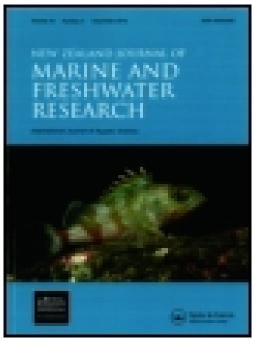

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Silver jubilee review

Coastal oceanography and sedimentology in New Zealand, 1967–91

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Abstract This paper reviews research that has taken place on physical oceanography and sedimentology on New Zealand's estuaries and the inner shelf since c. 1967. It includes estuarine sedimentation, tidal inlets, beach morphodynamics, nearshore and inner shelf sedimentation, tides and coastal currents, numerical modelling, short-period waves, tsunamis, and storm surges. An extensive reference list covering both published and unpublished material is included. Formal teaching and research programmes dealing with coastal landforms and the processes that shape them were only introduced to New Zealand universities in 1964; the history of the *New Zealand Journal of Marine and Freshwater Research* parallels and chronicles the development of physical coastal science in New Zealand, most of which has been accomplished in last 25 years.

Keywords estuary; sediments; tidal inlets; beaches; coastal erosion; inner shelf; tides; currents; waves; tsunamis; storm surge; numerical modelling

INTRODUCTION

New Zealand's coast is one of the longest (11 000 km) and most diverse of any country in the world (Fig. 1). The country's elongate and north-south orientation straddling the circumpolar westerlies, its varied geology, and temperate to subtropical climate provide a wide range of coastal environments (e. g., Healy & Kirk 1982; Hume & Herdendorf 1988a). These features result in a wide range of problems and issues for authorities who manage the coast, and therefore an exciting variety of research problems for the coastal scientist. The "physical coastal" community is not large but it is very active, and the great diversity of New Zealand coastal environments have resulted in various research groups persuing common interests in different environmental settings. Poor portability of results from one section of the coast to another has been offset by the growth of comparitive experience.

The first 25 years have been about the establishment of the discipline, forming and developing its links with related disciplines (e.g., marine biology, marine geology, coastal engineering, planning), and reconnaissance and description of distinctive New Zealand coastal environments. Over the period a very strong input has been made to coastal management and planning in the country in a variety of ways, including project design, impact assessment, strategic planning, and the development of policy and law.

Formal teaching and research programmes dealing with coastal landforms and the processes that shape them were only introduced to New Zealand

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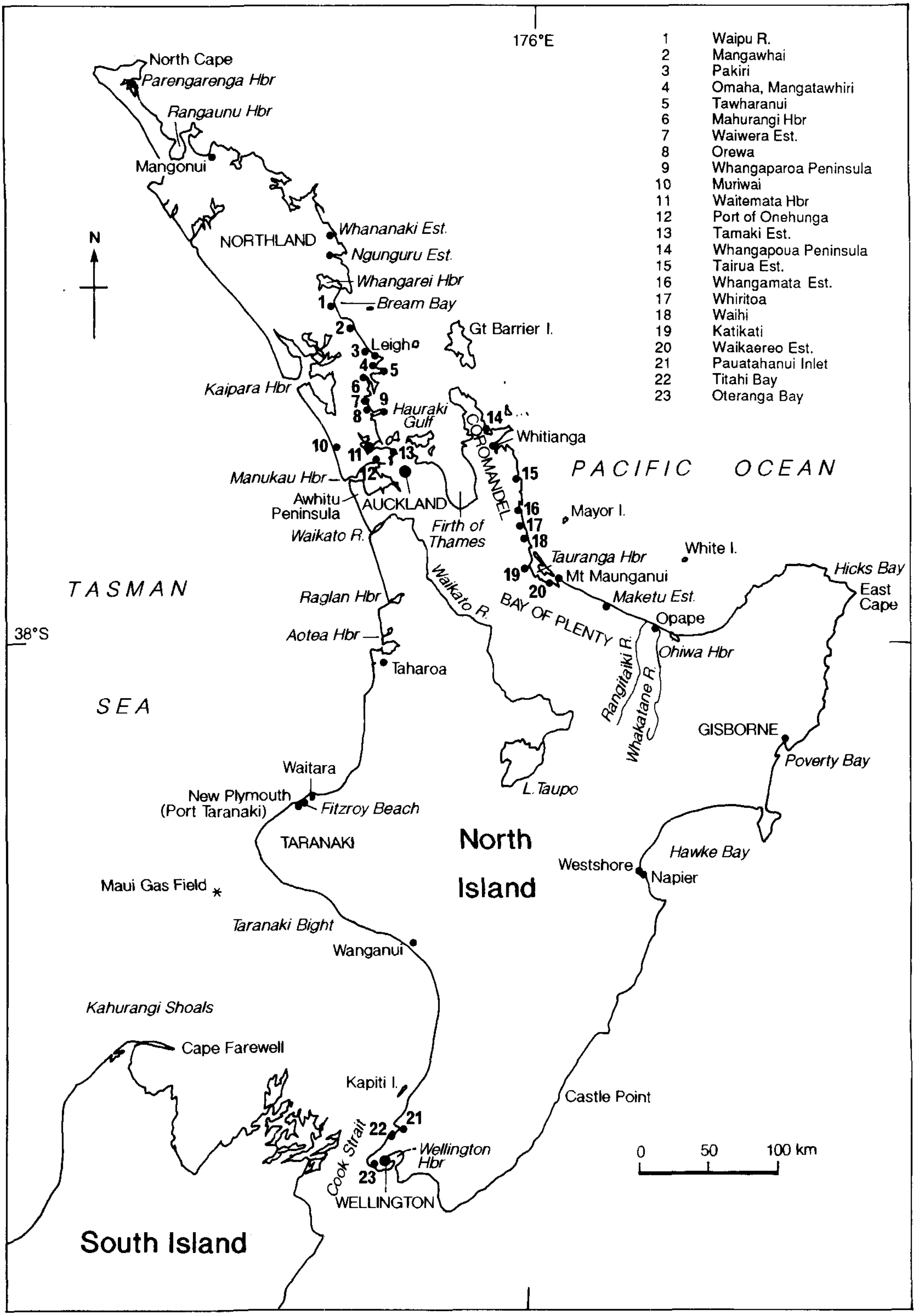

Fig. 1A Map of the North Island, New Zealand, showing places mentioned in the text.

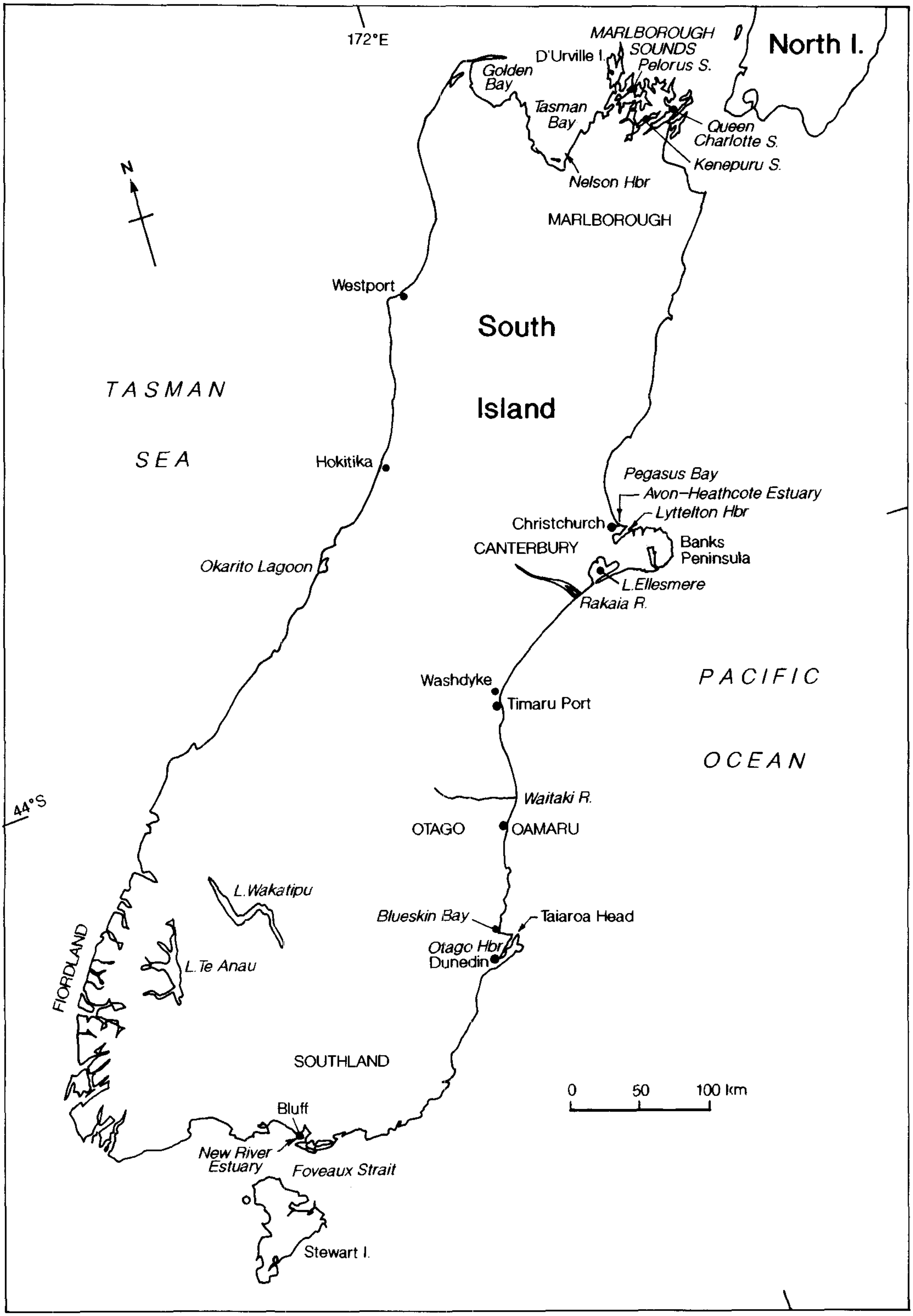

Fig. 1B Map of the South Island, New Zealand, showing places mentioned in the text.

universities in 1964 by R. F. McLean at the University of Canterbury. Thus the history of the *New Zealand Journal of Marine and Freshwater Research* (*NZJMFR*) parallels and chronicles much of the development of physical coastal science in New Zealand, both in respect of the ebb and flow of ideas and scientific problems, and in the increasing range of roles fulfilled by graduates from the various "schools" and groups in universities, government agencies, and territorial authorities.

This review summarises research that has taken place on physical oceanography and sedimentology on New Zealand's estuaries, tidal inlets, beaches, and the inner continental shelf since c. 1967. An extensive reference list covering both published and unpublished material is included.

ESTUARINE SEDIMENTATION

There were few studies of sedimentation in New Zealand estuaries before about 1970; they were restricted to the major port areas which were sounded regularly by port authorities for the purpose of assessing maintenance dredging requirements. Probably the first published study of sedimentation in a New Zealand estuary was by Brodie (1955), who used historical bathymetric and textural data to assess changes in depth and sediment dispersal in Lyttelton Harbour. About the same time the Hydraulics Research Station of Wallingford (United Kingdom) made a general assessment of sedimentation in the Waitemata Harbour (Kestner & Benson 1959).

In the early 1970s, there was rising concern about the impacts of changing land use practices (particularly urbanisation) on the water quality, biology, and sedimentation in estuaries. This led to the initiation of some major environmental studies in the Avon-Heathcote Estuary, Pauatahanui Inlet, and the Waitemata Harbour, and some general sedimentological investigations in other estuaries. In some instances the sedimentary work was undertaken as part of biological investigations (e.g., Knox & Kilner 1973) and in others, the sedimentary geology was the main concern (e.g., Macpherson 1978). The first reports dedicated to the description of the distribution and origin of surficial sediments in New Zealand estuaries were those by Gregory & Thompson (1973) as part of the Waitemata Harbour study and by Sherwood (1973) in Raglan Harbour (also Sherwood & Nelson 1979). Further work in the Waitemata Harbour resulted in the first application of seismic reflection to the determination of the thickness of unconsolidated Holocene sediments in a New Zealand estuary (Hicks & Kibblewhite 1976). Wells-Green (1979) reported the first local physical model study in a New Zealand estuary as part of an investigation to solve sedimentation problems about the Port of Onehunga.

The Pauatahanui Environmental Program spawned the most concerted estuarine study ever seen in New Zealand at that time. Driven by the concern about the effects of catchment run-off on the estuary, the sediments were mapped (McDougall 1976), historical changes in channel and bank morphology were measured (Irwin 1976), and cores were dated by radiocarbon, Pb-210, and pollen methods (Healy 1980) in an attempt to understand factors influencing sedimentation rates during the Holocene. This was the first time these dating methods were applied to estuarine sediments in a New Zealand estuary. Although the Pb-210 dating was unsuccessful (possibly owing to bioturbation), the C-14 data indicated rapid sedimentation (11 mm yr^{-1}) at about 8000 yr BP (when sea level was rising rapidly) followed by slower sedimentation (2 mm yr^{-1}) over the period 3610–1360 yr BP when sea level had stabilised at near its present level. The pollen recorded the removal of the podocarp forest cover by burning and its gradual replacement by bracken associated with Polynesian settlement, and the appearance of grasses and exotic pollen, such as pine, associated with European occupation. Present-day rates of sedimentation in the estuary were determined from estimates of catchment run-off (Healy 1980) and by direct measurements of the changes in the sediment surface level about steel rods (Pickrill 1979a).

The late 1970s and 1980s saw numerous studies of estuarine sedimentation undertaken as part of student theses. Typically these included mapping the textural and mineralogical characteristics of surficial sediments, perhaps with some current measurements, to complete descriptions of depositional environment, e.g., Sherwood (1973) at Raglan; Davies-Colley (1976) at Tauranga; Richmond (1977) at Ohiwa (also Richmond et al. 1984); Murray (1978) at Maketu; White (1979) at Waikaraeo; Kruger (1980) at the Avon-Heathcote Estuary; Millar (1980) at Whangarei; Thoms (1981) in the New River Estuary; Willet (1982) at Aotea Harbour; Paton (1983) at Ngunguru; Dahm (1983) at Tauranga; and Johnstone (1984) at Mahurangi. Although some of the works were primarily descriptive, others investigated temporal changes in sedimentation patterns and source-sink relationships. Through the work of Davies-Colley (1976), Kruger (1980), Thoms (1981), and Burton & Healy (1985), we improved our understanding of the pathways of sediment transport in estuaries and the processes of sediment exchange between catchment, estuary, and the adjacent coast. Curtis (1985a, 1985b), examining sedimentation in Lyttelton Harbour, demonstrated that the dredge spoil dump grounds have a finite capacity, and that muddy spoil is continually recirculated between the harbour floor/channel/spoil grounds in a closed system. Black (1983) developed a numerical sediment transport model to quantify and predict sedimentation rates in the lower reaches of Whangarei Harbour, and this was subsequently applied in Tauranga Harbour.

The 1980s saw several investigations aimed at determining the effects of changes in catchment use and run-off patterns on sedimentation in estuaries. Macpherson (1981) made an assessment of the effects of logging on sedimentation in Okarito Lagoon. As part of the Upper Waitemata Harbour catchment study, Hume (1983) and Hume & McGlone (1986) used historical bathymetric data, cores dated by C-14 and pollen, and sediment run-off records to determine changes in sedimentation over the last 6000 years. This work expanded on the Pauatahanui information and showed small-scale forest clearance, and low sedimentation rates associated with Polynesian settlement, large-scale forest clearance, and farming practices accompanied by a 3-fold increase in sedimentation rate associated with European settlement, followed by a slight decrease in sedimentation rate to the present day. Similar sequences of land use changes influencing estuarine sedimentation have subsequently been described in Nelson Harbour (Hume 1988), in Manukau Harbour (Murray-North Ltd 1988; Hume et al. 1989; Williamson et al. 1991), in Coromandel estuaries (Harrison 1988; Hume & Dahm 1991), the Firth of Thames (Middleton 1987; Naish 1990), and Whangamata Estuary (Sheffield 1991). These studies show sedimentation rates of a few mm yr^{-1} characterise the intertidal areas of many New Zealand estuaries (which are similar to those of other temperate latitude estuaries: Rusnak 1967), and an increase in sedimentation rate (sometimes accompanied by a coarsening in texture) from Polynesian through to European times. In another approach, Swales (1989) constructed the first (New Zealand) sediment budget for a tidal creek, which drained an urbanised catchment, by comparing sediment run-off from the catchment with bathymetry changes in the Pakuranga tidal creek of the Tamaki Estuary.

There have been few studies of sedimentation in New Zealand's fiords and sounds. Pickrill (1987) described the transport and deposition of fine-grained particulate material in New Zealand fiords where suspended solids inputs are very low. Lauder (1987) described sedimentary processes in Queen Charlotte, Pelorous, and Kenepuru Sounds.

New Zealand estuaries are active sediment traps, receiving sediment from both the land and the sea. Sedimentation has been studied as part of general descriptions of the estuarine environment, assessments of sedimentation in marinas and ports, and as part of efforts to understand the effect of various land use practices on estuarine sedimentation because of their impact on navigation, water quality, and biology. Studies of sedimentation rates have been hampered by the lack of bathymetric charts for areas outside our major ports, and the fact that no one method can be relied on to date sediments. Without dates, sedimentation rates are difficult to derive and palaeoenvironmental interpretations are tenuous (e.g., Trotter 1990). Radiocarbon dating has proved most useful although contamination has given spurious dates in some instances (Deely 1991). Pollen dating has proved to be most useful for palaeoenvironmental reconstruction although bioturbation can make interpretation difficult. Little use has been made of Pb-210. Marker horizons are rare in New Zealand estuaries but in some instances, contaminants (Hume, Fox, & Wilcock 1989) and wood debris layers (Hume & Gibb 1987) have proved useful.

TIDAL INLETS

Tidal inlets are the entrances to estuaries formed where sand barriers or spits enclose bays. They comprise the narrow deep throat (or gorge) through which strong currents flow, and the associated sediment sand bodies in the estuary bay (flood tidal delta) and just seaward of the throat (ebb tidal delta). In New Zealand, tidal inlets mostly occur in the top half of the North Island where there are about 30 such features. In the South Island tidal inlets are located in the Tasman and Golden Bay areas, Canterbury, Otago, and Southland. A few occur on the offshore islands (e.g., Great Barrier).

Internationally, tidal inlets have been the subject of much research because of their important position on the coast. Tidal inlets protect the inner estuary and adjacent beaches from wave energy; the channels through the deltas (though ephemeral) provide access to sheltered harbours; sand stored in the associated tidal deltas is an important sand resource; and tidal inlets act as valves on the coastal sedimentary supply by regulating the sand exchange between estuaries and the open coast.

Before 1965, studies on New Zealand tidal inlets were limited largely to hydrographic charting of New Zealand's harbours and coastal waters by the British Admiralty (from about 1850), Royal New Zealand Navy, and harbour authorities. In the 1950s and 1960s, the Hydraulics Research Station at Wallingford, United Kingdom, was commissioned to undertake studies of several New Zealand harbours (e.g., Hydraulics Research Station 1963, 1968). However, the first specific work on tidal inlets was by Furkert (1947) who, following the pioneering papers by O'Brien (1931, 1969) on American inlet hydraulics, developed an empirical throat area/tidal prism relationship for a selection of 14 New Zealand inlets: his purpose was to draw to the attention of engineers the fact that reducing tidal compartments in harbours can result in entrance instability.

In the late 1960s and 1970s, several geomorphologic studies, based largely on the analysis of maps, sounding data, and aerial photography, highlighted the unstable nature of the tips of New Zealand sand spits and tidal inlets. Schofield (1967) described historical shoreline changes at Mangatawhiri (Omaha), Ngunguru, Whananaki, and Waiwera. Wright (1969) reported shoreline changes and the danger to shipping of the constantly shifting shoals and channels at the entrance to the Kaipara Harbour. Williams (1977) described massive shoreline progradation and recession at the mouth of the Manukau Harbour. Gibb (1977) reported large changes in entrance dimensions that had resulted in property loss at Ohiwa. Noble (1977) described inlet instability at Omaha. Murray (1978) reported the historical shifts in position of the Maketu entrance. Macpherson (1978) attributed changes in the Avon-Heathcote inlet tidal compartment to changes in catchment run-off patterns accompanying urban development.

In the mid to late 1970s, several factors stimulated tidal inlet studies. Firstly, Heath (1975) brought tidal hydraulics into the picture. Secondly, the first detailed field study of sediment transport and hydrodynamics in a New Zealand tidal inlet was undertaken at Tauranga Harbour (Davies-Colley 1976; Davies-Colley & Healy 1978a, 1978b). Thirdly, wide publicity surrounding beach erosion problems at Omaha (e.g., Schofield 1967; Beca Carter Hollings & Ferner Ltd 1976; Noble 1977; Healy 1981a) raised awareness of the interaction of tidal inlets with the adjacent beach and the possible detrimental effects of sand mining at an inlet. Inlet stabilisation by groynes and beach nourishment was implemented after much debate, but not everyone agreed with the cause of the erosion nor the means of remedying the problem (Healy 1981a). Building on Furkert's work, Heath (1975) showed that for many inlets about the New Zealand coast the entrance cross-sectional area is linearly related to the tidal compartment (prism). This became known as the "Furkert-Heath" relationship, and was used to characterise inlets as being in states of equilibrium, deposition, or scour. Interestingly, this took place at about the same time as comprehensive work on tidal inlet stability in United States inlets by Jarrett (1976), and drew comment by Mehta (1976) and comparison with United States inlets. In a follow-up paper based on further field data and examples, Heath (1976a) reported that the control on entrance dimensions was also dependent on the nature of the coast which determines the rate of supply of littoral drift to the entrance. The "Furkert-Heath" relationship has probably been quoted and applied in every tidal inlet study since, and subsequently Hume & Herdendorf (1988b) warned of its shortcomings and suggested correct usage.

The 1980s witnessed a boom in tidal inlet studies driven by coastal problems and university thesis work. Some work made a minor contribution to our understanding, addressing tidal inlet matters as part of wider estuarine studies (e.g., Millar (1980) at Whangarei; Willet (1982) at Aotea; Paton (1983) at Ngunguru; Richmond et al. (1984) at Ohiwa; Tonkin & Taylor Ltd (1986) on the Manukau bar). From other studies, more targeted at sedimentary processes, we learnt more about tidal inlets. As part of a study of sediment transport in the Avon-Heathcote estuary, Kruger (1980) investigated the exchange of sand between the estuary and the open coast, concluding that the estuary is either a net exporter or importer of sand, depending on meterological conditions. At the New River Estuary in Southland, Thoms (1981) demonstated that medium to fine sand is fed into the estuary from Foveaux Strait whereas very fine sand is primarily exported to the sea. Findlay (1984) and Findlay & Kirk (1988) undertook a detailed analysis of changes at the mouth of the Avon-Heathcote Estuary, disputing some of Macpherson's (1978) earlier interpretations about changes in tidal compartment. Similarly, Dahm (1983) undertook a detailed study of morphodynamic change at the inlet and associated tidal delta systems at Tauranga Harbour, and was the first to alert the Harbour Board to morphodynamic instability within the harbour. As part of the 1985 Australasian Conference on Coastal and Ocean Engineering, a workshop reviewed progress in tidal inlet studies in New Zealand (Hume & Herdendorf 1987). There was also a series of studies brought about by inlet/beach stability problems and port developments. Physical model studies on the Whakatane River mouth entrance, the first on a tidal inlet, were reported by Raudkivi (1980) as part of an investigation to solve navigational problems at a tidal inlet system with large river sediment transport and littoral drift. Healy (1985a) undertook historical stability analysis of the Whakatane River mouth where there was a historical reduction in tidal prism owing to loss of the Rangitaiki River distributary and reclamation in the small estuary. Kirk (1981) reported on the effects of sand mining on inlet stability at Parengarenga Harbour. Although sand mining had been a factor, Riley et al. (1985) and Schofield (1985) attributed climatic factors and sea level rise as the primary causes of beach erosion and inlet instability at Omaha.

In a different approach incorporating numerical modelling of shoreline changes, Kirk et al. (1986, 1987) and Hastie et al. (1986) applied tidal inlet stability theory to assess river mouth stability problems and solutions at Westport. McCabe (1985) and McCabe et al. (1985) reported on the Mangawhai inlet barrier overwash and breach during a storm in 1978 which created one of the few dual inlet systems on New Zealand shores. A series of studies at Maketu inlet (Burton & Healy 1985; KRTA 1986; Burton 1987; Rutherford et al. 1989) documented a well publicised and interesting case history where a river was diverted out of an estuary, changing it from a river mouth situation to a tidal inlet. In the 1980s, some detailed field studies at tidal inlets have greatly improved our knowledge. Pickrill (1985, 1986) studied sediment transport at the Rangaunu ebb tidal delta and the supply of sand from the inner shelf to the ebb tidal shoal.

By far the most comprehensive studies of New Zealand tidal inlets have taken place at Whangarei and Tauranga, prompted by port developments. Based on potential inlet instability (Healy 1981b) a hydrodynamic numerical model of current flows was applied by the Danish Hydraulic Institute at Whangarei (Danish Hydraulic Institute 1982, 1983). The model was calibrated using an extensive field data collection programme including tide level and velocity measurements and extensive surficial sediment sampling and side-scan sonar mapping (e.g., Healy 1981b; Black & Healy 1982a; Black 1983). Simultaneously with the DHI model, Black developed his own one- and two-dimensional hydrodynamic models, and linked these to a numerical sediment transport model. Subsequently hydrodynamic modelling (Barnett 1985a, 1985b) sediment transport modelling (Black 1984), and morphological analysis (Healy 1985b) was applied to Tauranga Harbour in a large and detailed study to ascertain the cause of channel instability first reported by Dahm (1983). These studies which applied numerical modelling to tidal inlet investigations greatly improved our quantitative understanding of tidal inlet processes. Subsequent hydrodynamic modelling studies of estuaries at Nelson (Kettel & Barnett 1986), Whitianga (Ministry of Works and Development 1986), and Otago (Barnett 1988) have subsequently served to improve our knowledge of tidal inlet hydrodynamics.

In the first overview of factors controlling tidal inlet stability at New Zealand inlets, Hume & Herdendorf (1990, in press) used morphological and empirical analysis to identify hydrological and stability characteristics. They demonstrated the important role that rock headlands play in giving the inlets positional stability and characteristics similar to those tidal inlets stabilised by jetties on United States shores. In another application, Hume (1991) applied empirical stability relationships, normally used on open coast tidal inlets, to assess the stability of "inlets" in the interior of harbours of the Auckland region. More recently Hicks & Hume (1991) quantified the huge volumes of sand stored in New Zealand's ebb tidal deltas and found that the amount of sand stored is primarily controlled by the size of the tidal prism and the ebb jet outflow angle. Other recent studies of inlets are those by Sheffield (1991) and Sheffield et al. (1991) at Whangamata, and Kench & Parnell (1991) at the Waipu River inlet in Bream Bay.

Current studies on tidal inlet stability in New Zealand are centred in the Bay of Plenty at the Tauranga (e.g., Healy et al. 1991) and Katikati (Hume et al. 1991) entrances to Tauranga Harbour.

New Zealand is an excellent place to study tidal inlet processes on headland-dominated shores because there are a variety of littoral drift conditions and the inlets are largely unmodified by engineering works. We still know little about the Holocene development of our tidal inlets, lack a quantitative understanding of the exchange of sand between inlets beaches and the inner shelf, and need to be able to interactively model tidal and wave processes that build New Zealand's tidal inlets.

BEACHES, EROSION, AND MORPHODYNAMICS

The earliest coastal investigations in New Zealand were carried out for the establishment of ports (e.g., Coode 1880; Saunders 1882). Although the processes of coastal sediment movement were not well understood at this time, the engineers were nevertheless fully aware of the effects of the process (e.g., Holmes 1919). The second phase of coastal investigations was driven by mineral exploration and the demand for aggregate for roading and the building industry (Nicholson et al. 1958; Nicholson 1969; Schofield & Woolhouse 1970). As part of the issuing of licences for coastal sand and shingle extraction, the coast was inspected and reports prepared (e.g., Rabone 1950). Although the annual reports on beach condition were often superficial, over time they resulted in a historical record of beach changes which provided useful background information and the basis of more modern investigations. Indeed, industrial demand has proved to be a continuing cause for coastal morphodynamic and sediment budget studies.

The earliest systematic work on New Zealand beaches was carried out by the Canterbury University Department of Geography, initially under the impetus of R. F. McLean. This work was subsequently carried on by R. M. Kirk and students. A major contribution of the Canterbury school has been to advance understanding of mixed sand and gravel beach (e.g., McLean & Kirk 1969; McLean 1970; Kirk 1970, 1974, 1975, 1980). Other studies by this school through the mid 1960s to mid 1970s included examining the Holocene evolution of many segments of the Canterbury and Marlborough coasts (Blake 1964; Armon 1974; Dingwall 1974; Pickrill 1976). Much of the work has been at the interface of coastal processes with coastal engineering and with planning. The group has contributed to the development of 10 New Zealand ports through dredging, sedimentation, and coastal management investigations.

Elsewhere during this period, beach studies tended to be regional surveys, such as that of Schofield (1970) which concentrated on the mineralogy and textural properties of the beaches of Northland. However, Andrews & van der Lingen (1969) added a significant contribution by relating grain textural parameters to beach structure and morphology at five South Island beaches. In a companion paper, McLean & Kirk (1969) developed models relating grain size and sorting to slope in east coast South Island beaches.

Beach erosion became a major issue in New Zealand during the 1970s, a decade of noticeable erosion events dating from the 1968 "Wahine Storm" through to the "July 1978" storm (Hume 1979). Before and during this decade had been a time of marked planning and development of coastal subdivisions, with scant regard having been accorded to coastal erosion setback issues. Thus in the early 1970s, little was available in the New Zealand literature on the subject of beach erosion, except for papers by Schofield (e.g., 1967 and 1975 on Mangatawhiri Spit). Healy (1975) introduced to the New Zealand literature the concept of the "dynamic equilibrium beach". There followed thesis investigations of beach morphodynamics by students from the University of Waikato, Earth Science Department, including studies at Waihi Beach (Harray 1976; Harray & Healy 1978), Whiritoa (Christopherson 1977; Willoughby 1981), and Taranaki (e.g., McLennan 1982).

Complementary "benchmark" papers by Gibb (1978, 1979) and McLean (1978) gave systematic descriptions of historical trends of erosion and accretion around much of the New Zealand coast, allowing the beach erosion issue to be viewed from historical and national perspectives. Based on cadastral plans, aerial photographs, and field evidence, Gibb (1978) presented measurements of shoreline change and erosion/accretion rates for 471 sites. McLean's (1978) paper focused on sites of progradation, explained the Quaternary depositional sequences, observed historical trends in terms of Holocene shoreline readjustments, and superimposed adjustments initiated by human activities, such as construction of port breakwaters.

The need for quantitative beach data was recognised in the mid 1970s. The then Ministry of Works: Water and Soil Division supported several beach survey programmes by universities and catchment boards in Bream Bay in Northland, Poverty and Hawke Bays, on the Taranaki Bight, and on the east coast of the South Island between Waitaki and Rakaia.

Perhaps the first regional-scale survey, in which beach erosion and accretion were related to the morphology, sedimentology, and mineralogy of the dune, beach, and nearshore systems, was the Bay of Plenty Coastal Erosion Survey of 1976–77 (Healy et al. 1977; Healy 1978a, 1978b, 1978c, 1978d). This covered the 130 km long Bay of Plenty littoral system between Waihi Beach and Opape. A major discovery was that the worst areas of beach erosion were associated with either tidal inlets or sand mining. In contrast a similar regional-scale study for the east Coromandel embayed beaches (Healy et al. 1981; Healy & Dell 1982, 1987) demonstrated that each beach was an isolated system, not exchanging sediment via a littoral drift system.

The 1968–78 decade of erosion on New Zealand beaches, at a time of extensive coastal subdivision development, led to several Planning Tribunal cases.

Indeed the coastal erosion debacle at Omaha Beach spawned multi-million dollar legal suits (Nobel 1977; Healy 1981a) and produced one of the most studied beach systems to date in New Zealand. These problems highlighted the need to find a method for quantitative estimation of "development setback" or "coastal hazard zones". The concept was approached from somewhat different points of view by Gibb (1981, 1983a, 1987), Gibb & Aburn (1986), and Healy (1980, 1981b), but has since become well established as a coastal planning and management tool (e.g., Northland Regional Council 1988, 1991; Taranaki Catchment Board 1988; Smith 1987). In developing an integrated survey and management plan for the 16 km of Christchurch urban foreshore, Kirk (1979a) isolated the dune system as a "buffer zone" against shoreline erosion. Regional-scale coastal hazard surveys generally provide a comprehensive review and synthesis of existing information for the relevant coasts. Kirk (1982, 1983, 1987) provides extensive reviews of the problems inherent in translating physical coastal information to a range of planning tools applied within the planning law.

Through the late 1970s and 1980s, working mainly on the coast south of Banks Peninsula, the Canterbury school continued to investigate mixed sand and gravel beach systems. Their continually improving knowledge base of processes in these complex systems was applied to several practical issues, including coastal erosion, sedimentation, and the impacts of river flow manipulation on gravel river mouth stability and supplies of littoral sediment. Kelk (1974) and Stephen (1974) studied process interactions at river river mouths, Neale (1987) traced gravel "slugs" moving northwards from the Waitaki River mouth, and Kirk & Hewson (1978) reported on the littoral sediment budget south of Timaru. Timaru itself has been the focus of several studies relating to the development of the port (Tierney 1977; Tierney & Kirk 1985; Hastie 1983; Fahy 1986). Studies of the coast "downdrift" at Washdyke have looked at coastal erosion (Benn 1987) and modelling the future equilibrium shoreline planform (Todd 1989). Beach restoration-renourishment was carried out at Washdyke (Kirk & Weaver 1982), and at present an 8 ha artificial beach is being "grown" from longshore drift to protect the weather breakwater at the Port of Timaru (Kirk & Tierney 1985). Similar sedimentation and beach erosion problems have spurred studies at the Port of Taranaki (Kirk 1980; Gibb 1983b; Hicks & Gibb 1987).

Since the late 1970s beaches in the Auckland/Northland area have been investigated by the Auckland school of coastal studies in Geography. Peek (1979) compared the morphodynamic responses of east and west coast beaches. Cato (1987) examined the beach/dune interactions at Muriwai on the west coast of Auckland. Anderson (1984), in a study of the dynamics of the Mangawhai high dune system, and Murray-Brown (1984) at Parengarenga, provide the only studies of the extensive and unusual Northland dune systems. Macdonald (1986) developed a sediment budget for the Awhitu Peninsula, using a variety of techniques including aerial photograph analysis. Other beach studies include those by Lees (1981) from Mangawhai to Karepiro Bay, Kelly (1984) around the Tawharanui and Whangaparaoa Peninsulas, Robinson (1985) at Orewa, and Meyberg (1990) at Omaha for which was developed a 3-dimensional view of beach change and rhythmic topography at a small scale. A large data set describing beach change in the Northland area has been obtained from Parengarenga, where 10 years' data at intervals of 3–6 months have been collected (Adam 1984; Hosking & McLean 1989; Parnell et al. 1990). Hilton (1989, 1990) provided data on beach change in the Pakiri embayment.

In recent years, beach renourishment has become recognised more often as a cost-effective management option for stemming shoreline erosion. In a review of New Zealand cases, Healy et al. (1990) describe beach renourishment at a wide variety of situations including open coast and sheltered harbours, and sand and mixed sand gravel beaches. They concluded that renourishment occurred for four reasons, or more frequently combinations of reasons:

(i) as a method of beach reconstruction after catastrophic or identifiable chronic erosion: for example, to curtail spit and beach erosion at Omaha the beach was nourished with sand pumped from the estuary behind the sand spit (Beca Carter Hollings & Ferner Ltd 1976), and combined beach reconstruction and nourishment was undertaken at Washdyke Beach (Kirk & Weaver 1982, 1985);

(ii) to appease local perception that popular beaches have been eroding. Examples include Orewa Beach and the Wellington Harbour beaches of Belaena and Oriental Bays (Lewis et al. 1981; Carter & Mitchell 1985);

(iii) as a by-product of nearby marina or port development works. For example, the placement of 420 000 m^3 of dredge spoil at Pohara Beach in Golden Bay (Kirk 1978), and the use of dredge spoil to nourish Pilot Bay Beach in Tauranga Harbour (de Lange & Healy 1990);

(iv) as a coastal management strategy to restore dunes against the effect of possible rise in sea level. This has occurred at Westshore Beach near Napier, at New Plymouth, and more recently at Mt Maunganui Beach where the beach was nourished from nearshore dredge spoil dumping (Foster 1991; Foster et al. 1991).

Wave refraction analyses for coastal process studies have been used since the 1960s (e.g., Gibb 1962; Dingwall 1966; Pickrill 1977). Wave refraction computer programs written by K. Black (Black & Healy 1981) were widely applied by students at the Marine Geosciences Group at the University of Waikato (Willet 1982; Miller 1983; McCabe 1985; Burton 1987; Sheffield 1991), leading to recognition of the importance of wave focusing in concentrating wave energy at the shoreline, and thus influencing beach erosion (McCabe et al. 1985; Healy 1987; Black & Healy 1988).

During the 1980s, a major effort was made at the international level to understand the effects of edge waves and other infragravity waves on beach processes and morphology. This led to the Wright-Short model of beach morphodynamic states, based mainly on south-east Australian examples. Following this approach, Willyams (1980) and Siemelink (1984) examined changes in beach morphodynamic state at Pegasus Bay using 100-day time series record. More recently, Fulton (1991) applied the Wright-Short model to Coromandel beaches. A more pragmatic approach of attempting to understand the sedimentology and limits of the beach system seems to have been more the New Zealand methodology. Such an approach is understandable given the wide variety of beach sediments and wave energy environments.

Recent work has included attempts to link spates of beach erosion with quasi-regular interannual fluctuations in mean sea level and storminess associated with La Niña/El Niño Southern Oscillation phenomena. Identifying these links are important advances in our ability to forecast beach erosion and to predict the impacts on coastal processes of global climate change. Indeed the need to predict the impacts of, and plan ahead for probable rises in sea level and changes in wind and wave climates associated with an intensifying Greenhouse Effect, should be a major guide on the direction of beach process research in the coming decade (Hicks 1990; Hay et al. 1991). Foremost amongst these needs are accurate quantitative models of beach profile (e.g., Dean et al. in press) and planform (shoreline position) response.

NEARSHORE AND INNER SHELF SEDIMENTATION

If processes of beach erosion and accretion are to be understood, important issues are the offshore limit of the dune-beach-nearshore bar system and the degree of beach/inner shelf interaction. The zone of interest for these is the relatively shallow shelf, extending perhaps to a depth of about 50 m depending upon wave energy. This section reviews work on nearshore and inner shelf sedimentation, focusing on studies that examine the past and present relationships between beach and inner shelf sediments.

The earliest studies of inner shelf sediments were undertaken as part of deepwater oceanographic work programmes (e.g., McDougall 1961; Pantin 1966). The regional mapping of the beaches and inner shelf of Northland and Auckland by Schofield & Woolhouse (1969) and Schofield (1970)—spurred by the hunt for industrial mineral, sand, and gravel deposits—provided the first insight into relationships between beach and inner shelf sediments in that area. By mapping textural and mineralogical characteristics of beach and inner shelf sands, these authors demonstrated the origins of the east coast sands, their connections with the ancestral Waikato River, and their proximal origins in sea floor sweeping under rising sea levels. This led to the concept of a finite sand resource. Dingwall (1966) showed how Banks Peninsula beaches were being nourished by offshore sands from the Canterbury shelf. Later, Nicholson (1979) showed how this was also occurring on the Otago shelf, with transport to beaches in the vicinity of Blueskin Bay. Cullen (1966) showed how fluvial gravels forming the floor of Foveaux Strait had been reworked by waves and currents.

Gillie (1979) investigated mixed sand and gravel deposits off the Northland east coast; he was probably the first to measure physical processes that drive sediment transport on the beaches and inner shelf. Relict fluvial coarse sands and gravels on the inner shelf were differentiated from modern marine sediments in a wide-ranging study involving monitoring beach and sea bed profiles, coring, sediment trapping, tracing, seismic measurements, and measuring wave and bottom surge.

The East Coromandel Shelf Study, which followed the Coromandel Coastal Survey, set out to investigate the effects of beach sand extraction and the capability of a pocket beach system to withstand continuing loss off sediment budget. This inner shelf study started in 1983 (Dell et al. 1985), and is just completed (Bradshaw 1991). It involved coastal oceanography and sea bed drifter studies (Bradshaw et al. 1991), bottom surficial sediment texture and mineralogy, side-scan sonar mapping, and shallow continuous seismic sub-bottom profiling. From the sub-bottom interpretations, Bradshaw established examples of Pleistocene analogues to modern estuarine, barrier, and nearshore marine deposits; he also identified the bottom currents and sediment transport pathways and mechanisms on the inner shelf out to 50 m depth, for the shelf from Waihi Beach north to Matarangi. Mobile shelf sand was identified as fine sand sheets, megaripple fields, and sand wave fields. A similar study was undertaken on the inner shelf off Pakiri by Hilton (1989, 1990). He described sediments and bedforms of the inner shelf and at the abrupt inner shelf–mid shelf boundary. Unlike other studies, Hilton (1990) incorporated in his interpretation an analysis of the macrobenthos and carbonate sediment. A morphodynamic model proposed a generally quiet outer zone with landward transport in the nearshore during calm to moderate conditions, and significant transport in the nearshore with onshore transport over the outer zone during storms.

Some essentially beach studies also extended to the inner shelf. For instance, Riley et al. (1985) and Schofield (1985) used sea bed textural mapping and bathymetric analysis of the sea floor to examine factors contributing to beach erosion and inlet instability at Omaha. Willoughby (1981) undertook textural and factor analysis of beach and sea floor sediments at Whiritoa to help determine the limits of the sand system. McCabe (1985) and Burton (1987) undertook sea bed sampling and wave refraction studies to ascertain the influence of inner shelf processes on the inlets and beach at Mangawhai and Maketu, respectively.

Some of the contributions to our knowledge of inner shelf sedimentation have been made as part of investigations for entrance channel dredging associated with port works and dredge spoil dump grounds. At the Port of Timaru, work with fluorescent traces and with indirect methods such as rollability analysis of sands revealed that up to 650 000 m^3 of sand passes the entrance channel each year in depths of less than 11 m. Daily average rates in the range of 0.46–1.20 m^3 per m width of sea bed were determined and it was shown that mean dispersal times per dredge load of spoil dumped (1 300 m^3) were in the range of 2.5–6.2 days (Tierney & Kirk 1978). Based on this, the port entrance channel was extended seaward to the 11 m depth contour, and up to 2 km across the line of littoral drift. Later dredge dumping was resited to benefit erosion on downdrift shores. Similar studies have been carried out at Oamaru, Otago, Bluff, and Westport.

Dahm & Healy (1980, 1985) reported on migration of dredge spoil dumped off Tauranga Beach and its separation into a fine and coarse sand facies under the influence of waves and currents. Harms (1989) described dump mound erosion and probable onshore movement of spoil off Mount Maunganui Beach, and this was reinforced from benthic biological surveys (Healy et al. 1988; Foster et al. 1991). Arising from this work, Healy, McCabe, & Thompson (1991) and Healy, Harmes, & de Lange (1991) were able to demonstrate that long-term on average some 20 cm depth per m^2 per year of sandy sediment is moved on the shelf in water depths out to 25 m depth, and that thus the shelf is considerably mobile overall. Interestingly, the slow onshore migration of sand from the dump grounds is now necessary to maintain the beach sediment budget, because dredging the shipping channel through the adjacent ebb tidal delta has interrupted the flow of littoral drift nourishing Mount Maunganui Beach.

In Poverty Bay, Nelson & Healy (1982) and Miller (1983) found that much of the dredge spoil mound from the Port of Gisborne was being redistributed over the Poverty Bay sea floor, and possibly migrating to the beach. Hume, Roper, & Bell (1989) undertook studies of the currents and patterns of sediment dispersal and ecological impacts of dredge spoil disposal in a mixed mud/sand environment (depths of 0–15 m) off the Port of Napier, and addressed the use of sandy spoil to nourish Westshore Beach.

As part of environmental assessments for the disposal of dredged material at a new Hauraki Gulf disposal site, Kingett Mitchell & Associates (1991) reviewed studies of oceanographic and sedimentological factors pertaining to the offsite transport of disposed material and changes to the sea bed.

TIDES AND COASTAL CURRENTS

Extensive reviews of the physical oceanography of the oceans and coastal seas around New Zealand have been presented in two of the previous decades. The first (Heath 1973a) followed the completion of investigations to define the geostrophic circulation around New Zealand. The second was for the period up to 1982 (Heath 1985), by which time considerable progress had been made in our understanding of coastal, fiord, and shelf oceanography. A significant factor in this advance was the introduction of internally recording current meters which allowed long-term current records to be obtained. Further detailed reviews for specific areas of New Zealand have been presented for the North Cape to East Cape region of the North Island (Harris 1985) and the Greater Cook Strait region (Harris 1990). These latter reviews focus on the physical oceanography of both coastal and, particularly, the outer shelf areas, but also cover the geography, sea floor sediments, and meteorology of the respective regions. The reader is referred to these reviews for much of the research which was carried out before 1982, although certain aspects are revisited in this review along with work appearing in the past decade. Useful bibliographies for estuarine and coastal regions in New Zealand have been presented by Estcourt (1976), for the Northland-Auckland region by Hume & Harris (1981) and for the Manukau-Waitemata Harbours by Hume (1984b), among others listed by Heath (1985).

Tides and mean sea level (MSL)

The New Zealand tidal regime is most interesting in that the phases of both the main lunar (M_2: 12.4 h period) and solar (S_2: 12.0 h period) tides embrace the complete range of phases from 0 to 360° (Heath 1977). This means that at any time there is a high tide somewhere on the New Zealand coast. In general, the spring tide on the New Zealand coast occurs between a few hours (e.g., Timaru) up to 8 days (e.g., Wellington) after a full or new moon (Heath 1985). Tide ranges in New Zealand are largely meso-tidal. The greatest and smallest tide ranges both occur in the greater Cook Strait area, with the mean spring range reaching 4.2–4.6 m in Golden Bay, but only 0.6 m across the Strait at Oteranga Bay (Harris 1990). Other areas which exhibit large spring tide ranges are Onehunga, on the Manukau Harbour (3.4 m), Kaipara Harbour (3.3–3.6m), and Nelson (3.4 m) (N.Z. Nautical Almanac 1990).

Our knowledge of coastal tides is somewhat limited by the fact that permanent tide gauge installations are usually located inside harbour entrances, where shallow-water over-tides caused by frictional dissipation and other non-linear depth effects are also present. The installation of more accurate and reliable tide gauges at the major ports has been proceeding over the past decade, incorporating digital recorders, rather than chart output which necessitated laborious digitising and were thus a further source of potential errors. At present there is no published or accessible database of reliable and updated tidal harmonic constituents for sites around the New Zealand coastline, apart from the earlier collation by Heath (1977). This contrasts with the seas around the United Kingdom and Europe, where detailed co-tidal (phases) and co-amplitude maps have been produced for the main constituents from harmonic analyses of tide and bottom pressure data, and also indirectly from current observations, along with results from calibrated hydrodynamic models. However, information on tidal constituents for the permanent tide gauge sites can usually be obtained from the Royal New Zealand Navy (Hydrographic Office) or government research agencies (Department of Scientific and Industrial Research, Department of Survey and Land Information). With the increasing use of numerical coastal modelling, knowledge of the main tidal constituents are important in setting tidal boundary conditions and for calibrating the tidal elevation results; this was demonstrated by Bowman et al. (1980), who found deficiencies in the M_2 constituents for several of the tide gauge sites.

In some constricted areas, the time of high tide changes very rapidly over relatively short stretches of coastline, namely in Cook Strait, where a 4-h change in phase occurs (Heath 1978a), through Foveaux Strait, and around the northern tip of the North Island. As a consequence, strong tidal flows are encountered in these regions.

Historical trends in relative mean sea level around New Zealand since about 1900 have been analysed (Hannah 1988a, 1988b, 1990) using tide level data from the ports of Dunedin, Lyttelton, Wellington, and Auckland. Hannah used a least-squares analysis to isolate the long-term trends in relative sea level from the shorter-term variances caused by long-period lunar tides, pressure, and temperature variations. The latest analysis (Hannah 1990) shows: that all four ports exhibited a statistically significant linear rate of rise in sea level ranging from 1.3 mm yr^{-1} at Auckland to 2.3 mm yr^{-1} at Lyttelton, with an overall mean trend of 1.7 mm yr^{-1} for the east coast of New Zealand; and that these trends showed no conclusive evidence of any acceleration of rate of rise in sea level (such as one might expect from a developing greenhouse effect). These rates of rise, which have been rigourously established, are consistent with the "near global" sea level rise in the range 1–2 mm yr^{-1} over the past century (Warwick & Oerlemans 1990). Several predictions for future greenhouse-forced sea level rise have been made by New Zealand scientists (e.g., Gibb 1988; Hannah 1988b, 1989) and are discussed by Hicks (1990). Recently revised predictions of sea level rise and the implications for coastal management in New Zealand are further discussed by Healy (1990), Gibb (1991), and Komar et al. (1991).

The long-term need for open coast sea level recorder sites has become increasingly important, given the multitude of predictions of greenhouse-forced sea level rise that have been made in the scientific literature in the last decade. Tide gauges sited in harbour and estuarine locations are of less value for this purpose because the tide propagation is distorted by shallow-water effects and freshwater run-off. At present there are few open coast tide gauge stations in New Zealand. At Moturiki Island (Mount Maunganui) a reasonable record extends back to 1971 (Bell 1985). Shorter records exist for open coast gauges at Castle Point, the west coast of the South Island (Hannah 1990), and the Chatham Islands (a recent installation). The Moturiki and Castle Point stations have suffered periods of unreliability and are sited in areas of active tectonic movement, particularly at Castle Point (Pillans 1986). A further South Island station at Taiaroa Head (Otago) has been suggested (Barnett 1988), being an area of known tectonic stability. Such open coast sea level monitoring sites are also being sought in the mid to higher latitudes of the Southern Hemisphere by international agencies such as UNEP (United Nations Environmental Programme) and the PSMSL (Permanent Service for Mean Sea Level), based at Bidston (United Kingdom), in collaboration with the Inter-governmental Oceanographic Commission.

Inter-annual mean sea level fluctuations of the order of 10–20 cm occur around the Pacific Basin in response to macro-scale variations in atmospheric pressure and circulation in the equatorial region, i.e., the Southern Oscillation/La Niña-El Niño phenomenon (Wyrtki et al. 1988). Based on data analyses of the Moturiki sea level data (Bell 1985), inter-annual variations in mean sea level (MSL) span a range of 9 cm in the period 1972–89, with the two lowest annual levels occurring during El Niño events in 1978 and 1983. In another analysis of the Moturiki dataset, Hay (1991) and Hay et al. (1991) found a significant correlation of MSL with the Southern Oscillation Index between positive lag periods of 3 and 19 months, with a maximum correlation at 11 months. The persistent easterly winds associated with La Niña periods cause a set-up of water level in the western Pacific, which in turn depresses the thermocline. Owing to the inertia in the Southern Pacific system, the drop in sea level when the La Niña system weakens is not immediate along the north-east coast of the North Island, which accounts for the lag period experienced (Hay et al. 1991). Seasonal fluctuations in sea level have also been studied, being influenced by both changes in the density of sea water and changes in oceanic circulation (Heath 1976b).

Coastal currents and circulation

New Zealand has many estuaries, coastal embayments, and an extensive submarine platform (or shelf). Many early studies of the physical oceanography of these areas were made as background to biological, geological, or engineering studies (Heath 1985). More recently a multidisciplinary approach has been used, particularly in estuaries (e.g., Upper Waitemata Harbour: Williams & Brickell 1983; Pauatahanui: Healy 1980; Avon-Heathcote: Knox & Kilner 1973) and fiords/sounds (e.g., Pelorus Sound: Gibbs et al. 1991). However, much of the oceanographic investigations in open coastal waters remains as background to engineering studies (e.g., ocean outfall investigations, harbour developments, dredge material disposal, and pipeline/cable routes) and hence is often only found in the "grey" literature.

Until 1970, analyses of coastal currents around New Zealand were made using the geostrophic method (Heath 1968; Harris 1985), mean currents inferred from changes in water mass properties (e.g., salinity, temperature, water clarity), and drift card or dye experiments. Details of these research efforts were reviewed by Heath (1985). Although the direction of the mean circulation and the relative rates of flow in specific areas had been reasonably well established, little was known of the absolute speeds and non-seasonal variability that might be expected of the general circulation (Heath 1973b). Currents measured by the Royal New Zealand Navy over single tidal cycles, using current poles, had been made at many tidal stations around New Zealand and are shown on most hydrographic charts, published by the Navy Hydrographic Office. Some of these data were used by Carter & Heath (1975) to ascertain the role of mean circulation and tidal currents on the transport of bottom sediments on the continental shelf. However, more extensive current measurements, both spatially and temporally, were needed to verify circulation patterns obtained by the indirect quasi-geostrophic methods (Heath 1973b). Heath (1973b) and Stanton (1973) both used a towed Geomagnetic Electrokinetograph (GEK) in 1970–71 to measure currents around southern and northern New Zealand, respectively. The other more significant trend in direct current velocity measurements also occurred in 1970, when Plessey recording current meters (RCMs) were moored adjacent to oil rigs off the west coast of the North Island (Heath 1978b). These deployments yielded continuous current velocity data at 10-min intervals for between 11 and 21 days. Other early RCM deployments were carried out by Dr D. M. Garner (University of Auckland) around Goat Island (off Leigh) in 1972 and a short 3-day deployment in 1973 in Pelorus Sound using a Geodyne current meter, which recorded the current velocity on film (Heath 1974a). The Goat Island deployment, for 50 days at 14 m depth in 20 m water depth, was discussed briefly by Harris (1985). Details of RCM deployments in New Zealand coastal waters (< 100 m depth) since their introduction in 1970 are summarised in Table 1. (A reasonable effort was made to include most of the known deployments in this compilation, except the short-term Navy deployments, to convey the considerable extent of this database nationwide). In the total of c. 200 RCM deployments (21 meter-years of data), a large proportion have been carried out in the last 10 years. A further breakdown of the usage statistics indicates that c. 112 deployments (consisting of 50 per cent of the entire current database) were made as part of coastal outfall (sewage and cooling water) studies. Major outfall studies for which extensive oceanographic surveys were undertaken include: 43 deployments for the Wellington–Lower Hutt outfalls study in Cook Strait (Beca Carter-Caldwell Connell 1980; Wellington City Council 1988; Bell 1989); 28 deployments for the Waitara-Motunui outfall studies in the North Taranaki Bight (Taranaki Catchment Commission 1985); and 19 deployments for the Auckland Regional Council outfall investigations in Manukau Harbour and offshore from Awhitu Peninsula (Beca Steven 1989).

With the use of RCMs commonplace for coastal outfall studies, large amounts of current velocity data can now be obtained, but the full potential of these data is not always fully utilised. Methods of analysing, presenting, and using oceanographic data, in particular coastal currents, were given by Williams (1985b) and Bell (1988). Bell et al. (1988) reviewed various techniques which are used to deploy RCMs in coastal waters and demonstrated some of the problems resulting from bio-fouling, interference from fishing boats, shoaling waves, and flooded river debris. Several types of RCMs have been used in New Zealand's coastal waters over the past 20 years. Of particular note is the long period in which the non-averaging Aanderaa RCM4, although not ideally suited for shallow-water coastal deployments (Bell et al. 1988), was nevertheless the only affordable instrument available. The shrouded paddle-rotor variant, the RCM4S, went some way to alleviating the current velocity errors caused by wave or swell pumping of the earlier Savonius rotor. However, since the mid 1980s there have been rapid changes in the technology with the introduction of less expensive vector-averaging RCMs (e.g., the InterOcean S4) which measure the current using non-moving electromagnetic sensors and which have a solid-state

Table 1 Coastal RCM deployment statistics since 1970, grouped by regions. Data sources: Taranaki Catchment Commission (1985), Beca Steven (1989), Harris (1985, 1990), *NZJMFR* papers, various consultancy reports, University of Waikato theses, and DSIR Marine and Freshwater deployment files. RCM types: ADCP, Acoustic Doppler Current Profiler; IO, InterOcean 135; NB, Neil Brown; Pl, Plessey; RCM4, Aanderaa; S, shrouded rotor Aanderaa; S4, InterOcean S4.

Region	Total no.	Length (meter-months)	Purpose	RCM types
North Taranaki Bight	29	51	Outfall	RCM4, S4
South Taranaki Bight	3	3.5	Outfall	S4
Tasman Bay/ Marlborough Sounds	10	9	Model, oil well, research	RCM4,S, Geodyne
Cook Strait/ Wellington Harbour	62	62	Outfall, model, research, cables	S4, ADCP, Pl, RCM4, S
West Coast-South Island	8	34.5	Research	RCM4
Fiords/Stewart Island	7	2	Research, fish farms	RCM4, NB
East Coast-South Island	9	11	Model, research, outfall	RCM4, S, S4
South of East Cape	7	6	Outfall, dredge spoil	RCM4, S4
Bay of Plenty/ Coromandel	24	28.5	Outfall, model, research, sediments	RCM4, IO S4, ONO
Hauraki Gulf/ Bream Bay	18	27	Research, dredge spoil, sediments, outfall	RCM4, Pl?, S4
Manukau region	21	20	Outfall, sediments	RCM4,S, S4
Totals	198	254.5 (21 meter-years)		

data memory. Although still expensive, Acoustic Doppler Current Profiler (ADCP) instruments, which were used to measure "continuous" vertical profiles of currents in Cook Strait (Vennell & Collins 1991), will no doubt revolutionise the measurements of current flows and their vertical and spatial variability.

Numerous tidal gaugings in tidal inlets and estuaries around the coastline have been carried out over the past 20 years, particularly along the northeast coast of the North Island and for numerical model studies, by DSIR Marine and Freshwater (e.g., Hume et al. 1986) and the Earth Sciences Department of the University of Waikato (e.g., Burton 1987).

During the past 10 years, further circulation studies have benefited from RCM data. Heath (1986) used current meter observations from three sites across the Cook Strait narrows to investigate the semi-diurnal and compound tides and was also able to isolate periodic mean flows with periods of about 2 and 4 weeks associated with winds and an unexpectedly high 6.2 h M_4 overtide. Vennell & Collins (1991) deployed two Acoustic Doppler Current Profilers (ADCPs) at similar sites in the Cook Strait narrows along the new power cable route, together with other RCMs. They were able to define the cross-strait and depth variability in the M_2, S_2, and N_2 tidal current velocities and phase differences. For these constituents at both the mid-strait and eastern sites, the near surface tide was found to lag the tide 11 m above the bottom by up to 20° in phase. Strong 2–3 h bursts, with velocities up to 3 m s^{-1}, were also measured in the southerly tide during periods around spring tide on the North Island's tide. These result from the Karori tidal rip current and produce a residual anti-clockwise flow pattern. Allied with a long-term understanding of the circulation in Greater Cook Strait are recent studies which focused on the upwelling plume and consequential fronts occurring between the Kahurangi Shoals and Cape Farewell. RCM data and water mass properties were used by Heath & Gilmour (1987) and Shirtcliffe et al. (1990) to study the dynamical oceanography and the associated wind forcing of the region, the latter reference containing a detailed review of previous work in this upwelling region. Other coastal regions where the inner shelf dynamics have been elucidated using RCM and wind data are the Hauraki Gulf (Greig 1990), the east Coromandel coast (Bradshaw et al. 1991—who also used sea bed drifters), and studies associated with dredge spoil monitoring (e.g., Harms 1989; Foster et al. 1991; Warren et al. 1991).

Extensive surveys of water mass properties continue to complement our understanding of the broad circulation patterns of New Zealand's coastal embayments. For example, a hydrological survey of Hawke Bay by Francis (1985) sampling salinity, temperature, and Secchi disc depths, resulted in an alternative circulation pattern being advanced in addition to the pattern described by Ridgway & Stanton (1969). Fiords and shelf waters where recent circulation and mixing studies have been carried out include: the Southern Fiords (Stanton 1986); Marlborough Sounds (Bradford et al. 1987); outer Bay of Plenty (Ridgway & Greig 1986); and the South Otago Shelf (Hawke 1989).

COASTAL AND ESTUARINE NUMERICAL MODELLING

Numerical modelling has increasingly become an essential tool for most estuarine and coastal research or engineering studies. The main reason is that large areas of water bodies can be quantitatively simulated, in contrast to the limited number of relatively expensive in-situ measurements that can usually be made. Although field measurements will continue to be necessary to calibrate any numerical model (i.e., ensure the model predictions are simulating a real situation), once calibrated and subject to further verification, a numerical model has several advantages:

- cost-efficiency compared with an extensive field programme;
- the ability to study several "events" such as various tide, wind, and wave conditions, given the relevant boundary conditions;
- the only effective means of predicting the effects of anthropogenic or naturally occurring activities before they occur (e.g., dredging, dredge material disposal, reclamations, outfalls, tsunamis, and sea level rise);
- the ability to isolate smaller-scale features, such as separation eddies and wave focusing, which may not be elucidated by a broad coverage of field measurements;
- the model can be archived for later use.

Most of the applications of coastal numerical modelling have used the finite difference approach to solve the relevant depth-averaged equations on a two-dimensional rectangular grid covering the area of interest, although applications of finite element (O'Sullivan et al. 1982; D. G. Goring pers. comm.) and random-walk particle (Bell 1991) techniques have been used. Future model applications will no doubt include simulation of three-dimensional flows.

Hydrodynamic modelling

In New Zealand, some of the earliest numerical tidal flow models, based on finite difference rectangular grids were developed and used by: Bradford & Wooding (1974) for predicting the current flows around Mana Island–Titahi Bay coastal waters, for an outfall proposal using a 400 m grid; and Heath (1974b) who quite accurately modelled the semi-diurnal tide in Cook Strait with a coarse grid of c. 7 km. Since 1980, there has been a dramatic increase in the application of hydrodynamic models, as computer power became readily available and cost-efficient. A major non-linear hydrodynamic model study was carried out by Bowman et al. (1980), building on the work of Heath (1974b), to simulate the M_2 tidal effects in the greater Cook Strait region, including the South Taranaki Bight and the Maui gas field. A grid of 8 km squares was used containing 600 active water cells. The results reproduced tides and tidal currents with apparently good accuracy and also led to the definition of a 75 km diam. anti-clockwise eddy north of D'Urville Island. A further more detailed modelling study focusing on northern Cook Strait and Wellington Harbour was carried out for ocean outfall studies by Bell (1989, 1991; Bell et al. in press). This finite difference model was calculated on a nested grid, with the outer grid being 1 km squares and the inner grid, centred on the South Wellington coastal waters, being 333 m cells. Aspects of the interaction between the inflow and outflow of Wellington Harbour waters and the adjacent coastal waters and the bifurcating residual flow off the harbour entrance could be defined. The other main shelf area modelled has been the Hauraki Gulf where Bowman & Chiswell (1982) used the same type of model as in Cook Strait to ascertain the circulation pattern. The Hauraki Gulf was the subject of a further more extensive hydrodynamic model study on a 1.5 km grid out to the 100 m depth contour, to investigate the residual circulation, particularly wind effects, in the gulf for fisheries studies (Greig & Proctor 1988; Proctor & Greig 1989).

Because of the greater environmental pressures and the ongoing port developments in estuaries and harbours, several of these water bodies have been modelled. As part of the multi-disciplinary Upper Waitemata Harbour Study, a hydrodynamic model was developed to ultimately determine mixing and flushing of pollutants and nutrients (O'Sullivan et al. 1982). Allied with this study was the development of a simple box model approach to estimate the flushing characteristics of the Upper Waitemata (Williams 1986). The first major numerical modelling study on a fully commercial basis was carried out in 1982–83 by the Danish Hydraulic Institute (Danish Hydraulic Institute 1982, 1983) using System 21HD (a two-dimensional depth-averaged finite difference model) to predict the likely effects on the hydrodynamics and sedimentation of a proposed forestry terminal in the Lower Whangarei Harbour. Simultaneously Black (1983) developed one- and two-dimensional hydrodynamic models and applied them to Whangarei Harbour. Subsequent major harbour studies using the DHI model have been carried out in Tauranga Harbour (Barnett 1985a, 1985b; Healy et al. 1985; Williams 1985a); Port of Nelson (Kettell & Barnett 1986); Otago Harbour (Barnett 1988; Victory et al. 1989); and Wellington's Lambton Harbour (Barnett 1990). A tidal model study was undertaken for Otago Harbour by Wilson & Sutherland (1991) to complement the above study. A further development in hydrodynamic modelling, that of simulating surface waves and their amplification and dissipation within a harbour basin, was undertaken by Victory et al. (1989) for the Port of Taranaki using the short-period wave module of System 21HD. These detailed numerical model studies, together with the extensive field data base obtained during the course of such studies, have greatly improved our understanding of the hydrodynamics and mixing characteristics of these estuaries and harbours.

Sediment transport modelling

Significant advances were made internationally around 1979–83 in the area of numerical modelling of sediment transport on finite difference grids for coastal and estuarine areas. Included in this major thrust was the work of Black (1983) who developed a two-dimensional sediment transport model (2SS), which used the gridded flow patterns from a previously executed two-dimensional depth-averaged hydrodynamic model. This sediment transport model was verified and then applied in Whangarei Harbour (Black & Healy 1982), Tauranga Harbour (Black 1984), and Cook Strait (Black 1986). One of the novel features of the model was the provision of specifying the sediment availability for transport of bottom sediments for each grid cell, based on underwater observations and sediment charts. It is therefore possible to model a natural estuary which, in the New Zealand situation, is typically floored by zones of immobile shell-lagged sediments as well as zones of active sandy sediments. Both bedload and suspended sediment were modelled (Black et al. 1989). Further process studies using this modelling approach were undertaken for predicting the sediment threshold over tidally-induced mega-ripples in estuaries (Black & Healy 1986) and combining wave refraction and hydrodynamic modelling with field measurements to ascertain the mechanisms causing ripple bands on the ebb-tidal delta off the Whangarei Harbour inlet (Black & Healy 1988). Several of the above-mentioned hydrodynamic model studies (e.g., Nelson, Otago Harbour, and Tauranga) have in the first instance approached potential sediment transport problems such as channel infilling by inferring sediment transport potential and pathways from residual current velocities (averaged over a tidal cycle). A further refinement used in the Whangarei and Tauranga Harbour studies was the computation of sediment threshold residual currents where only the time portions of a tidal cycle, when the flow exceeds a specified transport threshold, are vectorially averaged.

Numerical modelling of sediment transport in coastal waters remains a relatively undeveloped area of research world-wide, particularly in areas where the tidal current alone is insufficient to transport bottom sediments but where wave-current interactions are important, e.g., the movement of dredged material from dump grounds, and in the surf zone where shoreline stability is a major problem.

SHORT-PERIOD WAVES, TSUNAMIS, AND STORM SURGES

Short-period waves

Wave data are of fundamental importance to coastal investigations (Kirk 1977b; Laing 1988; Steel 1990), although much of the research undertaken in New Zealand during the last 25 years has concentrated more on the application of wave data to various problems in the coastal and nearshore zones, rather than on the behaviour of waves themselves. Hence the data obtained are often limited in scope, both in terms of the parameters measured and the length of available record. In a review of available sea state wave data, McLean (1968) noted that "the utility of this qualitative 'sea state' data is limited — wave height..., wave period..., and wave direction are not specified".

Most studies of the New Zealand wave climate postdate the mid 1960s. They have been initiated for the purpose of providing input to coastal erosion and coastal processes research (e.g., Kirk 1977a; Pickrill 1977; Harray & Healy 1978), to assess coastal hazards (e.g., Frisby & Goldberg 1981), or to provide design parameters for engineering works (e.g., Kibblewhite et al. 1982). Kirk (1974) gave a brief discussion of the wave climate around New Zealand which highlighted the high-energy waves derived from the Southern Ocean. Pickrill (1979b) and Pickrill & Mitchell (1979) reviewed all available sources of available wave data, and (based mainly on ship observations of wave conditions) separated the wave climate of New Zealand into four major zones:

(i) Southern New Zealand: an extremely high-energy wave zone (H = 3.5–4.5 m, T = 10–12 s, SW–W). The waves display a slight seasonality and are typically steep, indicating a zone of active wave generation.

(ii) Western New Zealand: a lower-energy wave zone (H = 1.0–3.0 m, T = 6–8 s, SW–W). The waves are steep and display a quasi-periodic c. 5-day cycle, attributed to the passage of weather systems across the Tasman Sea.

(iii) Eastern New Zealand: a low-energy wave zone (H = 0.5–2.0 m, T = 6–9 s, S), due to sheltering from prevailing westerly winds by the New Zealand land mass. Wave steepness is variable, indicating a mixed swell and local sea environment, with a weak seasonal cycle.

(iv) Northern New Zealand: this zone was poorly defined by the available data, but was considered to be a low-energy lee shore (H = 0.5–1.5 m, T = 5–7 s, N–E) extending between East and North Capes. Wave steepness is variable and Pickrill & Mitchell (1979) considered that this zone should show a weak seasonality.

This overall subdivision of the New Zealand wave climate has persisted (Heath 1985; Williams 1985b), although the nature of the waves within the zones has been better defined. Reid & Cohen (1983) summarised ship observations of winds and waves in the Tasman Sea and around New Zealand for the period 1957–80, and Laing (1982) considered wave observations from ships in the Southern Ocean. However, most studies collecting wave data only considered nearshore waves.

During the 1970s and early 1980s, several beach observer programmes were used around New Zealand to monitor the nearshore wave conditions, normally for specific applied projects (e.g., Smith 1968; Kelk 1974; Brown 1976; Harray 1976; Christophersen 1977; Gibb 1978; Frisby 1980; McLennan 1982). A variety of wave parameters were measured by these programmes, including significant wave height and period, wave approach direction, wave breaker angle, and velocity of the longshore current. These programmes have been of particular importance to studies of nearshore sediment transport. However, the main advances in the definition of the New Zealand wave climate have come from instrumental records of waves, particularly in association with the Maui hydrocarbon field development off the Taranaki coast (Kibblewhite et al. 1982). Franklin (1973) provided some of the early instrumental data for the western zone consisting of 4 months of pressure transducer readings and limited data from a wave staff at the Taharoa ironsand development. Considerably more data became available during the environmental study for the Maui development (Kibblewhite et al. 1982). This study involved c. 10 years of wave monitoring using a Datawell Waverider buoy moored in 110 m of water close to the Maui platform. It has produced several theses and papers dealing with measured wave spectra (Chiswell 1977, 1979, 1981; Chiswell & Ewans 1978; Chiswell & Kibblewhite 1980; Ewans & Kibblewhite 1990) and with wave generation and forecasting (Chiswell 1979). Two of the more significant findings of this study related to the spectral form of the wave data and the strong correlation between the wave spectra and microseisms measured on land.

The mean spectral form of the measured wave data was closely approximated by the JONSWAP spectral form of Hasselmann et al. (1973), although the Maui data exhibited a slightly lower and broader peak (Chiswell & Kibblewhite 1981; Ewans & Kibblewhite 1990). This indicates that the western zone wave climate is essentially fetch-limited, although it is clear that there is a virtually unlimited fetch available for the swell component present (Harris 1990). Ewans & Kibblewhite (1990) also demonstrated that the shape of the best-fit spectral function is also dependent on the fitting procedure followed, accounting for some of the observed differences reported in the literature.

The Maui study also measured microseisms using a SL-210 long-period seismometer sited at Oaonui, onshore from the Maui platform. The monitoring system was first tested at Great Barrier Island (Ewans & Kibblewhite 1981) and at both sites a good correlation between the observed wave spectra and microseism activity was achieved (Ewans 1984). The success of these investigations led to Electricorp Production developing the use of microseism data for long-term wave monitoring and as a measure of available wave power (Brown 1989).

Wave recording instruments have also been deployed for shorter periods at other sites around New Zealand. Harris et al. (1983) discuss the measurements made over 9 months by a Datawell Waverider buoy moored in deep water 3 km offshore from Hicks Bay, East Cape. The data obtained were extrapolated to cover the northern New Zealand zone (Harris et al. 1983; Harris 1985), indicating that wave conditions were duration-limited and that a JONSWAP spectral form could be applied. Hastie (1985) deployed an OSK 3239 Direct Wave Height Recorder for 1 year 2.5 km offshore from Timaru. The data were not subjected to spectral analysis, but standard monochromatic wave analyses indicated a distinct seasonality, with higher waves occurring in winter. Examination of the joint probability plots presented by Hastie (1985) indicates a mixed wave steepness with a bimodal distribution typical of a combination of longer period swell and shorter-period local sea. This agrees with the findings of Pickrill & Mitchell (1979) and the minor differences in the recorded wave height (0.3–3.3 m) and period (8–12 s) reported by Hastie (1985) are consistent with shoaling of the deep-water conditions they defined.

The Port of Tauranga Ltd installed a permanent wave recorder in 13 m of water offshore from Tauranga Harbour in 1989 (Healy et al. 1989). The data obtained since then indicate the presence of a persistent swell with a height of about 0.3 m and a period of 12–16 s with local sea superimposed (de Lange 1991b). No strong seasonal trends are evident, but a longer-term variation possibly associated with ENSO fluctuations may be present. This is attributed to the greater incidence of onshore north-easterly winds during La Niña phases (de Lange 1991b). Similar trends may be evident in the western zone where a higher incidence of onshore south-westerly winds occur during El Niño phases.

Some wave data have also been obtained for shallow-water conditions inside estuaries (Wells-Green 1974; Hume 1980; Black 1983; de Lange 1988). de Lange (1990) and de Lange & Healy (1990) evaluated the spectral characteristics of waves within an estuarine lagoon and distinguished two components, both of which could be fitted by a JONSWAP-like spectral function. One component represented external wave energy filtered by the harbour entrance, and the other consisted of local wind-generated waves.

Overall, the coverage of wave data obtained in New Zealand is poor, particularly the availability of directional wave data, and it is still often necessary to resort to numerical hindcasting techniques. It is clear from measured wave spectra that the wave climate around New Zealand consists of a persistent background swell and local wind-generated waves. The local wind-generated component tends to dominate, particularly when dealing with extreme conditions, and this component may be represented by either a fetch-limited or duration-limited JONSWAP spectral function. Numerical models have been developed for New Zealand based on these spectral forms. Laing (1983, 1985) presented the results of a directional-frequency spectral model based on the output from the numerical weather prediction model used by the New Zealand Meteorological Service and either an unlimited spectral model defined by Pierson & Moskowitz (1964) or a fetch-limited JONSWAP model. The model was tested against Maui and Great Barrier Island deep-water wave data and showed good agreement. This model has subsequently been used by the Meteorological Service to predict deep-water wave conditions around New Zealand (Laing 1988). The model was subsequently extended to attempt to predict shallow-water wave conditions using a depth-limited form of the JONSWAP spectral function (Laing 1990). The agreement between the model and wave conditions measured in the Canterbury Bight is not good but still encouraging.

Data provided by numerical models are more useful if they can be calibrated against measurements. In an annotated bibliography, Pickrill (1979b) records 124 sources of wave data for 1950–78, and it is clear that the number of data sources have increased greatly since then. Initially a newsletter, *Ocean Waves*, was circulated to attempt to identify sources of wave data. This was followed in 1987 by the establishment of the New Zealand Ocean Wave Society. The Society is developing a database of available wave information for New Zealand, with a preliminary version to be released by early 1992.

Examination of the data available indicates that a wide variety of techniques have been used to measure waves. Some measurements were made by devices developed locally (e.g., Franklin 1973; Aimes 1975; Hume 1980; de Lange 1988), but increasingly imported off-the-shelf equipment is being used (e.g., Hume et al. 1991; de Lange 1991b). Perhaps one of the more unusual wave recording systems is the wave radar under development by the DSIR Physics and Engineering Laboratory. The original system was a DECCA D7 Marine Radar installed in a caravan at Fitzroy Beach, New Plymouth (McLennan 1982; Ireland & Woodward 1983). Progressively more sophisticated devices have been developed (Poulter et al. 1988; Poulter & Smith 1989) and the deployment of microwave radar for real-time acquisition of nearshore directional wave data appears promising.

The major problem with wave research, and the application of wave data to coastal problems, is a shortage of long-term directional wave data, i.e., data records of at least 5 years' duration. The Maui record is the longest available, and these data represent deep-water conditions. Few records of longer than 1 year's duration exist for shallow-water conditions, and directional instrumental data are almost non-existent. The need for such data in coastal hazard management is stimulating support for the acquisition of long-term wave data for coastal sites around New Zealand. The next 25 years may see the collection of long-term wave data representative of the four wave climate zones similar to the WIS database maintained by the Waterways Experiment Station in the USA.

Tsunamis

Tsunamis are long-period waves (typically 20–30 min) generated by large short-duration disturbances of the sea floor. The Pacific Ocean experiences many tsunamis as a result of tectonically active margins. The largest tsunamis experienced in the south-west Pacific this century occurred following the Chilean Earthquake of 22 May 1960 and the Alaskan Earthquake of 28 March 1964. The first event led to the development for New Zealand of tsunami travel time charts for distantly generated tsunamis (Gilmour 1961, 1963a). Since then tsunami research has concentrated on the local generation and effects of tsunamis in New Zealand.

Laing (1954) produced the first compilation of tsunamis experienced in New Zealand. This formed the basis of further compilations of historical tsunamis. Gilmour & Ridgway (1982) and Ridgway (1984) compiled a list largely based on the earlier list of Laing with the addition of more recent events. de Lange & Healy (1986a) compiled a list based on a search of archival material relating mainly to the north-eastern coast of the North Island (de Lange 1983). This is still the most extensive New Zealand tsunami database available, but coverage is incomplete for southern regions.

Interest in tsunamis following the Chilean and Alaskan events led to a specialist research symposium, held in conjunction with a meeting of the International Union of Geodesy and Geophysics Tsunami Committee, in Wellington during 1974 (Heath & Cresswell 1976). Although the papers presented covered the entire Pacific region, Heath (1976c) presented one on the local harbour responses to the 1960 Chilean tsunami. This highlighted resonance within harbours as a potentially hazardous response to tsunami excitation. It became clear later that resonance could also be induced on the shelf, resulting in tsunami-induced shelf edge waves (Heath 1979b).

By the 1980s, there was a growing awareness of the potential hazard represented by tsunamis (Ridgway 1981), although this had been raised earlier by Eiby (1968). Some aspects of the risk were covered by the compilation of historical tsunamis and their effects (e.g., Ridgway 1984), but this was largely superficial. Eiby (1980, 1982a, 1982b) investigated three locally generated tsunamis in considerable depth, focusing particularly on the generating mechanisms, but also considering their effects at the shore. He concluded that the coastline north of Gisborne was most at risk from locally generated tsunamis. Heath (1979a) also indicated that this region and Banks Peninsula were high-risk regions owing to amplification of distantly generated tsunamis by shelf resonance, a finding supported by historical records of tsunami occurrence (de Lange & Healy 1986a).

Overall it was recognised that distantly generated tsunamis were a lower potential risk than locally generated tsunamis (Burton 1988) owing to the longer travel times (Gilmour 1961, 1963b), and reflection of tsunami wave energy by the continental shelf break (Goring 1980; de Lange 1983). Attention therefore focused on locally generated tsunamis, and although it was recognised that the majority of tsunamis are generated by earthquakes, volcanically generated tsunamis were perceived to be a threat (Heath 1985).

Latter (1981) identified 10 basic mechanisms by which volcanic activity may generate tsunamis, some of which have potential to occur in the vicinity of New Zealand. The major volcanic tsunami hazard identified before 1980 was White Island in the Bay of Plenty. Finite difference and finite element numerical model simulations were undertaken during the early 1980s to assess the risk from White Island (Weir & White 1982; de Lange 1983) and other volcanoes in the vicinity of the Bay of Plenty (de Lange & Healy 1986b). The simulations involving White Island considered five possible mechanisms and involved two different modelling approaches, and produced almost identical results (de Lange & Healy 1986b). These studies showed that eruptions at White Island could generate tsunamis, either directly from the eruption or via associated earthquake activity, but that because of wave attenuation by the shelf break and the shelf, the waves would not be catastrophic at the shoreline unless the eruption or earthquake displaced more than 10 km^3 of sea water. Therefore volcanogenic tsunamis from White Island were considered to be a minor risk. Mayor Island was considered to be a slightly higher risk, but still of minor importance (Weir & White 1982; de Lange 1983; de Lange & Healy 1986b). These results appear to be treated with unwarranted scepticism by later authors who consider a Krakatoa-like event from either White Island or Mayor Island as having a high probability, but they do not present justification (Buck 1985; Nairn et al. 1991).

Numerical modelling continues to play a major role in the assessment of tsunami hazard to the present day. Butcher & Gilmour (1987) developed numerical models for Wellington and Lyttelton Harbours to assess the impact of tsunami-induced seiching. This study allowed the response of Wellington Harbour to the Chilean and Alaskan tsunamis to be better defined (Gilmour 1990). Gilmour & Stanton (1990) undertook modelling of local earthquake-generated tsunamis for the Wellington Regional Council as part of their Regional Natural Disaster Reduction Plan. Similar numerical modelling of locally generated tsunamis in the Wellington region was also undertaken for the Museum of New Zealand Project, and for distantly generated tsunamis in the Mercury Bay area for a marina development at Whitianga, but these studies remain unpublished.

Following consultation with the scientific community, the Ministry of Civil Defence established in 1989 a National Civil Defence Scientific Advisory Committee which includes input from a Tsunami and Storm Surge Hazard Working Group. This group acts to co-ordinate tsunami research in New Zealand. Based on consideration of a review of the status of tsunami research in New Zealand undertaken by Burton (1988), the Working Group has identified public education, improving the existing historical tsunami database, and further modelling of locally generated tsunamis as immediate priorities for future research.

Storm surges

A storm surge is defined as a super-elevation of the sea surface resulting from a drop in barometric pressure combined with onshore wind stresses. Storm surges occur frequently around the New Zealand coast, but to date have received little attention from researchers. de Lange (1983) notes that some historical reports of "tidal waves" probably represent storm surges.

Early work by Gilmour (1963b), Agnew (1966), Agnew & Smith (1973), Heath (1979a), Hume (1979), and Kirk (1979b), described surge ranging from 0.3 to 0.8 m associated with storms on various parts of the New Zealand coast. These studies and subsequent work show that storm surges experienced in New Zealand are smaller in elevation but greater in extent than those experienced at lower latitudes such as the Gulf Coast of the United States or in the Bay of Bengal (de Lange 1988). However, the maximum surge levels recorded are comparable in magnitude to maximum tsunami run-up levels associated with distantly generated tsunamis (de Lange 1988).

The role of storm surge in defining coastal hazard zones has been appreciated for some time, and Frisby & Goldberg (1981) developed an analytical approach for predicting storm surge elevations which has been applied to various locations around New Zealand (e.g., Gibb 1981; Healy 1983, 1985a; McCabe 1985; de Lange 1991a). However, for planning purposes it is preferable to calibrate analytical approaches with real data.

The first systematic compilation of historical storm surges was that of Hay (1991) who considered storm surges in the Bay of Plenty and discovered 153 events between January 1873 and August 1990. During the same period, fewer than 30 tsunamis were experienced throughout the entire New Zealand region.

The Tsunami and Storm Surge Hazard Working Group of the National Civil Defence Scientific Advisory Committee consider the development of suitable databases and models of storm surges around New Zealand as a high priority for future research.

INFORMATION TRANSFER AND THE ROLE OF NZJMFR

It became apparent when searching the literature for this review that a huge resource of technical literature and data bases on coastal oceanography and sedimentology were available in the "grey" literature. This literature comprises student theses and consultants' and in-house reports from a wide range of sources, often related to environmental impact assessments. This resource is growing in proportion as government departments and universities are forced to seek alternative sources of commercial contract funding. It is difficult to access the information which is poorly registered on electronic data bases or embargoed by the clients who commission the work. The "grey" literature reports are on a wide variety of topics including sewage outfalls, motorways, power station cooling water systems, wharf developments, ports, dredge spoil disposal, marinas, LPG terminals, gas and water pipeline crossing of estuaries, synthetic fuel plants, logging terminals, water from the sounds, sand and gravel mining, coastal erosion and protection, beach nourishment, reclamations for rubbish tips and road/rail causeways, pulp mills, inlet stability, river mouth stability, offshore gas fields, oil spills, and effects of logging on estuaries. This large quantity and wide variety of work demonstrates the usefulness of the findings of coastal oceanography and sedimentology. The "grey" literature makes a substantial contribution towards our understanding of the coast, and efforts should be made to improve its registration on electronic data bases or publication in scientific journals.

Conferences and newsletters of the Marine Sciences Society, and to a lesser extent of the Geological Society, have been a regular forum for disseminating the results of current research, although the papers on coastal oceanography and sedimentology presented at the meetings have been few and erratic in number compared with papers on the biological sciences. In 1985 the (7th) Australasian Conference on Coastal and Ocean Engineering was held in Christchurch, New Zealand, for the first time. This conference very successfully provided a focus for reporting coastal oceanographic and sedimentologic research findings in papers (Institution of Professional Engineers, N.Z. 1985) and at workshops held on tidal inlet stability (Hume & Herdendorf 1987), ocean outfalls (Roper & Williams 1985), and gravel river mouth stability. Another conference in this series was held in Auckland in December 1991 where about 40 papers reported research and developments in coastal oceanography, sedimentology, and engineering taking place in New Zealand (Bell et al. 1991). The N.Z. Ocean Wave Society, established in 1987, holds symposia in conjunction with the above conferences serving to co-ordinate activities on wave research.

The *New Zealand Journal of Marine and Freshwater Research* has clearly helped disseminate the findings of coastal and oceanographic research carried out in New Zealand in the last 25 years. It has also served as a useful vehicle for mostly descriptive work that perhaps would otherwise have remained buried in the "grey" literature. Yet much research is still reported elsewhere. The reasons for this do not lie in the selection procedures of the journal, but rather reflect the nature of submissions. Scientists tend to publish in international journals to get international recognition for New Zealand science and to improve their own career prospects.

New technology and ever increasing international contacts make New Zealand scientists look toward future research with optimism. However, the ever changing work place environment and the financial restrictions forced by political processes cast a shadow over the future research effort on coastal oceanography and sedimentology in New Zealand.

CONCLUSION

Looking back

It should be apparent from this review that much has been achieved during the last 25 years, a period which has witnessed the establishment of physical coastal science as a discipline in New Zealand.

Many of the studies mentioned here have contributed to systematic description of the distinctive coastal environment of the country and to progressive isolation of problems for ongoing research. Notable are the large contributions made by the Waikato school led by Healy, the Canterbury school led by McLean and Kirk, and DSIR Marine and Freshwater (which now includes New Zealand Oceanographic Institute and ex Ministry of Works: Water and Soil Division coastal groups). Several studies have made significant contributions to international knowledge. Notable among these is the work by the Canterbury school on mixed sand and gravel beaches, Black's pioneering numerical sediment transport modelling in tidal inlets, and the refinement of stability relationships for tidal inlets by Heath and Hume.

A feature of coastal research in New Zealand, as indeed in most other countries, is that it has been—and yet remains—fragmented and lacks underpinning by co-ordinated, ongoing programmes of baseline data collection and monitoring, and a national body with the responsibility to oversee these. McLean noted in 1976 that coastal research was carried out in a project or crisis-oriented context. The "user-pays" market force philosophy since the late 1980s has done little to alter this situation to date. While university and DSIR groups all have long-term basic research programmes, it is the general rule (with only a few exceptions) that we try to manage the coast with precious few quantitative records of what actually occurs there. If the past decade has seen a marked increase in the databases of current, tide, and wave information, then these remain patchy and dispersed amongst different agencies. Given piecemeal demands for coastal knowledge and the highly variable—and relatively unstudied—nature of the coast, it is not surprising that different research groups and individuals have pursued very different themes and problems, drawing on a common body of principles and techniques from (and returning a few to) the international community.

A benefit of these individual studies, however, has been the production of a generation of versatile and practical coastal practitioners. Overseas visitors often remark that New Zealand coastal scientists are notable for their level of involvement in "hands on" coastal management at all levels. This strong pragmatic streak—rooted perhaps in the New Zealand character—has placed a high value on comparative analysis and experience of similar problems in diverse coastal settings and has given coastal scientists a deep involvement in the development of coastal management (itself an emerging discipline) at project, local, regional, and national levels. The development of coastal hazard mapping and management strategies is a good example, whereas many of our ports and numerous coastal engineering projects have also benefited from the partnership of coastal science and modelling with engineering, law, planning, and economics. Indeed, looking back, it is pleasing to trace the growth of the discipline and its spread of practitioners through a widening range of science, consulting, planning, policy, and regulatory agencies.

Looking forward

Two broad sets of issues will drive coastal research in the coming decade; within these there are several specific physical problems to solve. The first set of issues is bound up with climate change, sea level rise, and the consequences for coastal land use. In many ways, the fears (often ill-informed) expressed about sea level rise serve to raise old questions about coasts rather than new ones; the prospect of a rising sea level may simply lend urgency to studies that we should be doing anyway. Such questions include the role of mean sea level on equilibrium shoreline position, patterns of long-term trends and short-term fluctuations in sea level in the New Zealand region, and the coastal response to these trends and fluctuations.

The second set of issues relate to the New Zealand Resource Management Act (1991). Broadly, this requires a commitment to sustainable use of resources; specifically, it provides more fully for coastal management than any previous legislation. Whereas in the past, "coastal protection" usually meant protection of developed assets near the coast rather than protection of the coast per se, the Resource Management Act now places the emphasis more firmly on the coast itself and on hazard avoidance. Coastal scientists will be challenged by the implementation of the Act, and the National Coastal Policy when it emerges, not least by the need to provide the physical understanding required for new management imperatives.

The individual scientific problems to be pursued in the near future are largely those that have already been isolated from past studies and have been brought into sharp focus by the climate change and resource management issues. Much of this work will involve detailed observations and modelling in various coastal environments of processes that presently may only be appreciated at the conceptual level, using state-of-the-art data collection technology (e.g., satellite imagery and navigation, integrated bathymetric survey systems, acoustic Doppler current profilers, directional and radar wave recorders) and sophisticated numerical models. A challenge will be to understand the combined effects and interactions among these processes, such as wave-current interactions and the effects on sediment transport. One such application area concerns sand transport and morphologic change at tidal inlet-delta systems, where inlet configuration and sand storage is liable to change if sea level rises and where there are potential sand sources for beach renourishment and aggregate. A second application area concerns the nature of inner-shelf and beach sediment interaction, which is a fundamental requirement for the management of beach sand levels and offshore sand mining. At present, we have little knowledge on the rates of shoreward transport of sand and of how sensitive these are to changes in sea level and wave climate. The dispersal of dredge spoil from nearshore dump grounds is a related issue requiring greater quantitative knowledge.

Areas of coastal oceanography in need of future attention are: the effects of local winds, remote forcing, and freshwater run-off on vertical and horizontal circulation in embayments; estuarine mixing and water exchange between estuaries and the shelf; an understanding of the frictional dissipation of tides within inlets and estuaries and its effect on water circulation and sediment transport; the dynamics and influence of shelf waves on coastal circulation; and separation eddies around coastal headlands. Coastal research needs also to include: a national inventory of sand resources as potential sources for beach renourishment sand (to offset sand losses related to possibly accelerated rise in sea level), and incorporation of a quantitative approach to assessing storm surge and tsunami hazards into coastal hazard surveys and coastal management plans, to set these hazards in a realistic perspective against coastal erosion which tends to have dominated coastal hazard assessments to date.

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Erratum

Burns, C. W. 1991: Silver jubilee review—New Zealand lakes research, 1967–91. *New Zealand journal of marine and freshwater research 25(4)*: 359–379. The labels A–G in Fig. 1 (p. 361) were inadvertently left off. From top to bottom, parts A–C are in the left-hand column, and parts D–G on the right.