River–beach interaction on mixed sand and gravel coasts: a geomorphic model for water resource planning

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Abstract

A distinctive sequence of river mouth offsetting and freshwater lagoon development is described from mixed sand and gravel coasts on the east coast of the South Island, New Zealand, particularly the Rakaia river. Though total annual sediment load exceeds $4 \times 10^6$ t, the Rakaia is a ‘small’ river in that the coarse fraction nourishing beaches and the regional longshore drift is insufficient to maintain either the river mouth or the adjacent coasts against long-term erosion by the sea. Dominance of marine over fluvial processes is an important overall control of the lagoon and spit development sequence.

Long, narrow spits grow generally, but not exclusively northward for up to 3 km at the Rakaia under the influence of longshore drift in low to moderate stages of river flow. Under higher river flows the spits are breached, the lagoon circulation alters and a ‘slug’ of the regional drift sediments temporarily stored in the spits is bypassed to the downdrift coast. River-injected materials contained in flood formed subtidal deltas also contribute to the drift and to marked modulation of the regional net longshore sediment transport which displays a ‘pulsational’ character at downdrift sites.

The river mouth lagoons are non-tidal and non-saline owing to generally steep bed gradients in the braided rivers and to low tidal range, though backwater effects are observable and some salt enters by storm overwash and spray. Permeability variations within enclosing spits are important in both the process of mouth offsetting and in flood breaching. A range of potential and actual environmental impacts on such river mouths relating to use of freshwater resources for activities such as hydroelectric power generation and irrigation is discussed in the light of the fact that the coastal lagoons present important concentrations of recreational, wildlife and fisheries values. Irrigation drawoff and hydroelectric power generation can affect the magnitudes of river flow and its temporal pattern at the coast, as well as delivery of coarse sediments to the spits enclosing the mouth, thus markedly altering the interaction with marine processes in the river mouth region. Water resource development on the river has the potential to increase freshwater flooding adjacent to the mouth, to cause protracted closure of the mouths and to accentuate coastal erosion.

Introduction

Geomorphic form and process interaction occurring where rivers meet the sea are complex but best known at tidal inlets, estuaries and lagoons developed in sandy shores where tides are the principal forcing function, there is ingress of saltwater and measurable freshwater dilution of it. However, many river mouths, particularly on coasts dominated by coarse-grained sediments, are not subject to appreciable saltwater ingress and are characterized by process regimes that are inadequately explained by tidal hydraulics. In New Zealand and elsewhere, understanding of the controls of such river mouths is essential in the light of their conservation...
importance for in-stream recreation, wildlife and fisheries, and for management of lower catchment flood and coastal erosion hazards. Such information is also needed because of competing substantial out-of-stream economic development potentials relating to irrigation and hydropower generation.

The paper describes the distinctive forms and processes that occur at many river mouths on the east coast of New Zealand. These are non-tidal and non-estuarine in character [though previously incorrectly classified and described as estuaries (Hume and Herdendorf 1988)]. Typically, these systems occur where broad, braided, gravel-bed rivers discharge a large annual sediment load of wide particle size range (silt to coarse gravel) from rapidly eroding high country inland. South Island catchment-specific sediment yields average 1856 ± 261 t km⁻² yr⁻¹ compared with the world average of 182 t km⁻² yr⁻¹, and are among the highest known sediment yields (Griffiths and Glasby 1985). The rivers debouch into a predominantly meso-tidal, high-energy oceanic swell environment, dominated by mixed sand and gravel beaches.

Particular attention is focused here on the mouth of the largest river in Canterbury, the Rakaia (Fig. 1). The principal processes are described and a descriptive model of river–beach interaction is presented based on the Rakaia and several similar rivers. This is used to consider freshwater resource development and planning implications for the mouth region by drawing on a process analogy with wave mechanics. The mouth is viewed here as the unstable outcome of two independent, powerful systems that intersect at the coast. Where two 'signals' (in this case, marine and fluvial) having differing magnitude and frequency distributions interact (or 'beat'), a 'heterodyne' is produced that is a cross-product of the two. The outcomes are 'signals' that are sometimes marine dominated, sometimes fluvial, and often 'sums or differences' of the two. Any change in the driving functions (such as discharge modification resulting from water abstraction or storage) produces other, quite different cross-product sets which will have different geomorphic expression and a strong resource impact.

Figure 1. Location of the Rakaia river and other rivers discussed in the text.
The Rakaia was the focus of a major resource allocation debate concerning the extent of future water resource utilization offshore (such as irrigation of farmland) versus preservation of its water and water-based resources, largely for on-river uses (fishing and boating) (Bowden 1983). The eventual outcome has been a Conservation Order for the Rakaia but numerous other New Zealand rivers of similar fluvial and coastal character (many of which have already been developed in various ways for irrigation, hydroelectric power generation, or both), present potential or actual environmental impacts as a result of water resource developments that are comparable to the Rakaia.

The large river – small river concept

Zenkovich (1967: 551–85) noted that for several rivers in Kamchatka and on the Black Sea coast, mouth offsets of several kilometres can occur where strong littoral drift affects outlets developed in coarse-grained materials. Further, the landforms and water bodies occurring at river mouths display a large range of forms that have been unevenly studied. Zenkovich advanced a classification of types based on the concept that the dominating factors concern the relative influence of river-derived sediment load on the stability trend (erosion or accretion) of the adjacent coastline. A fundamental distinction was made between 'large' and 'small' rivers. Large rivers contribute abundant sediment load to the coast so that it either maintains a stable position against losses due to abrasion and longshore transport, or it actively accretes. The mouths of large rivers and the included water bodies are, in this view, controlled more by river influences than by marine forces. By contrast, small rivers produce insufficient sediment load to protect the coast from direct marine erosion and attendant storm sea penetration. Also, the mouth landforms and water body geometries are controlled mostly by marine forces. The terms 'large' and 'small' are thus relative with respect to the receiving coast. An important implication of this is the fact that total river sediment load is less pertinent than the proportion of (bed) load coarse enough to nourish the coast.

Zenkovich (1967: 552) notes that most of the available literature was concerned with large rivers (particularly with deltas) and with fluvial processes but that there was little information concerning small rivers or the marine forces at their mouths. Thus ‘there is scope for research on formations of mixed marine and alluvial origin’. The concept can be extended in the present context to state that a small river is one where the distinctive and highly changeable character of the lagoon and enclosing spits is determined by the interaction of the river, groundwater and the sea, the overall influence of the river being subordinate to that of the sea. The process analogy with wave mechanics stated earlier is thus in close agreement with Zenkovich's notion of overall regime. Both can be used as a basis for geomorphological modelling of small rivers and both can be readily applied to assessing water-resource-related development impacts.

The 'small river' concept is highly pertinent to the Rakaia and many of its neighbours since previous studies have shown that the changing morphology of the lagoon responds to the interaction between longshore drift on the ocean beach and the incidence of higher flow states in the river. A repeated sequence of form changes occurs on a coastline that displays a long-term trend of chronic erosion, so that river-derived sediment load is clearly insufficient to stabilize or overcome erosion. This characterization may appear strange, since the Rakaia is the largest river in Canterbury and a physically dramatic landscape system (see Table 1 and Plate 1). It contributes more than $4 \times 10^6$ t of sediment annually and is also
culturally appraised in New Zealand as a 'large' river in view of the extensive and prolonged research and debate which led to a national Conservation Order to protect wildlife, recreational and scenic values. A large portion of these values attach to the mouth and lagoon system. It will be demonstrated that 'smallness' in the sense used here is central to the understanding and management of the Rakaia and other similar rivers.

Table 1. Hydrological characteristics of some east coast, South Island rivers

<table>
<thead>
<tr>
<th>Catchment</th>
<th>Area (km²)</th>
<th>Channel slope (m m⁻¹)</th>
<th>Mean rainfall (m yr⁻¹)</th>
<th>Mean discharge (m³ s⁻¹)</th>
<th>10-year flood discharge (m³ s⁻¹)</th>
<th>Specific sediment yield (t km⁻² yr⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Waiau</td>
<td>1980</td>
<td>0.010</td>
<td>2.00</td>
<td>90.0</td>
<td>1868</td>
<td>1300</td>
</tr>
<tr>
<td>Hurunui</td>
<td>2680</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>1000</td>
</tr>
<tr>
<td>Waipara</td>
<td>741</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>621</td>
</tr>
<tr>
<td>Waimakariri</td>
<td>3210</td>
<td>0.006</td>
<td>1.90</td>
<td>120.0</td>
<td>2708</td>
<td>1669</td>
</tr>
<tr>
<td>Rakaia</td>
<td>2640</td>
<td>0.010</td>
<td>3.00</td>
<td>200.0</td>
<td>3764</td>
<td>1641</td>
</tr>
<tr>
<td>Ashburton</td>
<td>540</td>
<td>0.010</td>
<td>1.40</td>
<td>8.0</td>
<td>170</td>
<td>574</td>
</tr>
<tr>
<td>Rangitata</td>
<td>1775</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>946</td>
</tr>
<tr>
<td>Opihi</td>
<td>2372</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>1000</td>
</tr>
<tr>
<td>Waitaki</td>
<td>12118</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>144</td>
</tr>
<tr>
<td>Clutha</td>
<td>21078</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>94</td>
</tr>
</tbody>
</table>

Source: Compiled from Griffiths (1981: Table 1) and Griffiths and Glasby (1985: Table 1)
River mouths and recession of the central Canterbury coast

The coastal geomorphology of the central Canterbury Plains and the historical trends in shoreline position are well known (Speight 1930, 1950; Kirk 1969, 1987). The coast comprises a series of weakly consolidated sand and gravel outwash fans truncated by marine erosion consequent upon the post-glacial rise in sea level. These now form steep cliffs backing a narrow mixed sand and gravel beach system. The highest cliffs occur near the Ashburton river (up to 24 m) and decline northward and southward. In the vicinity of the Rakaia the cliff approximates the height of the storm beach ridge (about 4 m above msl) and the old fan deposits include a number of swamps, lagoons and associated deposits. The present river mouth is incised into the older surfaces but floodwaters readily escape the channel, especially on the south bank. In the north the Lake Ellesmere Basin has been enclosed during the last 4000–7000 years by an extensive depositional complex of beach ridges and dunes derived from net northward drift of the cliff sediments (Armon 1974) (Fig. 2).

The typical forms, processes and sedimentary characteristics of Canterbury mixed sand and gravel beaches were described by Kirk (1985). The high-energy coast is exposed to frequent and severe storm wave action emanating from the Southern Ocean to the south and southeast. Runup from storm waves of up to 5 m in height is the principal erosive agent. Southerly waves promote a strong northward transport of sands and gravels toward Kaitorete Barrier and Banks Peninsula, but lower-energy easterly and northeasterly waves are responsible for a lesser counterdrift southward. Transport of sediments thus occurs in both

![Figure 2. The Rakaia river mouth and adjacent coast.](image-url)
River–beach interaction and water resource planning

directions along the coast and the gross transport is much greater than the net northward annual displacement. Since deflections of river mouths are caused by longshore drift of beach material in response to local wave refraction patterns it follows that either northward or southward deflections can be observed depending upon sea state and weather, though northward movement is both more common and more strongly developed owing to the greater power of southerly wave action.

The combination of a high-energy environment and weakly resistant coastal structure is reflected in rapid, continuing and long-term coastal erosion. Abundant fine material carried as suspended load in the rivers and lesser quantities of coarse bed load delivered through lagoon systems to the shore have been insufficient to maintain the coast against erosion. Analysis of fan slopes and cliff heights suggest that 4–6 km of land have been removed from the plains margin during the last 4000–7000 years. Coastal retreat thus presents both dramatic and long-term aspects that can be expected to continue, or to increase in the event of any acceleration in sea-level rise. There is abundant historical and contemporary evidence of coastal instability from old maps, ground surveys and air photography. Speight (1950) recorded that the Little Rakaia Stream, which once flowed into the northern end of the lagoon, had bridges at road crossings; these are now gone. In 1950 the stream bed was dry and almost infilled with beach sediment thrown landward during coastal retreat. By 1967, the landward toe of the beach stood against the former inland bank of the stream (Kirk 1969) and in 1983, the old channel was completely infilled and beach gravels were encroaching on farmland behind. Palmer (1982) noted that at Taumutu a small arm of Lake Ellesmere was slowly being infilled as sand and gravel was driven inland. The original Taumutu Pa (Maori village) has long been eroded away and subsequent Pa and other Maori cultural sites may be threatened in future.

Table 2 and Fig. 3 present erosion rates and patterns derived from comparative analysis of air photographs while Table 3 lists values for coastal retreat measured at culvert sites between the Rakaia and Taumutu. As can be seen, erosion rates vary along the shore but are sustained through the region of the Rakaia mouth in both updrift and downdrift directions. It is also evident that short-term advances of the shore can occur along the southern coast of the lagoon adjacent to the main stream channel. This reflects periodic deliveries of gravel to the shore by high river flow. Such inputs notwithstanding, mean maximum rates of recession for the lagoon barrier as a whole were 1.95 m yr\(^{-1}\) over the period 1943–76. Table 3 shows that average retreat rates of the beach crest at four sites north (downdrift) of the river were 0.9 m yr\(^{-1}\), a value consistent with that obtained from photography for a closely comparable time span.

There is little doubt as to the pace and pattern of coastal retreat in the area. From previous research in the Canterbury Bight (Kirk 1981) it is known that net losses of beach materials can be ascribed to the following factors (in decreasing order of quantitative importance): net northward longshore drift, storm overwash to the landward face of the beach, and abrasion of gravel to fine sands and silts that are transported offshore and deposited on the continental shelf.

**River mouth behaviour**

The mouth of the Rakaia is broadly similar in morphology and behaviour to most river mouths on the Canterbury coast (Kelk 1974; Kirk et al. 1977; Kirk and Hewson 1979; Hicks 1979). As shown in Figs 2 and 3, the lower Rakaia has two principal channels, both of which are braided. Inland the river is deeply entrenched within old fan deposits but for the lower 15 km the channels occupy similar levels to
Table 2. Rates of coastal erosion between Wakanui (south of the Rakaia) and Birdlings Flat (north of the Rakaia), determined from air photographs

<table>
<thead>
<tr>
<th>Location</th>
<th>Dates</th>
<th>Mean rate (m yr(^{-1}))</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wakanui</td>
<td>1942–76</td>
<td>-0.84</td>
<td>Gibb (1978)</td>
</tr>
<tr>
<td>Seaview</td>
<td>1942–76</td>
<td>-0.69</td>
<td>Gibb (1978)</td>
</tr>
<tr>
<td>Scafield Road</td>
<td>1942–76</td>
<td>1.36</td>
<td>Gibb (1978)</td>
</tr>
<tr>
<td>Corbetts Road</td>
<td>1942–76</td>
<td>-0.34</td>
<td>Gibb (1978)</td>
</tr>
<tr>
<td>Kyle Road</td>
<td>1942–76</td>
<td>-0.43</td>
<td>Gibb (1978)</td>
</tr>
<tr>
<td>Mainwarings Road</td>
<td>1942–76</td>
<td>-0.62</td>
<td>Gibb (1978)</td>
</tr>
<tr>
<td>South Rakaia</td>
<td>1942–76</td>
<td>+0.36</td>
<td>Gibb (1978)</td>
</tr>
<tr>
<td>South Rakaia Huts</td>
<td>1952–76</td>
<td>+0.90</td>
<td>Kirk (this investigation)</td>
</tr>
<tr>
<td>South Rakaia Channel</td>
<td>1952–76</td>
<td>+0.67</td>
<td>Kirk (this investigation)</td>
</tr>
<tr>
<td>South Rakaia Lagoon</td>
<td>1952–76</td>
<td>-0.67</td>
<td>Kirk (this investigation)</td>
</tr>
<tr>
<td>Central Lagoon</td>
<td>1952–76</td>
<td>-0.90</td>
<td>Kirk (this investigation)</td>
</tr>
<tr>
<td>North Rakaia Lagoon</td>
<td>1952–76</td>
<td>-1.27</td>
<td>Kirk (this investigation)</td>
</tr>
<tr>
<td>Rakaia Road</td>
<td>1943–75</td>
<td>-0.66</td>
<td>Gibb (1978)</td>
</tr>
<tr>
<td>McEvedys Road</td>
<td>1943–75</td>
<td>-2.08</td>
<td>Gibb (1978)</td>
</tr>
<tr>
<td>Taumutu</td>
<td>1943–75</td>
<td>-3.07</td>
<td>Gibb (1978)</td>
</tr>
<tr>
<td>Birdlings Flat</td>
<td>1862–1952</td>
<td>+0.58</td>
<td>Gibb (1978)</td>
</tr>
<tr>
<td>Birdlings Flat</td>
<td>1952–66</td>
<td>0.00</td>
<td>Gibb (1978)</td>
</tr>
</tbody>
</table>

\(a\) Sites are listed in order from south to north (downdrift)

\(b\) Positive values indicate progradation of the beach crest, negative values indicate erosion (landward retreat) of the beach crest

Table 3. Coastal erosion rates determined from resurvey of beach profiles at drainage culverts for four sites north (downdrift) of the Rakaia River mouth

<table>
<thead>
<tr>
<th>Location</th>
<th>Dates</th>
<th>Mean rate (m yr(^{-1}))</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rakaia No. 1 Culvert</td>
<td>1962–65</td>
<td>-0.97</td>
<td></td>
</tr>
<tr>
<td>Rakaia No. 2 Culvert</td>
<td>1962–65</td>
<td>-0.00</td>
<td>Beach face lowered but no crest retreat</td>
</tr>
<tr>
<td>McEvedys Culvert</td>
<td>1943–62</td>
<td>-0.88</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1962–65</td>
<td>-0.93</td>
<td>Mean = -0.90 m yr(^{-1})</td>
</tr>
<tr>
<td></td>
<td>1965–69</td>
<td>-0.89</td>
<td></td>
</tr>
<tr>
<td>Forsyths Culvert</td>
<td>1962–65</td>
<td>-0.97</td>
<td></td>
</tr>
</tbody>
</table>

\(a\) Sites are listed in order from south to north

Source: Data derived from surveys compiled by North Canterbury Catchment Board and Regional Water Board, now held by Canterbury Regional Council
Figure 3. Typical South Island river mouth morphologies. Most are mixed sand and gravel systems but for comparison truly estuarine mouths developed in sandy coasts are also shown (Waimakariri river and Clutha mouth). Locations are shown in Fig. 1.
those of the hinterlands. The main channel and the Little Rakaia flow into a coastal lagoon (generally much less than 1 km wide normal to the coast) separated from the sea by narrow, highly changeable sand and gravel spits. Commonly there is a single outlet to the sea but up to three have been observed, the positions of which vary in response to changing conditions of sea, tide, wind and river flow. The lagoon is thought to act as a temporary sediment trap for river-borne gravel. Its character is influenced by these sediment accumulations; river flow level and its distribution between the two branches; the position of the outlet, sea-state and tide; and the configuration of the inner margin of the spit beaches. The latter are extensively altered by current scour and by storm washover lobes.

Previous studies of the mouths of east coast, South Island rivers (Kelk 1974; Kirk et al. 1977; Hicks 1979) have shown that lagoon morphologies display a definable sequence resulting from the interplay of longshore drift and variations in river flow. The lagoon water body is thus a transient feature created by northward displacement of the mouth due to littoral drift along the enclosing beach. Figures 3 and 4 show typical lagoon configurations at three times since 1952, while air photographs over the period 1943–83 have shown that mouth positions were deflected up to 3 km north of the principal southern flood channel, although most movement occurred in a 2 km segment of shore bounded by the northern and southern channels. Channel outlet widths varied between 30 and 90 m and northward orientation of the outlet was the most common configuration.

During floods (see Table 1) the Rakaia breaches the barrier opposite the main (southern) channel and flows directly into the sea, changing the lagoon's shape, area and flow characteristic. The Ashburton mouth can close for periods of up to several weeks, forming a continuous barrier beach. Flood breaching results in disappearance of the Ashburton lagoon until it is re-established by longshore drift and ponding of the river water. Kelk (1974) has shown that the sequence of lagoon growth and decay occurs at approximately 12–19 month intervals for the

Figure 4. Changes in the morphology of the Ashburton and Rakaia river mouths 1952–76 from air photographs. Upper numbers are gross changes in beach crest positions over 24 years, while the lower values are average rates of change in m yr⁻¹. Heavy lines mark the coastlines in 1952. Source: Kirk et al. (1977: Fig. 2).
Ashburton, though breaching can occur at any time. The Rakaia appears to undergo similar processes though mouth closure is unknown, as is the duration of the sequence, which is highly variable in time, controlled by the interplay of low river flow, littoral drift on the beach and river floods. In floods, subtidal gravel deltas may be deposited seaward of the surf zone. Spit breaching thus provides direct injection of river bed load and displaced beach material into the coastal sediment transport system. The larger proportion of Rakaia flood flows are generally contained in the south branch (often flooding adjacent holiday homes). Injection of gravels thus occurs mainly at the updrift end of the system.

A feature of all the river mouths is the rapid onset of mouth displacement following flood breach and subtidal delta growth. It is reasonable to infer that flooding and delta building produce a morphology that is out of equilibrium with the local wave field so that local recirculations are initiated through refraction changes in the vicinity of the mouth until the shoreline is adjusted. These circulations can be either updrift or downdrift depending upon prevailing conditions until net northward drift is again established. The mechanism for mouth offsetting is thus inherent to the mouth morphology (high river flow state) and can also develop under a wide range of sea states. Hicks and Inman (1987) describe similar processes for the incorporation of sand into the regional littoral drift at an ephemeral delta on the California coast.

Under more moderate river flow conditions the lagoon outlet channel becomes aligned obliquely to the spit beaches and its position migrates northward. The southern spit elongates under the influence of wave-induced northerly longshore drift, which persists until higher river flow again truncates the beach. Scour of the northern banks under channel migration is a hazard that threatens developed assets on several rivers. During spit elongation, current scour by river flow in the channel bends of the lagoon interacts with reduction of subtidal deltas by longshore drift to maintain a moving open mouth to the sea. Northward migration of up to 3 km can occur. Because of the concentration of freshwater flow in the outlet and the hydraulic head in the river channel (lower channel gradients average 4.6 m km\(^{-1}\)), direct tidal penetration of saltwater into the lagoon is extremely limited. Though there are observable tide-related variations in lagoon water level, they are backwater effects rather than indicators of true estuarine circulations. Saltwater enters the lagoon by storm wave washover and as spray during storms but strong net outflow to the sea occurs at all stages of the tide. The mouths are thus outlets rather than inlets. Sandy coast inlet tidal hydraulics (for example, characterization of stability by relation of the tidal prism to entrance cross-sectional area and littoral drift) are thus inappropriate to this type of system. It appears that the lagoon acts as a source of coastal sediments during and immediately after high river flows and as a sink or trap during moderate to low flows.

All of the central and South Canterbury sections of the Canterbury Bight display long-term trends toward natural coastal erosion at average rates of 1–2 m yr\(^{-1}\). Both erosion and storm wave saltwater inundation present hazards to drainage and land use additional to river flooding along the coast around the Rakaia. The lagoon processes described above thus occur within an overriding trend towards landward displacement of the entire coastal system.

Three conclusions of wider geomorphological significance concerning littoral drift processes can be drawn from the above since the sequence of mouth changes acts as a modifier of drift in the mouth region (Kirk 1987). First, river flow can clearly only dominate the system in episodes of high flow and for short periods of time. For most of the time the system responds either directly to coastal processes
or to constraints imposed by them. The Rakaia is clearly a ‘small’ river in the sense proposed by Zenkovich (1967). Secondly, the method by which drift bypasses a river mouth such as the Rakaia is important. On sandy coasts sediments are thought to bypass inlets either by bar bypassing in the surf and nearshore, or by tidal bypassing involving tidal entrainment first into and then out of the inlet, or by both. At rivers such as the Rakaia only bar bypassing is possible after floods but most sediment travelling as beach drift will bypass in the process of the spit growth–breach sequence (‘spit bypassing’). Thirdly, the consequent effects on the spatial and temporal character of the regional longshore drift must be considered. Floods clearly inject ‘pulses’ of coarse sediments into the coastal system, which vary in size and time. Commencing with spit growth from the downdrift side, the lagoon sequence accumulates and stores sediments from updrift locations during the elongation phase. This can induce starvation of downdrift shores and so temporarily accelerate erosion there. After flood breaching the quantity of sediment contained in the beach between the low flow (northern) and high flow (southern) mouths is freed so that it is effectively bypassed. The spit is usually driven ashore and added to the downdrift beach. Such river mouths cause large-scale irregular variations in the regional longshore transport regime and lead to temporal and spatial variations in the rate of coastal erosion along the downdrift coast. Such pulsational transport has been identified from the Waitaki river in South Canterbury by Neale (1987).

Sediment budget analysis
Such river mouth behaviour can be quantified by means of a sediment budget. Figure 5 represents the principal coarse sediment transfers and storages within

\[
\Delta \text{st} = (P_1 - P_0) + (N_1 - N_0) + R + C + (L_1 - L_0) + (E_1 - E_0)
\]

**Figure 5.** Schematic sediment budget and storage equation for a mixed sand–gravel river/beach/lagoon system such as the Rakaia mouth. Terms as defined in the text. \(P_1\) is longshore drift into the mouth region and \(P_0\) is the drift out of the section. Onshore transport in the beaches (\(N_1\)) is distinguished from offshore (\(N_0\)) and lagoon sedimentation is divided into storage (\(L_1\)) and losses to the coast (\(L_0\)). Onshore (\(E_0\)) and offshore (\(E_1\)) sediment transport by wind are not significant on the Rakaia coast. Source: Adapted from Kirk *et al.* (1977: Fig. 3).
Rakaia river mouth lagoon system adapted from the work of Kirk et al. (1977) on the Ashburton river. There are five principal landscape units among and between which significant exchanges of energy and materials may occur: the river \((R)\), the eroding fans surrounding it \((C)\), the beach \((N, P)\), the lagoon \((L)\) and the ocean. The wind term \((E)\) is neglected since no coastal sand dunes occur. The equation in Fig. 5 thus represents either the net annual coarse sediment storage (positive values) or the net loss (negative values) within the system.

For analytical purposes transfers occurring within a 10 km length of shore centred on the Rakaia were considered. The lagoon length was taken to be 4 km measured parallel to the strike of the shore. As with any such budget analysis, a large number of variables acting at differing time scales contribute to the net state so that it is inevitable that data deriving from quite different measurement techniques and scales must be utilized in order to attempt the analysis.

**Longshore transport \((\Delta P)\)**

While no direct longshore transport studies have been made at the Rakaia, investigations have been made on similar beaches having the same exposure to wave action at Timaru and in North Otago (Kirk 1981; Kirk and Hewson 1979; Neale 1987). *Total* transport of the order of \(10^6 \text{m}^3\text{yr}^{-1}\) and *net* northward movements in the range \(10^4-10^5 \text{m}^3\text{yr}^{-1}\) were proposed by Kirk and Hewson (1979). It is also known that a minimum of \(60000 \text{m}^3\text{yr}^{-1}\) accumulate from littoral drift on South Beach, Timaru (Tierney 1977), with intra-annual variations of about \(+\ 25\%\) per cent (Neale 1987). Although these values are approximate it seems reasonable to adopt an *average* net northward transfer \((\Delta P)\) of \(100000 \text{m}^3\text{yr}^{-1}\) for the Rakaia river mouth, subject to appreciable temporal 'pulsation' (perhaps \(+\ 50\%\) per cent) due to bypassing by the spit growth–breach sequence.

**Onshore-offshore exchanges \((\Delta N)\)**

Retreat of the beach crest occurs at an average rate of \(1.06 \text{m yr}^{-1}\), each metre of beach crest recession representing an average loss of \(50\text{m}^3\) of sediment per linear metre of coastline. Thus gross displacement from the 10 km of beach face is \(530000 \text{m}^3\text{yr}^{-1}\). Since it is also known that about 10 per cent of the foreshore losses are washed over the beach crest onto the landward slope and the lagoon during storms (Kirk 1981), there is a temporary storage represented by the term \(N_1\) (Fig. 5) amounting to \(53000 \text{m}^3\text{yr}^{-1}\). Thus \(\Delta N\), the net offshore loss, is some \(477000 \text{m}^3\text{yr}^{-1}\). An appreciable portion of this loss occurs as fine sands and silts which result from the incessant abrasion of predominantly Greywacke gravels in the surf and runup zones. Applied to 10 km of the Rakaia coast, abrasion coefficients presented by Adams (1978) yield an estimated \(33000 \text{m}^3\text{yr}^{-1}\) of gravel reduced to fines each year in the prevailing high energy surf (that is, 7 per cent of the net annual beach loss is by abrasive destruction of materials).

**River contribution \((R)\)**

According to a specific yield procedure developed by Griffiths (1981), the Rakaia has a catchment area of \(2640 \text{km}^2\) and a total annual sediment yield of \(4.3 \times 10^6 \text{t}\), much of which is suspended load (see Table 1). Griffiths (1983) advises that perhaps only 150000 t of this \((about 80000 \text{m}^3\ or \ about 3.5\%\ of total load)\) will be coarse sands and gravels delivered as bedload to the mouth. This estimate is
based on research on numerous South Island rivers (Griffiths 1981) and is consistent with values determined for the Ashburton by Kirk et al. (1977) and for the Waitaki by Kirk and Hewson (1979). Hence 80 000 m$^3$ yr$^{-1}$ is the best available average value for a notoriously difficult variable to quantify. Herein lies the main reason why very active rivers like the Rakaia, draining rapidly eroding mountain lands, are nonetheless unable to maintain their coasts against erosion (and hence are 'small' rivers). Only a tiny proportion of the load carried is competent under the action of beach processes once delivered to the coast. It is acknowledged that the value chosen is an average. Peak flood bedload discharges deposited as subtidal deltas appear to involve quantities approaching or exceeding the annual average adopted here.

**Cliff contributions (C)**

The coastal cliff is formed in unconsolidated sands and gravels and can be reliably estimated from air photographs and ground surveys. Total cliff length is 6 km, average height is 4 m above mean high water mark and retreat rates are consistent with the average for the beach crest. Cliff inputs to the beach are thus estimated at 25 440 m$^3$ yr$^{-1}$, less a small (undefined) proportion of fines.

**Lagoon storage ($\Delta L$)**

This term is very difficult to estimate since the river mouth lagoon sometimes acts as a sink (by washover of sediment from the beach and by direct injection from the river), and sometimes as a source for the adjacent beach (as in large floods). Further, net storage in the long term is zero because the coast is retreating and the lagoon is progressively displaced landward. For the Ashburton, short-term lagoon storage can be up to 80 per cent of the coarse sediment load (Kirk et al. 1977), so that two values for $\Delta L$ are employed here, 0 and 64 000 m$^3$ km$^{-1}$.

**Budget analysis**

The storage equation presented in Fig. 5 can be shortened to:

$$\Delta st = \Delta P + \Delta N + R + C \pm \Delta L$$

(1)

giving budget estimates of:

$$\Delta st = -335 560 \text{ m}^3 \text{ yr}^{-1}$$

(2)

for 80 per cent lagoon storage and

$$\Delta st = -271 560 \text{ m}^3 \text{ yr}^{-1}$$

(3)

for zero lagoon storage.

Table 4 presents the budget as percentages of total and net loss. Over the 10 km of coast average annual losses are thus in the range 27–33.5 m$^3$ m$^{-1}$ of shore. Since average losses through beach retreat are 47.7 m$^3$ m$^{-1}$, this figure can be used as a regional comparison that would apply if the river were not present. In this way the 'smallness' of the river can be quantitatively estimated. It can be seen that the effect of river sediment load is to reduce the overall sediment budget deficit by 43 per cent at zero lagoon storage condition. Alternatively, it can be stated that at zero lagoon storage (high river flow) the effect of all inputs combined amounts to only 57 per cent of the coarse bed load quantity required to satisfy the sediment demand of marine processes and present a stable coast. At 80 per cent lagoon storage (low
Table 4. Results of sediment budget analysis presented as percentages of total and net transfers

<table>
<thead>
<tr>
<th>Term</th>
<th>Percentage of total transfers</th>
<th>Percentage of net transfers (80% lagoon storage)</th>
<th>Percentage of net transfers (no lagoon storage)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Net longshore (P)</td>
<td>14.6</td>
<td>29.8</td>
<td>36.8</td>
</tr>
<tr>
<td>River (R)</td>
<td>11.7</td>
<td>23.8</td>
<td>29.5</td>
</tr>
<tr>
<td>Cliff (C)</td>
<td>3.7</td>
<td>7.6</td>
<td>9.4</td>
</tr>
<tr>
<td>Net foreshore loss (N)</td>
<td>70.0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Washover to lagoon (N₁)</td>
<td>7.8</td>
<td>15.8</td>
<td>19.5</td>
</tr>
<tr>
<td>Abrasion loss</td>
<td>4.8</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Quantities (m³ yr⁻¹)</td>
<td>683 440</td>
<td>-335 560</td>
<td>-271 560</td>
</tr>
</tbody>
</table>

river flow) the budget deficit increases by the storage term (20 per cent). Total transfers in the system are estimated to be 683 440 m³ yr⁻¹, a value approaching the estimated total annual longshore transport.

It should be noted from Table 4 that by far the most important sediment supply is via net longshore drift, emphasizing the dominating role of marine processes in the development of appreciable mouth offsets between major floods in the river. Longshore drift per se is a sediment source unlikely to be affected by water resource development. This result also underscores the importance of the river and the spit growth sequence in modulating the regional longshore drift. During spit growth downdrift shores will be comparatively starved of sediment and so erosion of backshore deposits will be enhanced. Updrift at these times erosion will decelerate. After breaching, sediment supply will increase markedly at downdrift sites, temporarily decelerating backshore erosion. Updrift sites will witness an increase in backshore and cliff erosion.

Measured as a percentage of total transfers, the river contribution to the coast is significantly lower for the Rakaia (11.7 per cent) than is the case for the Ashburton (22 per cent) (Kirk et al. 1977) or the Waitaki (46 per cent) (Kirk and Hewson 1979). There thus seems to be little prospect that water resource development on the Rakaia could contribute markedly to regional coastal erosion and/or saltwater inundation of coastal farmland through reduced beach sediment supply. In this respect the Rakaia is similar to the Ashburton, both standing in marked contrast to the Waitaki, where a hydroelectric dam commissioned in 1935 appears to have accentuated natural coastal sediment budget deficits (Kirk and Hewson 1979). Table 4 also shows that direct erosion of the coastal cliff represents only 3.7 per cent of total transfers, a situation in marked contrast to that at Ashburton, where cliffs up to 24 m high contribute 34 per cent of bulk transfers.

River regime and spit processes

In addition to sediment budget characteristics, model development requires consideration of the river flow regime and its influence on controlling processes in spit formation and breaching. In the Rakaia typical discharges range from <100 m³ s⁻¹ to >1000 m³ s⁻¹. Mean discharge is 200 m³ s⁻¹ at the Gorge, large floods can occur at any time of year (see Table 1) and extreme events can produce flows of up to 4000 m³ s⁻¹.
The precise manner in which these flows are distributed to the lower channel is poorly known. Hicks (1979: 6-7) observed that for much of the distance across the plains the river is deeply incised into old fans. In the vicinity of State Highway One (see Fig. 2) the channel emerges onto the last post-glacial surface and the bed widens to several kilometres before the river divides around Great Island. From there to the sea the slope remains constant at 4.6 m km⁻¹ and total bed width decreases slightly. At times when the river mouth is deflected to the north the main river channel becomes up to 2 km longer, flowing through a low gradient reach parallel to the coast. In floods water enters the lagoon from the higher gradient of the southern channel and exits directly to the sea through one or more breaches so that the lagoon is severely truncated. Much of it becomes backwater. Flood falling limbs deposit appreciable quantities of suspended fines in the lagoon, whence this material is percolated into the beach gravels of the spit to have important influences on mouth dynamics.

Little is known of relationships between channel flow and groundwater inland of the lagoon. Hicks (1979) reported significant losses to groundwater at the point where the channel emerges from the incised reach. However, it is not known whether there is re-emergence of groundwater in the lagoon or at the coast. It is therefore necessary to model the system in terms of discharges measured at the Gorge, an acknowledged constraint.

High flow effects. Groundwater effects are minimal for these events so that Gorge records are adequate indicators of flow at the coast. For the period 1953-83 annual flood magnitudes ranged from 1498 m³ s⁻¹ (1971) to 4330 m³ s⁻¹ (Bowden 1983). While such high-magnitude, low-frequency events are spectacular (producing flow over 3 km of channel width and flooding the surrounding lands), delivering large volumes of both fine and coarse sediments, spit breaches are caused more frequently by much smaller flow events. It is thought that most flows larger than the mean discharge (200 m³ s⁻¹) have the capability to initiate breaches, particularly after prolonged periods of spit extension (low river flow). From limited observations it is known that barrier breaching occurs during rising stages of river flow. The rate of mouth outflow becomes inadequate for dispersal and ponding occurs which raises the head difference between the river and the ocean so that groundwater throughflow to the beach is strongly established. Eventually, outflow from the seaward face of the beach and the head are sufficient that the beach is disrupted by ‘pipe flow’. The storm crest collapses seaward to initiate the breach, which is rapidly widened and deepened.

Low flow effects. Low flow is an event producing less than 150 m³ s⁻¹ at the Gorge (Hicks 1979: 5). Records show an absolute minimum of 68.7 m³ s⁻¹ in July 1982, and a 10-consecutive-day minimum of 90 m³ s⁻¹ (Bowden 1983). The Rakaia is in part snow fed, with highest minimum flows in summer and lowest minima in winter. Lowest flows occur in April and August outside the recognized ‘irrigation season’. Since mouth closure is unknown for the Rakaia a minimum instantaneous flow of 68.7 m³ s⁻¹ at the Gorge is sufficient to maintain the lagoon in an open configuration regardless of groundwater losses on the plains. Oceanic storms (and hncc northward longshore drift) are more frequent in winter and since this is also the season of least river flow, it follows that the greatest potential for spit growth also occurs in winter. Reduction of flow by irrigation abstractions may reduce or eliminate this seasonal variation. Determination of a discharge at which mouth closure would occur, and the corresponding return period, is difficult. A 10-day
sustained low flow $<70$ m$^3$s$^{-1}$ has a theoretical return period of 50–100 years but has not occurred in 23 years of gauging. Also, it is not known how much water exits through the mouth and how much percolates through the enclosing spit. The probability of mouth closure is also likely to be some function of the degree of longshore spit extension such that the greater the deflection the less the cross-sectional area of the outlet.

Approximate data from the Ashburton and Opihi rivers are useful for comparison because both are subject to irrigation drawoff and both mouths close for protracted periods. The Ashburton is known to close at flows $<5$ m$^3$s$^{-1}$ and can be opened by diverting a sustained flow of 15 m$^3$s$^{-1}$ over three days from the Rangitata via a canal. The Ashburton closes at discharges close to the mean and opens for flows about twice the mean (see Table 1). The mouth can be closed for up to four weeks and water ponds behind the beach until sufficient head is achieved to initiate breaching (Kelk 1974). Mean flow in the Opihi near the mouth is about 20 m$^3$s$^{-1}$, but summer (irrigation season) flows are generally much lower. On average, a flow of $<5$ m$^3$s$^{-1}$ occurs for a sustained summer period of 2–3 months. Under these conditions the mouth closes at $<5$ m$^3$s$^{-1}$ and self-opens for discharges in the range 15–20 m$^3$s$^{-1}$ if low-energy wave conditions prevail outside the lagoon. In heavy seas and strong longshore drift conditions the mouth closes at river flows of 15–20 m$^3$s$^{-1}$. Mean discharge in the Rakaia is much higher than the indicated threshold values for closure and natural minimum discharges are similarly well above the limiting conditions. Bearing in mind the differing roles played by longshore drift in the sediment budgets of the Ashburton and Rakaia river mouths it seems reasonable to conclude that a minimum flow of 45–50 m$^3$s$^{-1}$ at the lagoon outlet would be sufficient to maintain the Rakaia opening.

**Spit beach throughflow.** This is important in two ways since not only do high rates of throughflow reduce the discharge available to maintain the mouth open against longshore drift, but they also initiate frequent, early breaching in rising river stages, so reducing the length of offsets in the mouth. Groundwater throughflow in beaches is a function of the available water head and the permeability of the deposits. At the Rakaia river mouth both the beach and river deposits consist of coarse gravels and sands which are inherently highly permeable, but the river materials contain admixtures of very fine sand and silt from suspended load that produce marked reductions in throughflow.

Previous studies indicate substantial differences of opinion as to the permeability of east coast, South Island mixed sand and gravel beaches. Thus, Kelk (1974) concluded that the Ashburton mouth barrier was effectively impermeable at all but the highest river stages. In contrast, Pemberton (1980) concluded that a barrier at Wainono Lagoon in South Canterbury had the very high (but natural) permeability coefficient of 521 s$^{-1}$ m$^{-1}$. He argued that a 2·2 m head in the lagoon would be sufficient to cause self-breakout dispersal of a median flood peak of 326 m$^3$s$^{-1}$ along 2·8 km of coast.

Because of this, two throughflow estimates were made. First, mean grain size and sorting values from beach surface sediment samples were used to estimate permeabilities (Shepard 1963). Velocities of 0·9–18 cm s$^{-1}$ and averaging 13·1 cm s$^{-1}$ were obtained in this way. Over 3 km of spit length and a head difference of 1 m between the lagoon and the sea a throughflow of 393 m$^3$s$^{-1}$ is obtained. Were the spit constructed of well-sorted gravels, up to 40 per cent of the annual flood would reach the sea through the beach rather than via the mouth. These results are clearly more in keeping with Pemberton (1980) than with Kelk
(1974). It has been noted that breaching at the Rakaia occurs with the river mouth open and involves strong throughflow in the higher levels of the beach during rising river stages when head differences are strong.

Secondly, internal examination of the deposits and direct measurement of throughflow was carried out. Major differences exist in structure between the landward and seaward slopes of the spit and composition is variable along its length. Notably, the landward slope possesses a surface cap of well-sorted gravels and sand beneath which is a complex, interbedded structure of well-sorted washover materials and poorly sorted river gravels. Scattered throughout are thin, in-washed layers of very poorly permeable river silts that have filtered in from suspended load. Velocities measured in the foreshore water table after high tide ranged from 1.92 to 5.28 cm s⁻¹, with a mean of 3.41 cm s⁻¹. These spit throughflows average 102.3 m³ s⁻¹, much lower than the values theoretically appropriate to surface deposits.

Percolation losses through the spit are small at times of low river flow due to a weakly developed head and low overall permeabilities on the back of the spit. Consequently most of the river flow reaches the sea through the mouth. In times of rising and higher discharge, the relatively impermeable landward slope of the barrier contributes to ponding of lagoon water and hence development of a strong head between the river and the sea. As the level rises it encounters the better sorted surface layers, strong throughflow is established and breaching ensues.

A model for water resource planning

It is clear that the Rakaia river mouth system, like others of its type along the east coast, South Island, is physically complex and extremely unstable. Such systems are sensitive to water resource development in the contributing catchments because the relationship between river discharge and coastal processes must inevitably be subject to alterations which exhibit synergistic properties. Using the same analogy from wave mechanics, any change in input magnitude and/or frequency must result in quite different interaction products with new magnitude and frequency signatures. The forms that these products take, together with attendant environmental benefit–cost considerations, are highly germane to resource allocation decision-making and to land use planning. Basic geomorphological research and modelling of them is therefore a fundamental input. Kirk et al. (1977) drew attention to potential effects that might result from abstractive, distributive and/or retentive development of catchment water resources that could modify both the sizes of flows reaching the mouth and their temporal pattern. Water resource planning in New Zealand has commonly considered allocations of water from flows above some minimum (base or 'recreational' flow) regarded as desirable to sustain recreation, fisheries and wildlife.

Kirk et al. (1977) argued that impacts on the mouth system stem mainly from reduction of low-flow river discharges. Since the size of the lagoon is controlled by interaction between littoral drift and low-flow water volumes, increased drawoff (for irrigation, for example) may either increase the size of the lagoon (by greater mouth deflection), so adding to temporary sediment storage volume, or, more seriously, it may result in closure of the mouth. Closure of the Rakaia mouth would adversely affect fisheries on the whole river and recreational amenities of the lower channel area since breaching would occur less frequently. Appreciable irrigation drawoff might thus bring on seasonally early decline towards natural winter minimum flows and/or delay the normal spring increase in minimum flow. Further,
there is a feedback link from low-flow morphologies to high-flow conditions. If the enclosing spit was extended or if the mouth was closed for a protracted period, littoral bypassing and coastal erosion would continue unabated. Coastal process would achieve greater dominance within the system. It is considered likely that this would result in the building of a sizeable barrier across the mouth that would then pose greater flooding and channel margin erosion problems for adjacent land. Breaching would occur at a larger critical discharge and at higher river stages. Two communities at Rakaia mouth are already subject to flood hazard, the southern one having been inundated several times in recent years.

The various processes and relationships described above have been summarized and incorporated into a descriptive model of the Rakaia river mouth system for use in water resource planning. The model is presented with estimated values appropriate to the Rakaia in Fig. 6. It is important to note that all the events set out in the model occur within an overriding trend towards coastal erosion. The Rakaia is a far from pristine system since it is utilized for hydroelectric power generation and water is added from the Rangitata via a canal. Most other rivers to which the model might apply are also already subject to water resource development of one or more kinds. The model thus does not represent a ‘natural’ system, but rather one for which either an explanation is sought for consequences of past development, or for which new developments are contemplated.

Very low flow (<45 m³ s⁻¹). At some discharge below this value mouth closure would be certain. In view of the importance of longshore drift in the Rakaia sediment budget, a higher flow is necessary to maintain a permanent lagoon system and open mouth. A closed, ponded lagoon would develop progressively higher water levels until inflow from the river was balanced by seepage through the barrier. At times of higher river flow the rising stages of floods would pond before breaching ensued. In this pre-breach phase bank scour and flooding of hinterlands would occur.

Moderate flow (45–200 m³ s⁻¹). Most of the morphological changes presently occur in this flow range and it is also here where irrigation extractions will effect greatest change to the pattern of river flow. Not only would drawoff reduce the flow downstream of the abstraction points, but it would also produce more protracted intervals of lower discharge. The principal effect would be to induce greater elongation of the spit to occupy more northerly positions than at present. Greater extension implies a smaller outlet cross-section for fish ingress and attendant water quality changes (temperature). Such a change may also affect angling since fishing success is related to channel accessibility and cross-sectional area. Because irrigation drawoff is a summer phenomenon there would be a seasonal change in the lagoon sequence from present winter maximum barrier growth to occurrence throughout the year. This necessarily implies the existence of offset mouths for a greater total duration during the year and enhanced erosion at north Rakaia Huts.

High flow (>200 m³ s⁻¹). Since irrigation drawoffs would have a negligible influence on higher flows in the river, no direct effects are anticipated. Barrier breaching and injection of coarse gravel would be unaffected. However, important indirect changes would occur because greater spit growth and longer outlet channels will mean that greater ponding will occur to higher stages before floodwaters could initiate spit breaching. The outcome would be an increase in flooding potential and bank scour for the hinterlands of the river (and for communities located thereon).
Figure 6. Descriptive model of mixed sand and gravel lagoon/spit/barrier processes. Threshold values are set for the Rakaia as functions of river discharge. Note that mouth closure does not presently occur so that spits rather than barriers form there.

Conclusion

This paper has advanced and explored the ‘small river’ notion of Zenkovich (1967) as it applies to the Rakaia and other east coast, South Island, New Zealand rivers reaching the sea through mixed sand and gravel beach systems. These systems are non-estuarine and non-tidal though they have been classified as estuaries in
previous work. Previous water resource planning has largely ignored impacts on the
mouth systems. Inapplicability of sandy beach tidal hydraulic models and
relationships has posed the question of how such river mouths can be satisfactorily
understood in both geomorphological and resource management contexts.

It has been shown that except for short periods during floods, marine processes
dominate fluvial ones and that the river output of coarse sediments is insufficient to
maintain the coast and lagoon against long-term retreat. Sediment budget analysis
enabled quantitative estimation of the relative roles of marine and fluvial processes
in the mouth system. The ‘small river’ concept was extended to include the
interactive processes that enable description of the lagoon morphologies and time
scales as relationships vary between river discharge and beach processes. Because
costal processes are unaffected by water resource use in the catchment, the nature
of the interaction between river and sea can alter dramatically in the direction of
greater marine dominance if the magnitudes and temporal patterns of river flow are
altered. Also, an important feedback exists between spit changes that occur at low
river flow and the behaviour at breach under high flow. Reducing low flows
encourages spit growth and intensifies flood and bank scour hazards at subsequent
high flow.

River mouth systems of the Rakaia type are not well known in the scientific
literature. A series of characteristic landform changes and some of their principal
controls have been described here. Among these the spit bypassing mechanism for
littoral drift and river-injected bed-load, the consequent modulation (pulsing) of
the regional littoral drift both downdrift and updrift, and the dual role of
permeability as a control of both river mouth breaching and spit elongation with
teleconnections to lower channel flooding and erosion are of more general interest.
A descriptive model of mouth systems incorporating these relationships has been
presented and its application to water resource planning discussed. The Rakaia
river mouth lagoon, and others of its type, occupy only a small part of the
catchment, are physically complex and unstable, yet are extremely important parts
of the river system, particularly for fisheries, and are vital to sustainable
management of the river resources. They also present a range of significant wildlife
and recreation values, as well as land use and environmental hazard issues that
must be addressed by water resource and other planners before development. The
model presented here enables all these issues to be approached.

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