Significant coastal lagoon systems in the South Island, New Zealand

Coastal processes and lagoon mouth closure

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R.M. Kirk and G.A. Lauder

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CONTENTS

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R.M. Kirk* and G.A. Lauder†

*Department of Geography, University of Canterbury, Christchurch
†Department of Conservation, West Coast Region, Hokitika, New Zealand

ABSTRACT

Two distinctly different kinds of coastal lagoons are identified on the east and south coasts of the South Island, New Zealand. So-called 'river mouth lagoons' (the mouths of the Rakaia and Waiau Rivers) are one type, referred to here as 'hapua'. Published research on the physical evolution and processes of hapua is summarised. The second type is the 'coastal lake', for which the term 'Waituna-type' lagoon is used. Waituna Lagoon, Southland, is a quintessential example, others are: Waihora/Lake Ellesmere, Wairau Lagoon, Washdyke Lagoon, and Wainono Lagoon. These lagoons develop landward of barrier beaches formed from sands and gravels mainly derived from greywacke terrains subjected to Quaternary glaciation. Lagoons occur in interfan depressions or at the extremities of major outwash fan complexes, on microtidal coasts with very high wave energies and strong longshore transport of sediments. The coasts are either in erosion, or adjacent to 'hinge-points' around which entire coastlines are rotating to face dominant swell directions. Long-term erosion has greatly reduced present areas of Waituna-type lagoons over the last few thousand years. Entire lagoon systems and interconnections between coastal water bodies have been lost. Waituna-type lagoons are normally closed to the sea. Accumulated head, and scour by the water in the lagoons opens them. Wave processes, particularly longshore transport in storms, close them. Artificial opening of Waihora/Lake Ellesmere and Waituna has increased the frequency and duration of openings and lowered water levels. This has greatly reduced areas, water volumes, and wind-driven processes (waves, seiches, and currents) in the lagoons. US research on mid-latitude coastal lagoons shows that relative sedimentation rate is critical. Where rates are faster than sea level rise, lagoons will infill and be short-lived. Where sedimentation rates and sea level rise are roughly equal, a lagoon will maintain a constant water volume while sediments accumulate. Where sea level rise is faster than sedimentation, relative deepening will occur and the water volume will increase. Obtaining adequate data on sedimentation rates in Waituna-type lagoons is a high priority for their management.

Keywords: coastal lagoons, classification, lakes, hapua, river mouth lagoons, erosion, sedimentation, winds, management, Waituna, Waihora/Lake Ellesmere, Wairau, Washdyke, Wainono Lagoon, South Island, New Zealand

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1. Introduction

This report concerns the nature of coastal inlet and lagoon barrier processes occurring predominantly on mixed sand and gravel coasts of the south and east shores of the South Island of New Zealand. Coastal inlets and lakes of these types also occur on the east coast of the North Island. These have not been studied by the authors. Concerning physical processes and trends in ecosystem and landform development (and in sharp contrast to knowledge about estuaries), very little is known about coastal lagoons, despite their significant conservation and other values.

Coastal lagoons on alluvial coasts are often associated with wetlands and native fisheries of conservation value, for example Waituna, in Southland, and Lake Onoke, in the Wairarapa (see Figure 1 for the location of features mentioned in this report). Conservancies are involved in advocacy on water values, coastal management and wetland management which relates to the opening and closing of the gravel coastal barriers controlling the water levels and water exchange in these lagoons. Repeated management problems with inlet and lagoon barriers experienced by South Island Conservancies of the Department of Conservation warrant consideration on a scientific basis.

The inlets of the Bay of Plenty and Auckland coast have been studied by the Water Quality Centre, Hamilton, and later by the National Institute of Water & Atmospheric Research, in the last few years. However, sediment type, backshore form, and wave regime are significantly different in the South Island, and the South Island Conservancies have identified a need for separate guidelines on lagoon and barrier management.

The establishment of guidelines must proceed from a sound, working understanding of the nature and trends of physical coastal processes that have formed and that continue to modify coastal lagoons. This is approached in this report in three ways.

- Pertinent aspects of the international scientific literature are presented. The literature is small since very few other technically advanced nations with elaborately developed agriculture and associated drainage (and other infrastructure) systems have the type of coastal lagoons impounded by mixed sand and gravel beaches common in southern New Zealand. It is not that the lagoons themselves are unique (though they are not common) but rather that the uses made of them and especially of the surrounding lands and contributing catchments modify the natural processes to form a situation that is unique.
- Pertinent aspects of previous lagoon and coastal studies carried out in southern New Zealand are presented. This material relates to a number of different coastal lagoons along the east and south coasts. It demonstrates, among other things, that there are at least two distinctly different types of coastal lagoon system to be found there.
- A detailed investigation has been made of Waituna Lagoon in Southland, the results of which are reported here. This was done because of the identified importance of Waituna in Southland Conservancy, and as an effective way of adding to the overall knowledge base about South Island coastal lagoons.

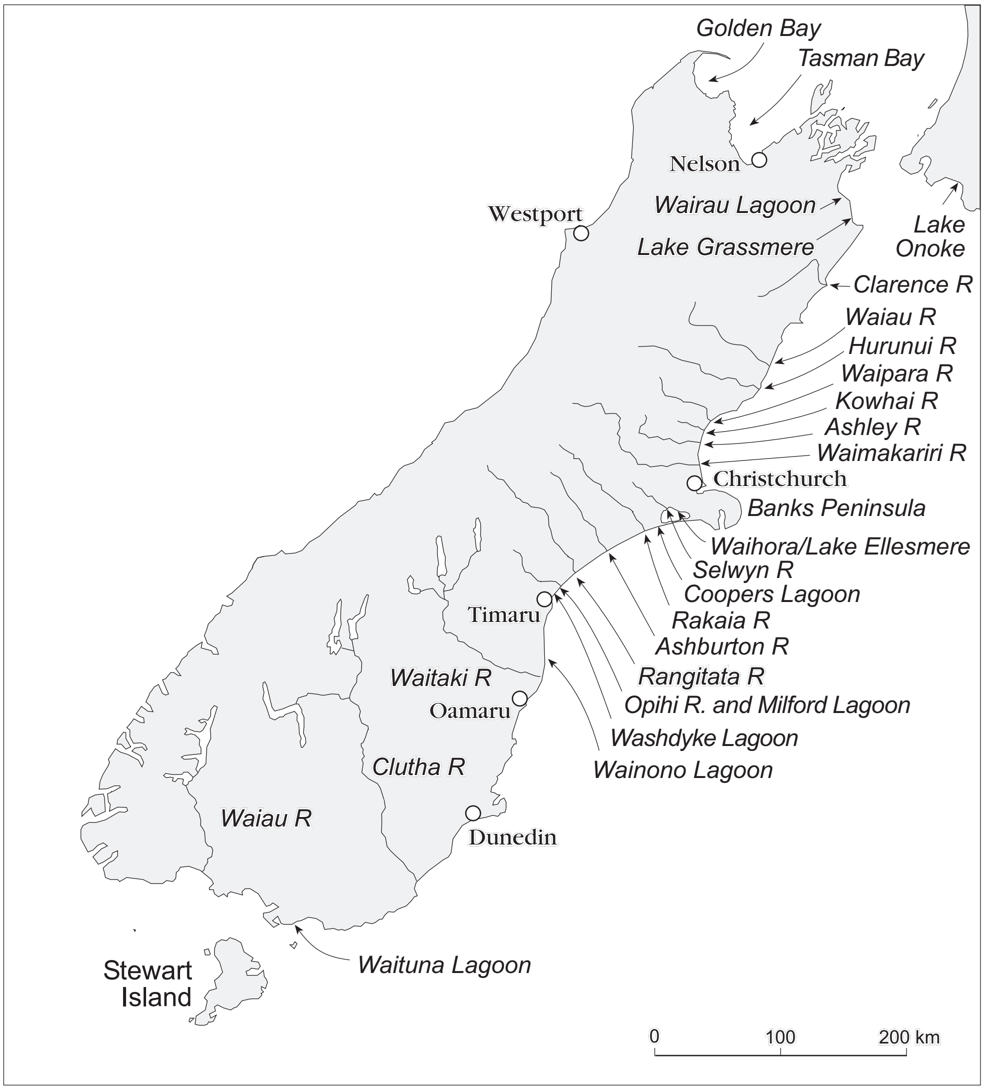


Figure 1. Map of the South Island, New Zealand, showing the locations of the rivers and lagoons mentioned in this report.

2. What is a lagoon?

The term 'lagoon' is commonly applied to bodies of ocean water surrounding tropical islands and where the water bodies are semi-enclosed within fringing coral reefs. In marked contrast, the term is also commonly applied to elongated bodies of water, more or less parallel to the coast, occurring at river mouths in temperate and high latitudes. This report deals with the latter, often referred to as 'coastal lagoons'.

As noted in a recent review of coastal lagoon processes edited by Kjerfve (1994), coastal lagoons constitute a common coastal environment around the world. However, like estuaries (with which they have often been erroneously classified), they display a great variety of physical types and characteristics. Kjerfve (1994) also notes that coastal lagoons can span the range of salinities from hypersaline to completely fresh. There are thus at least two problems of definition. The first is that it is far from clear how lagoons can be satisfactorily defined. The second is that the term is used for several distinctly different coastal systems, although no clear specification has yet been made of either the number or characters of the systems that might be assigned to a class of coastal system tagged 'lagoon'.

These lagoons are not estuaries, and therefore their dynamics cannot be estimated by reference to standard texts on tidal hydraulics (which presume a diurnal exchange of tidal waters). The lagoons, especially those with mixed sand and gravel barriers , constitute a class of coastal system in their own right, for which there is virtually no established technical literature. Such lagoons are also of prime interest as sites at which sea level rise and other aspects of prospective global climate changes might have significant effects.

While coastal lagoons in New Zealand have been identified as very important in conservation terms, they are systems that belong to an important class of coastal phenomena for which scientific study has barely begun.

2.1 DISTINGUISHING COASTAL LAGOONS FROM ESTUARIES

Hume & Herdendorf (1988) characterise 16 types of estuary in New Zealand based on morphology. In their fig. 4 (p. 268) they present eight sets of hydraulic relationships thought to control the tidal circulation of the full range of types and they discuss coastal resource management implications thought to relate to each. The hydraulic relationship plotted is that between entrance cross-sectional area (of the inlet at the coast) and the 'tidal compartment' (the volume of water that enters and leaves an estuary on each tidal cycle). It has been known since the 1930's that this relationship is an important morphological control of estuarine entrance stability.

It is important to note that Hume & Herdendorf (1988, fig. 4, p. 268) show a line in their graph for River mouths (Types 8–10). At least some of the features classified in this group (e.g. Rakaia River) are lagoons rather than estuaries. Hume & Herdendorf (1988, p. 264) acknowledge in discussion that 'spit-lagoon river mouths (Type 10) have effectively no tidal prism at all, though there is (at low river flows) a tidal backwater effect that raises freshwater levels in the lagoon'. The plot is thus a source of confusion since it does not distinguish estuaries from lagoons. It is also in error in that it implies at least one controlling hydrologic relationship—the inlet section/tidal compartment ratio—for Type 8–10 features (e.g. for lagoons) that it is acknowledged elsewhere in the same paper does not, in fact, physically occur in at least some of the features in the class.

For this reason as much as any other, it is worth presenting opinion on the definition of 'estuaries' in conjunction with that on the character of 'lagoons'. Following Cameron & Pritchard (1963) an estuary is taken here to be: ' a semi-enclosed coastal body of water having a free-connection with the open sea and within which the sea-water is measurably diluted with fresh water deriving from land drainage'.

Kjerfve (1994, p. 2) refers to a wide variety of coastal systems (including estuaries) by the collective term 'inland coastal-marine connected waters' and classifies these into six types (estuaries, coastal lagoons, fjords, bays, tidal rivers, and straits).

In this scheme estuaries are:

> an inland river valley or section of the coastal plain, drowned as the sea invaded the lower course of a river during the Holocene sea-level rise, containing sea water measurably diluted by land drainage , affected by the tides and usually shallower than 20 m. This ... is consistent with the definition of Cameron & Pritchard (1963). It is only this type of system that should be referred to as an estuary.

Note that none of the 'inland coastal-marine connected' bodies of water of the east and south coasts of South Island that are the subject of this report meet this definition, i.e. none is properly characterised as estuarine.

2.2 DEFINITION OF TYPES OF COASTAL LAGOON

Kjerfve (1994, pp. 2–3) offers the following definition:

> A Coastal Lagoon [is] an inland body of water, usually oriented parallel to the coast, separated from the ocean by a barrier, connected to the ocean by one or more restricted inlets, and having depths which seldom exceed a couple of meters. A lagoon may or may not be subject to tidal mixing, and salinity can vary from that of a coastal fresh water lake to a hypersaline lagoon, depending on the hydrologic balance. Lagoons formed as a result of rising sea level during the Holocene or Pleistocene and the building of coastal barriers by marine processes.

Lagoons of at least two types common on the east and south coasts of the South Island, New Zealand, conform to this definition, with the added restriction that tidal circulation is not dominant in either type (see section 3).

Kjerfve (1994, pp. 4–5) goes on to distinguish three sub-types of lagoons. 'Choked' lagoons usually have a single long, narrow entrance channel and occur on coasts with high wave energy and significant longshore drift. Although these lagoons may experience tides that may co-oscillate with tides in the coastal ocean, the entrance channel serves as a dynamic filter that largely eliminates tidal currents and water level fluctuations inside the lagoon. Choked lagoons may have long flushing times, dominant wind forcing, and/or intermittent stratification due to solar radiation or river runoff events. As will be shown in section 3, several east coast South Island lagoons can be characterised as 'choked' lagoons, and both types to be identified satisfy this definition.

'Restricted' lagoons comprise large and wide water bodies, usually oriented shore-parallel, and they have two or more entrance channels. They thus have well defined tidal circulation, are influenced by winds, and are vertically well mixed. Their salinities may range from brackish to oceanic values. Moutere Inlet and the Waimea 'Estuary', both in Tasman Bay, are South Island examples of 'restricted' lagoons.

'Leaky' lagoons are elongated shore-parallel water bodies, sometimes with many entrances in which tidal currents are dominant. 'Leaky' lagoons are common in tropical environments and on the extensive barrier shores of the Americas. There are no examples of this type in the South Island of New Zealand.

2.3 DISTRIBUTION OF COASTAL LAGOONS

According to Nichols & Boon (1994), coastal lagoons occur all over the world and on every continent except Antarctica. Together with barriers, flats and marshes they occupy about 11% of the world coastline, the longest single stretch being the 2800 km stretch of 'leaky' lagoons landward of barrier islands on the east coast of the USA. Lagoons are most common on low-lying aggrading coastal plains with a history of submergence during the last 10,000 years. An abundant supply of sediment is required for barrier building to impound the lagoon, while an adequate exposure to wave action is necessary to transport the sediments.

In the view of Nichols & Boon (1994), microtidal coasts (tide ranges less than 2 m) are the most favourable for barrier beach building by waves and for consequent lagoon containment. In direct contrast, macrotidal environments (tidal rage greater than 4 m) exhibit few barrier-lagoon systems because of stronger tidal currents. Some of the best developed, largest barrier beach shores in New Zealand occur in Tasman and Golden Bays where tide ranges are up to and above 4 m.

A distinctive association of lagoon-types with climate is also reported by Nichols & Boon (1994). Their 'mid-latitude' lagoons are characterised by catchments and basins having an annual surplus of precipitation over evaporation (though seasonal deficits may occur). This leads to vigorous stream flow from catchments that typically have moderate specific sediment yields (a range of 10–100 tons/km^2/year is suggested). Sedimentation in the lagoon is thus dominantly fluvial in origin (rather than marine), though significant biogenic sediment production can also occur.

3. Two types of coastal lagoon, South Island, New Zealand

The definition of 'choked' lagoons (and many of the identified characteristics) applies to at least two distinctly different kinds of coastal lagoon found on the east and south coasts of the South Island. These two types might be referred to descriptively as 'river mouth lagoons' and 'coastal lakes'. Neither type is fully described in the international literature and nor is a distinction drawn between them.

3.1 'RIVER MOUTH LAGOONS'—HAPUA

The first and more extensively researched type of South Island coastal lagoon is that occurring at the mouths of many of the braided, gravel-bedded rivers of the east and south coasts. Figure 2 (from Kirk 1991), presents sketch maps of a range of these features along with two sandy coast mouth systems (Waimakariri River and Clutha River). In Southland the best known example is the mouth system of the Waiau River, while in Canterbury and Otago the most prominent examples are those on the Rakaia River and the Waitaki River, respectively. This type of system has been researched in respect of physical origins and processes because of water resource development and conservation issues in the associated river catchments (e.g. flooding, irrigation, and hydro-electric power generation schemes plus a range of in-stream issues relating to recreation and wildlife).

It is our understanding that the tangata whenua (local Maori people) have long referred to this type of coastal lagoon by the term 'hapua'. In our view this term is useful to distinguish this kind of lagoon from other kinds of coastal lagoon and from estuaries.

Hapua have been described (though not under this name) and investigated from several rivers on the east coast of the South Island (e.g. Hurunui, Rakaia, Ashburton, Opihi, and the Waitaki) and from the Waiau River in Southland. Kirk (1991) provides a good guide to these studies. The lagoon system at the mouth of the Waiau River has been the subject of extensive scientific investigation in connection with the Manapouri–Te Anau Power Scheme. Work and findings related to the river mouth lagoon are reported in Kirk & Shulmeister (1994). Hart (1999) provides a detailed review and new data on processes controlling hapua at the Ashburton and Hurunui river mouths.

A sediment budget model for hapua and a conceptual model for water resource management in such lagoon systems (from Kirk 1991) are presented in Figures 3 and 4. Longer-term evolution and structure are examined for barrier beaches around the Ashley, Kowhai, and Waipara Rivers by Shulmeister & Kirk (1993).

Hapua take the form of generally coast-parallel bodies of predominantly fresh water impounded by a long, narrow spit formed of coarse sediments by longshore drift offsetting at a river mouth. Mouth offsetting occurs in moderate to low river

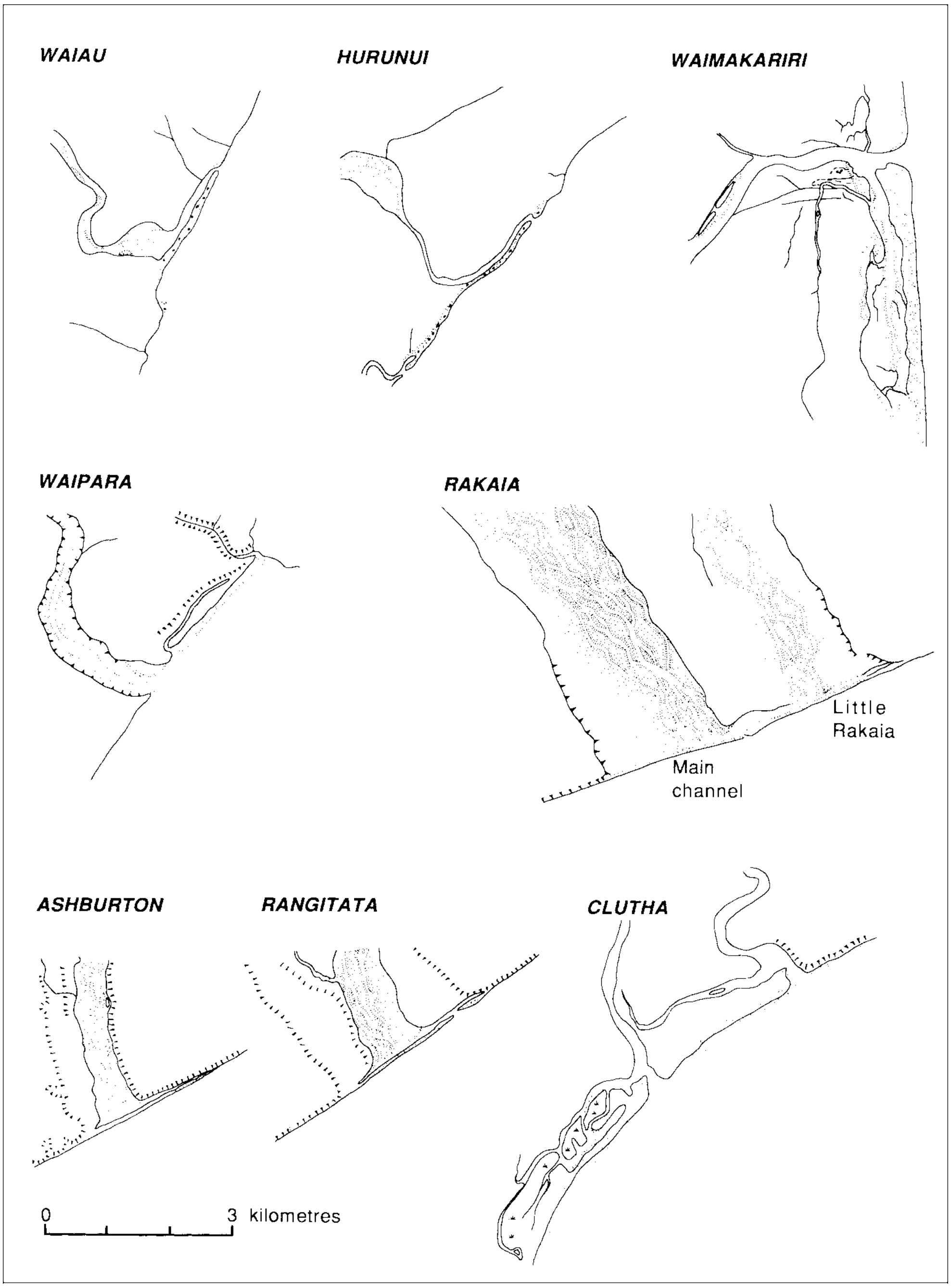
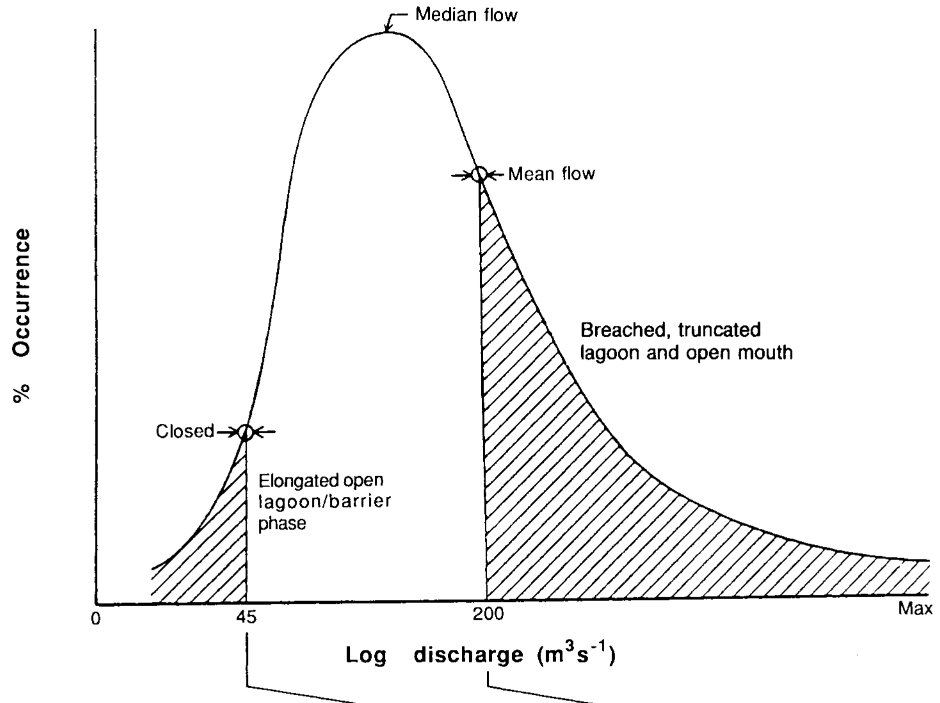


Figure 2. Typical South Island river mouth lagoon (hapua) morphologies. Most are mixed sand and gravel systems, but two truly estuarine river mouths (Waimakariri and Clutha) developed in sandy coasts are shown for comparison. *Reproduced from Kirk (1991, fig. 3) by permission of Applied Geography.*

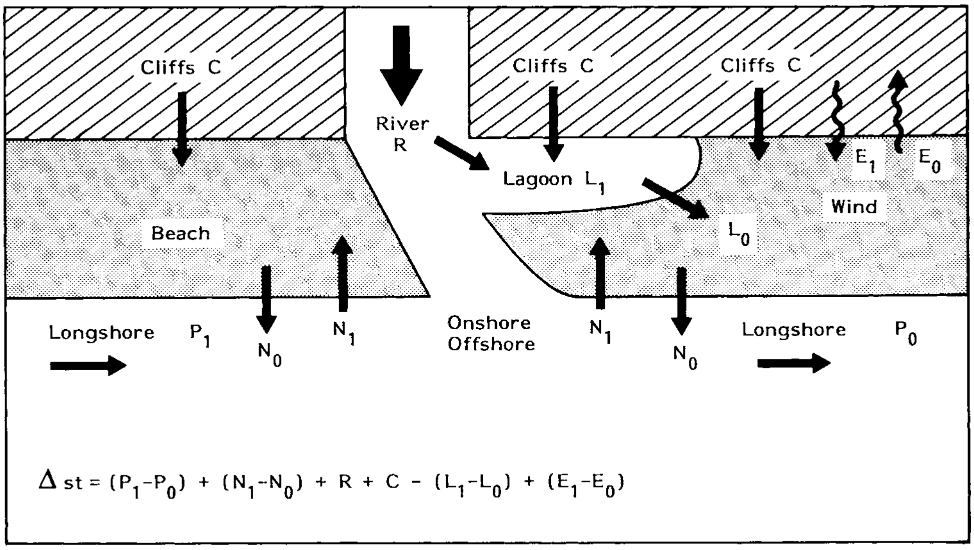
flow conditions. Extreme mouth offsets (i.e. lagoon lengths) of up to 6 km are known (Ashley River), but 2–3 km is more common (Rakaia River). The lagoons are highly variable and go through a distinctive sequence of creation and destruction because the impounding spits are prone to breaching directly opposite the site of principal river channels in times of flood. A lagoon 'sequence' averaging 12–19 months is known for the Ashburton River, and Hart (1999) demonstrates shorter cycles of change lasting from a few days to a few weeks.

Hume & Herdendorf (1988, p. 264) refer to these as 'spit-lagoon river mouths' having effectively no tidal prism, though there is (at low river flows) a tidal backwater effect that raises freshwater levels in the lagoon. 'In essence, these lagoons are a section of the river that flows parallel and adjacent to the coast, and that receives some salt by spray and washover.' In addition to the drift



River flow	Low	Moderate	High (floods)
Throughflow	Minimal	Low	High in breach phase
Mouth stability	Closed	Open to sea. Mouth migrates northward	New mouth formed by breaching. Sometimes multiple mouths
		Offset either south or north, usually to north	Deltas formed to seaward by injection of gravels to lagoon
Lagoon	Closed	Open to sea; elongates northward	Truncated. Much of low flow lagoon becomes backwater
Sedimentation	Siltation in closed lagoon (sink)	Reworking of fines sink for coarse sediments	Active source of coarse sediments to lagoon and beach
		Source/sink of fines	Scour of land adjacent to channels

Figure 3. Schematic sediment budget and storage equation for river mouth lagoons (hapua). *From Kirk (1991, fig. 5, where terms and quantities are defined for the Rakaia and other rivers). Reproduced by permission of Applied Geography.*



$$\Delta\, st = (P_1 - P_0) + (N_1 - N_0) + R + C - (L_1 - L_0) + (E_1 - E_0)$$

Figure 4. Descriptive model for hapua processes, with threshold values set for the Rakaia in this case. *From Kirk (1991, fig. 6) reproduced by permission of Applied Geography.*

offsetting which creates the lagoon and flood breaching which attenuates it, multiple mouths are possible from floods in rapid succession. At sufficiently low flows (especially where these are reduced and/or prolonged through water resource development in the catchments) it is possible that hapua mouths will close, so ponding the drainage and cutting the inlet off from the sea. Hart (1999) shows that river flows corresponding to mouth closure and mouth breaching are markedly different from river to river. Breaching may occur from either the river side or the ocean, or both.

Table 1 provides approximate river flow, bed slope, and other conditions that control these events for the Rakaia and other rivers on the east coast, South Island. Kirk & Shulmeister (1994) give similar information for the Waiau River, western Southland.

Thus, hapua generally occur in coarse-grained sediments (mixtures of sands and gravels) where the contributing rivers have braided channels and moderately steep bed gradients. Discharge is widely variable and generally not less than about 15 cumecs at low flow. Other important boundary conditions of hapua are that they occur in microtidal regimes (tidal range less than about 2 m) and are dominated by high-energy wave regimes in which longshore drift is very strong (in respect of either gross total during the year or the net quantity in one direction along the shore, or both).

It is an essential feature of the character and behaviour of hapua, and one not recognised anywhere in the international literature of lagoons, that they are the particular products of what have been termed 'small rivers'. According to Zenkovich (1967, pp. 551–585) 'small rivers' are those that deliver insufficient sediments to the sea to maintain their coasts against erosion by the sea. It is clearly established by research to date that most hapua in the South Island (though not all) are associated with coasts that are in long-term net erosional retreat. For example, the Rakaia coast in central Canterbury was shown from air photograph analysis to be erosional at rates of 0.9–1.95 m/year over the period

TABLE 1. HYDROLOGICAL CHARACTERISTICS OF SOME EAST COAST SOUTH ISLAND RIVERS. (From Kirk 1991, p. 270.)

CATCHMENT	AREA (km^2)	CHANNEL SLOPE (m/m)	MEAN RAINFALL (m/yr)	MEAN DISCHARGE (m^3/s)	10-YEAR FLOOD DISCHARGE (m^3/s)	SPECIFIC SEDIMENT YIELD ($t/km^2/yr$)
Waiau	1980	0.010	2.00	90.0	1868	1300
Hurunui	2680	–	–	–	–	1000
Waipara	741	–	–	–	–	621
Waimakariri	3210	0.006	1.90	120.0	2708	1669
Rakaia	2640	0.010	3.00	200.0	3764	1641
Ashburton	540	0.010	1.40	8.0	170	574
Rangitata	1775	–	–	–	–	946
Opihi	2372	–	–	–	–	1000
Waitaki	12118	–	–	–	–	144
Clutha	21078	–	–	–	–	94

Source: Compiled from Griffiths (1981, table 1) and Griffiths & Glasby (1985, table 1)

1943–1976. It is well established that this erosion is long term (i.e. occurring over thousands of years). It is thus paradoxical that such large and impressive rivers, having high sediment deliveries (especially in floods), are unable to deliver sufficient sediments to offset the annual erosional demand by waves (e.g. for longshore transport).

Nichols & Boon (1994) characterise 'mid latitude' lagoons as having moderate specific sediment yields (in the range 10–100 tons/km^2) from their contributing catchments. Kirk (1991, table 1, p. 270) shows that the range of specific sediment yields contributed to South Island hapua is from 94 tons/km^2/year (Clutha River) to 1641 tons/km^2/year (Rakaia River). Hapua thus have fluvial sediment inputs up to two orders of magnitude greater than are reported for other mid-latitude lagoons.

The apparent paradox of very large sediment supply to eroding coasts was resolved by Kirk (1991), who demonstrated that much of the sediment load delivered was fine sand and silt that was dispersed to the continental shelf. Coarse sediments (gravels and sands) from which coastal barriers could be constructed amounted only to 2–20% of total river load.

It is well established that the sequence of lagoon and spit changes described above is maintained while hapua are progressively displaced landwards by long-term chronic coastal erosion. The sizes and shapes of these lagoons are thus not altered by coastal erosion. It is considered that sea-level rise (either the historically observed rise on the east coast of the South Island or any accelerated rise that might eventuate as a result of global climate change) will not alter the nature of lagoon 'cycles' or their dimensions.

It is equally clear that landward translation of hapua under coastal erosion progressively increases the degree of erosion and flooding hazards for communities (e.g. fishing huts) and infrastructure (e.g. roads) situated adjacent to river mouths. Principal environmental impacts on hapua result from modification of the river flow regimes through such activities as irrigation and hydroelectric power development.

3.2 'COASTAL LAKES'—WAITUNA-TYPE LAGOONS

The second type of lagoon common on the east and south coasts of the South Island, New Zealand, is what might be termed a 'coastal lake'. In terms of the classification proposed by Kjerfve (1994) this type of lagoon is exceedingly 'choked' with respect to exchanges of water with the ocean via an inlet or inlets. The water body is typically fresh or brackish, and the lagoon is more usually closed from the sea than open to it.

By far the best examples (and among the more significant in conservation terms) are Waihora/Lake Ellesmere in Canterbury and Waituna in Southland. Lagoons of this type form an interlinked chain of habitats which run the length of the east coast of the South Island: from Wairau Lagoon and Lake Grassmere in Marlborough, through Waihora/Lake Ellesmere and Coopers Lagoon in central Canterbury, and Washdyke and Wainono in South Canterbury, to Waituna in Southland.

It is proposed here to name this kind of lagoon the 'Waituna' type to distinguish it clearly from hapua. Significantly, the coastal dynamics of this kind of lagoon are quite well known, e.g. Waihora (Armon 1974; Hemmingsen 1997) and Washdyke (Kirk 1992), but comparatively little study has been made of the nature of the lagoons themselves as coastal hydrological systems.

Their distinctive characteristics could be listed as:

- Associated with mixed sand and gravel coasts
- Occur on coasts undergoing long-term erosion
- Occurrence on microtidal coasts
- Occur in high wave energy regimes having strong longshore sediment transport
- Associated with positive hydrological balances (excess of precipitation over evaporation) and moderate temperature regimes
- In comparison with hapua, river inflow is moderate to small
- In comparison with hapua, catchment-specific sediment yields are small. Coarse sediment supply to the lagoon (e.g. gravels) is slight to nil, though high suspended loads occur in floods
- Openings to the sea are rare and short-lived unless created by human action
- Natural water levels are generally higher and have a smaller range than those now occurring through ongoing human intervention. Lower average water levels relate to agricultural uses of low-lying land marginal to lagoons
- Ocean salt content of the water body is low. It is derived from salt spray, from overwash of the enclosing barrier beach, or from inlet throughflow by the tide in the later stages of artificial openings
- Freshwater residence times in the lagoon are typically long
- Wind waves and currents are an important, if not dominant, agent of mixing within the lagoon. Wind set-up and surge can also produce large and erratic variations in the water-covered area of low-lying areas at the downwind ends

Almost nothing is known of the detailed water level regimes, internal circulation or sedimentation regimes of such lagoons. However, Waituna-type lagoons are significantly vulnerable to human use of the surrounding lands and contributing catchments through changes to their hydrological regimes, and their sediment and chemical input loads. They are also more vulnerable than hapua to global climate change through alterations to input fluvial hydrology and through the possibility of accelerated sea level rise that may increase rates of coastal erosion.

3.2.1 Coastal geomorphic character and development

Waituna-type lagoons share the first five characteristics in the above list with hapua, but in every other key respect they are very different. Three of these shared characteristics are especially important, namely an association with mixed sand and gravel shores (particularly with sediments derived from greywacke terrains subject to Quaternary glaciation) and a strong association with high wave energy coasts, these undergoing long-term erosion.

Unlike hapua, which are usually translated landwards under long-term coastal erosion, Waituna-type lagoons are progressively reduced in area by erosion. An extreme case is Washdyke Lagoon at Timaru (Kirk 1992). The barrier beach enclosing Washdyke Lagoon eroded at average rates of –3.32 m/year for the period 1865–1987 (with variations over time in the range 2–9 m/year). The coast is in long-term chronic erosion, a condition exacerbated by construction of the Port of Timaru commencing in 1879. Since research by Department of Geography, University of Canterbury, for Timaru City Council, the former Harbour Board has significantly ameliorated, but not eliminated this erosion.

In 1881 Washdyke Lagoon had an area of 253 ha. By 1955 this had been reduced by erosion to 79 ha (a 66% reduction) and by 1984 it was only 48 ha (an 80% reduction over the area existing in 1881).

In the severe South Canterbury floods of 1986 a 90 m-long breach occurred in the barrier beach enclosing Washdyke Lagoon. In our view it is probable that Washdyke Beach will breach permanently (and the lagoon will be lost altogether) within a few years unless mitigation measures such as those initiated by the Regional Council are given full effect.

Prior to 1933 a smaller lagoon existed south of Washdyke at Waimataitai. Through erosional processes closely similar to those described for Washdyke the Waimataitai barrier was in rapid erosional retreat. It breached and the lagoon was lost in 1933. Events at Washdyke mirror this sequence, later in time and on a larger scale.

In very high-energy sea states on this coast, breakers up to 5 m high produce runup which overtops the beach crest at many places. Up to 1000 ha in South Canterbury are subject to seawater inundation in this way. Todd (1988) documents 32 such overtopping events since 1882.

Further north, Milford Lagoon (north of the mouth of the Opihi River) lost 58 ha in the period 1881–1955. At Wainono Lagoon in South Canterbury long-term coastal retreat rates in the range 0.6–1.0 m/year are known. Breaching of the coast has occurred at Waimate Creek in recent years.

It is apparent from field study and from maps that most of the Waituna-type coastal lagoons occupy either low-lying interfan-depressions between the crests of the Quaternary outwash fans of the principal rivers, or similarly low-lying positions at the extreme edges of such fans. For example, Waihora/Lake Ellesmere occupies a coastal re-entrant formed between the major fans of the Waimakariri and Rakaia Rivers. Wainono Lagoon occurs on the northern margin of the Waitaki fans, and Washdyke Lagoon occurs at the southern margin of the Opihi fan complex. The interfan depressions are also sites that capture the drainage of smaller 'foothills' rivers such as the Selwyn, Washdyke Creek, Hook, Makikihi, etc. In Southland, Waituna Lagoon itself occupies a similar position, between older terraces of the Oreti and Mataura Rivers. However, not all the coasts of Waituna-type lagoons have been chronically erosional, including that holding Waituna itself. For example, the Kaitorete Barrier enclosing Waihora/Lake Ellesmere is presently in equilibrium, as is the coast containing the Wairau Lagoons.

Remarkably similar histories of formation have been established for these three, which are the principal Waituna-type lagoon systems. These all occur at hinge-point 'inflections' or 'loci' in the coast. They each involve close proximity to an updrift coast in an erosional state (which provides abundant sediment for barrier building and nourishment), without being erosional themselves.

3.2.2 Wairau Lagoons

Figure 5 (from a diagram by Pickrill 1976, fig. 2) shows the 'Wairau Bar' and an associated complex of beach ridges and other features that record the history of development of the Wairau Lagoons over the last 5000–6000 years. The main pattern of coastal depositional features is a narrow 'stem' forming the boulder bank in the south and a broad, arc-shaped 'fan' of beach ridges extending seaward on the northern side of the valley, from Tuamarina (6 km inland) to Rarangi (on the coast).

Pickrill (1976) demonstrates convincingly that the lower Wairau Valley was a shallow arm of the sea during the Holocene. As sea-level rise slowed towards the present rate, the bay became enclosed by a spit growing northward from sources of coarse sediments located in the south (i.e. from the rapidly eroding gravels and sands forming White Bluffs). This spit grew across the 'Wairau Bay' to the cliffed shoreline of the Sounds Block, thereby enclosing the 'Wairau Lagoons'.

Continuation of the sediment supply and its steady downdrift progress along the 'Wairau Bar' led to sustained accretion against the Sounds Block in the north. The outcome has been progradation of the northern portion of the plain by more than 6.5 km at average rates exceeding 1 m per year. At the same time, the Wairau River has aggraded its plain landwards of (and into) the lagoon system.

The development of the Wairau Lagoon thus involves a re-entrant in the coast, an eroding source of abundant gravels in an updrift situation and sufficient wave energy to both erode the source and propel the products across the re-entrant. The outcome has been lagoon formation behind a barrier that has rotated markedly in a clockwise direction (viewing it to the north or downdrift) over the past 5000–6000 years. The 'locus', 'hinge', or 'axis' (all of these terms having been used at one time or another) is situated toward the northern end of the 'Wairau Bar' in the vicinity of the present (natural) river mouth.

3.2.3 Waihora/Lake Ellesmere

The geomorphological development of Waihora/Lake Ellesmere was investigated by Armon (1974) prior to the work of Pickrill on the lower Wairau Valley. Hemmingsen (1997) presents a comprehensive account of the evolution of the lake and its coastal landforms. The evolution of Waihora/Lake Ellesmere is set out in the two parts of Figure 6. It involves a sequence of coastal changes having both striking similarities with, and distinctive differences from, that at Wairau Lagoon. Waihora/Lake Ellesmere is somewhat less than 5000 years old and it has been through many dramatic changes in that short span of time.

What is now Waihora/Lake Ellesmere was in successive stages over the last 5000 years: first, a part of the Canterbury Plains, then a bay, then an estuary, and finally a lake (i.e. a Waituna-type lagoon). If left to develop, the lake will again become a saltwater estuary in the next few centuries. At various times in its history the lake has had up to twice its present area and depth. The Waimakariri River has also periodically avulsed to enter the sea through the lake (Hemmingsen 1997; Soons et al. 1997).

The more distinctive features of the landscape of Waihora/Lake Ellesmere and its environs include the Kaitorete Barrier which encloses it. This was formed by

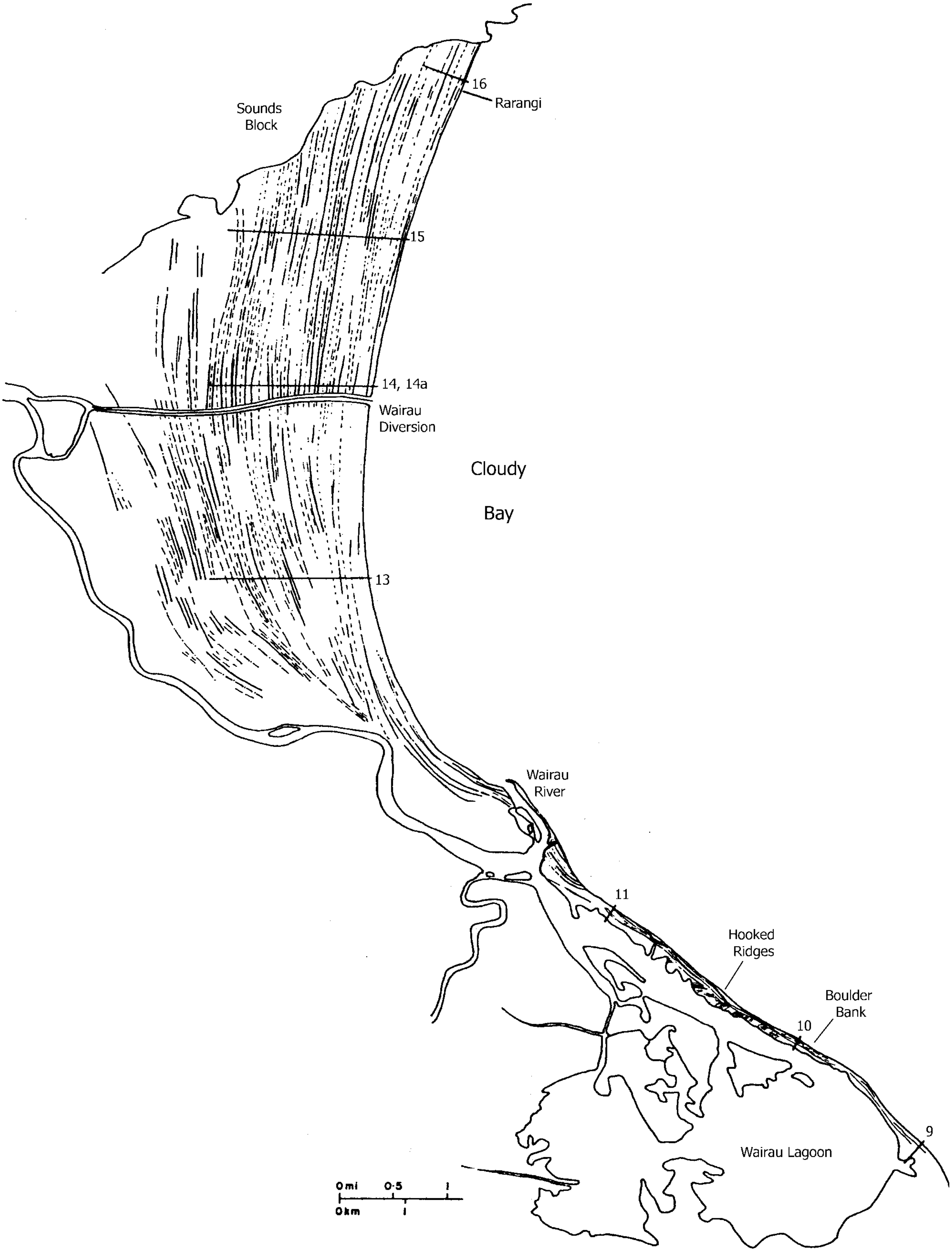


Figure 5. Beach ridges and other coastal landforms enclosing the Wairau Lagoon. *Adapted from Pickrill (1976, fig. 2). Reproduced by permission of New Zealand Geographer.*

the northward drift of sand and shingle from the southern rivers, and the rapidly eroding edge of the plains in central and south Canterbury under the powerful influence of southerly waves. It is commonly referred to as a 'spit' or as 'Kaitorete Spit', but this is incorrect, for at least two reasons: first, a spit is usually widest at the updrift end and tapers away downdrift to a narrow tip (or to hooks at the distal end), but Kaitorete is narrow in the south (updrift) and widest in the north (downdrift); secondly, Kaitorete is attached to the land at both ends (however tenuously in the south). The proper term for such a feature is 'barrier beach', hence Kaitorete Barrier would be an appropriate name. These details are not merely academic, they are powerful clues to the origins of the Lake.

Also worthy of note is the impressive 'birdsfoot delta' built by the Selwyn River into Waihora/Lake Ellesmere since its enclosure by the coastal longshore drift of sand and gravel. The Selwyn is a 'foothills' river rather than originating at the Main Divide in the Southern Alps, and it occupies the interfan depression between the major fans of the Rakaia and Waimakariri Rivers. Its delta in Waihora/Lake Ellesmere is a consequence of a sediment-laden river discharging into a comparatively quiet water body. Originally Waihora/Lake Ellesmere had much higher water levels, was about double the area, and much of the delta was constructed underwater. The lake is now held at much lower than natural levels through deliberate management policies that have been in place in one form or another for most of this century.

The origin of Waihora/Lake Ellesmere is primarily the story of the formation of Kaitorete Barrier with its apparently paradoxical shape. During the Quaternary, sea levels have fluctuated by more than 100 m, falling in ice ages when water was locked up as ice on land, and rising in warmer interglacial times.

Some 20,000 years ago, when the last glaciation was drawing to a close, valley glaciers advanced in Canterbury and powerful rivers flowed away from them delivering vast quantities of sand, gravel and silt to the coast. In Canterbury at that time, sea level was about 130 m lower than now, the coast was up to 50 km east of its present position, the plains were about double their present width, and Banks Peninsula stood as a volcanic hill mass towards the edge of the plain but well inland of the coast, which was continuous through Canterbury.

Subsequently, world sea levels began to rise quite rapidly, although glaciers in the Southern Alps remained advanced for some thousands of years. This rapid rise of sea level drowned what is now the continental shelf and caused a similarly rapid westward migration of the coast.

Figure 6 shows the principal features affected by these changes, particularly the approximate contours of the ancient fans of the rivers (since planed by the rising sea), and several past positions of the coast.

By 13,000 years ago the rising sea level was approaching the eastern end of Banks Peninsula. Between 13,000 and 10,000 years ago, the eastern bays of the Peninsula and Akaroa Harbour were flooded and the peninsula had formed a headland dividing the Canterbury Bight from Pegasus Bay. Also by about 10,000 years ago the coast was approaching the area now occupied by Lake Ellesmere. At this time the area now occupied by Waihora/Lake Ellesmere (see Figure 6), was a depression in the surface of the Canterbury Plains occurring between the northern flank of the Rakaia River fans and Banks Peninsula, and occupied by the Selwyn River. It is also clear that the Waimakariri River may have discharged its load through this area at various times in the past.

Figure 6 also shows a straight or gently curved coast of the Canterbury Bight at 10,000 years ago and one which is well seaward of the present shore. The coast consisted then, as now, of unconsolidated sands and gravels of the fans of the major rivers (most notably of the Rakaia River). The Canterbury Bight then, as it is now, was fully exposed to the fury of southerly waves. The combination of weakly resistant materials and high energy ensures a rapid rate of coastal erosion and strong net northward transport of the resulting load of sands and gravels fed to the shore. In addition to the sediments derived from direct and

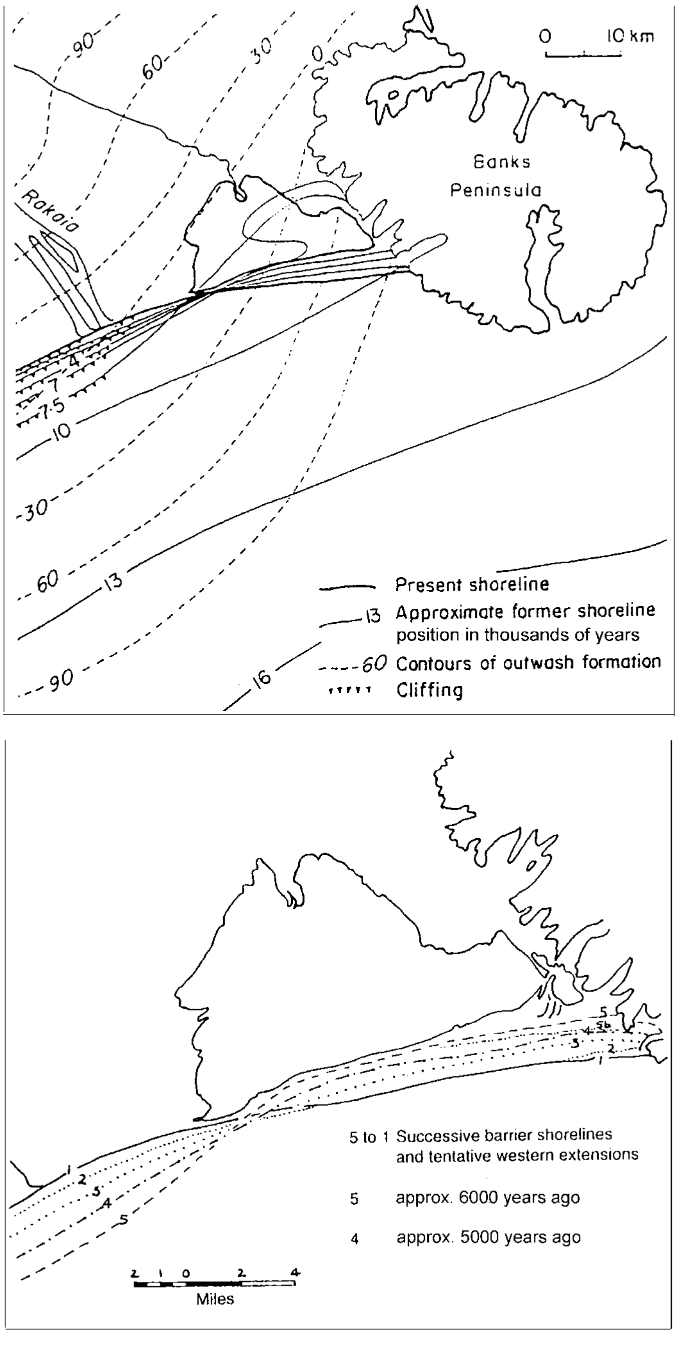


Figure 6. Geomorphic evolution of Waihora/ Lake Ellesmere over the past several thousand years. Upper diagram shows past positions of sea level (thousands of years before present) and the northward growth of a spit to enclose the lagoon. Lower diagram shows clockwise rotation of the coast since closure around a ‘hinge’ east of Taumutu. *After Armon (1970, 1974) and Kirk (1994, figures 1.1 and 1.2). Reproduced by permission of Lincoln University, and (lower) New Zealand Journal of Geology and Geophysics.*

extensive erosion of the margin of the plains there are large additional amounts of sands and gravels that have continued to be delivered by the rivers.

To summarise, important elements in the development of Waihora/Lake Ellesmere have been:

- Rapid rise of sea level, drowning the seaward edge of the plains.
- Rapid erosion of the coast to the south which has changed its position and provided, in addition to direct river-borne sediments, a massive supply of sea-borne sediments.
- Strong net northwards longshore drift by waves, moving the sediments toward Banks Peninsula and providing the materials to construct the barrier that now encloses the lake.

By about 7000 years ago the rate of sea level rise was slowing, and by 5000 years ago levels similar to the present were attained. Kaitorete Barrier developed (and impounded the lagoon) during this short, most recent period of relatively stable sea levels. The maximum landward incursion of the sea was probably reached at about 5000 years ago. At this time the area now occupied by the lake was a bay in the northern end of the Canterbury Bight. The interfan depression between the Rakaia fan and the peninsula was flooded by the sea, which covered only the eastern half of the present site of the lake.

Once sea level became comparatively stabilised near its present level, coastal features (and those of the lake) as we know them today began to develop very rapidly. In the south the rivers, particularly the Rakaia, continued to pour out a wide range of sediment sizes comprising silts in suspension, and sands, gravels and cobbles as bed load in floods. Perhaps more importantly, the soft, southern coast continued to rapidly erode (and retreat) during southerly storms, and drove large amounts of sand and gravel northwards toward Banks Peninsula and across the mouth of the bay in the seaward, northern edge of the Rakaia River fan.

By about 4000 years ago this northward drift of sediments had resulted in the construction of a true spit that grew progressively northeastwards across the bay now occupied by Waihora/Lake Ellesmere. Within perhaps a further 1000 years the tip of this spit lay close to Banks Peninsula and the area now occupied by the lake was an estuary. Lake Forsyth was still occupied by the sea.

The steadily growing spit reached Banks Peninsula (at Birdlings Valley) and closed the lake basin from the sea at about 3000 years ago, to form Waihora/Lake Ellesmere. Old hooked recurves from the spit can be seen in the lake floor at its northeastern end and are very clear on air photographs. On land, a prominent gravel beach ridge in Birdlings Valley marks the closure of the lake. Hemmingsen (1997, p. 179) and Soons et al. (1997) provide evidence of at least one avulsion of the Waimakariri into the lake and concurrent breaching at the northern end some time after 1555 years ago.

Since impoundment, a dramatic reversal has occurred in the shape of the barrier enclosing the lake as the coast has rotated about a locus, or 'hinge-point', near Taumutu (see Figure 6). The rotation has occurred in a clockwise direction because erosion has continued to the south while a steady buildup of sediments occurred against Banks Peninsula in the north. Continued retreat of the coast in the south and accumulation in the north has caused the removal of the base of the spit that first closed the basin and formed the lagoon. The reduction in width at the base caused the 'mouth' to move to its present position at Taumutu on the southern end of the lake. In this position there has been at least one estuarine phase of the lake. Combined with the continued accumulation against Banks Peninsula in the north, the net effect of rotation of the coast has been to produce an apparently reversed 'spit' shape, narrowest at the updrift end in the south.

Progressive development of the barrier enclosing the lake has had three other interesting consequences. First, growth of the barrier resulted in increased water levels in Waihora/Lake Ellesmere. Water levels built up to elevations at which it was possible for outflow to the sea to occur across the beach ridges. Secondly, early in its history the lake broke out to sea at its northern end near Birdlings Flat. However, the rapid pace of coastal accumulation there together with rapid narrowing of the barrier at its southern end soon led to the outlet switching to its present position at Taumutu. Thirdly, the progressive thickening of the northern end of the barrier has impounded Lake Forsyth. Like Waihora/Lake Ellesmere it was first a bay, then an estuary, and finally a lake. There are reports that the entrance to Lake Forsyth was still navigable to small coastal schooners in the 1860s.

Kaitorete Barrier is some 4800 ha in area and is about 15 m thick. It contains more than 700,000,000 m^3 of sediment transported north from the rivers and the eroding southern coast in just a few thousand years. In contrast, comparisons of maps and air photographs show that the barrier is no-longer growing, and the coast of most of Kaitorete Barrier has been stable at its present position since the 1980s. The achievement of stability has been attended by the growth of a substantial dune belt along the seaward margin, whereas previously the barrier had produced few dunes and consisted mainly of a steady accumulation of mixed sand and gravel beach ridges.

Although the barrier remains in equilibrium, the coast to the south continues to erode at rates of up to 1 m/year (on average) and sediment continues to be transported northward. The gravels in the modern beach are rapidly ground down to sands and silts by abrasion in the surf. It is evident that today, sediment supply to the barrier is only sufficient to maintain it against abrasion losses, and replace the sands being blown back into the dune belt and stored there.

Another consequence of the attainment of a stable coastal position has been the concentration of semi-precious gemstones in the beach at Birdlings Flat. These stones originate from volcanic rocks along the inner margin of the Canterbury Plains. Along with the greywackes of the Southern Alps these materials are drifted north along the coast by wave action, after delivery to the shore either by rivers or as a result of erosion of older fan gravels. Eventually all these materials lodge in the beach against Banks Peninsula. Because the gemstones are much more resistant to abrasion than the greywackes they become concentrated over time as a stable residue in the beach at Birdlings Flat.

Kaitorete Barrier is very narrow at its southern end (see Figure 6). Continuing coastal erosion (even at present rates) could result in a breach of the barrier in the next century, thereby destroying the lake and re-creating an estuary.

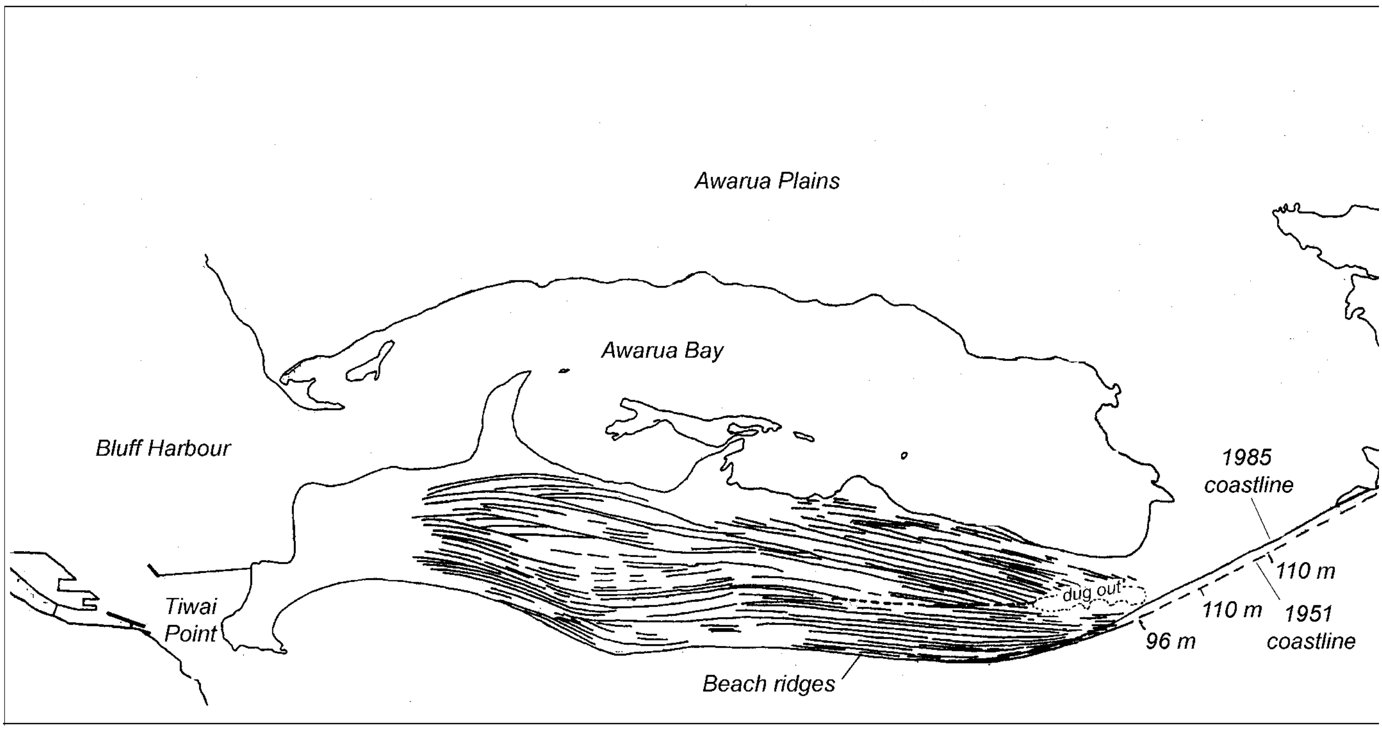


Figure 7. Geomorphic evolution of Waituna Lagoon, showing erosional changes in the modern shore over the period 1951–1985 and the prograded beach ridges that enclose Awarua Bay from the sea.

Within historical time Waihora/Lake Ellesmere had connections by drainage behind the coast to Coopers Lagoon and ultimately to the hapua formed at the Rakaia River mouth. Coastal retreat in the south has now removed these ancient drainage ways (just a few signs remain), separating the various lagoons. Well pipes that were in the kitchens of houses in the 1860s can still be located in the Rakaia lagoon floor. Other lagoons that once had drainage or 'chain' connections (now broken) landward of eroding coasts include Milford, Washdyke, Wainono, and Waituna.

3.2.4 Waituna Lagoon, Southland

As part of this study, the geomorphic evolution of the Waituna Lagoon has been investigated in the field and by mapping from repeated vertical air photography. A map of the Waituna coast, and data on changes in the modern shore over the period 1951–1985 is presented as Figure 7.

The barrier beach enclosing Waituna Lagoon is narrow. Waituna Lagoon itself has an area presently of about 1850 ha. To the west is Bluff Harbour and Awarua Bay, which forms an eastward extending arm of the harbour. The Oreti River lies further west, but seems to have extended through the harbour area in the past. Bluff Harbour and Awarua Bay are two arms of a true estuary.

Both air photography and field investigation make it clear that Waituna has been larger in the past, and that it has had a drainage connection with Awarua Bay. Whether or not Waituna was truly estuarine (and had a more saline water body) has yet to be established. Tiwai Point (which encloses Awarua Bay from the sea) presents a complex mass of prograded beach ridges that mark former positions of the oceanic shoreline (see Figure 7).

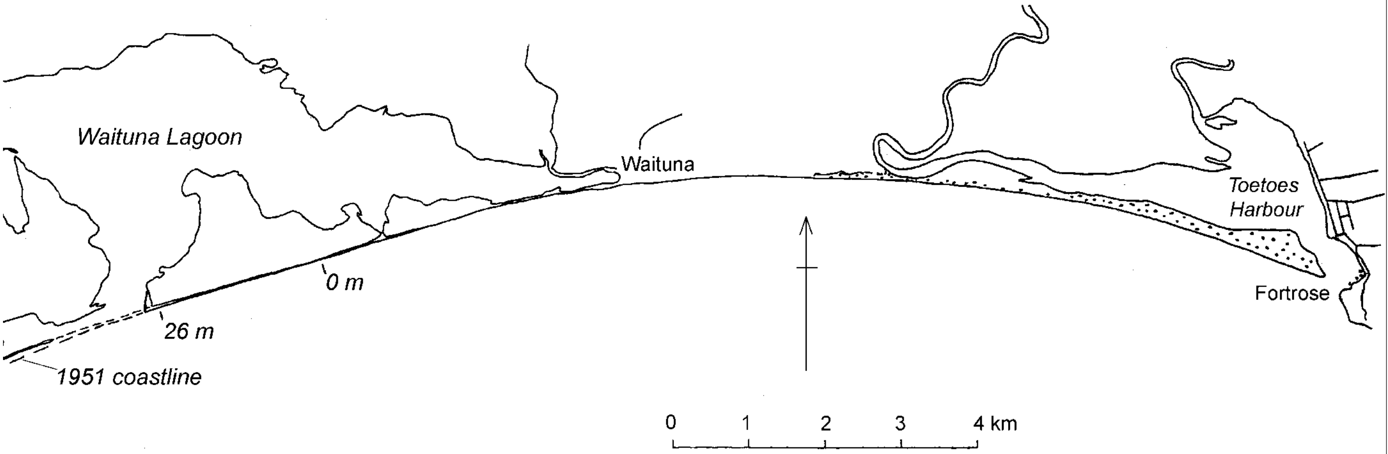


Figure 7. *Continued.*

Waituna Lagoon is presently of the 'coastal lake' type and is rarely open to the sea naturally. Instead it is opened at least once each year by machinery, to enable grazing of the surrounding low-lying lands, and sometimes to facilitate wildfowl shooting. The barrier enclosing Waituna Lagoon is a mixed sand and gravel ridge with no capping sand dune, which shows that it is overtopped by storm wave runup. To the east of Waituna Lagoon, a single mixed sand and gravel beach ridge is backed by a prominent erosion scarp cut in older stream fan gravels, indicating that the coast is erosional in the longer term. Another indication is the extensive occurrence of remnant coastal forest with numerous tree stumps in position of growth; these outcrop in the present beach at all elevations from the breaker zone to the beach crest over a 1–2 km length of shore about 2 km east of Waituna Lagoon.

Net longshore transport is to the east, though it is apparent that drift occurs in both directions along the shore from time to time. With distance eastward the shoreline becomes progressively sandier, i.e. the average grain size of the beach materials decreases. In consequence, the beach ridges further east towards the mouth of the Mataura River are capped by a single line of poorly vegetated and badly eroding sandy foredunes. Storm washover occurs through 'blowouts' in these dunes and across the spit enclosing Toetoes Harbour. Toetoes Harbour was not investigated in detail, but appears to be estuarine at low flow values in the Mataura River. At high flow it is probably fluvially dominated. The sandspit separating the harbour from the ocean has several features along its inner shore marking past river flood break-throughs. It also carries remnants of hooked recurves marking former positions of the spit tip.

Taken as a whole, this coastal landform assemblage presents remarkable similarities to the systems at Wairau Lagoon and Waihora/Lake Ellesmere.

The shoreline of Tiwai Point makes a sharp angle to the northeast at its eastern extremity (Figure 7). A large number of the ridges making up Tiwai Point are truncated by the present coastline east of this inflection or 'hinge' point, on the Waituna Lagoon side. The older ridges constituting Tiwai Point were evidently built to an eastern (Waituna) shore lying much further seaward than the present one, i.e. Waituna Lagoon was much larger over some period in the past few thousand years (perhaps twice its present area) and it has been reduced by coastal erosion.

Viewed from the updrift (western) end, the shoreline at Waituna (and further east toward Toetoes Harbour) has rotated northward (anti-clockwise) about a locus or 'hinge' at the eastern end of Tiwai Point. This closely parallels the rotation at Waihora, but is in the opposite direction relative to the direction of net longshore drift.

No materials are to hand with which to date this sequence of events. However, the causative processes seem readily apparent. Neither the rivers further west (such as the Oreti), nor Bluff Hill nor the estuary at Bluff Harbour are a continuing source of coarse sands and gravels to nourish the Waituna coast. It has been well established by previous studies that most of the sand and gravel in the present coastal plain has been reworked from the floor of Foveaux Strait (which was a land connection to Stewart Island in the last glacial period of low sea level). Consequent on the last post-glacial sea level rise, considerable volumes of coarse sediments were swept up from the newly drowned sea floor to form coastal landforms. Very large accumulations occurred at Tiwai Point, in the wave shelter of Bluff Hill. Subsequently much of this accumulated material (stored in beach ridges) has been reworked and transported eastward in the net longshore drift to nourish the barrier enclosing Waituna Lagoon and the spit enclosing Toetoes Harbour.

Under present conditions, therefore, the largest (and virtually the sole) source of coarse sediments to nourish the Waituna Lagoon coast is the material stored in beach ridges on Tiwai Point. These ridges are now being progressively destroyed by wave action and fed eastwards in the net longshore drift. The 'store' of sediments in Tiwai Point is thus being progressively exhausted. These processes explain the pattern of shoreline rotation from a locus migrating progressively west (updrift) on to Tiwai Point. The downdrift coast retreats ('rotates' or pivots northward under erosion) about this locus.

The pattern of longer-term processes described here is well supported by recent patterns of shoreline change as determined from air photographs made 34 years apart in 1951 and 1985. The annotations along the coast (in Figure 7) indicate that erosion rates have been rapid in the west (averaging 2.82–3.23 m/year on the west of Waituna Lagoon. Near the present entrance of the Lagoon the average rate was 0.77 m/year and, as expected, rates declined further eastwards since the shore was better (though not sufficiently) nourished by longshore drift. At this rate, Waituna Lagoon is reducing by about 0.62 ha/year through coastal erosion alone. Assuming it was applicable over longer periods of time, the area of Waituna Lagoon could have been halved during the last 3000 years.

In the long term, coastal erosion on Tiwai Point is likely to become more intense, as well as more extensive. At observed rates of retreat on the eastern end of Tiwai Point, it would require perhaps 230 years to open an eastern (second) inlet to Bluff Harbour via Awarua Bay. Accelerated sea level rise, and/or changes in storminess that might accompany any climate changes under the 'enhanced greenhouse effect', could also greatly increase the depletion rate of Waituna Lagoon.

3.3 CONCLUSIONS

The river mouth lagoons (here named hapua), and coastal lakes (here named Waituna-type lagoons), are not known to the international scientific literature dealing with coastal lagoons, except for recent writings from New Zealand. However, the international literature does establish some processes and overall controls for lagoon development in humid, mid-latitude environments.

Neither hapua nor Waituna-type lagoons are dominated by marine or salt water, and neither type has any appreciable tidal compartment. Hapua are dominated by much larger and more variable fluvial flows on steeper, gravel-bedded (usually braided) rivers. Waituna-type lagoons have much smaller fluvial inflows and generally finer-grained input sediment loads.

Waituna-type lagoons in the South Island have distinctive formative processes and these present remarkably similar late Quaternary histories in widely differing parts of the South Island. The lagoons are all products of coarse-grained coasts subject to high wave energies and strong net longshore sediment transport.

Three of the largest lagoons of this type (including Waituna itself) occur in close proximity to 'hinges' or loci of coastal change, about which the modern coast is rotating against the longshore drift regime. Precise relationships with the 'hinges' are variable depending upon the relative positions of the lagoon inlets and the 'hinge' point of coastal change, but the relationship is a major determinant of long-term lagoon character. At Wairau Lagoon the 'locus' of coastal change is at the distal end of the spit ('Wairau Bar') enclosing the lagoon. At Waihora/Lake Ellesmere the 'locus' is at the southern end of the lagoon while the updrift shore is eroding and the enclosing downdrift barrier is stable. At Waituna the locus is west (updrift) of the lagoon and the enclosing downdrift barrier is erosional.

The barriers enclosing many lagoons of this type are wholly (and often very strongly) erosional, so that they are essentially ephemeral or 'vanishing' features at the time scale of hundreds or thousands of years. Some of these lagoons (like Waimataitai at Timaru) have ceased to exist this century, while others (like Washdyke Lagoon) are in a very precarious state.

Whatever the case, it should be an element of management planning for Waituna and other lagoons of its type that they are not static, unchanging resources to be preserved in some 'stable' state. Rather they are quite rapidly changing (and disappearing features) that are short-lived in the landscape.

4. Coastal processes

4.1 MICROTIDAL COASTS

The east and south coasts of South Island, New Zealand, are classified as microtidal, in that the tidal ranges are generally less than about 2 m, this is important to the development of both hapua and Waituna-type lagoons. Ranges greater than 2 m are classed as mesotidal. Tidal range is important because smaller tidal ranges are, in general, associated with less vigorous tidal currents. Tidal inlets have been described by Bruun & Gerritsen (1960) as the outcome of two counteracting tendencies. On the one hand, there is the potential for sediment moving along-shore under wave action to choke inlets and close them. On the other hand, constriction of the tidal flow through them will accentuate the power of the tidal streams to keep the inlet open by scour.

In the hapua on east and south coasts of the South Island, the tidal currents of the microtidal regimes are unable to compete with the powerful freshwater flows of the rivers, so there is negligible tidal penetration to the lagoon and no tidal compartment. Conventional tidal hydraulics are thus inapplicable to hapua.

In Waituna-type lagoons also, tidal currents are of small influence. Transport of the mixed sand and gravel sediments along and over the barriers that enclose the lagoons are wave-dominated phenomena.

4.2 HIGH WAVE ENERGIES

Most hapua and Waituna-type lagoons are exposed to effectively unlimited fetches for wave generation in the Southern Ocean. There is also a close relationship between beach sediment particle size and foreshore slope angle, such that coarser materials have steeper slopes. On steeper slopes there is a greater concentration of wave energy/unit area than on flatter ones. As has been demonstrated by Kirk (1980), mixed sand and gravel beaches have completely different morphologies and process characteristics from sand beaches. They present essentially as a ‘bank’, about half of which is permanently submerged, with only the upper, wave-worked, crest portion being visible.

Along the east coast of the South Island, beneath the waves there is a marked ‘step’ and a break of slope descending into 5–7 m of water. At the base of this slope there is another abrupt break of slope to a very gently sloping sea floor mantled in fine and very fine sand. The beach system thus presents two quite separate, but interrelated sediment transport systems: one involving coarse sediments (especially gravels) in the beach; and the other moving fine sands in the nearshore. As a result of our research at Timaru, it is known that the ratios of net (northward) longshore transport in the systems are about 10:1. That is, the wave-driven coarse sediment transport system on the beach transports annually about one-tenth of the quantity of fine sands moving on the sea floor.

Because of the steep underwater face of the beach system, mixed sand and gravel beaches do not have a surf zone. Instead they display a single line of breakers occurring at the 'step'. The position of the breaker line does not shift with either the tidal cycle or with variations in incident wave energy (as occurs on sand beaches). Longshore transport is thus a direct function of the angle of wave breaking on the 'step', and most longshore transport is produced on the foreshore by runup and backwash. Both foreshore and backshore are wholly dominated by the runup and backwash of broken waves, since net onshore transport (accretion) and net offshore transport (foreshore erosion) are also controlled by the balance between swash and backwash.

Longshore transport of coarse sediments is best known on the South Canterbury–North Otago coast, where it has been studied intensively. Gross longshore transports are known at more than half a million cubic metres per year, but net (northward) transports are measured by accumulation against Timaru Harbour at about 60,000 cubic metres per year.

Neale (1987) has demonstrated the existence of 'slug' transport on this type of beach. Slugs are apparent as 'pulses' of gravels released from rivers in floods, and/or by erosion of gravel cliffs in very severe storms. Such events inject large, discrete bodies of sediments into the coastal system. These are subsequently dispersed in the longshore drift, but are recognisable in their passage along the coast as quasi-rhythmic increases and decreases of local beach sediment volumes (as revealed, for example, by repeated beach profile surveys). Neale (1987) shows that the comparatively poorly nourished sections of beach between 'slug' crests are particularly vulnerable to erosion, to overtopping by storm wave runup, and to the possibility of coastal breaching.

The average net velocity northward of a slug was found to be 1200 m/year (with a range of 300–5610 m/year). It requires 40–45 years for Waitaki River gravels to travel the 48 km north to Timaru, and 5–8 years for a slug to pass a given point on the coast. A beach profile will vary by about ±8 m in its average width, and by about ±45 m^3/metre of shoreline in volume, during the passage of a slug.

In summary, longshore transport is intense, confined to a narrow zone of the shore, and temporally variable, not only on a daily time scale reflecting variations in weather and sea state, but on a scale in the range 5–10 years. This latter scale may be especially important to the incidence of lagoon breaching and self-opening in Waituna-type lagoons.

Broken wave swash and backwash also control the maximum elevation of the foreshore (given the grain sizes of the sediment present at a site). The highest berm on the foreshore (beach crest) stands at an elevation above mean sea level (m.s.l.) that has been found to be approximately 1.3 times the height of the highest breakers occurring.

Landward of the beach crest there is usually a landward slope (called the backshore) on which overtopping waves commonly construct a series of 'washover fans'. Where these become enlarged sufficiently to breach the beach crest an incipient breach of the coast as a whole exists. Such breaches can be very rapidly enlarged and deepened by runup. Washover fans not infrequently extend across the full width of the backshore and into the lagoon.

At Timaru, Hastie (1985) operated a submersible wave recorder 2.5 km off the port from October 1981 to October 1982. Significant wave heights ranged from 0.32 to 3.33 m with a mean of 0.97 m. Maximum wave height was 6.3 m.

Significant periods were in the range 5–17 seconds with an average of 10 seconds. These values are likely to be in the right ranges for all hapua and Waituna-type lagoons on the east and south coasts of the South Island.

As discussed earlier, both types of lagoons are associated with eroding coasts. It is significant to the 'roll-over' and breaching of the enclosing barrier beaches that up to 20% of foreshore sediment volume losses during storms occur by washover or through the beach crest to the backshore. Barriers, therefore, partly 'recycle' themselves as part of the overall process of coastal retreat. However, the principal sediment losses from barriers on Waituna-type lagoons are by continued net longshore transport, and by abrasion of the gravels to fine sands that are then dispersed to the nearshore sand transport system.

In hapua, substantial buildups of sediment may occur in the enclosing spits as the river mouths offset in a downdrift direction. This buildup will comprise sediments arriving by longshore transport from the updrift coast together with flood deposits from the river itself. Each major flood breaches the coast at the spit root, thus freeing a very large 'slug' of sediment in the spit to bypass the river mouth to the downdrift shores. Simultaneously, such floods inject a new 'slug' of coarse bed load (usually in the form of a fan or delta around the flood mouth position) which will re-commence the sequence. It should be clear from this that sediment by-passing at hapua through the 'lagoon cycle' described earlier in this report is, itself, an important way in which longshore transport of sediment is rendered 'jerky' or pulsational along a given coast.

5. River inflows

It was suggested earlier that fluvial inflows to Waituna-type lagoons are generally lower and much less variable than those for hapua. While this seems self-evident from consideration of the catchments and settings of the Waituna-type lagoons, a major impediment to their improved management is the difficulty of obtaining data on this.

For example, despite the national and international significance of Waituna Lagoon as a wetland, an extensive search for hydrological data relating to it has revealed only one stream flow gauging run, made in March 1981 (Table 2). Apparently this was a period of unusually dry conditions, with very low flow in most Southland rivers. Inflows to Waituna Lagoon (Table 2) were very low indeed. Under such conditions it might be expected that seepage of groundwater would be the dominant water input to the lagoon.

An unsigned report dated 8 March 1948, held by Southland Regional Council, describes the planning for flood control works in the creeks contributing to Waituna Lagoon. Waituna Creek has a catchment area of 112 km^2 and a maximum watershed elevation of 60 m above sea level. The design for the 10-year annual exceedance probability (AEP) flood was for 20.4 cumecs.

Other Waituna-type lagoons have generally small, lowland catchments with low inflow rates to the lagoon, and data are similarly difficult to obtain. However,

TABLE 2. AVAILABLE STREAM GAUGING DATA FOR WAITUNA LAGOON, SOUTHLAND.

STREAM	LOCATION OF GAUGING RUN	DATE	DISCHARGE (cum/sec)
Waituna	Highway Bridge	30 Aug 54	0.605
Waituna	Gorge Rd HW Bridge	30 Nov 54	0.064
Waituna Creek	SH 92 Bridge	4 Mar 84	0.004
Andersons Creek	Waituna-Gorge Rd	4 Mar 84	0.003
Currans Creek	Kapuka St H School	4 Mar 84	0.000
Moffat Creek tributary	Miller Rd	4 Mar 84	0.003
Moffat Creek	Moffat Rd	4 Mar 84	0.009
Waituna Creek tributary	Marshall Rd	4 Mar 84	0.008
Waituna Creek	Awarua Swamp	4 Mar 84	0.078

Source: Southland Regional Council.

some fragmentary information is available. The Hook River and other streams contributing to Wainono Lagoon in South Canterbury, have a flood scheme designed for a 50-year AEP event estimated to total 452 cumecs at the peak. Waimate Creek which feeds the ‘Dead Arm’ further south has a flood peak of only 47 cumecs, estimated for the same probability of occurrence.

The Selwyn River draining to Waihora/Lake Ellesmere is a very much larger river than the others described thus far. However, it is hydrologically small compared with the Main Divide rivers feeding to hapua. The Selwyn has a catchment area of 164 km^2, a mean flow of 3.0 cumecs, and a 10-year AEP flood of 134 cumecs (Griffiths 1981).

By far the largest river draining to a Waituna-type lagoon is the Wairau. It has a catchment area of 505 km^2, a mean flow of 25 cumecs, and a 10-year AEP flood of 367 cumecs. None of these rivers begins to compare with the Rakaia (catchment area 1641 km^2, mean flow 200 cumecs, 10-year AEP flood 3674 cumecs) or the Waiau in western Southland (before 1969, mean flow, 560 cumecs; after control, 137 cumecs). The Waiau has been much affected by control for the Manapouri–Te Anau Power Scheme commencing in 1969, but it remains an impressive river. Prior to control, it had up to 20 flow events/year that exceeded 800 cumecs, and since control, 11 events have exceeded this magnitude in 21 years.

A number of important consequences stem from the generally small catchments and comparatively low fluvial inflow of Waituna-type lagoons. These have strong management significance. The first is that water residence (turnover times) will be relatively long in Waituna-type lagoons (and very short in hapua). Unfortunately, no data are to hand which would enable specification of average residence times. This is an item that should be high in priority for further research. A second consequence is that the catchments will have generally small capacity for either hydrologic or sedimentological storage. In turn this means that changes in land use in the contributing catchments will be very quickly reflected in changes to the hydrological regime and/or sedimentation in

Waituna-type lagoons. In short, they can be polluted very easily through runoff and through groundwater contamination. Flood works in the contributing catchments will render the catchments 'flashy' so diminishing low flows and ensuring a very concentrated delivery of flood water during high-energy events. These events will be rainfall-dominated (i.e. generated by discrete meteorological events) that will punctuate long periods of diminished inflow. A third consequence is that sedimentation in Waituna-type lagoons will involve a high proportion of fine sediments. They will tend to become progressively silt- or mud-dominant, particularly in close proximity to the mouths of inflowing streams.

6. Specific sediment yields

Few data are available concerning specific sediment yields or sedimentation rates for Waituna-type lagoons. However, yields should be generally lower than for hapua and rather dominated by finer sediment particle sizes and/or organic matter.

According to Griffiths & Glasby (1985) the specific sediment yield of the Wairau catchment is 1118 tons/km^2/year, a value as high as that for any of the hapua (see Table 1). However, most of this is aggraded in the coastal plain landward of the lagoon, and the coarse bed-load does not reach there.

The Selwyn River catchment has a specific sediment yield of 584 tons/km^2/year (Griffiths 1981; and Table 1). Again, coarse bed-loads (gravels) do not reach the lagoon but the yield value is similar to that for a hapua at Ashburton River mouth (catchment specific yield, 574 tons/km^2/year).

Most Waituna-type lagoons will have specific sediment yields very much less than those of the Wairau and Selwyn Rivers. Values generally less than 20 tons/km^2/year should be expected. This is another matter that should be the subject of further research.

As noted by Nichols & Boon (1994) for mid latitude lagoons on the east coast of the USA, one important measure of the longer term stability (equilibrium?) status of a lagoon is the relationship that exists between sedimentation in the lagoon and relative sea-level change in the ocean bordering it. Nichols & Boon (1994, p.190) note that, 'the shallowness of many lagoons and infilling processes like bay-head deltas, swamp encroachment and segmentation has led to the geomorphic view that lagoons are generally ephemeral features destined to be filled to a marsh-depositional plain in a few thousand years'. For this to occur, the rate of infilling must exceed the rate of submergence for sites where sea level is rising. It is well established from previous research (e.g. Hannah 1990) that sea level has been rising along the east coast of the South Island of New Zealand for at least the period since the turn of the century.

By similar reasoning, if the rate of sedimentation in a lagoon has kept pace with its rate of submergence, a kind of sedimentation equilibrium has been established. In this case, lagoonal deposits will accrete upwards, keeping pace with sea-level rise, increasing their thickness while maintaining the same lagoon volume capacity. Should the rate of sedimentation in the lagoon be less than the rate of sea-level rise, the volume of the lagoon will increase as it becomes deeper.

If sea-level rise accelerates over the next century, as hypothesised under the 'enhanced greenhouse effect' group of projections (Warwick et al. 1996), the implications for Waituna-type lagoons will be profound. They will also be quite variable depending upon the relationship that exists between sedimentation rates in the lagoons and the rate of accelerated sea level rise. Again, we presently have no information on sedimentation rates in Waituna-type lagoons that would enable prediction of lagoon response to either presently occurring or future accelerated sea-level rise. We do not know whether particular lagoons are likely to rapidly decrease in area and volume under accelerated sea level rise, whether they will remain much the same as they presently are, or whether they will become deeper. Determining this should, in our view, be a matter of some urgency for those Waituna-type lagoons to which we attach greatest conservation significance.

The relative vertical rates of change being discussed here as a control on lagoon stability are quite separate from (and therefore additional to) any acceleration of the rates of erosion (retreat measured in the horizontal) of the coastal barriers enclosing Waituna-type lagoons. Horizontal erosion rates are known to be in the order of metres per year (rather than in the order of decimetres or tens of metres). Relative sea-level rise is known to be of the order of millimetres per year (rather than tenths of millimetres or centimetres). There are therefore two orders of magnitude difference between these two major control factors (erosion and relative rise of sea level). The response to climate change of Waituna-type lagoons will therefore be a critical function of change in volume through relative sedimentation versus reduction in area and spatial dimensions through coastal erosion.

Figure 8 presents data from 20 lagoons on the east coast of USA showing relative sedimentation rates in numerous lagoons. The data are for both 'short term' (historical) rates and 'long term' (geological rates) for given lagoons. The line of

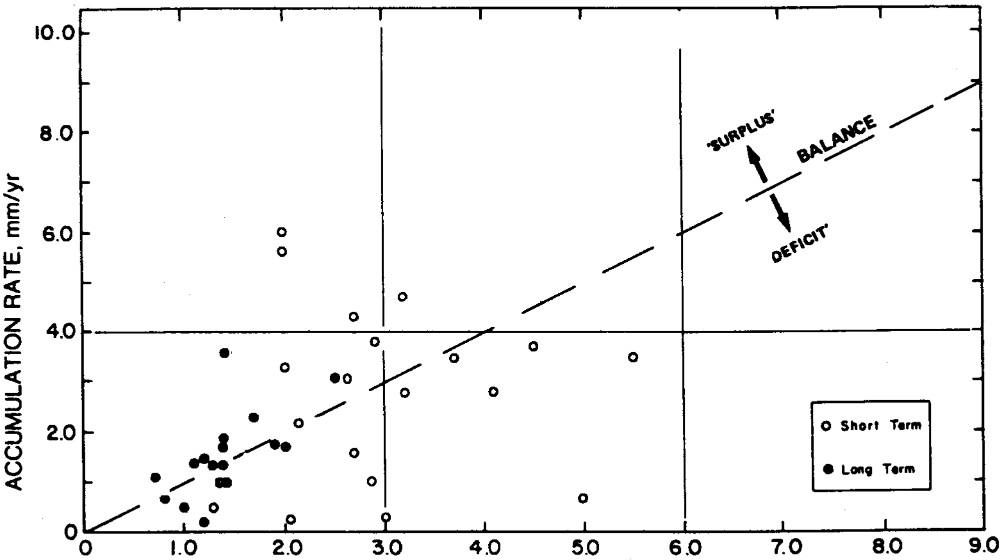


Figure 8. Relative sedimentation in 20 east coast USA lagoons. Short-term rates (decades) are represented by circles, long-term rates (millennia) by dots. The dashed diagonal line indicates parity between accumulation rate and relative sea-level rise. *Adapted from Nichols & Boon (1994, fig. 7.15) by permission of Elsevier Press, Amsterdam.*

exact correspondence between sedimentation rates and relative sea level rise is superimposed and it can be seen to separate so-called 'surplus' lagoons (that are infilling or accreting) from so-called 'deficit' lagoons (where sea level rise exceeds sedimentation and the lagoons are gaining volume). It can also be seen that approximately equal numbers of lagoons belong to these two categories. More significantly perhaps, the bulk of the lagoons studied fall close to the line and are, therefore, approximately equilibrium features in the senses of relative sedimentation and volume change. In the USA, lagoons with strongly active river delta growth at their heads are those that have the strongest 'accretionary' status. 'Deficit' lagoons there are mainly those where submergence has been accelerated through oil and gas extraction from the surrounding country.

Nichols & Boon (1994, p. 191) conclude: 'Since the lagoons compared exhibit a range of accretionary differences between two end-members, lagoon evolution should be viewed as a continuum that reflects the resultant effect of accretion and submergence'. This concept is set out in a model in Figure 9, whereby the sediment accumulation rate is considered to be a function of the relative rate of sea level rise. For a given lagoon status, the combination of rate of accretion and relative sea level rise will determine the volumetric capacity of the lagoon, the import-export status of sediment fluxes, and the resultant evolution and geometry of the lagoon as a whole (including the sediments it contains).

This conceptual model is applicable to Waituna-type lagoons in New Zealand, and the status of particular lagoons will have a strong bearing on their management. Again, this reinforces an urgent need for data on relative sedimentation rates in Waituna-type lagoons.

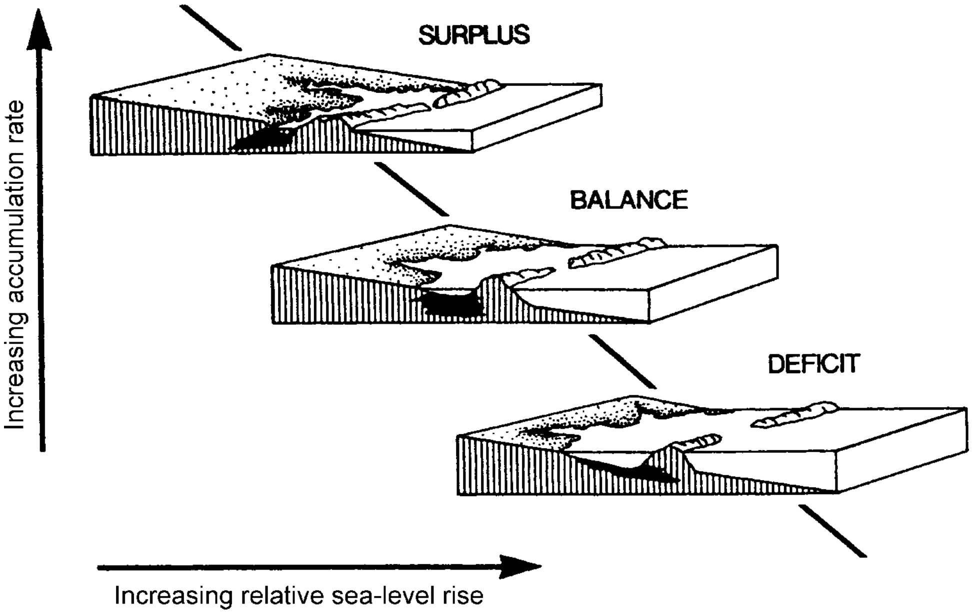


Figure 9. Lagoon equilibrium status as a function of sediment accumulation rate and relative sea-level rise. *Adapted from Nichols & Boon (1994, fig. 7.16) by permission of Elsevier Press, Amsterdam.*

7. Climate and weather

7.1 RAINFALL/EVAPORATION

As with most sites in the east and south of the South Island both hapua and Waituna-type lagoons are thought to have positive water balances during most of the year, i.e. there is an excess of precipitation over evaporation. However, some smaller Waituna-type lagoons do reveal pronounced drying tendencies during summer when both rainfall and inflow are low and evaporation is high (e.g. Cooper's Lagoon and Wainono). Despite the virtual absence of data on water body structures it is known that none of the Waituna-type lagoons become saline or hypersaline as a result of any seasonal fresh water deficit that might occur.

Some data are available for rainfall. Waituna Lagoon is known to have a mean annual rainfall of 1117 mm. Values for Waihora/Lake Ellesmere are not known ,but the catchment of the Selwyn has a mean rainfall of 1300 mm/year. Similarly the Wairau catchment (as distinct from the Wairau Lagoon) has a mean annual rainfall of 2000 mm.

7.2 WINDS

In Waituna-type lagoons where there is no tidal compartment and frequently very low freshwater inflows, wind and thermal effects on the water mass become the main means by which the water mass is mixed and also the principal means by which sediments are dispersed. On Waituna-type lagoons wind has three particular roles: wave action, seiches and surges, and currents.

The heights and periods of wind waves are direct functions of the wind velocity, the wind duration, and the fetch length (the length of water across which the wind is blowing). On narrow fetches in many lagoons the width of fetch and the depth of water are also important in limiting wave sizes.

Most Waituna-type lagoons are very exposed to the wind and have little in the surrounding topography to modify air flows (e.g. forest) so that sustained high wind speeds are not uncommon. For example, maximum one hour wind runs of 53 knots have been recorded on Waihora/Lake Ellesmere in southerlies.

An upper limit to wave action can be set by taking the most extreme case. For fetches of 23 km on Waihora/Lake Ellesmere in wind speeds of 26.5 m/second (53 knots) it is calculated from shallow water hindcast procedures published by US Army Coastal Engineering Research Centre (CERC 1984, fig. 3-28, p. 3-57) that significant wave heights of 1.25 m having significant periods of 4.6 sec will be generated. 'Significant' denotes that the values are the averages of the highest one-third of the wave heights and of the longest one-third of the periods respectively. These estimates are for a fetch with an average water depth of 3 m. Waves of the sizes estimated can evidently be very effective agents of both shoreline change and lagoon floor sediment transport in the generally shallow depths of Waituna-type lagoons.

In addition to erosion of the shore and sediment transportation on the lagoon floor, very steep, short wind waves on lagoons can lead to substantial longshore transports in generally downwind directions. This leads to the creation of spits and sometimes foreland complexes on lagoon shores. At an advanced stage the phenomenon of segmentation occurs, in which the lagoon shore becomes separated into a series of broadly arc-shaped 'bays'. The eastern shores of Te Whanga Lagoon (a very large Waituna-type lagoon) on the Chatham Islands display dramatic segmentation features.

The second aspect of wind on lagoons of the Waituna-type concerns seiching or surging. This refers to the fact that strong winds blowing along the fetch on lagoons can cause water to 'pile-up' at the downwind end. Such wind forcing can lead to resonant motions or seiching of the water in the lagoon basin. For example, seiches having periods of 19 minutes are known under strong westerly wind forcing on Lake Wakatipu.

Seiche amplitudes can be appreciable and can result in significant flooding of low-lying areas at the downwind ends of fetches on strong wind events. Such effects are especially strong in lagoons with shallow basins. A good example is Waihora/Lake Ellesmere, which is subject to strong winds on long fetches over shallow water in both southerly and northwesterly winds. Considerable information on the resulting seiche effects is provided by North Canterbury Catchment Board (1962). The Board operated two water level recorders (one at Taumutu in the south and the other at Kaituna in the north) and an anemometer (at Taumutu) from 1953 to 1962. In that time, 24 seiche events were recorded, the largest of which presented a 1.54 m difference in water levels between opposite ends of the lake (i.e. over 23 km, with the highest level occurring at the northern end of the fetch). The minimum seiche elevation reported was a height difference between ends of 0.79 m and the average difference in events was 1.07 m.

Since wave breaking is controlled by water depths, and seiches of these magnitudes are an appreciable fraction (up to 33%) of the total water depth in the lagoon basin, their physical effects (in addition to inundation of the downdrift shore) are considerable. In seiches, breaking waves not only reach further inland, but also they are able to be higher at breaking and thus more powerfully erosive.

It is evident from shoreline inspections at Waituna and Wainono Lagoons that the larger Waituna-type lagoons also experience seiche and surge phenomena in strong winds.

Thirdly, waves and seiching, together with the direct drag of the wind on the water surface, lead to creation of currents in Waituna-type lagoons. These currents, are in fact, principal agents of mixing and fine sediment dispersal in the lagoon basins. As well as creating waves, the frictional drag of wind on the water surface results in generation of surface wind-drift currents. These develop speeds of about 2–3% of wind speed and move in directions 10°–15° to the left of the wind direction (in the southern hemisphere owing to Coriolis effects from the earth's rotation). On Waihora/Lake Ellesmere in southerlies surface wind-drift currents will thus flow generally north or west of north. In northwesterlies the currents will flow east of north towards Kaituna.

However, at least two other components of current are present to complicate the circulation. Seiching has been shown to establish a water surface gradient of as much as 1.54 m per 23 km and will thus be attended by transient currents having periods equal to those of the seiches. Finally, strong winds result in variations in wave heights from place to place around the lagoon shore, and these, too, lead to currents (from areas of larger waves to areas of smaller ones).

It should be apparent from the foregoing that strong, complex current patterns (on which the direct stirring actions of wave orbital velocities are superimposed) are established in strong wind conditions on Waituna-type lagoons. These currents mix the water body and disperse fine sediments over the lagoon floor, and may also transport suspension and wash load from inflowing streams and rivers. As well they will be moving sediments eroded from some places on shorelines to sites of deposition both in deeper waters and further downshore. As demonstrated by Hemmingsen (1997), Ellesmere/ Waihora had twice its present area and depth in pre-European times. It has also been noted that a characteristic of many present Waituna-type lagoons is an artificially maintained range of water levels with low maxima. Thus, wave action and currents were much stronger in pre-European Waituna-type lagoons.

7.3 CLIMATE CHANGE

Historical trends in mean sea level (m.s.l.) have been examined for four of the main ports in New Zealand by Hannah (1990). He demonstrated that for all four locations (m.s.l.) had been rising since 1900 as a result of climate change. The rate of rise was linear and showed no evidence of any acceleration such as might be expected under the 'enhanced greenhouse effect'. Over the four main ports the average rate of rise had been 1.18 ± 0.8 mm/year since 1900. At Lyttelton the average rate of rise was 1.80 ± 017 mm/year. At Port Chalmers it was rather less at 1.0 ± 0.17 mm/year.

Hannah considered that the most likely scenario was for an increase of between 0.22 and 0.4 m by the year 2050. These estimates are slightly higher than the projections for increase in global average sea levels, in which a 'best estimate' rise of 0.2 m (range of uncertainty 0.07–0.39 m) by 2050 was indicated. These estimates were issued by the Intergovernmental Panel on Climate Change (IPCC). Warwick et al. (1996) examined a 25% reduction in the expected rise of global mean sea level stemming from the IPCC (1995) Second Assessment Report. Hannah's (1990) figures for Port Lyttelton and Port Chalmers provide the only available reliable figures against which to assess relative sedimentation in Waituna-type lagoons.

8. Openings to the sea

It is not strictly correct to refer to the occasional openings between Waituna-type lagoons and the sea by the term 'inlet' because that usage implies a dominance of marine (tidal current) processes. The terms 'outlet' (dominated by freshwater flow) or 'opening' (human-created) is more correct.

Before human intervention, most Waituna-type lagoons had very much higher average water levels and larger water level ranges than has been the case under subsequent management. Because the water levels were higher, the areas (and volumes) of most such lagoons were very much greater than at present.

As the highest storm berms on the enclosing barriers are built by the swash of breakers up to 5 m high, and runup typically extends to elevations of about 1.3 times the breaker height, the natural maximum water levels might be as much as 4 m above m.s.l. The largest beach ridge on Kaitorete Barrier ('Speight Ridge', see Armon 1974) faces the lagoon and was formed by northwest winds, waves, and seiches. This ridge is far above the human-controlled lake level (confined to mean high-water mark +1.0 m).

Under human management, lagoon maximum water levels have been reduced and the range of levels has contracted. Lagoons have not only shrunk in area, and become reduced in volume and in average depth, but they have also become very much less active environments (because fetches for wave action, seiching, current formation, etc., have also been reduced).

The levels of most Waituna-type lagoons are now human-controlled using a variety of mechanisms such as: direct excavation (Waihora/Lake Ellesmere, Waituna); breakout at maintained beach crest levels (for example, Washdyke Lagoon breaks out in floods that exceed +3.96 m above m.s.l., low flows being passed by culvert through the beach); by 'box' structures (as at Waihao in North Otago); or by culverts and pipes (as at Coopers Lagoon). Under control by excavation it is usual for plant to be mobilised to the beach barrier when water levels on the lagoon attain some pre-agreed maximum elevation. The opening is usually maintained for a variable length of time until sea conditions (usually large southerly storm waves with strong net longshore transport across the opening) close it up again. If closure occurs before lagoon water levels have lowered to a level held to be satisfactory it is usual for repeated excavation to occur.

There is nothing natural about the present operating ranges of water level of most Waituna-type lagoons. It is also important to note two other points. First, the distribution of plants, animals (e.g. nesting sites for birds) has become adjusted during this century to these new, artificial water level regimes. Secondly, there is, at best, very poor record keeping of water levels on any of the Waituna-type lagoons.

Using data supplied to one us (RMK) in 1967 by the then North Canterbury Catchment Board we have made an analysis of 120 records of the opening and closing of Waihora/Lake Ellesmere at Taumutu between August 1901 and November 1966. No data are to hand for the present operating regime of the lagoon. Over the 66-year period, the lagoon was open to the sea for a total of 3804 days (15.8% of the time). This is a much higher proportion of time open than would have been the case in pre-European times. These figures illustrate very well that Waituna-type lagoons are seldom open to the sea and are not dominated by marine processes. In the terms used by Kjerfve (1994) Waihora/ Lake Ellesmere is completely 'choked' about 84% of the time.

Durations of openings had an average value of 41.4 days, with a range from one day [sic] to 123 days. The data are strongly skewed towards shorter opening durations, and the median duration of opening was 29 days. This is not surprising since the long-term average for the passage of weather fronts across the New Zealand region (and which are accompanied often by episodes of strong wave action) is 9 days. Cumulative frequency analysis shows that 17% of the openings were less than 10 days in duration, 36% were less than 20 days, and 71% were less than 40 days.

The maximum recorded level at which the lake was opened was 2.16 m above m.s.l. (well below maximum storm berm elevation on the beach. The mean elevation at the time of opening was 1.45 m above m.s.l. while the minimum was 0.9 m. Lagoon closure occurred at an average elevation of 0.53 m above m.s.l. The highest level at which closure was recorded was 1.3 m above m.s.l. and the lowest was 0.0 m, i.e. at m.s.l.

Unfortunately, water level records are not available for most Waituna-type lagoons, including Waituna itself, although a few observations have been recorded (Tables 3 and 4).

At Waituna, there is no water level recording in the lagoon itself, but observations have been made on a gauge board attached to the Waghorn Road bridge since 1964. In the 66 years from the first recorded artificial opening made in 1908 until 1974, there is no information as to how levels were determined, or if they were at all. It is believed, but not verified, that the Waghorn Road gauge board has not been levelled-in so that its datum is unknown and it serves as a rather arbitrary indicator of water level behaviour. Nonetheless, observations from this board are used by members of the Lake Waituna Control Association in making decisions about openings. By monitoring the gauge board the Association members inform the Southland Regional Council of lagoon levels and request permission to open the lagoon. This is usually done when the level on the board reaches an indicated value of 2 m. Data from the board are presented in Table 4. Clearly, a major contribution to lagoon management can be made at Waituna by measuring water levels in the lagoon to an established, verified, datum (preferably m.s.l.).

Table 3 is compiled from a correspondence file ('Waituna Lagoon Opening Job No. B 435') held at Southland Regional Council. The file records openings made in only 8 of the 63 years from 1908 to 1971. It is thus highly probable that numerous openings of the lagoon were not recorded. However, the observations do show a preponderance of openings in the last third of the year (August to November). Rather intriguingly, the anonymous 1948 report on the design of floodworks on the streams feeding Waituna Lagoon that was discussed earlier makes mention of the opening of the lagoon. The author noted that, 'the outlet is sometimes blocked by material thrown up by the sea, which causes a rise of as much as 6 feet in the level of the lagoon'. This is a clear reference to maximum levels similar to those known today. It also confirms a freshwater scouring role in the opening process and marine (wave) action in closure.

TABLE 3. RECORDED INSTANCES OF THE ARTIFICIAL OPENING OF WAITUNA LAGOON, SOUTHLAND SINCE 1908*.

1908	First recorded opening.
1950	Letter from Chief Engineer to Chairman of Southland Catchment Board indicating that the outlet should be opened "at the first opportunity". Exact date not found.
1952	Letter dated 3 April Chief Engineer approves opening Waituna Lagoon outlet. Exact date not found.
1957	Open in August. Exact date not found.
1964	Opened at or about the 17 July.
1968	Opened September. Exact date not found.
1969	Letter dated 9 June Chief Engineer approves opening Waituna Lagoon outlet. Exact date not found.
	Letter dated 11 November Chief Engineer approves opening Waituna Lagoon outlet. Exact date not found.
1970	Closed July. Exact date not found. Opened 5 October.
1971	No information found for this year.

* Note that openings are recorded for only 8 of the 63 years, suggesting that many openings were not recorded. Data is from a correspondence file held at Southland Regional Council (Waituna Lagoon Opening Job No. B 435).

In contrast to the paucity of the earlier records, Table 4 presents a much more detailed set of observations for the period since August 1972. There was no year in which openings were not either attempted or did occur. Analysis of the data in this table show that Waituna Lagoon was open for a total of 2870 days between April 1972 and August 1992, some 39.3% of the time. This is more than double the duration of time for which Waihora/Lake Ellesmere has been open over a rather different span of years. The difference is probably accounted for by the likelihood that the net longshore sediment transport regime at Waituna is not as energetic as that at Waihora/Lake Ellesmere. If it is freshwater buildup in the lagoon that leads to opening events (whether natural or artificial), it is marine processes, most notably longshore drift in large waves, that are responsible for closure.

This interpretation for Waituna Lagoon tends to be confirmed by a mean duration of opening of 89.7 days. The maximum duration of opening was 350 days (from June 1989), i.e. almost a year. Four other years (1983, 1984, 1986, and 1991) had openings with durations longer than 200 days. The minimum duration of opening was zero days (in 1974) with an instance of a one-day opening in 1973.

No openings have occurred in the summer months (November to February inclusive). Most have occurred in June and July (7 occurrences each), and May and October are the next months in which numerous openings have been made (5 occurrences each). There were 4 openings in the month of September, but only two occurrences in August.

The indicated maximum level at which the lagoon was opened was 2.75 m (in May 1988—the wildfowl hunting season). The mean level of the data in Table 4 is 2.26 m on the board gauge. No data are available on the water levels at which the lagoon closed.

TABLE 4. OBSERVATIONS AND DATA ON THE OPENINGS OF WAITUNA LAGOON, SOUTHLAND.

DATE OPENED*	DATE CLOSED	LEVEL (m)	DAYS OPEN	HIGH TIDE
25 Apr 1972	31 May 1972	2.4	35	1400
22 Jul 1972	8 Aug 1972	2.2	17	1200
20 Sep 1972 (East end)*	10 Oct 1972	2.2	20	1200
8 Jun 1973	9 Jun 1973	-	1	2100
16 Jul 1974	beaten by tide	-	-	-
17 Jul 1974	-	-	-	-
29 May 1975	19 Jun 1975	2.2	21	1730
17 Sep 1975	10 Nov 1975	1.9	23	-
26 Jul 1976 (Hansens Bay)*	23 Aug 1976	2.4	28	1400
12 May 1977	6 Jun 1977	2.0	24	2145
7 Oct 1977	3 Nov 1977	2.0	27	1000
14 Aug 1978	10 Oct 1978	2.2	56	1020
24 Feb 1979	1 Jul 1979	1.85	126	1030
26 Sep 1979	22 Mar 1980	2.2	175	0900
22 Jun 1980	27 Jun 1980	2.2	5	1000
27 Aug 1980	30 Oct 1980	2.6	63	1500
24 Jul 1981	8 Sep 1980	2.15	47	0845
21 Oct 1981	26 Apr 1982	2.0	182	1015
2 Jul 1982	18 Jul 1982	2.1	16	1150
13 Sep 1982	3 Oct 1982	2.2	20	1132
3 Jan 1983	30 Jun 1983	2.2	175	1900
5 Sep 1983	1 Jun 1984	2.1	273	1240
4 Oct 1984	1 May 1985	2.02	210	1034
26 Jul 1985	17 Sep 1985	2.35	52	0910
16 May 1986	8 Jun 1986	2.3	23	0730
14 Aug 1986	4 May 1987	2.65	259	0910
5 Aug 1987	23 Aug 1987	2.35	17	1025
19 May 1988	19 Jul 1988	2.75	63	1042
20 Sep 1988	8 Mar 1989	2.3	168	1000
24 Jun 1989	10 Jun 1990	2.6	350	0740
23 Feb 1991	1 Jun 1991	2.5	98	0940
21 Oct 1991	23 May 1992	2.22	210	1300
10 Aug 1992	24 Oct 1992	2.7	86	1200
5 Jul 1994	5 Sep 1994	3.45	62	
12 Jul 1995		3.0		

Source: Lake Waituna Control Association records supplemented by information supplied by Southland Regional Council.

* All openings have been made at the western end of the lagoon, except where otherwise specified in this table (see also Fig. 7).

9. Conclusions

In considering our conclusions regarding management guidelines we have had regard to a number of documents not yet referred to in this report. They include a draft management plan prepared for the 'Waituna Wetlands Scientific Reserve' (Department of Lands and Survey, Invercargill, August 1984), a letter by R.R. Sutton, Lorneville, RD 4 Invercargill (dated 18 May 1976) to Southland Acclimatisation Society on the subject of Wildlife Values in the Waituna Wetland Reserve, and Kelly (1968) (a paper dealing with botanical aspects of Waituna Lagoon).

Adverse impacts

From examination of this literature, together with that relating to the management of other Waituna-type lagoons, it is possible to identify a range of possible adverse impacts on the lagoons and their surrounding ecosystems, which it would be desirable to 'avoid, remedy or mitigate', to borrow the words of the Resource Management Act 1991.

These adverse impacts are: fire; acceleration of coastal erosion; modifications to (especially reductions of) fluvial inflows; land-use changes in catchments that increase sediment yield to lagoons; and climate change, which may manifest through changes to freshwater inflow, relative sedimentation rates, and accelerated sea level rise.

Information deficiencies

To these potential impacts it is very important to add a number of basic information deficiencies that have been identified by this report. It is absurd that wetlands of national and international significance are managed without benefit of any reliable information on their controlling physical systems. In the case of Waituna, a wetland of very high reputation, it is not even clear if the single board used to visually record water levels (outside the lagoon proper) has a known relationship to a datum such as m.s.l.

This report has reviewed available information for coastal lagoons on the east and south coasts of the South Island in the light of the international scientific literature of lagoons. That body of literature is not large and contains few studies of lagoons that have morphogenetic contexts and physical makeups like those commonly found in the South Island. To a significant extent, New Zealand workers have had to 'home grow' the necessary experience to inform management. It should also be very clear from the list of often very elementary data deficiencies identified in this report that the knowledge base is still at an early, very rudimentary state. As a matter of some urgency, consideration should be given to ways in which this situation can be improved, at least for those lagoons identified as being of greatest significance in wildlife and conservation terms.

Lagoon types

The east and south coasts of South Island, New Zealand, present at least two distinctly different lagoon types, recognised in this report for the first time. So-called 'river mouth lagoons' which have been described before, (e.g. from the Rakaia and Waiau Rivers) have been designated in this report by their original name—hapua. The character and main controls of hapua have been summarised in this report, and a model for their management has been provided in Kirk (1991). So-called 'coastal lakes' form the other kind of lagoon, here termed Waituna-type lagoons since the lagoon of this name in Southland is such a splendid example of the physical process and landform characteristics of the type.

Waituna-type lagoons are dominated by freshwater inflow, by a variety of influences related to the action of wind on the lagoon water body, and most are associated with coarse-grained, microtidal coasts having high wave energies and strong longshore drifts. Most of the coasts are in long-term erosion so that the area of Waituna-type lagoons is being steadily (and in some cases very rapidly) reduced. At least one (at Waimataitai, Timaru) has ceased to exist altogether this century and another (Washdyke) is under severe threat of complete loss.

Three of the principal Waituna-type lagoons (including Waituna itself) have a particular association with inflections in the longshore behaviour of coasts. Each of the three (Wairau, Waihora/Lake Ellesmere, and Waituna) has close proximity to coasts that are 'rotating' about loci or 'hinge-points'. This correspondence is remarkable and it owes a considerable amount to the fact that Waituna-type lagoons have tended to form either in the lower, re-entrant, interfan depressions between outwash fans of the main divide rivers (e.g. Waihora, Waituna), or towards the outer extremities of major fans (e.g. Wainono).

Present areas of this type of lagoon are generally greatly reduced in comparison with areas at perhaps 5000–7000 years ago. Most Waituna-type lagoons had drainage linkages with other lagoons and estuaries in the recent geological or historical past. For the most part these links no longer exist.

Not only are Waituna-type lagoons subject to profound change through ongoing coastal erosion, but they are also subject to presently unknown kinds of change that will be determined by the relative sedimentation rates of particular lagoons, about which almost nothing is known either. It has also been shown that mean sea level has been rising around the east coast, South Island, at least since 1900. It is very important to the future of Waituna-type lagoons whether or not sedimentation rates in particular cases are less, equal to, or more than the mean rate of sea level rise. Lagoons that are infilling more rapidly than sea level rise will be losing water volume and will have short effective 'lifetimes'.

Sedimentation

The relative sedimentation ratio is extremely important in the assessment of lagoon behaviour under climate change scenarios through the 'enhanced greenhouse effect', particularly to the prospects for accelerated sea level rise. It should therefore be a high research priority to determine sedimentation rates in the major coastal lagoons. This information is as central to formulating sound management plans for lagoons under present conditions of sea level rise, as it is to making an informed assessment of the hazards that might (or might not) be posed by climate change.

Allied to the need for sedimentation studies there is a need to improve knowledge of specific sediment yields from the generally small catchments of Waituna-type lagoons. This information should be obtained in the context of land-uses prevailing in the catchments, because Waituna-type lagoons seem especially sensitive to both hydrological changes in the catchments (e.g. more rapid routing of flood peaks into them), and to sediment loads generated by land-use. For example, it is known that parts of lowland Southland are undergoing rapid and extensive conversion from grazing sheep to dairy farming. There are major differences in the intensity and character of runoff and sedimentation from these two kinds of pastoral production.

Water levels and circulation

In addition to needs for data of the most elementary kind on water levels in (rather than somewhere near) lagoons, there is a need for studies of water circulation and hydrology in Waituna-type lagoons. This report has identified a number of important processes related to winds as the main agent of water mixing and sediment transport. The report has presented most of the few data available on seiching and some typical calculations for hindcast wave conditions. No actual data on current systems are to hand.

All Waituna-type lagoons had higher maximum water levels and larger ranges of water levels under pre-European conditions than under more recent management. The contraction in range (to a maximum that seems generally to be lower than m.s.l. +2 m) has not only reduced the water level excursions and greatly decreased the areas of the lagoons, but it has also considerably reduced the energy levels and physical dimensions of waves, seiches, and wind-driven circulation currents of various kinds. The effect has been to ‘quieten’ the environments, compared to natural regimes.

All Waituna-type lagoons have ‘openings’ involving scouring by freshwater, whether the openings are allowed to occur naturally after a buildup of ‘head’ in the lagoon, or whether they were commenced by horse-drawn scoops (as earlier this century) or are caused by bulldozer. ‘Box’ and culvert type outlets work in the same fashion. All Waituna-type inlets have effectively nil tidal compartments, though some ingress of salt water may occur late in an opening. The tides do not open or keep open artificial inlets to Waituna-type lagoons. Most Waituna-type inlets are closed from the sea much more than they are open to it, though long periods of an open condition can occur where longshore sediment transport on the enclosing barrier beach is slight during the opening. Artificial openings are much more frequent than natural openings were. Though not very much seems to be known about lagoon water volume residence times, it is likely that the artificial increase in the frequency of openings has shortened the turnover time for water in the lagoons.

All Waituna-type inlets are closed by wave action, especially by large waves breaking at strong angles to the shore (so that locally high rates of longshore transport occur in coarse sediments).

Management of potential hazards

With the exception of the potential hazard of fire (in peat land in Southland, as well as in vegetation communities marginal to Waituna-type lagoons), it is suggested that management of the other potential hazards to lagoons together with their very considerable resources and conservation potentials must proceed from sound scientific understanding and the application of informed principles of trends in the behaviour of the physical system supporting the ecology. This report established a need for a small number of key items of information central to management. These are:

- Establish and monitor rates of coastal erosion and/or accretion to help determine lagoon area and volume change trends.
- Establish the relative rate of sedimentation in the lagoon.
- Establish a reliable lagoon water level recording system and archive the data in forms that are not anecdotal. As well as the maximum water level needed to 'justify' an artificial opening, information is needed on minimum water levels, the temporal frequencies of water levels making up the range, and the patterns of change.
- Initiate studies of hydrological processes (especially those related to wind), hydrological turnover, water residence times, and both water yield and sediment yield from contributing catchments.

It is considered that management of Waituna-type lagoons will remain largely physically ill-informed unless at least the first three of the above information requirements are satisfactorily addressed.

It would be very unfortunate, in the light of new legislative and policy imperatives, as well as of national concerns expressed about the possible consequences of climate change, if we continue to try and manage lagoons of high significance without an appropriate underpinning knowledge base yielded by monitoring and by ongoing fundamental research.

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