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River-mouth lagoon dynamics on mixed sand and gravel barrier coasts

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ABSTRACT

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This paper examines the dynamics of river-mouth lagoons on mixed sand and gravel coasts receiving high wave energy. The role played by rivers in these non-estuarine systems is recognised as essential for carving out space for the coast-parallel waterbody, defining its physical scale, and for driving cycles of lagoon behaviour from closure to breaching. The role played by waves, by contrast, is not fully recognised in that it is limited to barrier building across river mouths and gradual lagoon-outlet offsetting along the shore. Field observations and water-level records were used in combination with river-flow, wave, and hourly-camera records at the Ashburton river mouth, New Zealand, to establish the importance of wave versus river forcings of lagoon dynamics. Several new behaviours were identified, including storm-induced lagoon breaching, rapid longshore migrations in outlet position and outlet channel truncations in response to storm-wave overtopping. Similar dynamics forced by combined river-flood and storm events were also common. Despite the observed complexity of river, wave and lagoon processes, characteristic morphologies and equilibrium states were apparent, with the lagoon appearing to be dominated by wave processes at all but the highest river-flow stages. Analysis of the frequency of the observed events is used as the basis of a new understanding of lagoon behaviour, from which management implications are drawn.

ADDITIONAL INDEX WORDS: *storm breaching, wave dominated, permeability*

INTRODUCTION

Gravel river-mouth lagoons have been documented on the wave-dominated, fluvioglacial and paraglacial coasts of New Zealand, Canada, Ireland, the United Kingdom, Argentina and Russia (CARTER, 1984; CARTER et al., 1989; FORBES et al., 1995; KIRK, 1991; ORFORD, FORBES and JENNINGS, 2002; ZENKOVICH, 1967). These non-estuarine systems (Figure 1) are globally rare but locally common around New Zealand, where they are known as hapua. They provide key links for migrating fish, mahinga kai (traditional Māori food and resources) and are associated with ecologically-significant wetlands (JOWETT, RICHARDSON and BONNETT, 2005; SINGLE and HEMMINGSEN, 2001).

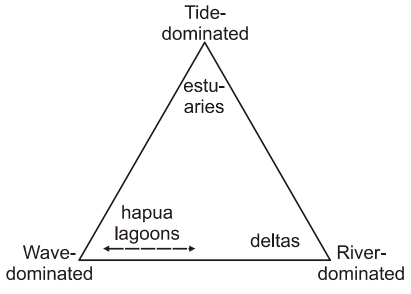

Figure 1. River mouth classification according to the dominant process agents of waves, tides and rivers

Management concerns associated with these systems include sustained outlet closure during periods of low river flow, which can lead to the flooding of adjacent farmland and cessation of fish passage from the ocean to the lagoon. In order to avoid lagoon closure, river flows are maintained above minimum thresholds, where possible, via limits on water abstractions.

Most research into these narrow shore-parallel coastal waterbodies has focused on the enclosing barriers rather than on the lagoon systems themselves. Current models explain lagoon behaviour primarily as a function of river flow (KIRK, 1991). These models were derived from studies of lagoons on large rivers (~200 m^3 s^{-1} mean annual flow). However lagoons exist at the mouths of a range of braided and meandering rivers, many of which are smaller (mean annual flow >100 m^3 s^{-1}) and potentially less-dominant (CARTER, 1984; HART, 1999).

While the presence of a river is recognised as essential in carving out space for these lagoons, and for defining their physical scale, the current assumption that lagoon behaviour can be predicted from river flow alone contradicts several lines of evidence, including lagoon occurrence only on wave-dominated coasts (CARTER et al., 1989; FORBES et al., 1995; KIRK, 1991; ORFORD, FORBES and JENNINGS, 2002; ZENKOVICH, 1967); and field evidence that wave processes play a dominant role in forcing lagoon dynamics at all but the highest river flow stages (KIRK, 1991; HART, 1999). CARTER (1984, 441) observed that “perhaps surprisingly, there are no published examples of coarse barrier breaching by marine processes, although there are many examples of over washing by storms”. Since then coarse barrier breaching by marine

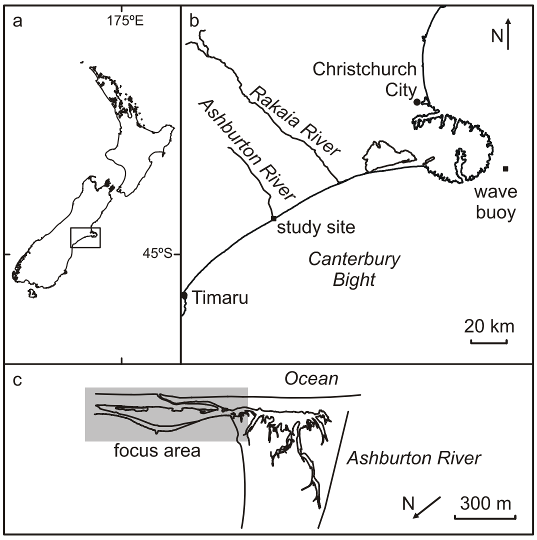

Figure 2. Location of the Ashburton lagoon study site (a-b) and field investigation focus area (c)

processes has been inferred from morphological evidence (TAYLOR and FROBEL, 2003), although no direct observations of this process have been published.

This paper explores the role of high-energy wave events in forcing river-mouth lagoon behaviour during a summertime low-flow season that included barrier beaching by marine, and by fluvial, processes. The dynamics of a small river-mouth lagoon are examined using data on fluvial, wave, lagoon and barrier processes from field and automatic-camera observations. Analysis of the frequency of the observed events is used as the basis of a new understanding of lagoon behaviour, from which management implications are drawn.

METHODOLGY

The Ashburton River is 130 km long, flowing from the foothills of the Southern Alps (Figure 2). The catchment is 1816 km^2 and the mean annual flood is around 100 m^3 s^{-1}. The lower catchment has been modified for agricultural use, flood control and water abstractions. The river bed and ocean are separated by a long gravel barrier up to 60 m wide, behind which a lagoon commonly extends for 1 km north from the true-left river bank. The coast has a semi-diurnal, microtidal regime while the lagoon is not subject to tidal ingress, but to a backwater effect whereby lagoon drainage through the outlet and barrier decreases at high tidal stages causing lagoon water levels to fluctuate up to 0.2 m each tidal cycle. Landward of the lagoon stand 21 m high poorly-consolidated, actively eroding cliffs. The riverbed and lagoon comprise an important avian habitat while the surrounding area is used for habitation and recreation, including fishing.

An intensive 90-day summertime field investigation of the Ashburton river-mouth lagoon was conducted from 23rd December, 1998 to 21st March, 1999, during which the lagoon was surveyed at the level of the low-tide water line approximately fortnightly using a Sokkia electronic total station. During each survey, water temperature (°C) and salinity (‰) were measured throughout the lagoon using a YSI salinity-conductivity meter. Lagoon water levels were recorded at ten-minute average intervals from days 22 to 90 with a Greenspan pressure sensor. Visual analysis of 12 months of hourly digital images of the lagoon from July 1998 was used to determine morphological changes between the fortnightly summertime surveys and to contextualise the observed frequencies of behaviours within an annual context.

Processes driving the changes documented in the field surveys and image record were interpreted using visual evidence of wave overtopping from the camera images in conjunction with available river, tide and wave data. The latter included the synthetic river flow record (m^3 s^{-1}) from 1996-1999 from the Ashburton River gauge nearest the coast (SH1), tidal predictions from Land Information New Zealand, and wave-rider buoy records of offshore significant wave height (m) from January, 1999. There is a less than 6 hour delay between river flow measured at the gauge site and the flow at the coast. Data from the wave buoy, in 30 m deep water off Banks Peninsula, records offshore conditions before any significant shallow-water wave transformation (GORMAN, BRYAN, and LAING, 2003). This site is exposed to the same dominant southerly swell-wave environment as the field site. Both the river flow and wave buoy records include some gaps due to instrument failure.

RESULTS

The surveyed planform changes in the Ashburton lagoon and outlet over the summertime observation period are mapped in Figure 3. At the start of this 12-week period the outlet channel was elongated, stretching approximately 165 m north from the main river channel. From days 1 to 15 the channel elongated a further 60 m through the barrier, then between days 16 and 28 the channel was truncated by half, its seaward end moving 115 m south. From days 29 to 43 the location of the entire outlet

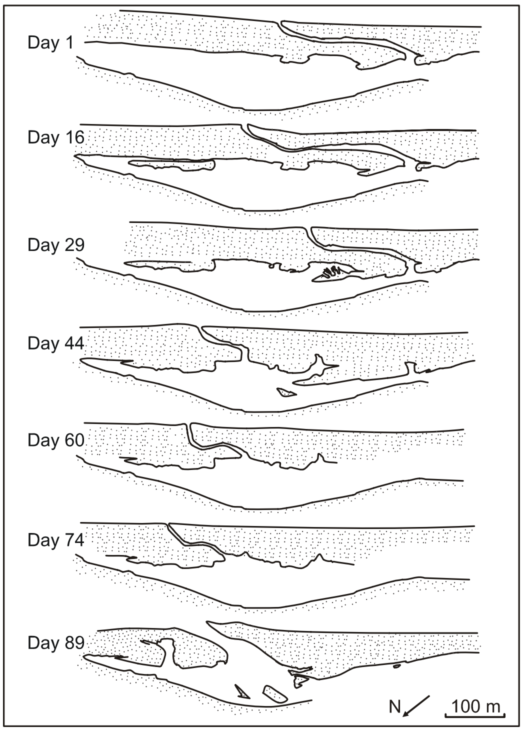

Figure 3. Surveyed planform changes in Ashburton lagoon (with barrier and lagoon backshore above water level shaded)

Table 1: Summary of lagoon water fluctuations and associated morphological changes during the summertime monitoring period.

Day	Lagoon level fluctuation (m)	Driving processes	Morphological changes observed
24	1.0	wave overtopping	Outlet channel truncated by 100 m
30	0.5	wave overtopping	Outlet widened and moved 20 further north
32	0.6	11.6 $m^3 s^{-1}$ flood	Outlet widened and moved 20 m north
36	1.0	wave overtopping	Breach through end of outlet channel
40	1.9	wave overtopping	New outlet breached 120 m north
41	1.3	10.1 $m^3 s^{-1}$ flood	Rapid outlet migration 30 m north
51	0.5	wave overtopping	Outlet widened and migrated 20 m north
62	0.5	wave overtopping	Channel truncated by 30 m
68	0.7	14 $m^3 s^{-1}$ flood	Channel truncated by 30 m
69-73	0.5 to 1.0	wave overtopping	Outlet widened and migrated 15 m north per day
82	1.0	38.9 $m^3 s^{-1}$ flood	New outlet is formed via breaching

shifted to a new northern position and the old channel was abandoned and infilled. Two more phases of change were recorded: from days 44 to 73 the new, northern outlet elongated slowly with its seaward end migrating 40 m north; and from days 74 to 89 the outlet channel widened from 7 m to 23 m.

The processes driving the surveyed morphological changes were clearly reflected in lagoon water level fluctuations, which responded to river flow, storm-wave overtopping and changes in the outlet channel position and capacity. Assessment of the data shown in Figure 4 along with observations from the field and automatic camera images were used to construct Table 1, which summarises major fluctuations in the lagoon water level over the study period, the process events that induced them, and the resultant changes in the outlet and barrier beach morphology as described below.

Ashburton River flows during the 12-months in which the study took place were similar to those since records began in 1996 (July 1998-1999 mean annual flow 15.6 $m^3 s^{-1}$ versus long-term average of 16 $m^3 s^{-1}$), including the nature of the low-flow study period (3.3 $m^3 s^{-1}$ 7-day minimum flow for study period and long-term). Fluctuations in the lagoon level induced by river flow are shown in Figure 4 by the coincidence of peaks in both variables. In response to small floods on days 32 and 41 lagoon water levels increased by 0.5 to 0.6 m for 2 tidal cycles (25 hours). On both occasions the outlet widened and moved 20 m north (Table 1). On day 68 another small flood induced a 0.7 m increase in the lagoon water level for 3 tidal cycle's duration. In response the lagoon outlet widened and was truncated 30 m in length (Table 1).

Another flood-induced increase in lagoon levels occurred on day 82 (Figure 4). During this flood a second outlet was scoured out from the lagoon side of the barrier 120 m south of the existing one, allowing the lagoon water level to drop more than 1 m as it drained. Over the course of the flood, islands of exposed sediment appeared in the lagoon and the width of the barrier increased updrift of the outlet due to sediment deposition, while the barrier near the main river channel was scoured and narrowed by river flow. Floodwaters submerged the wider riverbed during this event and took two weeks to drain to pre-flood levels.

From the camera images it was observed that wave overtopping of the Ashburton barrier is a frequent event. An average 5 overtopping events per month occurred during the December to March summer season while an average 7 events per month occurred for the 12-month study period. During each event swash inundated the barrier crest for 2 to 4 hours around high tide.

During the summertime investigation wave overtopping-induced increases in the lagoon level and salinity were associated with several outlet-channel truncations (Table 1). On day 24, for example, storm wave overtopping at high tide induced a 1 m increase in the lagoon level (Figure 4), resulting in truncation of the seaward end of the pre-storm outlet channel, which was abandoned as a new seaward end formed through the foreshore 100 m (Figure 3). On day 62 storm wave overtopping caused a 0.5 m rise in the lagoon level, resulting in the seaward end of the outlet channel being truncated by 30 m (Table 1). Washover-induced outlet channel truncation was also observed during a trip to the lagoon 7 days prior to the field investigation. All of these truncation events occurred with uninterrupted fluvial base flows of about 5 $m^3 s^{-1}$ (Figure 4). Storm waves were also observed to induce rapid migrations in outlet position. On days 30 and 51 wave overtopping caused 0.5 m fluctuations in lagoon levels causing the outlet to widen and migrate 20 m north over single tidal cycles (Table 1). In response to extended washover events from day 69 to 73 the lagoon water level fluctuated by up to 1 m each tidal cycle, causing the outlet to widen and migrate north 15 m per day.

In addition to outlet truncations and migrations, wave overtopping was observed to induce barrier breaches (Figure 5). On day 40 the lagoon water level increased by 1.9 from low to high tide, falling by 1.7 m by the following low tide. This water level fluctuation resulted from one of the more extreme wave overtopping events observed during the 12 month study period. The next day (41) a small flood caused the lagoon water level to fluctuate by 1.3 m over the course of atidal cycle. A series of morphological changes accompanied these two events. At high tide on day 40 the waves broke on the upper foreshore, completely inundating the barrier and lagoon and leaving little hydraulic head between the lagoon and sea. On the falling tide the hydraulic head increased rapidly so the lagoon was able to drain both through the small outlet and though the porous barrier sediments. Drainage through the barrier resulted in a pipe failure and subsequent development of a new outlet 120 m north of the first outlet, with the latter closing completely by day 41 as the sea storm passed and the lagoon drained back to pre-storm levels.

On the afternoon of day 41 the lagoon level rose again as a river flood arrived at the coast coincident with the high tide. In response to this second rise in lagoon levels the newly-formed outlet migrated 30 m further north and large volumes of sediment were deposited in the lagoon. These storm and flood events occurred between the surveys on days 29 and 44. The camera images between these dates show that the storm breach on day 40 caused 120 m of the 160 m change in the outlet position between these surveys.

Figure 5. Camera images of a storm wave-overtopping induced barrier breach between day 40 at 11:10 am (left) and 12:55 pm (centre), and day 41 at 7:46 am (right). Note the change in lagoon water level during, and in outlet position after, the storm event

DISCUSSION

The temporal and spatial scale of this investigation used in this study allowed direct links to be drawn between the observed morphological changes and individual storm and flood events. Several new types of river- and wave-induced behaviours were observed, the occurrence of which has important implications for the management of hapua-type lagoon environments.

Previous research suggested that small floods reduced the likelihood of lagoon closures by inducing outlet breaches closer to the main river channel, thereby increasing outlet efficiency and reducing barrier throughflow (Kirk, 1991). However, the majority of small floods observed during this study induced northward shifts in outlet position, further away from the main river channel, via migration or breaches. Results suggest that during summertime (when lagoon closures are most common), small floods commonly increase the length of outlet offsets, thereby decreasing their efficiency and increasing the potential for lagoon closure during subsequent low-flow periods.

Wave overtopping has been documented in previous coarse river-mouth lagoon studies (Taylor and Frobel, 2003) but its prevalence and importance are not fully described. The analysis of twelve months of hourly camera images indicates that wave overtopping can be an important morphodynamic driver in small hapua-type lagoons throughout all seasons.

In addition to the already recognised role of waves in barrier growth and outlet offsetting, three new behaviours were observed in response to overtopping: rapid outlet migration, outlet-channel truncation and barrier breaching from lagoon to sea. Similar overtopping-induced barrier breaches are well known to occur in New Zealand's coastal 'lakes' such as Washdyke, Timaru but this is the first time such a breach has been observed in a mixed sand and gravel river-mouth lagoon.

The washover-induced barrier-breaching process detailed here differs from that inferred from morphological evidence by Taylor and Frobel (2003), which suggests that waves scour the barrier, moving sediment lagoon-ward so that the breach forms from the ocean into the lagoon. In this investigation waves did not breach the barrier directly from ocean to lagoon, but rather raised lagoon water levels beyond that which the barrier could support, inducing a breach via pipe failure from lagoon to sea as the hydraulic head between the lagoon and sea increased on the falling tide. The permeability of the Ashburton barrier varies throughout its profile from 0.14 to 4.78 cm s^{-1} (Hart, 1999). Stratigraphic variation in permeability is a characteristic of many coarse barriers worldwide, making them particularly susceptible to pipe failure (Carter, 1988) and, potentially, to overwash breaches like those observed here.

Overall, results from this investigation indicate that the morphodynamics of the Ashburton lagoon are primarily event driven. During both the low-flow field season and the twelve month camera observation period little change in the lagoon and barrier could be attributed to gradual, everyday wave and river processes. Results also indicate that in this small lagoon sea storms are a more frequent summertime initiator of lagoon change than river floods, a finding which is likely transferable to other small river-mouth lagoons.

The wave-driven dynamics of the Ashburton lagoon differ markedly from the fluvial-driven dynamics described by (Kirk, 1991) for the Rakaia lagoon. Clearly there is a gradation in the relative influence of marine versus fluvial processes in different river-mouth lagoon environments, with the balance between these two agents affecting the types and frequencies of changes occurring. Along the high-energy coast of New Zealand's South Island this balance may be inferred, in gross terms, from the magnitude of the river discharging into the lagoon, although the balance between fluvial and marine influences is also affected by the permeability of barrier sediments.

One implication of the findings of this study is that the magnitude of river discharge may be used to indicate the applicability of Kirk's (1991) water resource model as a tool for managing individual lagoons, with those subject to smaller flows than the Rakaia being less suitable. For such lagoons more account needs to be taken of the influence of marine processes. A first step towards this would be to raise the minimum flow thresholds set using the former model to take account of variations in lagoon state caused by marine processes.

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