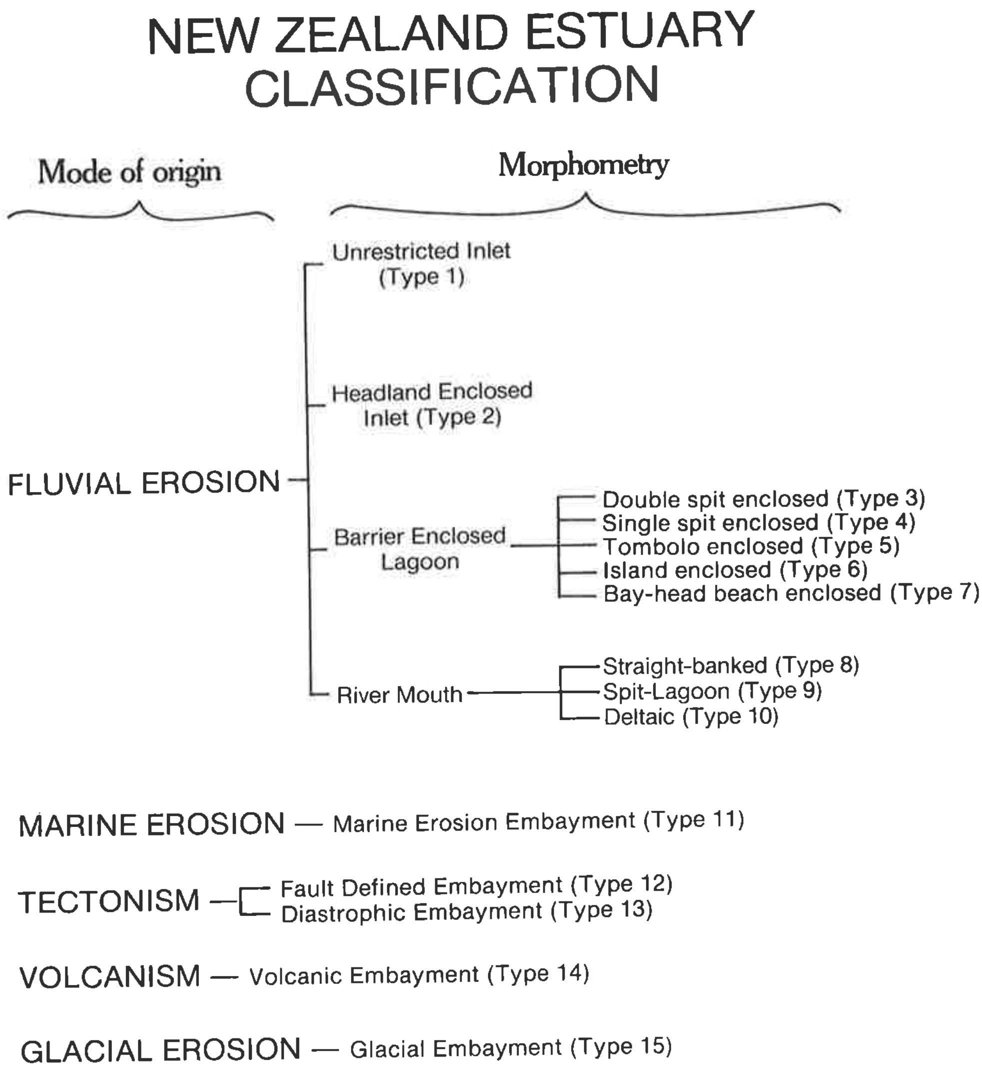


Figure 1. New Zealand estuary classification

(Type 4), tombolo (Type 5), barrier island (Type 6) and bay-head beach (Type 7) barriers that restrict exchange between the estuary and the sea. River mouth estuaries are characterised by high freshwater inflow from large catchments, and are subdivided into straight-banked (Type 8), spit-lagoon (Type 9), and deltaic (Type 10) estuaries which reflect varying degrees of fluvial and littoral sediment input to the systems.

Estuaries of marine erosion origin are those marine embayments (Type 11) characterised by very small catchments, little fluvial input, and wide rock headland entrances. Estuaries of tectonic origin are those fault defined embayments (Type 12) whose margins are defined by fault boundaries (inlet widths <2 km) and large diastrophic embayments (Type 13) of more complex origin (inlet widths >5 km). Estuaries of volcanic origin (Type 14) include small explosion craters. Estuaries of a glacial origin (Type 15) are represented only in the South Island by fiords which have deep stable inlets characterised by depositional sills. Compound estuaries are formed from two or more of the basic types.

Much of the literature on tidal inlet stability addresses barrier enclosed lagoon (Types 3-7) and spit-lagoon river-mouth (Type 9) situations. Deltaic river mouths characterised by high fluvial input (Type 10) are the subject of another workshop at this conference.

2. Inlet morphology

Morphologically a tidal inlet includes the narrow entrance channel together with the intertidal and submarine deltas that can form at one or both ends of the entrance channel. The major morphological units are the ebb tide delta, a lobate sand body formed seaward of the entrance channel; the tidal gorge, the narrow deep channel at the inlet entrance; and, the flood tide delta, a shield of sand which develops in the tidal basin, landward of the gorge. These and other morphological features are illustrated in Fig. 3.

Morphological stability has two main components: (1) location stability and (2) cross-sectional stability. Location stability describes the lateral migration of an inlet's entrance channel(s) within the physical bounds of the estuary. It is strongly affected by the type of inlet enclosure, the sediment texture, and of course, by entrance training works if present. The position of inlets shift in response to changes in littoral drift, tide and waves; this is often a cyclic process. Extreme events such as spit breaching caused by

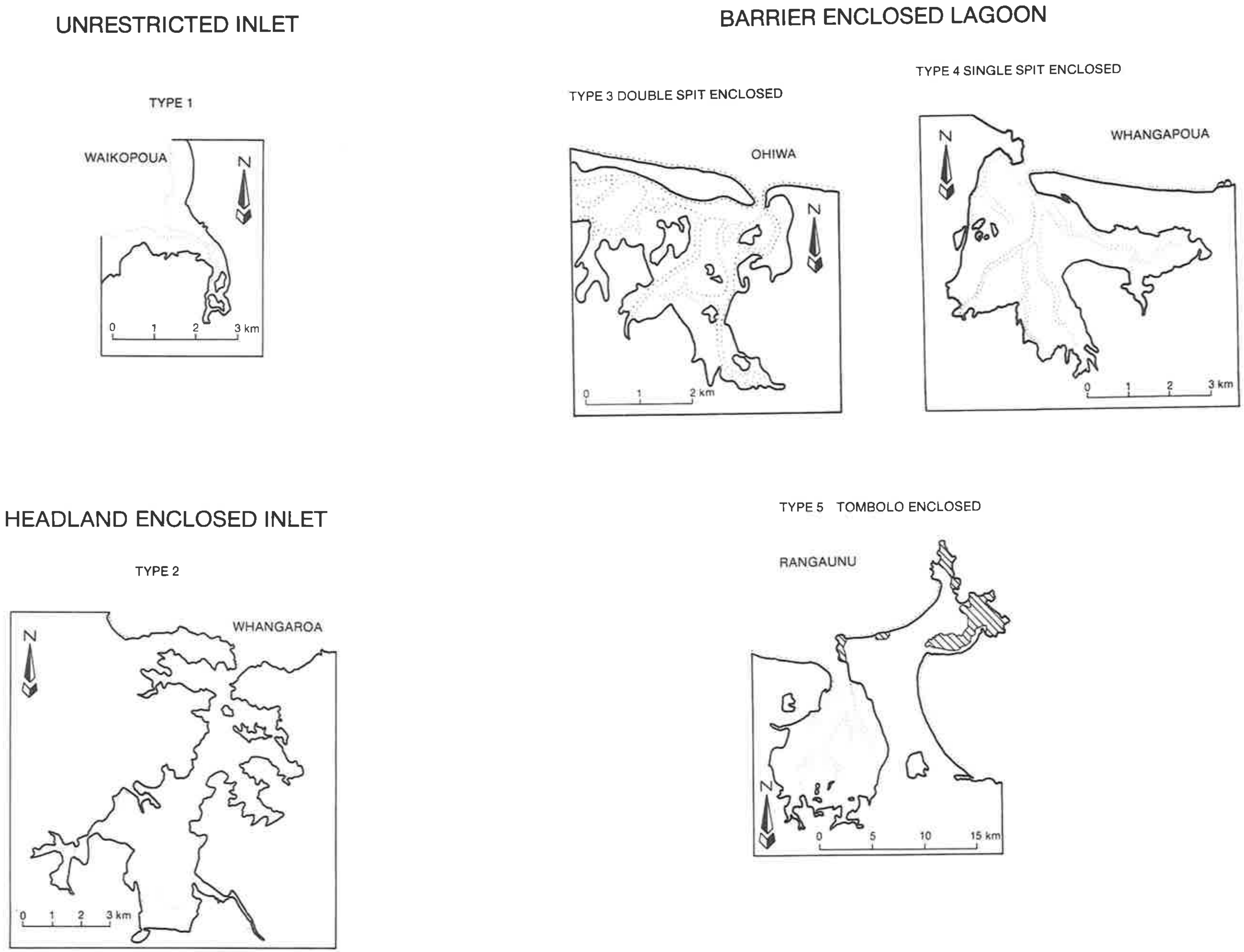


Figure 2. Examples of New Zealand estuary types.

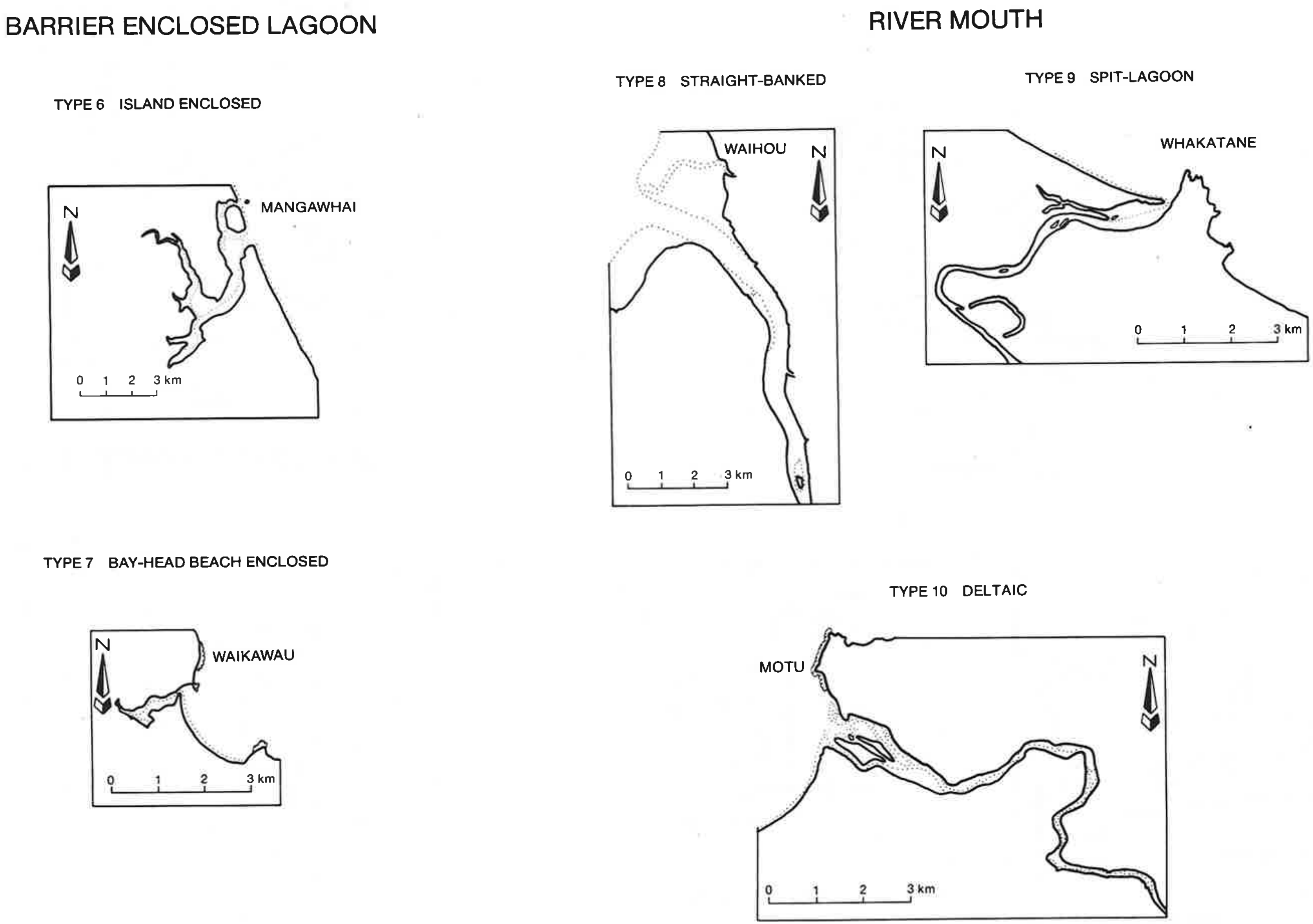
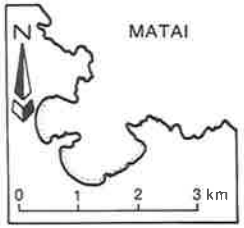


Figure 2 (Continued). Examples of New Zealand estuary types

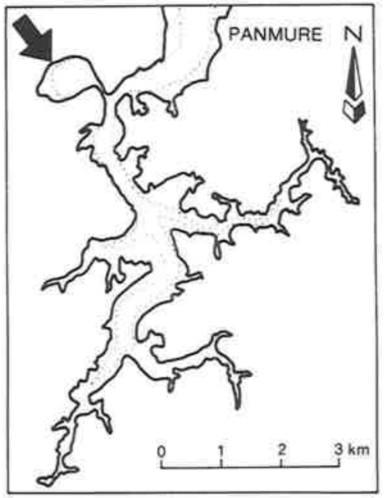
MARINE EROSION EMBAYMENT

TYPE 11



VOLCANIC EMBAYMENT

TYPE 14



FAULT DEFINED EMBAYMENT

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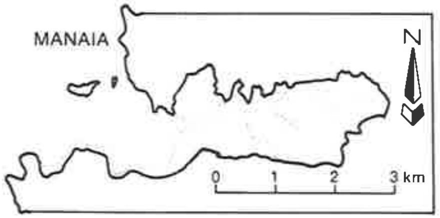
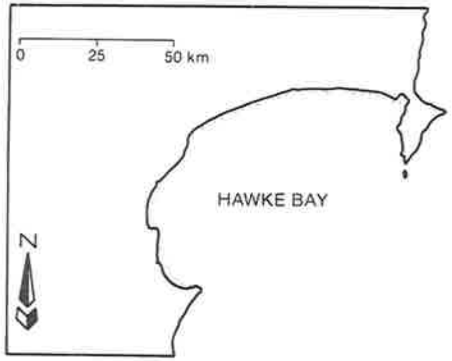


DIASTROPHIC EMBAYMENT

TYPE 13



GLACIAL EMBAYMENT

TYPE 15

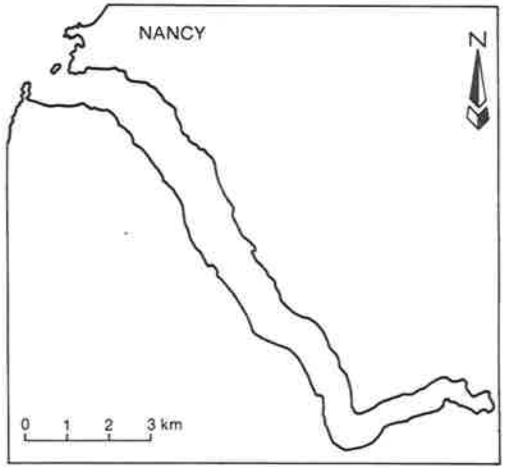
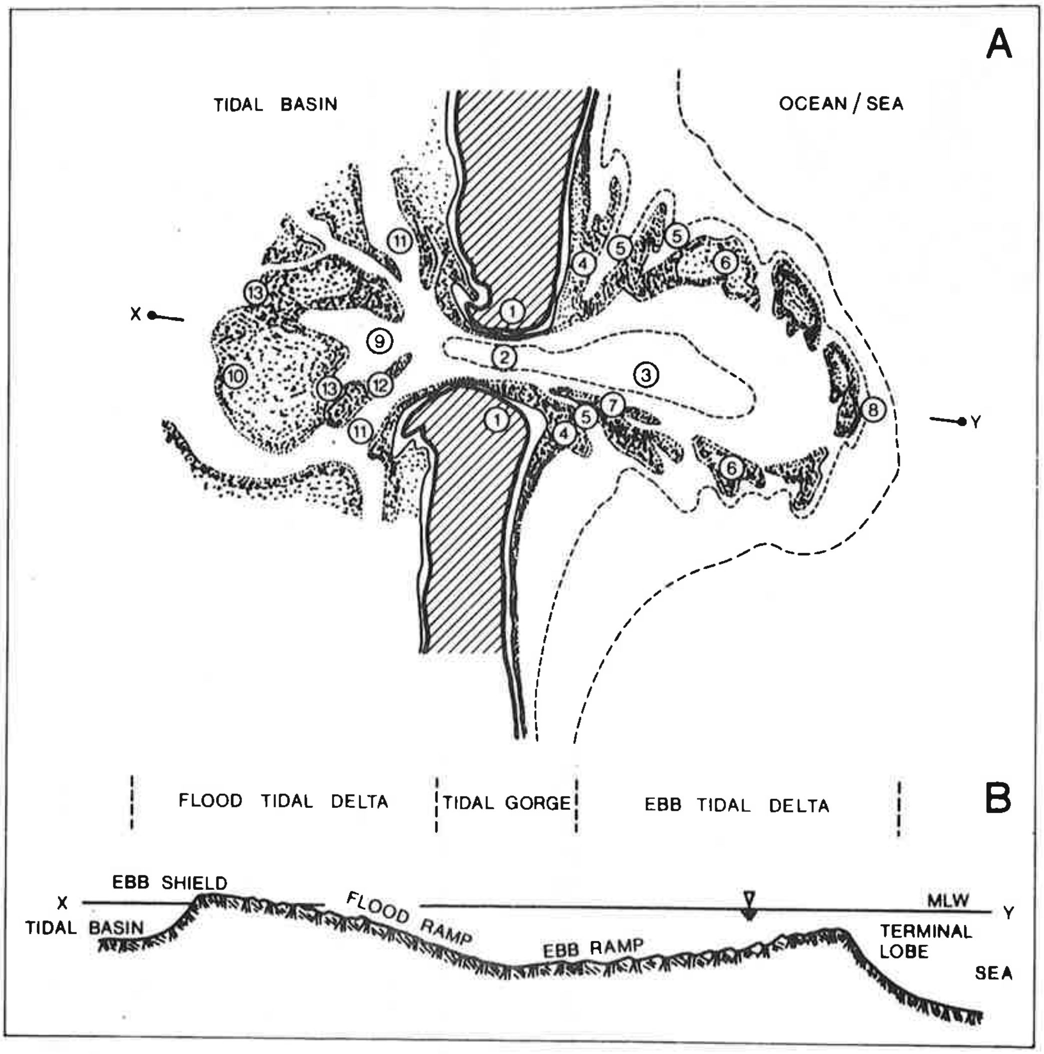


Figure 2 (Continued). Examples of New Zealand estuary types



1) coastal barrier or spit headland;
2) the tidal gorge;
3) the main ebb channel and ebb ramp;
4) swash platforms;
5) marginal flood channels;
6) marginal shoals;
7) ebb tidal levee;
8) ebb delta terminal lobe;
9) the flood ramp;
10) the ebb shield;
11) main ebb dominated inner channels;
12) ebb spit;
13) spill over channels.
B, cross section profile from x to y through the tidal gorge and over both flood and ebb tidal deltas.

Figure 3. Tidal inlet morphometry (from Smith, 1984). A, schematic diagram illustrating the principal morphological features of a tidal inlet on a sandy coast: (1) coastal barrier or spit headland; (2) the tidal gorge; (3) the main ebb channel and ebb ramp; (4) swash platforms; (5) marginal flood channels; (6) marginal shoals; (7) ebb tidal levee; (8) ebb delta terminal lobe; (9) the flood ramp; (10) the ebb shield; (11) main ebb dominated inner channels; (12) ebb spit; (13) spill over channels.
B, cross section profile from x to y through the tidal gorge and over both flood and ebb tidal deltas.

overtopping during storms commonly trigger an inlet migratory trend. Cross-sectional stability relates to the variability of the cross-sectional area of a tidal channel and its relation to tidal flow characteristics. Bruun (1978) uses the term 'dynamic stability' by which the elements involved attempt to maintain a situation characterized by relatively small changes in inlet geometry.

Assessing Overall Inlet Stability

Existing techniques include analysis of historical data, transferring results from case studies, application of conceptual models and use of empirical formulae. No single approach guarantees a complete evaluation of stability. The recommended method is to perform the analysis utilising a number of techniques looking for a consistent trend.

1 Tidal prism measurement

Changes in tidal estuary prism with time indicates changing hydraulic and sedimentologic conditions in an estuary and large scale sediment infilling or erosion. It is essential to carefully check datums, make field mesurements under 'average' or 'normal' conditions, and 'normalise' data to standard conditions for these comparisons.

2 Bathymetic and aerial photographic surveys

Historical bathymetric charts, maps, and aerial photographs are used to quantify the magnitude, locations, and patterns of past changes in inlet channel, shoal, and shoreline configurations. In New Zealand, vertical aerial photography generally dates back to about 1940 and bathymetric survey data to the mid 1800s. For many smaller inlets tidal hydrologic and bathymetric data are scarce. Analysis of bathymetric charts can also yield additional information on changes in tidal prism and the capacity of channels to carry flows. In all this work particular care must be taken in reducing all survey data to common datums or tidal conditions.

Historical trends can be analysed and used to predict future inlet configurations (based on the assumption that the identified trends will continue in the near future) (Smith, 1984). Another approach, is to compare the case under consideration with similar known cases. A classification of estuaries, as described earlier, is useful for this purpose.

3 Conceptual models

Comparison of inlet morphometry with conceptual models of inlets - delta complexes (e.g. Oertel, 1977; Hayes, 1980) provides a semi-quantitative means of predicting sediment transfers.

4 Ω/M_{total} ratio

The Ω/M_{total} ratio, introduced by Bruun and Gerritsen (1960), relates two important parameters that control inlet stability, namely the tidal prism (Ω in m^3) and the total littoral drift toward the inlet (M_{total} in m^3/yr).

Practical examples show that inlet stabilities may be graded as follows (Bruun 1978, p. 376) :

$\Omega/M_{total} >$ about 150:	Conditions are relatively good, little bar formation and good flushing
$100 < \Omega/M_{total} <$ about 150:	Conditions become less satisfactory, and offshore bar formation takes place
$50 < \Omega/M_{total} < 100$:	Entrance bar or shoals may be rather large, they may be penetrated by a channel improving navigation conditions. Breaking, however, may take place in the bar during storm
$20 < \Omega/M_{total} < 50$:	All inlets are typical "bar-bypassers". Waves break over the bar during most storms. The reason why such inlets "stay alive" at all is that often during a rainy season (like the monsoon) they get "a shot in the arm" by freshwater flows. For navigation they present "wild cases", unreliable and dangerous
$\Omega/M_{total} < 20$:	Are descriptive of cases where entrances may become unstable "overflow channels", impossible for navigation (except canoes).

The use of the Ω/M_{total} ratio for evaluating the relative degree of stability of a tidal inlet assumes that the tidal prism and littoral drift do not change from one season to another and that the tide is semi-diurnal and not very skewed (Bruun, 1976).

While Ω is relatively easy to compute, M_{total} is more difficult. It may have to be evaluated from neighbouring parts of the coast, estimated from dredging figures, calculated from littoral drift formulae, measured by tracer experiments, or determined by monitoring accretion about coastal structures.

5 Physical and numerical models

A review of the art and science of physical (hydraulic) and numerical modelling of inlet stabiity is beyond the scope of this paper. Some important references are presented in the bibliography.

Modern computing techniques and computers have realised solutions to some complicated hydraulic problems, particularly in the bay and throat areas of inlets, where wave action is minimal, and where tidal flows dominate the hydraulics. The weak links at present are in understanding the physics and in the formulation of sediment transport (bedload and suspended load) in tidal channels and in representing the mechanics and meandering and migration of tidal channels.

Assessing Inlet Gorge Stability

Inlet gorge stability can be assessed by the following methods, some of which provide a means of designing the theoretical stable cross-sectional area of the inlet gorge:

1 Area-prism relationships (A-Ω)

The cross-sectional area of the inlet throat and the tidal prism have been related according to the power function:

$$A = C\Omega^n$$

where

A = gorge cross-sectional area (m^2)
Ω = tidal prism (m^3)
C and n = constants.

in numerous studies (e.g. Le Conte, 1905; O'Brien, 1931, 1969; Jarrett, 1976; Heath, 1975; Krishnamurthy, 1977; Shigemura, 1980; Vincent and Corson, 1981; Costa, 1982). The A-Ω relationship reflects the fact that that the size of an entrance is one of the main factors determining the ability of water flow to transport sediment through the entrance (Bruun and Gerritsen, 1960). Entrances that conform to the relationship can be considered to be geometrically stable (i.e. have the ability to return to their initial configuration after a disturbance).

When the flow at some point in the tidal reach of an estuary (landwards of the mouth) is in equilibrium with its morphology, a similar, but less well correlated A-Ω relationship has been found to exist between the channel cross-sectional area (A) at any point and the upstream volume (Ω) (e.g. Pillsbury, 1956; Nelson, 1977; van der Kreeke and Haring, 1979; de Jong and Gerritsen, 1984; Hume, 1984).

A-Ω relationships have been used to determine the morphological stability of inlets, provide a simple method of estimating tidal prism from gorge profile data, and give a means of calculating a stable inlet gorge cross-sectional area.

2 Depth/width and similar relationship for inlet throats

Mehta (1977) and Bruun (1978) describe linear correlations between mean depth versus width at the inlet throat for North American inlets without jetties. They suggest that inlets that lie off the line must either alter in depth or width to reach a 'dynamic equilibrium'. Vincent and Corson (1981) derived 10 relationships, including depth/width, between inlet physiographic parameters such as channel lengths and depths to determine characteristic variations in inlet geometry and information on whether inlet geometry tends toward an equilibrium.

3 $V_{mean\ max}$ criteria

Bruun and Gerritsen (1960) introduced $V_{mean\ max}$ for the description of cross-sectional stability of the gorge. $V_{mean\ max} = V_{mm}$ = the mean maximum velocity ($m.s^{-1}$) over the cross-section at spring tide conditions.

$$V_{mean\ max} = Q_m/A$$

where

Q_m = peak discharge in section ($m^3.s^{-1}$)
A = gorge cross-sectional area (m^2).

The values obtained may be compared to those for other inlets of known stability reported in the literature.

4 First approximation cross-sectional area of the inlet gorge for design

purposes (Bruun, 1976)

$A = C_2 \Omega \pi / V_{mm} T$

where

A = calculated cross-sectional area at mid-tide (m^2)

Ω = spring tidal prism (m^3)

C_2 = non-sinusoidal correction coefficient (0.8-1.0)

V_{mm} = mean maximum velocity ($m.s^{-1}$)

T = measured tidal period (s).

Similarity of A calculated from this equation to that of A measured in the field, indicates inlet stability.

5 Stable cross-sectional area of the inlet gorge predicted by Bruun and Gerritsen (1960)

$A = Q_m / C(\tau_s / \rho g)^{1/2}$

where

A = "stable" cross-sectional area of gorge at mid-tide (m^2)

Q_m = maximum discharge measured during the tidal cycle ($m^3.s^{-1}$)

C = Chezy-factor = 30 + 5 log A ($m^{1/2}.s^{-1}$)

τ_s = mean maximum shear stress = $\rho g V^2_{mm} / C^2$ ($N.m^{-2}$)

ρ, g = density sea water, acceleration due to gravity

Similarity of calculated A with field measured A indicates inlet stability.

6 Stability shear stress τ_s

The mean maximum shear stress (or "determining shear stress") (Bruun, 1978) gives another measure of stability :

$$\tau_s = \rho g \, V^2_{mm} / C^2$$

The value of τ_s depends on the littoral drift and the sediment characteristics. Considering inlets at equilibrium on various coasts, Bruun (1978) found its value to be in a fairly narrow range.

light littoral drift ← $3.5 \ N.m^{-2} < \tau_{eq} < 5.5 \ N.m^{-2}$ → heavy littoral drift.

7 Stability/closure curves

The stability of a tidal inlet and its potential for closing, can be analysed using the O'Brien and Dean (1972) method. This method combines a cross-sectional area, A_c, similar to that of Escoffier (1940), with the simplified hydraulic analysis of Keulegan (1967). It is applicable to relatively small tidal bays.

1 For a given tidal inlet, the following data is required to carry out stability analysis:

T = tidal period (seconds)

A_b = bay/estuary surface area (m^2 or ft^2)

$2a_o$ = 2 x mean diurnal tidal amplitude ≡ mean tidal range on the ocean side of the tidal inlet (m or ft)

f = Darcy Weisbach friction coefficient (dimensionless) = $8\ gn^2/R^{1/3}$. Where n is Manning's coefficient; n = 0.025 is an (average value suggested by Mason, 1981)

R = hydraulic radius of the inlet cross-section (m or ft)
= $0.5 + (2.3 \times 10^{-4}\ Ac)$ is an empirical relationship derived by Mason (1981)

L = channel/deposition length of the inlet is taken to represent the distance between the ebb and flood tidal deltas (m or ft).

g = acceleration of gravity (9.81 $m.s^{-2}$ or 32.2 $ft.s^{-2}$)

π = 3.14

A_c = inlet cross-sectional area (m^2 or ft^2)

K = Keulegan repletion coefficient (dimensionless)

where

$$K = \frac{TA_c}{\pi A_b} \cdot \sqrt{\frac{g}{2a_o\ (1 + \frac{fL}{4R})}} \qquad \ldots(1)$$

V' = velocity coefficient (dimensionless)

This coefficient is obtained from Fig. 37 (b) (p. 47 Mason, 1981, by using a calculated value of K, equation (1) to find the point on the curve corresponding to V'.

$\bar{V}_{max}$ = maximum average current speed ($m.s^{-1}$ or $ft.s^{-1}$)

where

$$\bar{V}_{max} = \frac{V'\ \pi\ 2a_o\ A_b}{T.A_c} \qquad \ldots(2)$$

a_b/a_o = ratio of bay/estuary mean tide range to ocean mean tide range.

2 To obtain the initial value of inlet deposition length, L, one uses the most recent values of A_c, R, f, and a derived value of K from Fig. 37(c) (p.

47 Mason, 1981) using the ratio of bay/estuary to ocean tide amplitude (a_b/a_o), substituted into equation (1) to derive L. Alternatively, L may be obtained from measuring the distance between the tidal deltas on aerial photographs.

3 The derived value of L is then used in equation (1) with a series of A_c and R values to derive K values. Each K value is plotted on Fig. 37 (b) to obtain V' values. The V' values are then substituted into equation (2) with the corresponding A_c values to derive $\bar{V}_{max}$.

$\bar{V}_{max}$ values are plotted against the corresponding A_c values on the stability curve (Fig. 4).

The analysis may be undertaken for a series of probable inlet channel length values (L) to derive a series of stability curves (L_1 .... L_n) (Fig. 5). Various lengths are important because the length over which the cross-sectional area may change will influence the hydraulic response of the inlet.

By way of interpretation, the peaks of each curve represent the critical cross-sectional area (A_c* in Fig. 4) for that particular channel length. For areas less than the critical value, the inlet is unstable; i.e. an increase (decrease) in area causes an increase (decrease) in maximum velocity. For a tidal inlet to be naturally stable it must operate in the region $A_c > A_c$*; only in that region velocities increase with decreasing A, increasing the sediment transport rate and flushing of the channel.

If events result in the value of A_c to drop below A_c* the inlet is no longer stable because further decrease in velocities will result from a decreasing profile and the inlet will ultimately close (Escoffier, 1940).

Designing Improvements

In practice one is faced with: (1) stabilising an existing inlet either in anticipation of future development, or to rectify problems caused by development, or (2) designing a new inlet where no inlet existed before (rare in New Zealand).

The aim of inlet stabilisation is to achieve a permanent lateral location as well as cross-sectional stability. In the inner channels and gorge sections of the inlet, conditions are relatively simple because tidal currents are the major

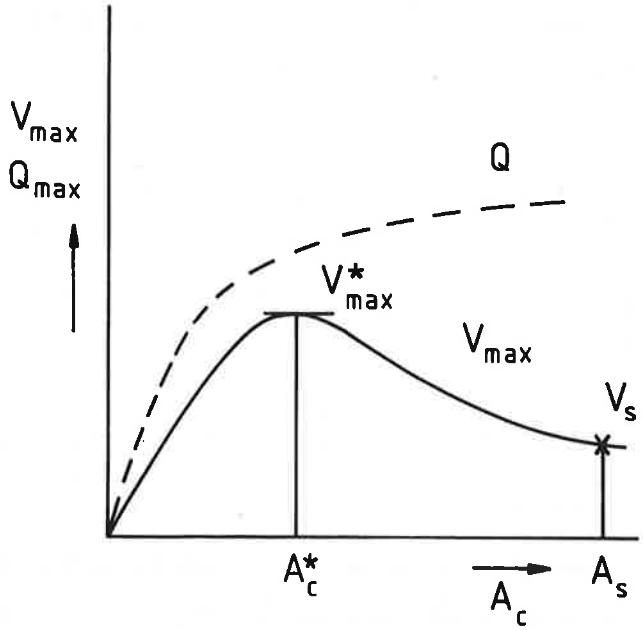


Figure 4. Escoffier closure curves. During closing both maximum velocities and maximum tidal discharges are changing: the velocities increase and the discharges decrease starting from an equilibrium position (A_s, V_s). After the critical region on the curve is reached (A_c*, V_{max}*), both velocities and discharges decrease until closure.

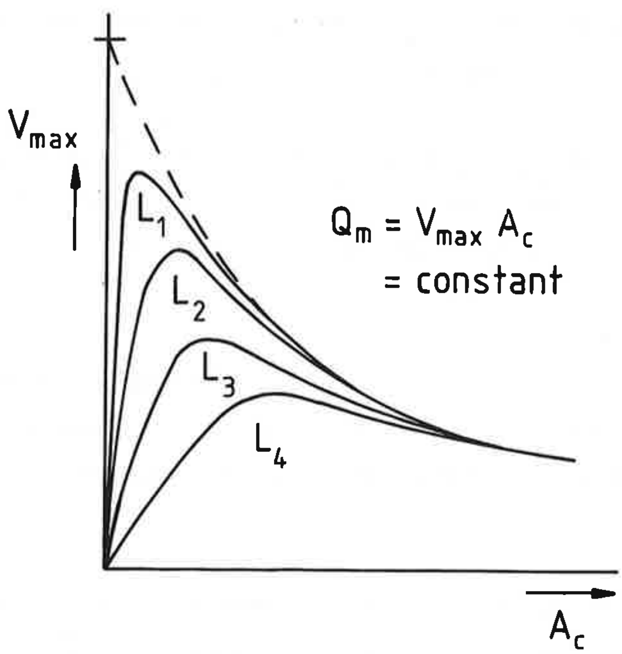


Figure 5. Closure curves for variable lengths (L) of inlet channel.

driving force and hydrodynamic models are successfully applied. However, the present state of numerical modelling does not permit detailed quantitative predictions of sediment transport and deposition seawards of the gorge. Even in simple situations where models may be applied, the necessary detailed field observation and calibration procedures will make them an expensive tool, often precluding their use.

The interim approach is therefore to use field measurements and well established numerical hydrodynamic models to calculate tide levels and currents, and to predict changes in bottom configuration from empirical relationships between the hydrodynamic parameters, littoral drift, and channel dimensions such as those described earlier. In practice, the method is applied as an iterative scheme where: (1) the changes in tide conditions are determined by field measurement and/or predicted from a hydrodynamic model; then (2) channel profiles and littoral drift are adjusted based on the empirical relationships between tide parameters and channel dimensions. In the process of improving inlets for navigation, adjustments are achieved using engineering works (eg, dredging, reclamation, building jetties, groynes, and weirs) that alter channel dimensions and littoral drift into the inlet. This process is repeated until stability conditions are fulfilled. Bruun (1978, p. 384-386) outlines this procedure.

In utilising techniques which are frequently applied overseas, we must bear in mind constraints imposed by the New Zealand scene. For instance, on the northeast coast of the North Island littoral drift is low ($<100 \times 10^3$ $m^3.y^{-1}$, Gibb 1978), and numerous headlands 'pocket' the coast into several reaches. Because the drift is low, the net annual drift can vary markedly in quantity and direction due to episodic storm events. Inlets formed between a rock headland and a barrier spit are common and provide important entrances to sheltered mooring areas. With the exception of several major ports there is little commercial development in the inlets; although there is increasing use by small inshore fishing craft, charter boats, recreational power boats, and yachts. However, there is usually little money for inlet improvements, and jetties are rare.

UTILISING EXISTING KNOWLEDGE AND TOOLS

Two key questions that could be addressed by this workshop are :

1 Are we making good use of existing knowledge and tools? If not, what is the best means of communicating the information to potential users?

The paper so far has demonstrated that there is considerable overseas information available on the subject of tidal inlet stability covering description, theory and engineering, and that only recently has detailed work begun in New Zealand.

2 Is the overseas information applicable to the New Zealand scene? Have New Zealand users tested it before application? Has it been applied correctly?

The area-prism relationship is one of the most universally applied techniques for assessing inlet stabilty. Application of this method provides examples for considering the above questions.

Example 1

For a range of 16 New Zealand inlets Heath (1975) determined:

$\Omega = A^{0.98}.10^{4.21}$ ($r^2 = 0.903$)

This relationship has since been applied to research and engineering situations (e.g. Kirk, 1981; Healy, 1981; Willet, 1982; Healy, 1983; McCabe, 1985; Paton, 1983) to assess the degree of inlet stability. For these applications inlets having a smaller A and/or a larger Ω than those predicted by the equation are designated "erosional", while those having a larger A or/or a smaller Ω are considered to be "depositional" inlets. However, in some cases interpretations have not been valid because the inlet in question has not plotted outside a specified confidence interval and also because comparisons are made beyond the original data field (Fig. 6).

Example 2

The predictive capability of area-prism relationships can be improved by identifying individual relationships for various estuary classes (Fig. 1). Recent analysis of 75 New Zealand inlets by the authors of this paper has shown that New Zealand inlets are best described by distinct A-Ω relationships (Fig. 7) that correspond to the major estuary classes. Power function transformations give improved correlations over linear, logarithmic or exponential regressions. The relationships are descriptive of the forces operating at the inlet. For instance, barrier enclosed lagoons on littoral drift shores have the lowest A-Ω ratio (i.e. smallest

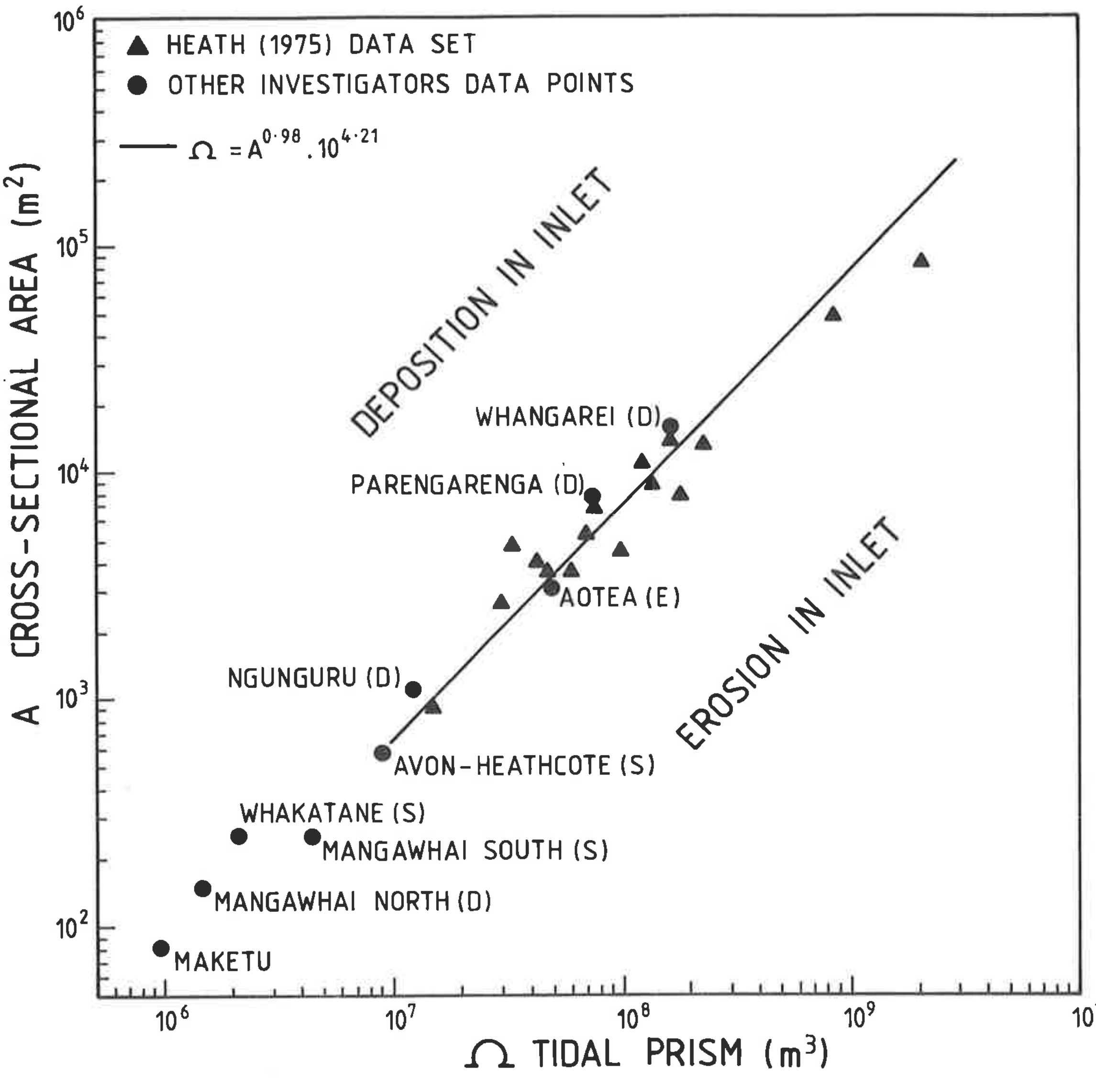
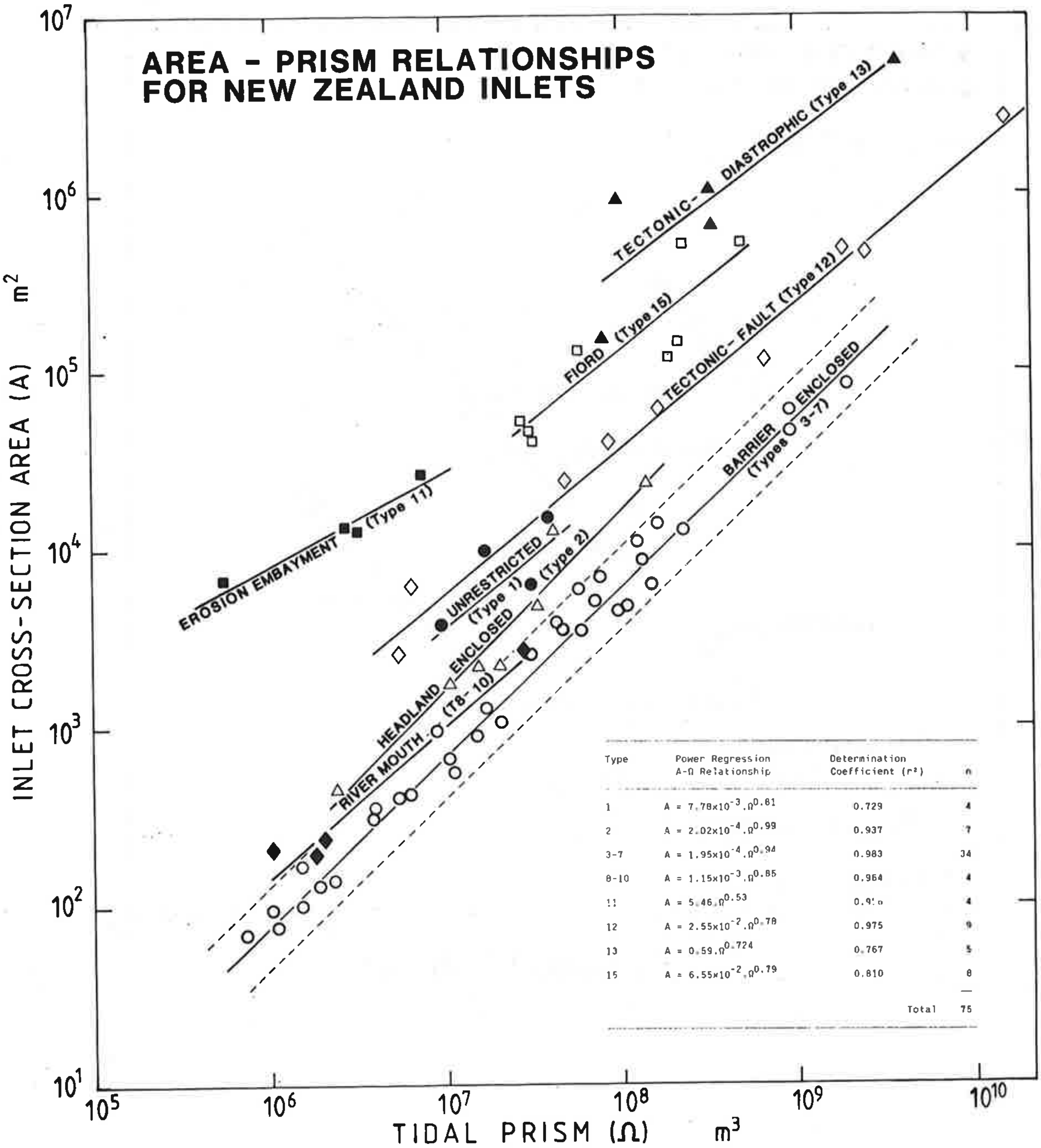


Figure 6. Interpretation by various investigators of the stability of some New Zealand inlets using the Heath (1975) relationship (S = interpreted as stable inlet, D = deposition in inlet, E = erosion in inlet).



Type	Power Regression A-Ω Relationship	Determination Coefficient (r^2)	n
1	$A = 7.78\times10^{-3}.\Omega^{0.81}$	0.729	4
2	$A = 2.02\times10^{-4}.\Omega^{0.99}$	0.937	7
3-7	$A = 1.95\times10^{-4}.\Omega^{0.94}$	0.983	34
8-10	$A = 1.15\times10^{-3}.\Omega^{0.85}$	0.964	4
11	$A = 5.46.\Omega^{0.53}$	[illegible]	4
12	$A = 2.55\times10^{-2}.\Omega^{0.78}$	0.975	9
13	$A = 0.59.\Omega^{0.724}$	0.767	5
15	$A = 6.55\times10^{-2}.\Omega^{0.79}$	0.810	8
		Total	75

Figure 7. Relationships between inlet cross-sectional area at mid tide (A),and mean spring tidal prism (Ω) for 8 different classes of inlet on the New Zealand coast (cf. Fig. 1). Dashed lines are 95% confidence intervals for an individual predicted point of the barrier enclosed class (Types 3-7).

inlet compared to tidal prism) reflecting continuous adjustments in inlet geometry made possible by sediment availability and strong tidal currents. At the other end of the spectrum are embayments of marine erosion and tectonic origins that occur on shores with negligible littoral drift and have comparatively wide inlets (high A-Ω ratio) because of weak tidal flows and low sediment availability.

FUTURE RESEARCH NEEDS

One of the aims of this workshop is to bring together the collective experience of those present to identify, for the Australasian situation, key areas for research on tidal inlet stability. In what areas do we need to do research or survey work to improve existing knowledge and tools? Suggested research and survey questions follow:

1 What is the role of extreme events (e.g. river floods, wave topping and barrier breaching, currents generated by extreme tides and effect on sediment transport of wave action on ebb tide delta) in determining inlet stability.

2 Should technical surveys, monitoring and documentation of the before and after situations of coastal developments be made to allow objective assessments of the effects on inlet stability?

3 What is the interrelationship between inlet-delta systems and adjacent barrier beaches.

4 What types of data do we need to collect (on a national basis) so that we can more fully understand how tidal inlets function and make better use of existing tools? (e.g. wave climate information to improve estimates of littoral drift, regular ground, or aerial photography surveys of inlet bathymetry).

5 What is the influence of marine benthic organisms (e.g. shell lags, diatom mats, and polychaete worms) on inlet stability? (Animal/sediment relationships).

6 What is the time-frame of events relating to location and cross-sectional stability?

7 Should further descriptive studies of different inlet types, their morphology and in particular the development of "situation-models" of inlets

which describe alterations in response to winds, waves and current forces be undertaken?

8 What is the best approach to application and testing of overseas models to the New Zealand scene?

TIDAL INLET STABILITY: WORKSHOP OPEN DISCUSSION

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The workshop discussion has been summarised under five themes. Technical papers referred to in the discussion are presented in Appendix III.

Empirical Relationships

1. The empirical relationships presented in the position paper were the focus of initial discussions, in particular the use of the area-prism relationship (Fig. 6). Initially the concept of 'stability' was discussed. It was agreed that stability refers to a state of dynamic equilibrium because all inlets make constant adjustments in inlet cross-sectional area in response to changes in physical parameters such as tidal flows and littoral drift. One school of thought was that those inlets conforming to the empirical relationship, and lying within the confidence limits, were 'stable', while those outside these bounds were 'unstable' and characterised by deposition or scour in the inlet. The other view was that a 'stable' inlet was one that if disturbed by an event such as a sudden influx of littoral sand, would plot off the line, but would respond by adjusting area and prism to move back onto the line. Whereas an 'unstable' inlet would show no recovery and keep moving to a situation of total closure or increasing throat area. D. Foster quoted an example of the latter circumstance from the Forster-Tuncurry entrance on the coast of New South Wales. Here, groyne entrance works resulted in an increase in tidal prism and inlet velocities which scoured the bed, increasing the throat cross-sectional area. Inlet velocities have in turn increased, the throat continues to scour and the situation is very unstable. This situation is likely to continue until the tidal range in the inlet reaches that of the ocean.

Prof. Gerritsen related the 'stability' concept back to the Escoffier curve described in his opening address (Appendix III). For the case of a tidal inlet connecting the ocean with the bay or lagoon, the velocities in the inlet depend

heavily on the forces from the bay. By plotting the maximum velocity against the gorge area of the inlet cross-section, then in normal conditions we usually find that a stable cross-section and a stable velocity belong together.
If the inlet closes, either by man or by nature, then the velocity increases and generally a curve develops, as described by Escoffier (1940), the so-called Escoffier Curve (Fig. 4). Observation of this curve shows there are generally two points with the same velocities, but quite different areas - an area that is stable (A_S) and an area that might look stable but is not stable. The reason being that, if on the right-hand side of the curve the velocity increases because of a natural event, for example a storm or hurricane dumps a slug of sand in the inlet and the cross-section decreases, then with increased velocity there is increased flushing capacity which tends to open it up again. In this way there is a tendency for the inlet to reach equilibrium. For the left-hand side of the curve, there is the situation where cross-sectional area is decreasing because of a natural event, leading to decreasing velocities and further area decrease. So the right-hand side of the curve is a stable curve because it tends to bring that situation to natural stability.

A-P relationships were first derived by O'Brien in 1931. However, there are other ways of plotting the data which are equally meaningful. One is to plot cross-sectional area versus $V_{mean\ max}$, the reason being that this velocity is an important parameter affecting sediment transport. It is also useful from an interpretive point of view to indicate the sediment grain size against each point on the plot. This gives a relationship that is more descriptive of the hydraulics of the situation. Inlets with low velocities tend to be typical of low littoral drift coasts, whereas high velocities are an indirect indication of significant sediment supply. $V_{mean\ max}$ velocities are typically in the order of 0.8-1.0 $m.s^{-1}$ for 'equilibrium' inlets, however they may be lower than this for certain inland waters.

2. Some speakers warned of reading too much into empirical relationships, particularly when used as predictive tools. For instance there are field errors involved in measuring area and tidal prism, particularly if the data are taken off bathymetric charts (the latter method should only be used as a first approximation). R. Nelson, referring to a three year study of the Barwon Heads inlet Victoria, Australia (see Nelson and Keats, 1980 in Appendix II), cautioned that the antecedent conditions that applied at the time of measurement markedly influenced such relationships. Their data showed that statistical uncertainties associated with predicting an inlet's equilibrium area from existing equilibrium equations are similar to those associated with the natural variability in throat dimensions of an inlet. That is to say, much of the scatter of the data could be accounted for by antecedent conditions which would be different for each inlet. Thus, attempts to refine equilibrium equations will not be profitable unless the response of individual inlets to various hydraulic and meteorologic events (floods, storms etc) is known.

3. While empirical models are one approach, it is important that more effort be applied to understanding and developing the more complex hydrodynamic theories behind these relationships. One obvious example is the Ω/M_{tot} ratio. What is that interplay between tidal prism and littoral drift that keeps an inlet open or shut? The Ω/M_{tot} ratio obviously affects the area-prism relationship.

It was noted that of all the empirical equations presented none had grain size represented in them. While this is not a problem when one is comparing inlets of similar sediment characteristics, it is indicative of the simplicity and potential shortcomings of the approach. We need to be developing models that take into account more of the variables that dictate inlet stability namely, littoral transport, fluvial sediment, stochastic freshwater inflow, grain size and density and tidal flow. Initially we need a better understanding of the physics of these processes, a point highlighted in Prof. Gerritsen's opening address (Appendix III). T. Healy gave an example of the problems in sediment transport modelling on North Island coasts where sediments are frequently bimodal (often biogenic and terrigenous components present) and particle density may vary markedly due to the predominance of pumiceous, quartzofeldspathic or magnetitic sands.

It is also important that inlet modelling improve the formulation of two-dimensional processes, rather than persue the simpler one-dimensional approach described earlier. This is particularly relevant considering that inlet processes are two-dimensional, littoral drift enters the inlet asymmetrically and flows across the inlet are two-dimensional. J. Hinwood described a model developed at Florida a few years ago which divided the entrance area into about six boxes or elements. In the two or three seaward boxes the effect of wave action in stirring sediment was considered so that a different critical threshold speed was used. This did in fact provide a difference between a shallow and a deep entrance area. The shallow inlet experienced relatively more stirring under the same wave action as the deep one. This model is a start on the two-dimensional approach, which is the only way to take into account some of the higher order variables.

Such an approach can overcome some of the difficulties seen in situations where the critical velocity (at least according to some criteria) appears to be achieved in a stable channel, and yet the channel is known to have regions of very high transport in different directions. So, the averaging being performed appears to be misleading us quite severely about the dynamics. We are trying to homogenise a problem that is dramatically non-homogenous.

4. T. Healy saw the need to improve the conceptual models of inlet processes. A method by which this could be achieved is by examining the data from studies where detailed field measurements had been made to calibrate numerical models.

Conclusions

1 Do not rely too heavily on empirical relationships, they are an over-simplification of complex processes. They are not magic formulae.

2 Be aware of the errors involved in field measurement of bathymetric and hydraulic parameters and how they influence accuracy of models.

3 Work towards incorporating empirical relationships into more complex hydraulic models that take account of the system in a two-dimensional sense.

4 Try and develop better conceptual models.

MORPHOLOGICAL CONTROLS ON INLET STABILTY

There was a short discussion on the influence of morphological controls on inlet stability. It was queried as to whether some degree of 'relative stability' was indicated by the fact that large New Zealand estuaries commonly have throats, 30 m or more deep, with a well defined entrance gorge, whereas small inlets tend to be much flatter in cross-section. One opinion was that the deep gorge of large inlets could be accounted for by the presence of a rock headland on one side of the inlet and the flatter profiles of small inlets equated with double-spit entrances. T. Hume reported that for inlets on the north-east coast of the North Island, inlet profile appears to be unrelated to estuary size. Small estuaries ($\Omega<10^6 m^3$) virtually all have a rock headland on one side and double spits are rare (and often temporal). These inlets show the entire range of flat symmetrical cross-sections through to asymmetrical inlets where there is a clearly defined gorge. Furthermore bed sediments range from extensive lag deposits across some throats (e.g. Whangateau) to mobile dune bedded sands (e.g. Whangamata) across others indicating a wide range of stability.

Conclusions

1 No distinct and consistant geomorphological controls on inlet stability are apparent from existing experience.

2 Some such controls are suspected, but more detailed field work and analysis are needed to define them.

RELATIONSHIP BETWEEN ESTUARIES AND THE INNER CONTINENTAL SHELF

The workshop discussed the relationship between sediments of the inner shelf and those of the inlet delta system. Sometimes in considering coastal sediment supplies to the delta systems we are inclined to consider littoral drift and ignore the role of across shelf (shore normal) sediment transport that can feed inner shelf sands to the littoral system.

These processes have been reported acting on the Coromandel Peninsula (Dell et al., Appendix III) and Bay of Plenty (Dahm and Healy, Appendix III) coasts, New Zealand, in papers at this conference. The inshore zonation of sediments along much of the pocketed, low littoral drift, east Coromandel coast, consists of a medium (to coarse) sand beach, a fine sand sea floor with small-scale symmetrical ripples down to 20 m depth, and a more complex zone of sediments between 20 and 40 m depth dominated by medium to coarse sands with symmetrical megaripples, but incuding patches of fine sand. Beyond 40-50 m depth muddy very fine sand deposits occur. It is postulated that during onshore storm swells the megarippled coarse sediment can move shoreward under the influence of bottom mass transport, certainly to depths of 20 m, probably shallower and perhaps onto the beach. The dynamics of these processes are still being investigated. Once in the littoral system the medium sands can nourish the inlet bar systems.

M. Geary and A. Griffin reported a similar zonation of sediments on the New South Wales coast, Australia. Here there is a gradual fining offshore from the medium beach sands, or alternatively there is an indistinct break between the medium and fine sands at depths anywhere between 5-25 m. Several kilometres out relict coarse deposits or very coarse sand, and fairly large lobes of sand have been reported in depths ranging from 30-50 m. Alternatively there may be fine sands to fine muds near the shelf edge. There does not appear to be active exchange of sediment between the medium beach sands that comprise the majority of shoals associated with the outer parts of inlets and the inner shelf fine sand facies. However the situation is very complicated and the pattern varies on different parts of the coast. For instance, the north coast of New South Wales is a highly dynamic, sandy littoral coast with fairly high littoral drift rates. Whereas the south coast is far more pocketed with less drift. Changes in ocean current patterns and bathymetry between the two areas combine to make the offshore sediment facies different.

Conclusions

1 Across-shelf sediment transport appears to be an important mechanism for supplying sand to the littoral zone to nourish beaches and inlet bar systems.

2 This appears to be particularly true on coasts of low longshore drift.

3 Further research is necessary to investigate the processes in more detail.

THE ROLE OF EXTREME EVENTS

1. J. Hinwood reported a project of the National Committee on Coastal and Ocean Engineering (Australia) that ran for about four years. The scheme was set up to produce reports on extreme events, and to define a few typical events. For instance a storm on a catchment that drained to an estuary, and was accompanied by strong winds producing waves and surge on the coast. While not specific to tidal inlets they contain information on inlet response to such events.

The Committee identified a Government department, usually as a lead agency, to gather data and to contact organisations beforehand to determine their general willingness to assist. Immediately following the event, a member of the National Committee and one or two staff members from the lead organisation attempted to assemble all the relevant information. This information included meteorology, stream gaugings, actual site observations and hydrographs. They also attempted to get into the field to assess the damage and other storm effects of an engineering interest that had occurred and would not otherwise have been recorded.

It proved fairly onerous, for an essentially volunteer operation. The organisations backing it had some difficulty in tying it to a specific project for costing and budgeting purposes, which is perhaps the reason the project lapsed. It did result in half a dozen reports on extreme events that are quite useful. Several reports were produced and are lodged with the Institute of Engineers (Australia) Library. There were only a few copies of each report produced; copies could be obtained by contacting the Institute of Engineers Library in Canberra. These reports are also held in the library of the Water Research Laboratory at the University of New South Wales.

2. Floods, as distinct from storms, can also have a very significant impact in modifying the inlet entrance shoals by dumping large quantities of sand on the seaward face over a few days. This rapid advance is followed by slow shoreward migration of the sand under tidal action over 12-18 months or more. Because shoal formation, rather than gorge depth, is a major consideration from the navigation standpoint it is important to research and model shoal geometry and the response to extreme events.

It was noted that changes in inlet throat profile tend to manifest themselves more as a deepening rather than a widening when scour is predominant. Conversely, large amounts of sediment from catchment erosion, can be dumped in the throat restricting navigation, necessitating dredging.

3. Tsunamis, storm surge and wave set-up were identified as 'floods' of marine origin that could enter inlets generating extreme water levels, resulting in significant increase in tidal currents and sediment transport. Tsunamis in particular, although rare events, present extreme conditions in shallow estuaries with a large expanse of tidal flats. For instance a tsunami of about 5 m in Tauranga Harbour (New Zealand) would result in an increase in tidal prism of 300-400%. On the Australian and New Zealand east coasts storm surge and wave set-up is common but generally less than 0.5 m. No-one could report knowledge of field measurements on the topic, however theoretical calculations were possible, and it was considered to be a poorly appreciated effect.

It was pointed out that phenomena that cause an increase in water velocity are likely to have an enormous effect on sediment transport because sediment transport increases as the 3rd-6th power of current velocity (depending which formula is used). Other accompanying effects include salinity intrusion which can markedly influence sedimentation patterns in an estuary.

Conclusions

1 Most workers intuitively recognise the important role of extreme events,

such as floods, storms and tsunamis, on inlet stability.

2 Documenting the hydraulic and sedimentological affects of such events has proved extremely difficult.

3 Documentation of case studies and eventually modelling inlet response to events, and subsequent recovery under normal tidal regime is an important area for future research.

ESTUARY MANAGEMENT AND THE EFFECTS OF ENGINEERING WORKS

1. One of the primary management concerns is that inlets remain as navigable waterways and be unaffected by engineering works, particularly in the shallow flood and ebb tide shoal area. This is of paramount importance rather than gorge depth. All are part of the inlet system. Several case histories were described to demonstrate the possible effects of engineering works on the inlet.

Prof. Gerritsen described large scale dredging that was undertaken at the entrance of the Western Scheldt, the entrance to the Port of Antwerp. Large quantities of sand were removed from the delta, and the effects were very clear on the inner delta and the estuary. By changing the depth of the delta, the whole of the estuary, as well as the inner delta, was affected.

Another good example is the development of the Dutch Rotterdam Waterway, the waterway between Rotterdam and the North Sea. In the period from 1906-1956 the waterway was doubled in size and in tidal prism, partly because of dredging operations, but also partly because after dredging the river lost its natural stability and started to deepen naturally. The examples demonstrate that one has to be careful, because it is easy to displace the equilibrium situation by carrying out dredging or training works in the estuary.

A comprehensive study was made of the effect of dredging in the Tweed River (New South Wales) some years ago, which is reported in the 1980 Proceedings of the International Coastal Engineering Conference. One million cubic metres of sand was taken out of the lower reaches of the Tweed River (the marine wedge, or the part that is the equivalent of the flood delta area) to nourish the updrift Kirra Beach. The net result of these estuary works was a dramatic increase in the net littoral feed into the estuary, and the entrance bar growth. In some respects, by taking the inlet sand to nourish Kirra Beach, if it is accepted that there was a littoral drift deficit, the operation 'robbed Peter to pay Paul'. The ultimate bypassing of the Tweed breakwater, which is now believed to be taking place, was deferred for some eight to nine years because of the impact of this dredging on the estuary.

Some engineering works have little effect on tidal inlet stability. As part of oil refinery terminal expansions at Whangarei Harbour, the Northland Harbour Board dredged the shipping channel through the ebb-tidal delta. Since then the ebb-tidal delta and shipping channel have been exceptionally stable, and has required no maintenance dredging in about 20 years. Reasons for this are that part of the dredge cut was through soft sandstone rather than mobile sands. But more importantly there is a very low sediment budget in the harbour and a very high biological productivity, so that there are tremendous numbers of bivalve shells which form a channel lag deposit and make it very stable.

2. T. Hume emphasised the important role of biological material in stabilising an inlet, but that this role is poorly understood and often unrecognised. In Whangarei Harbour shell material armours and stabilises the inlet. The estuary is the location of growing commercial exploitation of shellfish for the local and overseas markets. The management problem is to define the quota of shellfish for harvest when shellfish provide an important source of material for stabilising the inlet throat. Furthermore there is the problem of the oil refinery on the sand spit at the inlet throat. A major chemical spill from the refinery could kill off large numbers of shellfish, producing a large supply of shell material to the inlet. But what would be the long term supply? Inlet stability in this case is closely linked with biological productivity, making the situation very complex. W. de Lange made the point that densely packed beds of live shell fish can also provide a stabilising influence. Manzenrieder describes these phenomena (Appendix III).

3. Ways of predicting the effects of engineering work on the inlet system have been described in the background paper and were addressed at the workshop. In particular those changes that occur over shallow inlet bar systems.

The simplest means of prediction is by extrapolating case history data from one inlet to another. Good monitoring of the effects of engineering works is essential to facilitate this. The development of conceptual models , from aerial photograph and bathymetric data, of inlet morphometric changes in response to natural events and engineering works is another approach. Another way is by full hydrodynamic analysis of the situation by making tidal calculations, coupled with sediment transport equations. These, of course, have some limitations because of the lack of accurate knowledge about the sedimentation processes (see Gerritsen, Appendix III).

Another approach is by using empirical equations (see background paper) in conjunction with a hydraulic or numerical model. In this way one can actually model the general physical processes by incorporating the flow/cross-section dimension relationships determined for a particular area. By way of example, a study of 135 estuaries in New South Wales (about 1/3 of those were trained) looked at the relationship between gorge areas and depth over the entrance bar, i.e. the ruling depth which a mariner negotiates. A workable relationship was found, using plots, similar to those for area-prism, in terms of the depth in the gorge and the depth on the bar. The ruling depth on the bar was about half the depth in the gorge, based on spring tide flows.

Conclusions

1. Poorly planned engineering works such as dredging, reclamations and jetties can have a significant effect on inlet stability.
2. Conceptual and simple empirical models provide a ready means of assessing the likely impacts.
3. These are best used in conjunction with more sophisticated numerical and physical models.
4. Further research is needed to understand and quantify the physical processes.

CONCLUDING REMARKS (Prof. F Gerritsen)

I would like to address a few questions that were mentioned, just to give my viewpoint on some of these areas of interest. We have been talking about different solutions of the tidal inlet problem. I think they can be categorised as three basic approaches, as I mentioned in my (keynote) speech. There is the empirical approach which so far has given us the most support, because it gives some solid data. Then there is the semi-empirical or semi-theoretical approach in which we combine theoretical approaches with some physical data. Then, of course, there is the third approach, the hydrodynamic approach, that Dr Healy wanted to see developed.

I think that this is what we would all like to see, and that is the way we should go. I think we have to move toward a direction in which we try to define a stability problem as a hydrodynamic problem; where we have the effect of the closure on the tide, and the effect of the tide on the closure of the inlet and the stability, as well as the diameter of the sediment, and the equations of motion for the fluid and the sediment. They are all taken into account to arrive at the solution, which is the basic equilibrium condition.

I think we all realise that this is the goal toward which we should aim. We are still far from that solution. We have seen from our discussions here that the problem is very complex, and that there are different ways of looking at it from different points of view.

In the discussion, the relationship between tidal prism and inlet cross-sectional area was emphasised. In a recent study that we did in Holland for the Western Scheldt, we have looked at some other parameters like the maximum tidal flow, the maximum currents and the stability shear stress on the equilibrium profile. We feel that the tidal prism is a good measure, but there is also the maximum flow which is an equally good measure of stability, and can be used in certain conditions.

The semi-empirical approach gives the advantage in combining some theoretical work with some empirical work and I think the solution in which we use the stability shear stress has some advantages, because there again some theoretical aspects come into play like the Chezy coefficient, the diameter of the particles and some other elements of interest, the depth of flow for instance. They are all components of stability shear stress, and therefore affect the stability equation. We have also shown that by using, for instance, the Bijker formula, calculating transport from the combined effect of waves and currents, one can actually modify the stability shear stress for areas outside of the gorge, which are heavily affected by waves and in doing so, one can actually include areas heavily affected by waves into the stability equation, in the same way as we do for inlet gorges.

We also found that for the inner delta, the channels of the inner delta also behave very nicely in terms of statistical relationships.

In terms of the maximum velocity, we found that it might not be as good a measure as we had hoped it would be. We found, for instance, that the mean velocity over a tidal cycle is in some ways a better representation, and we found a very strong relationship between the mean velocity and the hydraulic radius or depth of the channel, as a stability measure. That, of course, is also related to the diameter of the particles and to certain conditions that may not always remain the same.

Thank you for the opportunity to address the closing of this workshop.

APPENDIX I. LIST OF WORKSHOP PARTICIPANTS

Name	Organisation	Town	Country
Abbott, J	Kingston, Reynolds, Thom & Allardice (Consultants)	Auckland	New Zealand
Apelt, C	Dept Civ. Eng., Univ. of Queensland	St Lucia, Qld	Australia
Bartlett, J	Port Stephens Shire Council	Raymond Tce, NSW	Australia
Bewick, D	Water & Soil Div., MWD, Head Office	Wellington	New Zealand
Bowen, D	Port of Launceston Authority	Launceston, Tas	Australia
Brewer, I	Northland Harbour Board	Whangarei	New Zealand
Britton, G	Sinclair, Knight & Ptners (Consultants)	Sydney, NSW	Australia
Brock, R	Port Stephens Shire Council	Raymond Tce, NSW	Australia
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Burns, N	Water Quality Centre, MWD	Hamilton	New Zealand
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Busch, L	Christchurch City Council	Christchurch	New Zealand
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Carter, D	Wellington Harbour Board	Wellington	New Zealand
De Lange, W	Dept Earth Sciences Univ. of Waikato	Hamilton	New Zealand
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Geary, M	Public Works Dept Univ. of NSW	Sydney, NSW	Australia
Ford, L	Beach Protection Authority	Brisbane, Qld	Australia
Gerritsen, F	Dept of Engineering, Univ. of Hawaii	Honolulu, Hawaii	USA
Gregory, M	Dept of Geology, Univ. of Auckland	Auckland	New Zealand
Griffin, A	Public Works Dept	Sydney, NSW	Australia
Haradasa, D	Water Research Laboratory Univ. of NSW	Manly Vale, NSW	Australia
Hastie, W.	R W Morris and Assoc. (Consultants)	New Plymouth	New Zealand
Healy, T	Dept Earth Sciences, Univ. of Waikato	Hamilton	New Zealand
Herdendorf, C	Water Quality Centre, MWD	Hamilton	New Zealand
Hilton, M	Leigh Marine Laboratory (Univ. of Auckland)	Leigh	New Zealand
Hinwood, J	Dept of Mechanical Eng., Monash University	Clayton, Vic.	Australia
Holland, L	Waikato Valley Authority	Hamilton	New Zealand
Hughes, S	Nelson Harbour Board	Nelson	New Zealand
Hume, T	Water Quality Centre, MWD	Hamilton	New Zealand
Hutchinson, P	Bruce Wallace Ptnrs (Consultants)	Auckland	New Zealand
Jackson, A	Gold Coast City Council	Gold Coast, Qld	Australia
Jarvis, R	Dept Harbours & Marine	Brisbane, Qld	Australia
Johnston, M	Rangitikei-Wanganui Catchment Board	Marton	New Zealand

Name	Organisation	Town	Country
Lauder, G	Dept Geography, Univ. of Canterbury	Christchurch	New Zealand
Leman, J	Wilkins & Davies	Auckland	New Zealand
Lesleighter, E	Snowy Mountains Engineering Corporation	Cooma, NSW	Australia
McBryde, D	Nelson Catchment Board	Nelson	New Zealand
McCabe, P	Tonkin & Taylor Ltd (Consultants)	Newmarket, Auckland	New Zealand
Monro, I	Murray-North & Monro (Consultants)	Auckland	New Zealand
Nelson, R	Civ. Eng. Dept., Univ. College (UNSW), Australian Defence Force Academy	Canberra, ACT	Australia
Nittim, R	Water Research Laboratory Univ. of NSW	Manly Vale, NSW	Australia
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Robertson, B	Otago Catchment Board	Dunedin	New Zealand
Service, B	Townsville Harbour Board	Townsville, Qld	Australia
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Wells-Green, P	Auckland Harbour Board	Auckland	New Zealand
Wynne, T	Dept of Environment & Planning	Adelaide, SA	Australia

Total Attendees: 57

APPENDIX II
TIDAL INLET STABILITY:
A BIBLIOGRAPHY 1975-1985

C E Herdendorf, T M Hume and J H Burton

Water Quality Centre
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Hamilton

The purpose of this bibliography is to bring together a list of references dealing with tidal inlet stability. There is a wealth of information on this subject in the scientific and engineering literature.

LISTING PROCEDURE

The bibliography contains :

1 A section of 32 pre-1975 publications on tidal inlets, considered "classics" on this subject by the compilers of this bibliography and,
2 Important 1975-1985 overseas publications, combined with a more exhaustive list of New Zealand works on this and related topics.

In both lists the references are set out in alphabetical order and chronologically by author. The references are also listed, by number, to facilitate a subject index at the end of the listings.

ASSESSMENT

An assessment of recent directions in tidal inlet research was attempted by analysing publication trends in this field for the past 10 years. Several types of scientific literature were canvassed, including :

1 Books;
2 Journal articles;
3 Conference proceedings;
4 Agency and consultation reports, and
5 University theses.

Because of our own particular needs and library resources, the literature search was biased toward New Zealand. Available literature was assembled and categorised based on the research emphasis into the following 11 topics :

1 Descriptive investigations.
2 Case studies (natural situations).
3 Case studies (engineering assessments).
4 Process studies (hydrology).
5 Process studies (sedimentology).
6 Process studies (biology).
7 Empirical methods.
8 Numerical models.
9 Physical models.
10 Engineering or management applications.
11 Comprehensive or synthesis reviews.

Books

In the past decade no less than 25 books have been published which deal exclusively with tidal inlets or have major chapters devoted to this topic. A few of these are regional in nature, but most utilise information from a wide spectrum, of geographic settings.

Scientific Journals

Preliminary review of the literature indicates that normally between 20-25 relevant papers are produced annually by researchers working on inlet stability problems. Papers dealing with various aspects of tidal inlet stability have appeared in at least 24 scientific journals. The following is a list of the 10 main journals (ranked by frequency) in which articles on this topic were published between 1975 to 1985:

Journal of Waterways, Ports, Coastal and Ocean Engineering (supersedes Journal of Waterways, Ports, Coastal and Ocean Division, ASCE)
Marine Geology
Estuarine, Coastal and Shelf Science (supersedes Estuarine and Coastal Marine Science)
New Zealand Journal of Marine and Freshwater Research
Journal of Sedimentary Petrology
Sedimentology

Sedimentary Geology
Shore and Beach
Coastal Engineering
Journal of Physical Oceanography

Conference Proceedings

Several conferences have been held which featured sessions on tidal inlets. The Coastal Engineering Conferences (normally held every two years) of the American Society of Civil Engineers are the most noteworthy along with several specialty symposia organised by the Waterways, Ports, Coastal and Ocean Division of the same society. A high percentage of the papers presented at these meetings deal with engineering case studies and applications. Because the meetings have been held at cities throughout the world, the proceedings have a wide geographic representation.

Agency and Consultation Reports

Agency and consultation reports are often among the most difficult to obtain, but can be very useful from a practical application point of view. The US Army Corps of Engineers, Coastal Engineering Research Center (Virginia) and Waterways Experiment Station (Mississippi) are exceptions in that their reports are distributed widely. In New Zealand, the Ministry of Works and Development and the New Zealand Oceanographic Institute are the leading agencies in publishing reports on various aspects of tidal inlet stability.

University Theses

In New Zealand, the bulk of research on tidal inlet stability has been undertaken as part of university research, notably by the Earth Sciences Department of Waikato University. To date the work has been descriptive and largely part of broader estuary research that has been undertaken on an estuary-by-estuary basis.

CONCLUSIONS

Table A.1 presents the percent frequency in which eleven common research topics of tidal inlet stability have appeared in books, journals, conference proceedings, agency reports, and theses over the past ten years. Descriptive investigations and case studies of natural situations provide 42%, while case studies of engineering works and applications add another 16%. Process research on sedimentology and hydrology of tidal inlets account for nearly 30%

of publication record. Empirical methods and numerical models result in 7% and comprehensive reviews are 3%. Together biological process studies and physical model investigations account for less than 2% of the publications. Books tend to be more heavily weighted toward synthesis reviews and applications while journals are strongest in process research. Conference proceedings and agency reports emphasise the engineering aspects, while theses are a mixture of descriptive and process research.

TABLE A.1

DISTRIBUTION OF RESEARCH TOPICS ON TIDAL INLET STABILITY PUBLISHED IN VARIOUS FORMS 1975-1985

RESEARCH TOPICS		BOOKS	JOURNALS	PROCEEDINGS	REPORTS	THESES	TOTAL*
1	Descriptive investigations	18.6%	24.8%	18.9%	12.3%	20.3%	53.7%
2	Case studies (Natural situations)	14.8%	29.2%	27.0%	15.3%	23.7%	59.5%
3	Case studies (Engineering assessments)	8.3%	4.8%	10.0%	8.2%	1.7%	18.3%
4	Process studies (Hydrology)	11.1%	11.6%	8.9%	16.3%	18.7%	32.3%
5	Process studies (Sedimentology)	17.6%	17.6%	13.0%	17.3%	23.7%	45.1%
6	Process studies (Biology)	0.9%	0.0%	1.2%	2.0%	3.4%	2.7%
7	Empirical methods	8.3%	4.49%	7.1%	6.1%	0.0%	14.8%
8	Numerical models	0.9%	0.8%	2.4%	3.1%	1.7%	4.3%
9	Physical models	0.9%	1.6%	0.6%	2.0%	0.0%	1.7%
10	Engineering or management applications	9.3%	4.0%	14.2%	13.3%	6.8%	23.7%
11	Comprehensive or synthesis reviews	9.3%	1.2%	3.0%	4.1%	0.0%	8.6%

*Some publications are listed under more than one topic

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INDEX OF SELECTED TOPICS 1975-1985

1 Descriptive Investigations

2 Case Studies (Natural Situations)

3 Case Studies (Engineering Assessments)

4 Process Studies (Hydrology)

4, 5, 11, 12, 13, 20, 22, 29, 35, 40, 43, 44, 45, 46, 53, 54, 58, 60, 61, 65, 68, 69, 70, 78, 79, 80, 81, 88, 89, 92, 94, 95, 96, 98, 99, 101, 106, 107, 109, 111, 114, 119, 129, 130, 131, 133, 143, 146, 150, 152, 161, 165, 166, 169, 170, 179, 181, 186, 187, 189, 194, 195, 196, 203, 206, 207, 215, 216, 222, 224, 225, 226, 230, 236, 238, 251, 253, 254, 255, 256.

5 Process Studies (Sedimentology)

1, 2, 3, 6, 10, 11, 12, 13, 14, 18, 20, 22, 23, 28, 29, 32, 34, 35, 37, 38, 39, 40, 41, 42, 43, 44, 45, 47, 52, 58, 59, 60, 62, 63, 64, 66, 67, 71, 72, 73, 74, 75, 76, 77, 80, 81, 84, 85, 88, 89, 92, 101, 105, 106, 108, 109, 111, 113, 119, 125, 128, 129, 130, 131, 132, 136, 138, 146, 148, 150, 152, 155, 158, 159, 161, 163, 164, 165, 169, 170, 171, 174, 178, 181, 182, 183, 185, 187, 188, 189, 190, 192, 194, 195, 198, 199, 201, 207, 208, 213, 214, 215, 216, 217, 219, 223, 230, 234, 236, 246, 252, 253, 255, 256, 257.

6 Process Studies (Biology)

35, 92, 155, 159, 165, 194, 235.

7 Empirical Methods

7, 15, 25, 27, 33, 35, 50, 53, 61, 69, 82, 89, 90, 93, 94, 113, 118, 131, 132, 134, 149, 149a, 156, 180, 193, 209, 210, 218, 219, 227, 233, 235, 238, 240, 242, 247.

8 Numerical Models

4, 11, 12, 35, 40, 101, 184, 185, 204, 212, 240.

9 Physical Models

102, 116, 117, 151, 168, 187, 213, 235.

10 Engineering or Management Applications

5, 7, 8, 11, 12, 19, 20, 21, 22, 24, 25, 26, 34, 40, 49, 50, 52, 54, 74, 76, 82, 87, 88, 89, 92, 97, 108, 118, 120, 121, 126, 128, 131, 132, 149, 150, 154, 160, 162, 165, 167, 170, 176, 180, 185, 192, 193, 196, 217, 219, 220, 221, 223, 232, 233, 235, 243, 249, 250, 252, 253.

11 Comprehensive or Synthesis Reviews

26, 35, 41, 45, 55, 91, 96, 109, 111, 118, 120, 131, 155, 172, 175, 177, 202, 219, 220, 233, 235, 243

APPENDIX III

TECHNICAL PAPERS ON THE SUBJECT OF TIDAL INLET STABILITY PRESENTED AT THE 1985 AUSTRALASIAN CONFERENCE ON COASTAL AND OCEAN ENGINEERING

Preprint Volume I

WATER AND SOIL TECHNICAL PUBLICATIONS

1.	Liquid and waterborne wastes research in New Zealand, 1976. ($2.20)	1977
2.	Sampling of surface waters. ($2.20)	1977
5.	Late quaternary sedimentary processes at Ohiwa Harbour, eastern Bay of Plenty with special reference to property loss on Ohiwa. ($2.20)	1978
11.	The Waikato River: a water resources study. ($13.20)	1979
12.	A review of the habitat requirements of fish in New Zealand rivers. ($5.50)	1979
13.	The Ruahine Range: a situation review and proposals for integrated management of the Ruahine Range and the rivers affected by it. ($8.80)	1978
14.	A survey of New Zealand peat resources. ($11)	1978
15.	Effects of urban land use on water quantity and quality: an annotated bibliography. ($11)	1980
17.	Investigations into the use of the bacterial species *Bacillus stearothermophilus and Escherichia coli* (H_2S positive) as tracers of groundwater movement. ($2.20)	1980
18.	A review of some biological methods for the assessment of water quality with special reference to New Zealand. Part 1. ($4.40)	1979
19.	The frequency of high intensity rainfalls in New Zealand, Part I. A. I. Tomlinson. ($8.80)	1980
20.	Regional flood estimation in New Zealand. ($11)	1982
21.	Coastal hazard mapping as a planning technique for Waiapu County, East Coast, North Island, New Zealand. ($8.80)	1981
22.	A review of some biological methods for the assessment of water quality with special reference to New Zealand. Part 2. ($4.40)	1981
23.	Hydrology of the catchments draining to the Pauatahanui Inlet. ($5.50)	1981
24.	Potential for contamination of the Heretaunga Plains aquifers. ($11)	1982
25.	Revised checklist of freshwater algae of New Zealand. Part 1. ($11)	1984
26.	Revised checklist of freshwater algae of New Zealand. Part 2. ($11)	1984
27.	Shoreline fluctuations and an assessment of a Coastal Hazard Zone along Pauanui Beach, Eastern Coromandel Peninsula, NZ. ($22)	1986
28.	Aquatic toxicity tests: comparative assessment of four acute tests and their potential application in N.Z. ($8.80)	1987

WATER AND SOIL MANAGEMENT PUBLICATIONS

1.	Regional planning and development. ($2.20)	1975
2.	Wetlands. ($2.20)	1975
5.	Forest operations guideline. ($2.20)	1978
6.	A guideline for the construction of access tracks and firebreaks. ($2.20)	1980
7.	A guideline to skifield development. ($2.20)	1980
8.	A wetlands guideline. ($5.50)	1982
9.	A water and soil guideline for mining. ($11)	1983
10.	A water and soil guideline for pipeline easements. ($4.40)	1985

Prices include G.S.T. and postage.