



## Contemporary process controls on the evolution of sedimentary coasts under low to high energy regimes: western Ireland

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### Abstract

Sedimentary environments, representative of the Irish west coast, have been studied to examine their responses at the microscale ( $10^{-1}$ – $10^0$  yr). This was achieved using a variety of techniques, including grain-size analysis, measurement of accretionary responses and radiometric dating. Monthly elevation monitoring of silt-dominated marshes shows an annual pattern in sediment accumulation. This reflects two processes: a) winter accretion attributable to storm events, and b) summer consolidation and contraction of the marsh sediments. Together, the results suggest that intertidal sedimentation is likely to be dominated by episodic processes, primarily storms. Examination of the tidal regime shows a weaker than expected influence of hydroperiodicity on intertidal accretion, although this influence remains distinctive, as expressed by a landward textural fining. Storms were also identified as of major importance in the functioning of higher-energy sandy coastal systems, again having a largely accretional influence, primarily through aeolian transport. Erosion at such study sites is probably controlled by the attainment of a critical threshold surface elevation, or by exceptional storm action, or a combination of both. The linking of microscale sedimentation rates with those at the meso- to macroscale, and assessment of their importance for coastal functioning, is difficult due to the geological averaging effect of the sedimentary record. Human impacts on this coast in historical times are large but difficult to quantify.

### Introduction

In the context of examining the functioning and modelling of coasts, much attention is being given now to the need to link the understanding of the macroscale ( $10^2$ – $10^3$  yr; Stive 1992) and the microscale ( $10^{-1}$ – $10^0$  yr) operation of coasts (Cowell & Thom 1994, De Vriend 1991). This study contributes to this approach, forming part of an integrated research programme dealing with the operation of western European coasts likely to be sensitive to the impacts of sea-level and sediment transfers. Partner studies (this issue) have been concerned primarily with evidence for the meso- to macroscale functioning of coasts. This study, in contrast, has concentrated upon the microscale, with observation particularly of coastal responses to *wind-wave climate* (the wave spectra generated by the wind blowing across the surface of the water), storms, tides

and sediment movements. The aim has been to provide contemporary baseline information for these coasts and to examine any evidence for linking these data with the longer term (i.e. meso- to macroscales, from sedimentary proxy records). In particular the study aimed to investigate whether coastal controls, identified as important in coastal operation at larger scales (e.g. Orford et al. 1995, Devoy et al. 1996a), are represented, and whether they are important in day-to-day coastal functioning.

Coasts are commonly referred to as being either wave-dominated or tide-dominated (Carter 1988). These factors, together with the driving force of sea-level changes (e.g. Orford et al. 1991, 1995, Devoy et al. 1996a), sediment supply, coastal configuration and shape, form the principal controls of coastal evolution (Roy et al. 1994). For sedimentary coasts, such as saltmarshes, Allen & Pye (1992) identified waves,

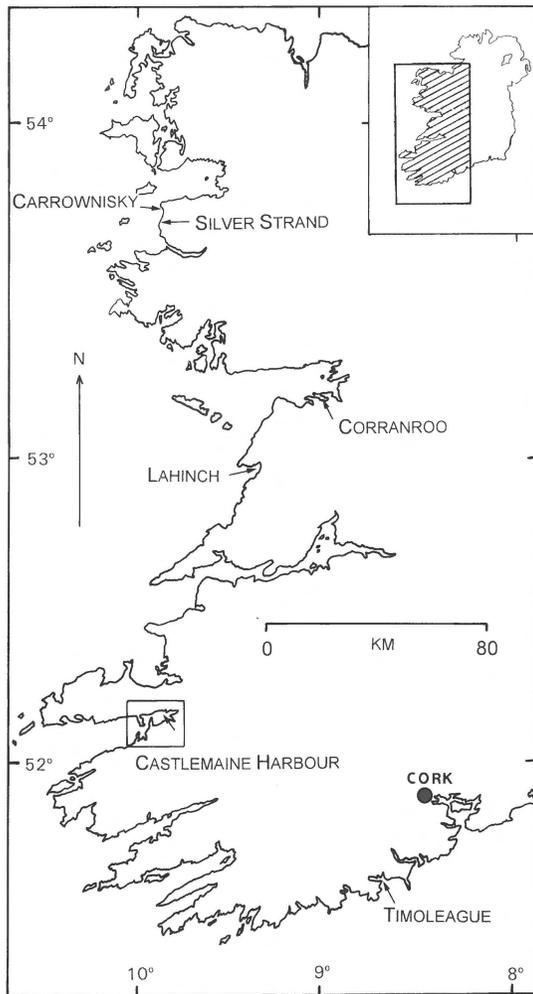


Figure 1. Location map of sites mentioned in text: see Figures 2 and 5 for greater resolution of Castlemaine Harbour and Carrownisky respectively.

tides and sea-level changes as the most important factors governing their morphological development. Pethick (1992), working on the Essex marshes (eastern UK), concluded that the intertidal mudflat and saltmarsh geomorphology was a response to wave energy. For saltmarshes and mudflats the wind-wave climate is regarded primarily as an erosive factor (Allen 1990, West & West 1991, Hydraulics Research 1991, Brampton 1992, MAFF 1992, Pye 1993), whereas the tidal regime is regarded as a depositional factor (Pethick 1981, Allen 1990, 1992, French 1993). Given the earlier long-term work on sea levels in western Ireland and the significance here of marsh environments (Carter et al. 1989b), this study has concentrated upon an examination of these two forcing factors.

Few studies have been undertaken of the paraglacial coasts of western Ireland (Carter & Orford 1988, Devoy 1992), although some knowledge of the Holocene coastal record and range of sedimentary environments has been established (Carter et al. 1989a, Carter 1991, Delaney & Devoy 1995, Devoy et al. 1996a). Yet this c. 500-km-length coastline (Figure 1) occupies a potentially important position in recording coastal process functioning on the European Atlantic margin, receiving the first impacts of Atlantic wave energy. The sand- and marsh-dominated coasts present are sensitive to sea-level and wave-climate changes and are likely to respond quickly to any future climate, sea-level and other coastal boundary control changes (Carter 1991, Devoy et al. 1996a). However, there is a lack of information on how these coasts operate; for example, whether a simple energy-gradient model provides a suitable first-order explanation of the coastal systems' organisation and functioning. Recognition that coastal processes frequently conform to an energy gradient (e.g. high wave energy with wave refraction and energy dissipation leading to sediment transfers) is now common (Komar 1983, Carter 1988). On other North Atlantic coasts (e.g. Carter et al. 1990a, b) wave energy and coastal erosion rates are seen as decreasing progressively landward, with the reduction of water depth and the increasingly crenulated configuration of a coast, the onshore transfer of sediments taking place between an outer 'erosion front' and the coast (Carter & Orford 1988). The testing of the applicability of such energy-gradient type concepts to these exposed Atlantic coasts (Devoy 1992) was undertaken in this study through the examination of a continuum of coastal sites, from sheltered estuarine saltmarshes to open-coast dune-machair<sup>1</sup> systems.

Previous studies of such environments in western Ireland also showed some distinctive features of this Atlantic margin which require further investigation. Saltmarshes on this coastline are different to those commonly found elsewhere in northwest Europe (Sheehy-Skeffington & Wymer 1991), in that they often lack a clear halophytic zonation. This may in part be attributable to the high annual rainfall here, aiding the competitiveness and productivity of freshwater

<sup>1</sup> Machair is a coastal landform and vegetation complex, consisting principally of aeolian-derived sand-sized sediment with a high calcareous content, and a relief often gently undulating or taking on the aspect of a relatively flat plain with a gentle landward slope. Seasonal grazing of the vegetation plays a significant role in maintaining the machair.

and euryhaline plants. Human intervention through long-term subjection to animal grazing may also be a factor. At the open coast, dune-machair systems show distinct north-south differences, often exhibiting a distinct northward increase in shell carbonate content. This is due to the effects of the North Atlantic Drift in changing the availability of marine carbonates. Dunes on these western coasts are generally massive in structure, lacking organic horizons and paleosols, as distinct from those on the northern and eastern coasts of Ireland and elsewhere in Europe (Carter et al. 1992, Devoy et al. 1996a). Further, an important factor possibly differentiating these Irish dune-machair and marsh environments from coasts elsewhere in Europe, is the particularly large human populations that these lands supported in the early 19th century (Smyth et al. 1996). People imposed heavy resource demands on these environments, ranging from the extensive reclamation of intertidal areas to the extraction of beach and dune sands for ground improvement (Devoy et al. 1996b).

## Sites

In this investigation a series of monitored coastal environments was established along c. 350 km of Ireland's west and southwest coasts (Figure 1). Work at these sites was linked to studies at other locations on the west coast (Wheeler et al. this issue) extending the detail and spatial coverage of coastal observations. The criteria for site selection in this study were based initially upon the following factors: degree of coastal exposure to wind-wave energy, availability of sediments for recording system changes, and links to suitable data sets for the analysis of wind-wave climate and tide controls (details of criteria used are given in Devoy et al. 1996b).

The primary study locations examined, ranging from low-energy, sheltered, to high-energy, open coastal systems, were: Castlemaine Harbour, County Kerry – low energy (41 stations, made up from 8 sub-sites, Figure 2), Timoleague, County Cork – low energy (22 stations), Carrownisky, County Mayo – high energy (22 stations), and Silver Strand, County Mayo – high energy (7 stations). The locations of Lahinch, County Clare – low to high energy (17 stations), and Corranroo, County Galway – low energy (13 stations), provide a series of secondary sites with less detailed observations. The sites studied span a range of energy values, with the largest site of Castlemaine Harbour

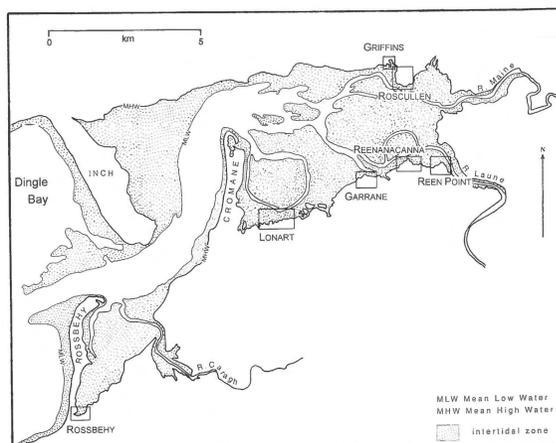


Figure 2. Location of sites within Castlemaine Harbour; Lonart consists of two adjacent sites: East-Lonart and West-Lonart.

possibly exhibiting an internal variation in energy conditions. Because of the large amount of data collected and the limitations on space for publication, the details from just two of these six sites are presented: Castlemaine Harbour and Carrownisky. These two sites are seen as representative of both the sedimentary responses and of the variations in energy regime identified on this coast. Castlemaine Harbour forms a predominantly low-energy saltmarsh and mudflat environment, whilst Carrownisky is a very high-energy sand-dune and machair system, fronted by a gravel and sand beach which has moved progressively onshore during the late Holocene (Delaney & Devoy 1995).

## Methodology

Monitoring stations were established along a series of shore-normal transects at each site; station layout was intended to record data from the range of geomorphic and environmental elements present at a site. The sediment accretion and erosion at all sites was determined by the measurement of elevation changes of the sediment surface, with reference to *in situ* paired accretion pins. This method uses changes in sediment surface elevation as a proxy for mass gains and losses of sediment (Duffy 1996). Observations were made at the primary sites on a lunar monthly basis (29.5 days) and at three-monthly intervals elsewhere (secondary sites) from 07/12/94 until 02/06/96 (18 months).

Primary wind data used in the analyses of the sedimentary responses of Castlemaine Harbour and Carrownisky, were taken respectively from the nearby

Valencia and Belmullet meteorological stations. Examination of the wind-wave influence at Castlemaine Harbour sub-sites was based upon hindcast wind data, using the shallow-water equations of the Shore Protection Manual (U.S. Army 1977, see also Bishop et al. 1992), which are valuable for these west-coast situations in allowing for the representation of restricted fetches (< 20 km). Details of these techniques and of other methods used in this study are given in Devoy et al. (1996b) and Duffy (1996).

For the supratidal, dune-machair system of Carrownisky, where wind effects are of primary importance, the Belmullet wind data was first classified into the respective lunar monthly periods of this investigation. Analysis required a further calculation of the following variables: the mean speed, the maximum ten-minute speed and the maximum gust occurring within each 24-hr period. Since accretionary responses recorded over 29.5 days were being investigated in this instance, further calculation was required to determine the average daily mean speed for each 29.5-day interval (similarly the average ten-minute maximum and the average daily gust for each monitoring interval). In addition to determining the lunar monthly average values, the monthly minima and maxima were determined for the three variables also, thereby giving nine variables in total. As aeolian transport is primarily thought to be best represented by a cubic relationship with wind velocity (Hsu 1987), the above nine variables have been squared and cubed, giving a total of 27 variables to be correlated with the accretionary changes.

Calculation of the tidal influence, as applicable to the extensive lower-energy, marsh sites of Castlemaine Harbour, was based upon hourly tide-gauge records from Cork Harbour (Glanmire gauge). In the absence of specific hydrodynamic models for this coast these data then had to be extrapolated for use in the study area using the corrections of the Tide Table (Hydrographer of the Navy 1994, D. Blackman 1996, pers. comm.). Field truthing of the data showed a good first-order fit in using this approach (via regular field observation of the frequency of inundation of marshes of known elevation). Surface elevations of all sampling stations were measured to Ordnance Datum Dublin (Poolbeg) (OD (D)) using precise surveying techniques (e.g. Goudie et al. 1990). Closing errors were established for each survey traverse (Table 1). After determining the absolute elevation of a station and then relating it to local chart datum (Castlemaine), it was possible to calculate, using the tidal records, the

total duration for which that point was inundated, the *hydroperiod* (see Cahoon & Reed 1995).

At three sites, 1.5-m-length vertical monolith samples were taken from sediment sections for the purpose of determining mesoscale ( $10^1$ – $10^2$  yr) salt-marsh accretion rates, using  $^{137}\text{Cs}$  and  $^{210}\text{Pb}$  radioisotope techniques (De Laune et al. 1989, Geyh & Schleicher 1990, French et al. 1994). Sediment sub-samples (c. 20 g) were extracted from the monoliths at either 5 or 10-mm intervals. The moisture content and wet and dry density of the sediment sub-samples were determined. Isotope measurements ( $^{137}\text{Cs}$ ,  $^{226}\text{Ra}$  and  $^{210}\text{Pb}$ ) were made on the samples at the Department of Applied Mathematics and Theoretical Physics, Liverpool University (see Devoy et al. 1996b for discussion). Dating of longer-term sediment accumulation, obtained from interleaved organic and inorganic coastal sedimentary sequences at Castlemaine and Carrownisky, was based upon standard  $^{14}\text{C}$  techniques (Devoy et al. 1996b). This allowed the calculation of meso- to macroscale accretion rates at the sites. In addition, Ordnance Survey (OS) maps (the 1840–1850 and 1890–1930 6'' scale series = 1:10 680), land-estate surveys and aerial photographs, were studied to help determine the spatial pattern of these longer-term changes and also to provide any evidence of human interference at sites. Investigation of site stratigraphies and sediment profiles was undertaken using hand-coring techniques and the study of field sections (Delaney & Devoy 1995, Devoy et al. 1996a). Sediment particle size and texture characteristics were determined either by sieving (Krumbein & Pettijohn 1938) or by laser diffraction (using a Malvern 2600c, see Loizeau et al. 1994), as appropriate.

## Results of coastal responses

### *Surface elevation changes: low-energy environments (Castlemaine Harbour)*

Measurements of changes in sediment surface elevation at all sites were taken in the first instance as a surrogate measure of mass sediment transfers. Net elevation changes recorded at the Castlemaine sites (Figure 2) are presented in Table 1. A visual inspection of the saltmarsh elevation changes for these sites shows an apparently erratic to random form, although some seasonal pattern may be present (Figure 3). Net elevation losses are largely restricted to the mudflat and degraded saltmarsh stations (DSM, defined as

Table 1. Castlemaine Harbour monitoring station details: a) station name, predominant vegetation; b) elevation (OD Dublin) with closing error (mm +/-); c) net change in surface elevation between 07 December 1994 and 02 June 1996; d) activity, which is the average monthly modular change in sediment surface elevation; e) mean grain size of surficial sediment; f) hydroperiod, duration and correlation coefficient 'r', i.e. an indication of strength and sign of relationship between accretionary response (monthly elevation change) and duration of tidal inundation over the same time intervals; g) wind-wave correlation coefficient 'r', i.e. an indication of the relationship between monthly accretionary response and the wind-wave power supplied. **Bold** coefficients under f) and g) are significant at the 95% level.

a Station	b Elevation		c Net change	d Activity	e Mean grain-size	f Hydroperiod		g Wind- wave
	m	+/-	mm	mm	$\mu\text{m}$	hours	r	r
Rossbehy 1 <i>Juncus</i> Saltmarsh	4.5	33	-1.6	1.7	19.2	65	0.19	0.20
Rossbehy 2 <i>Puccinellia</i> Saltmarsh	4.3	33	1.6	1.3	21.9	223	0.08	-0.06
Rossbehy 3 <i>Armeria</i> Saltmarsh (edge)	4.1	33	3.0	3.1	24.3	548	0.14	0.20
Rossbehy 4 Inner Mudflat	3.6	33	6.6	3.2	110.4	1798	-0.20	-0.11
Rossbehy 5 Outer Mudflat	3.4	33	-3.8	1.9	42.3	2386	-0.08	-0.04
West-Lonart 1 <i>Juncus</i> Saltmarsh	4.1	28	11.8	2.5	15.9	420	0.12	0.24
West-Lonart 2 <i>Spartina</i> Saltmarsh	3.5	28	22.8	3.0	16.5	1990	<b>0.47</b>	0.17
West-Lonart 3 <i>Juncus</i> Saltmarsh	4.3	28	2.8	1.3	17.9	170	0.32	0.24
West-Lonart 4 <i>Puccinellia</i> Saltmarsh (edge)	4.2	28	5.0	1.8	24.8	387	0.26	-0.25
West-Lonart 5 Degraded Saltmarsh	2.9	28	-1.2	1.6	29.2	3681	0.12	0.17
East-Lonart 1 Mudflat	2.7	28	-22.8	4.0	144.0	4428	0.43	-0.05
East-Lonart 2 <i>Puccinellia</i> Saltmarsh	4.1	28	4.0	1.9	30.9	531	0.04	-0.27
East-Lonart 3 Degraded Saltmarsh	2.2	28	3.0	1.2	24.7	5548	-0.18	<b>0.54</b>
Garrana 1 <i>Agrostis</i> Saltmarsh	4.5	37	1.0	2.3	16.0	86	0.21	-0.06
Garrana 2 <i>Juncus</i> Saltmarsh	4.2	37	2.4	4.8	17.6	275	0.16	0.22
Garrana 3 <i>Juncus</i> Saltmarsh	4.2	37	-5.2	2.9	23.6	264	0.30	0.37
Garrane 4 <i>Juncus/Puccinellia</i> Saltmarsh	4.3	37	10.2	2.1	24.5	215	0.27	0.41
Garrane 5 <i>Juncus/Puccinellia</i> Saltmarsh	4.5	37	7.2	1.6	15.4	83	0.31	0.43
Garrane 6 <i>Puccinellia</i> Saltmarsh (edge)	4.4	37	6.0	1.6	42.2	107	<b>0.48</b>	0.01
Garrane 7 Degraded Saltmarsh	2.9	37	-11.0	2.1	36.4	3681	-0.18	-0.14
Garrane 8 Inner Gravel	2.2	37	-15.4	1.8	3010.0	5575	0.11	0.02
Garrane 9 Outer Gravel	2.0	37	0.8	3.3	7120.0	6035	0.19	0.04
Reenanacanna 1 <i>Agrostis/Puccinellia</i> Saltmarsh	4.1	39	13.4	1.7	13.7	449	0.21	0.10
Reenanacanna 2 <i>Phragmites</i> Saltmarsh	4.6	39	12.6	2.6	14.1	46	-0.30	0.17
Reenanacanna 3 <i>Juncus</i> Saltmarsh	4.5	39	20.6	3.9	14.3	73	0.15	0.21
Reenanacanna 4 <i>Puccinellia</i> Saltmarsh (edge)	4.3	39	12.4	1.6	29.6	207	-0.28	0.03
Reenanacanna 5 Inner Mudflat	2.7	39	-47.2	12.6	25.8	4235	0.19	<b>-0.50</b>
Reenanacanna 6 Outer Mudflat	2.5	39	-48.8	11.1	25.2	4776	-0.12	<b>-0.73</b>
Reen Point 1 Outer Mudflat	2.8	25	-2.8	7.8	46.1	4045	0.16	<b>-0.52</b>
Reen Point 2 Inner Mudflat	2.8	25	-10.0	11.6	37.5	4002	0.06	-0.37
Reen Point 3 <i>Puccinellia/Triglochin</i> Saltmarsh	3.6	25	13.8	1.7	41.0	1624	0.00	-0.36
Reen Point 4 Degraded Saltmarsh	4.3	25	-20.2	1.9	25.8	153	-0.08	0.37
Roscullen 1 <i>Agrostis</i> Saltmarsh	4.0	11	14.8	2.6	19.0	596	<b>0.45</b>	0.07
Roscullen 2 <i>Puccinellia/Plantago maritima</i> Saltmarsh (edge)	4.4	3	4.6	1.1	234.5	120	0.15	-0.01
Roscullen 3 Degraded Saltmarsh	3.8	3	-21.8	2.0	37.3	1137	-0.03	<b>-0.54</b>
Roscullen 4 <i>Plantago maritima</i> Saltmarsh (edge)	4.7	11	1.8	0.9	81.9	7	0.30	-0.02
Roscullen 5 Sandy Mudflat	3.2	11	-75.6	8.7	331.4	3081	-0.21	-0.41
Roscullen 6 <i>Festuca/Agrostis</i> Saltmarsh (edge)	4.9	11	-9.4	2.1	1009.0	1	<b>-0.47</b>	-0.07
Griffins 1 <i>Agrostis/Juncus</i> Saltmarsh	4.6	6	7.5	3.0	22.0	49	-0.11	0.35
Griffins 2 <i>Spartina</i> Saltmarsh	3.2	6	-10.0	3.7	40.5	1911	-0.05	<b>-0.47</b>
Griffins 3 <i>Puccinellia/Plantago maritima</i> Saltmarsh (edge)	4.6	6	2.9	1.4	103.6	46	<b>0.65</b>	-0.24

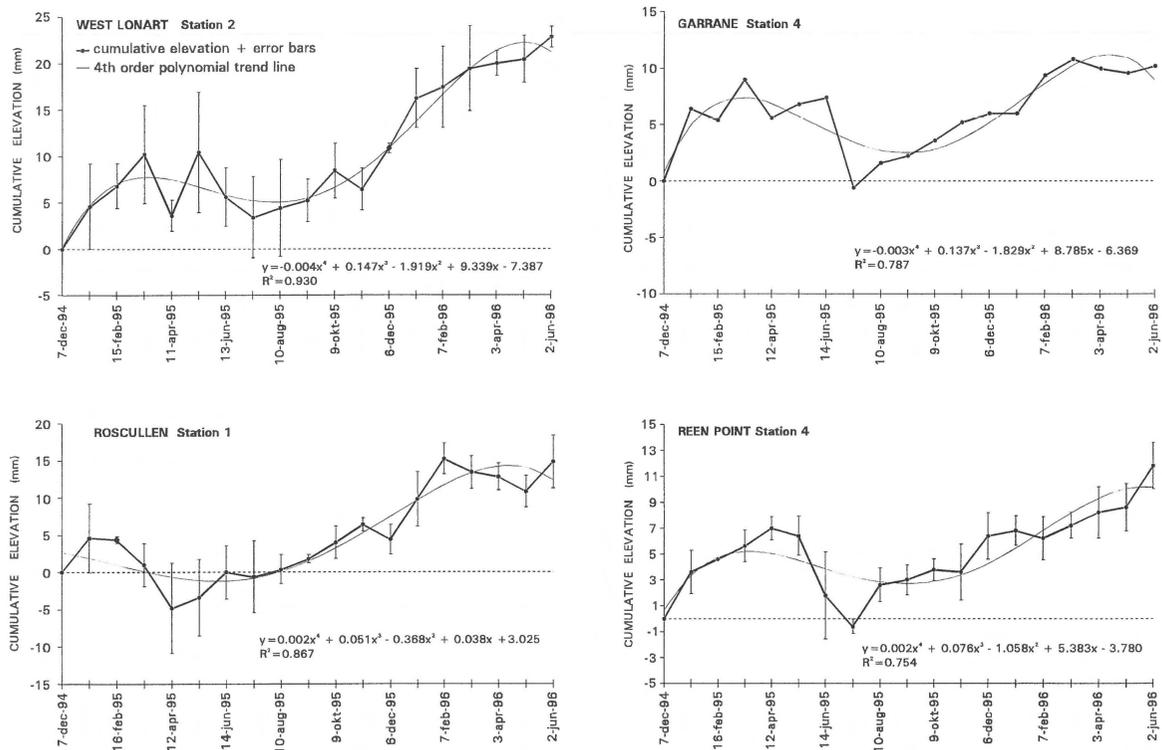


Figure 3. Changes in cumulative elevation (broader lines) of saltmarsh surface at four stations within Castlemaine Harbour (error bars are  $\pm 1$  standard deviation); a fourth-order polynomial has been fitted to this response in each instance (thinner curves), and the equation given;  $y$  = cumulative elevation,  $x$  = time elapsed,  $R^2$  = R squared value describing degree of fit of polynomial. See Figure 2 for locations.

eroding saltmarsh with sparse if any live vegetation cover). The DSM stations monitored at five separate sites all recorded net losses or very minor gains, with erosion appearing to increase eastward across the harbour (Figure 4). All the DSMs show relatively low activity indices (Table 1; *activity* is defined as the modular lunar monthly change in elevation). The response of the mudflats is varied, but again the greatest losses are recorded eastwards, in the inner harbour. It is these sediments with the lowest shear strengths, however, that record overall the greatest activity indices (Reenanacanna mudflat) and the greatest net losses (RosculLEN mudflat).

In an attempt to test further whether these elevation data were indeed stochastic in form, or showed any non-random organisation, polynomial trend analysis was applied. Nearly all the saltmarsh data show a good fourth-order polynomial fit (Figure 3). These results indicate that saltmarsh elevation maxima are achieved in the winter to spring period, whilst an elevation minimum occurred during the summer of 1995.

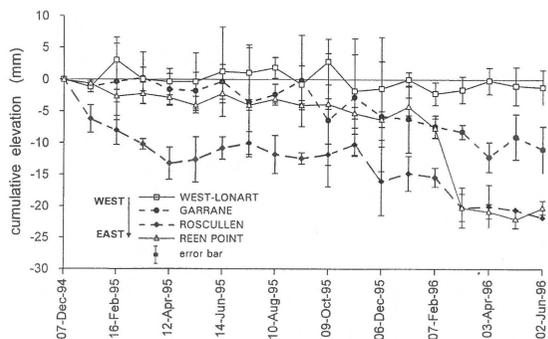


Figure 4. Changes in cumulative elevation for four degraded saltmarsh (DSM) stations within Castlemaine Harbour. Erosion rate increases at stations further to the east (see Figure 2 for locations); error bars are  $\pm 1$  standard deviation.

This trend was evidenced for all 26 saltmarsh stations within Castlemaine Harbour.

#### *Influence of hydroperiodicity (Castlemaine Harbour)*

Testing of the data from mudflat through to saltmarsh stations at Castlemaine, against tidal changes, was un-

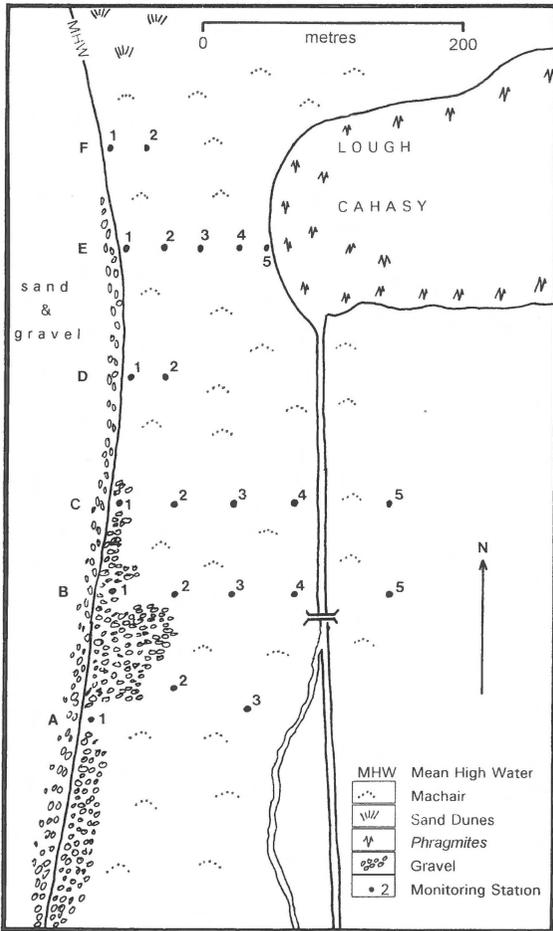


Figure 5. Location of monitoring station transects A to F at the machair site of Carrownisky.

undertaken for all sites. The duration of inundation, or hydroperiod, for each lunar monthly monitoring interval over the first 15 months of the study period was calculated for each station (Table 1), and is a direct reflection of station elevation within the tidal frame. As primarily the lower stations show net sediment loss (e.g. mudflats and DSM), it is understandable that a significant negative relationship exists between the hydroperiod and net accretion when considering all Castlemaine stations ( $r = -0.549$ ,  $n = 41$ ). However, examining only the saltmarsh (higher elevation) stations, then the relationship becomes weakly positive (inundation resulting in accretion,  $r = +0.209$ ,  $n = 26$ ), but not significant. Examination of the individual stations' responses to their hydroperiods (Table 1) shows that only five ( $n = 41$ ) have significant  $r$  coefficients. All of these stations are situated within c. 1.0 m of the

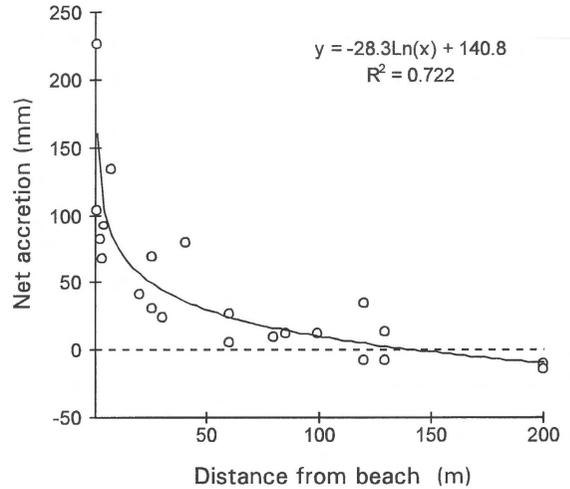


Figure 6. Variation in net accretion (after 18 months), for all stations on the machair surface at Carrownisky (Figure 5), with distance from beach. A logarithmic curve (equation given) has been fitted to the results.

marsh edge. The relationship for all five is positive, except that for Roscullean no. 6 ( $r = -0.470$ ), a station inundated for a total of only 1 hr over the 15 months (the effect of the tide was erosive in this particular instance).

#### Surface elevation changes: higher-energy environments (Carrownisky)

At the open-coast site of Carrownisky six approximately shore-normal sediment-monitoring transects were established from south to north to cover the back-beach and dune area (transects A–F, Figure 5). Measurement of sediment-surface elevation changes was undertaken as at Castlemaine and elsewhere in the study, covering the period 21/12/94 to 03/06/96. This work was complemented by extensive coring, trenching and lithostratigraphic study of the site (Delaney & Devoy 1995, Devoy et al. 1996a, b). All of the monitored stations are supratidal, though some are occasionally inundated under exceptional storm surges (see also Devoy 1992, Delaney & Devoy 1995). Consequently, examination of the accretionary responses at this site has focused upon aeolian activity as the principal cause for sediment transfers (using the wind variables outlined in the 'Methodology' section). The comparison of site-elevation and wind data, using established correlation indices, as at Castlemaine, is presented in Table 2.

A consistent sediment response is evident from transects A and B, showing declining net accretion

Table 2. Correlation coefficients for the relationship between accretionary response (mm) and 27 wind-speed (m/s) variables at Carrownisky, for the period 21 December 1994 – 03 June 1996; avg avg = average mean daily wind speed within a month; avg ten = average daily maximum ten-minute wind speed within a month; avg gust = average daily gust over each month; min avg = minimum mean daily wind speed recorded in a month; max avg = maximum mean daily wind speed recorded in a month; superscripts <sup>123</sup> represent coefficients of wind speed to the power of 1, 2, and 3. The net change in sediment surface elevation, activity, elevation relative to OD Dublin, and mean grain size are also given for each station. **Bold** coefficients are significant at the 95% level.

	A1	A2	A3	B1	B2	B3	B4	B5	C1	C2	C3	C4	C5	D1	D2	E1	E2	E3	E4	E5	F1	F2
	Edge			Edge					Edge					Edge		Edge					Edge	
avg avg <sup>1</sup>	0.2	-0.4	0.4	0.2	0.2	<b>0.5</b>	-0.1	-0.2	<b>-0.5</b>	<b>0.7</b>	0.4	-0.1	0.1	-0.2	<b>0.5</b>	0.2	0.0	<b>0.5</b>	<b>0.5</b>	<b>0.2</b>	0.2	0.3
avg ten <sup>1</sup>	0.3	-0.3	<b>0.5</b>	0.1	0.2	<b>0.6</b>	0.0	-0.1	<b>-0.6</b>	<b>0.7</b>	<b>0.4</b>	-0.1	0.1	-0.3	<b>0.5</b>	0.2	0.1	<b>0.5</b>	0.4	<b>0.2</b>	0.3	0.3
avg gust <sup>1</sup>	0.3	-0.3	<b>0.5</b>	0.0	0.2	<b>0.6</b>	0.0	-0.2	<b>-0.6</b>	<b>0.8</b>	<b>0.4</b>	-0.1	0.1	-0.4	<b>0.5</b>	0.2	0.0	<b>0.5</b>	0.4	<b>0.2</b>	0.3	0.4
avg avg <sup>2</sup>	0.2	-0.4	0.4	0.1	0.2	<b>0.5</b>	-0.1	-0.2	<b>-0.5</b>	<b>0.7</b>	0.3	-0.2	0.1	-0.2	<b>0.5</b>	0.2	0.0	<b>0.5</b>	<b>0.5</b>	<b>0.2</b>	0.2	0.3
avg ten <sup>2</sup>	0.3	-0.3	<b>0.5</b>	0.1	0.2	<b>0.6</b>	0.0	-0.2	<b>-0.6</b>	<b>0.7</b>	0.4	-0.1	0.1	-0.3	<b>0.5</b>	0.2	0.0	<b>0.5</b>	0.4	<b>0.2</b>	0.3	0.3
avg gust <sup>2</sup>	0.3	-0.3	<b>0.6</b>	0.0	0.2	<b>0.6</b>	-0.1	-0.2	<b>-0.6</b>	<b>0.8</b>	0.4	-0.1	0.1	-0.4	<b>0.5</b>	0.2	0.0	<b>0.5</b>	0.4	<b>0.2</b>	0.3	0.3
avg avg <sup>3</sup>	0.2	-0.4	0.4	0.1	0.2	<b>0.5</b>	-0.1	-0.2	<b>-0.5</b>	<b>0.7</b>	0.3	-0.2	0.0	-0.2	<b>0.6</b>	0.2	0.0	<b>0.5</b>	<b>0.5</b>	<b>0.2</b>	0.2	0.3
avg ten <sup>3</sup>	0.3	-0.4	<b>0.5</b>	0.1	0.2	<b>0.6</b>	-0.1	-0.2	<b>-0.6</b>	<b>0.7</b>	0.4	-0.2	0.0	-0.3	<b>0.5</b>	0.2	0.0	<b>0.4</b>	0.4	<b>0.1</b>	0.2	0.3
avg gust <sup>3</sup>	0.3	-0.4	<b>0.6</b>	0.0	0.2	<b>0.6</b>	-0.1	-0.2	<b>-0.6</b>	<b>0.8</b>	0.4	-0.2	0.0	-0.4	<b>0.5</b>	0.2	0.0	<b>0.4</b>	0.4	<b>0.1</b>	0.2	0.3
min avg <sup>1</sup>	0.2	-0.3	0.3	0.4	0.2	0.2	-0.2	0.1	0.0	0.3	0.1	0.0	0.1	0.2	<b>0.5</b>	0.3	0.1	0.4	0.2	<b>-0.2</b>	-0.2	-0.1
min ten <sup>1</sup>	0.3	-0.3	<b>0.5</b>	0.2	0.1	0.5	-0.1	0.0	-0.3	<b>0.5</b>	0.2	0.1	0.0	-0.1	0.4	0.1	-0.1	0.4	0.0	-0.2	-0.1	-0.1
min gust <sup>1</sup>	0.4	-0.2	<b>0.6</b>	0.1	0.1	<b>0.6</b>	-0.1	0.1	-0.3	<b>0.6</b>	0.3	0.0	0.0	-0.3	0.4	0.1	0.0	0.3	0.0	-0.3	0.0	0.0
min avg <sup>2</sup>	0.2	-0.3	0.3	<b>0.4</b>	0.2	0.3	-0.2	0.2	0.0	0.3	0.1	0.0	0.1	0.2	<b>0.6</b>	0.2	0.0	0.4	0.2	<b>-0.2</b>	-0.1	0.0
min ten <sup>2</sup>	0.3	-0.3	<b>0.6</b>	0.2	0.1	<b>0.5</b>	-0.2	0.0	-0.3	<b>0.6</b>	0.3	0.0	0.0	-0.2	0.4	0.0	-0.1	0.3	0.0	-0.2	-0.1	-0.1
min gust <sup>2</sup>	0.4	-0.2	<b>0.7</b>	0.1	0.2	<b>0.6</b>	-0.2	0.0	-0.3	<b>0.7</b>	0.3	0.0	0.0	-0.3	0.4	0.1	-0.1	0.3	0.0	-0.2	-0.1	0.0
min avg <sup>3</sup>	0.2	-0.3	0.3	<b>0.5</b>	0.2	0.3	-0.3	0.2	0.0	0.3	0.1	-0.1	0.0	0.1	<b>0.6</b>	0.2	0.0	0.4	0.2	<b>-0.3</b>	-0.2	0.0
min ten <sup>3</sup>	0.3	-0.3	<b>0.7</b>	0.1	0.1	<b>0.5</b>	-0.2	0.0	-0.3	<b>0.6</b>	0.3	0.0	0.0	-0.2	0.4	0.0	-0.1	0.3	0.0	-0.2	-0.1	-0.1
min gust <sup>3</sup>	0.4	-0.2	<b>0.8</b>	0.1	0.2	<b>0.6</b>	-0.2	0.0	-0.3	<b>0.7</b>	0.4	0.0	0.0	-0.3	0.4	0.0	-0.1	0.2	0.0	-0.1	-0.1	0.0
max avg <sup>1</sup>	0.4	0.2	-0.1	0.2	0.4	0.3	0.2	0.1	<b>-0.5</b>	0.4	0.3	-0.1	0.3	-0.3	0.2	<b>0.6</b>	<b>0.5</b>	0.3	0.4	0.2	<b>0.5</b>	<b>0.7</b>
max ten <sup>1</sup>	<b>0.6</b>	0.3	0.4	0.1	0.4	<b>0.6</b>	0.2	0.1	<b>-0.6</b>	<b>0.6</b>	<b>0.5</b>	0.1	0.3	<b>-0.5</b>	0.2	<b>0.5</b>	0.4	0.2	0.2	0.1	<b>0.5</b>	<b>0.6</b>
max gust <sup>1</sup>	<b>0.5</b>	0.2	0.3	0.1	0.4	<b>0.6</b>	0.3	0.1	<b>-0.6</b>	<b>0.6</b>	0.4	0.1	0.3	<b>-0.5</b>	0.3	<b>0.4</b>	0.4	0.3	0.2	0.1	<b>0.5</b>	<b>0.6</b>
max avg <sup>2</sup>	0.4	0.3	-0.1	0.2	0.4	0.3	0.2	0.1	<b>-0.5</b>	0.3	0.2	-0.1	0.3	-0.3	0.2	<b>0.6</b>	<b>0.6</b>	0.3	0.4	0.2	<b>0.5</b>	<b>0.7</b>
max ten <sup>2</sup>	<b>0.6</b>	0.3	0.4	0.1	0.4	<b>0.5</b>	0.2	0.1	<b>-0.7</b>	<b>0.6</b>	0.4	0.1	0.3	<b>-0.5</b>	0.2	<b>0.5</b>	0.4	0.2	0.1	0.1	<b>0.5</b>	<b>0.6</b>
max gust <sup>2</sup>	<b>0.5</b>	0.2	0.3	0.1	0.4	<b>0.6</b>	0.2	0.1	<b>-0.6</b>	<b>0.6</b>	0.4	0.1	0.3	<b>-0.5</b>	0.3	<b>0.4</b>	0.4	0.3	0.2	0.0	<b>0.5</b>	<b>0.6</b>
max avg <sup>3</sup>	0.4	-0.1	-0.1	0.2	0.4	0.2	0.2	0.1	<b>-0.5</b>	0.3	0.2	-0.1	0.3	-0.3	0.2	<b>0.6</b>	<b>0.6</b>	0.3	0.4	0.1	<b>0.5</b>	<b>0.8</b>
max ten <sup>3</sup>	<b>0.6</b>	0.4	0.4	0.1	0.4	<b>0.5</b>	0.1	0.1	<b>-0.7</b>	<b>0.6</b>	0.4	0.1	0.2	<b>-0.5</b>	0.2	<b>0.5</b>	0.4	0.1	0.1	0.1	<b>0.5</b>	<b>0.6</b>
max gust <sup>3</sup>	<b>0.5</b>	0.3	0.3	0.1	0.4	<b>0.5</b>	0.2	0.1	<b>-0.7</b>	<b>0.6</b>	0.3	0.0	0.3	<b>-0.5</b>	0.2	<b>0.5</b>	0.4	0.2	0.2	0.0	<b>0.5</b>	<b>0.6</b>
Net change (mm)	81.8	26.2	12.8	133.3	79.8	12.0	-7.4	-10.2	91.2	24.2	10.0	-8.0	-14.6	68.2	31.2	103.8	69.4	5.2	12.6	34.6	225.8	41.0
Activity (mm)	8.9	2.6	2.3	9.9	8.1	1.7	2.3	3.2	14.0	5.1	2.1	2.3	2.7	11.5	5.9	7.0	7.0	3.4	3.1	5.3	16.6	4.5
Station elevation (m)	7.8	6.3	5.9	7.4	6.7	6.4	5.9	5.8	7.5	7.0	6.7	6.1	5.8	8.5	7.1	8.6	7.8	7.1	6.9	5.6	9.9	8.0
Mean grain-size $\Phi$	2.2	1.0	1.1	1.9	1.7	1.2	1.3	1.5	1.6	1.0	1.2	1.7	1.3	1.6	1.0	1.4	1.4	1.2	1.4	1.5	1.4	1.4

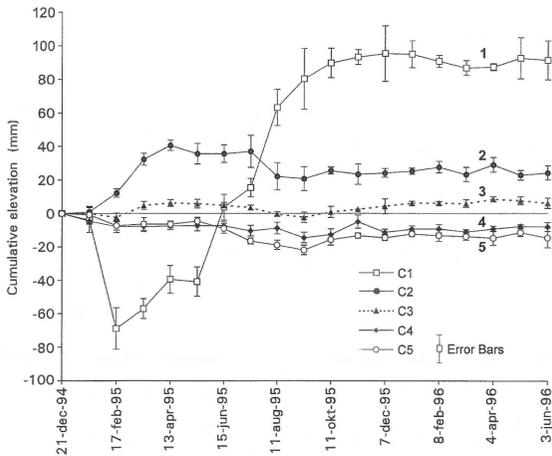


Figure 7. Changes in cumulative elevation of the sediment surface at transect C, Carrownisky (Figure 5); error bars are  $\pm 1$  standard deviation.

with increasing distance from the beach (Table 2). All transects show this decline in net accretion away from the beach, and this is well represented with a logarithmic decay curve (Figure 6). In transect B, passing from the edge station (no. 1, nearest the beach) to the middle station (no. 3), the relationship between accretion and wind speed becomes stronger (the response of B3 is significantly correlated with 20 of the 27 wind variables at the 95% level). In this instance, the most seaward station (B1) demonstrates generally the weakest positive relationship with the wind-speed variables. However, further from the beach, and lower, the relationship with wind speed becomes negative (Table 2).

The responses of the five stations on *transect C* (Figure 7) again show accretion decreasing landward, the most dynamic stations achieving a plateau in activity after October 1995. The two most landward stations undergo some erosion. There is, however, one major difference with the other transects in the response of the seaward-edge station, C1, to a Force 11 storm on 17 January 1995. In association with this event, most stations accreted significantly, although they were not actually inundated. At C1 an exceptional 60-mm sediment loss was recorded (real values were probably greater, as the measurements were taken during the storm). This is by far the greatest single erosive event recorded at Carrownisky. As seaweed was recovered from around the accretion pins on the subsequent monitoring visit, it is probable that this storm generated a surge event that actually overtopped the machair surface at this point. Significant

amounts of 100 to 400-mm-size cobbles were deposited at the station, but simultaneously an appreciable amount of sand was removed. The areal coverage of cobbles in the immediate vicinity of the accretion pins rose from zero to 20%. The area of cobble coverage subsequently decreased as the station recovered with renewed sand deposition. As at transect B, station C1 accreted steadily until October 1995. Thereafter it appears to have remained dynamically stable. The erosional trends of stations C4 and C5 are very similar to those of B4 and B5.

*Transect D:* The two stations at D show a very similar response to the adjacent stations C1 and C2. The accretionary response of the edge station (D1) is negative when correlated against the wind variables. However, 30 m landward at D2, although 1.5 m lower, the relationship between accretionary response and wind regime is a relatively strong positive one (although not with the maximum wind variables, see Table 2). The two stations on this transect are clearly behaving differently, as is illustrated by the poor relationship between their responses ( $r = +0.18$ ).

*Transects E and F:* Although stations F1 and F2 show a different degree of accretion (possibly a reflection of elevation, see Table 2), their accretionary responses have very similar relationships with the 27 wind variables. Both stations have correlations that are weak ( $r = +0.2$  to  $+0.35$ ) but positive with the mean wind speed, very weak and negative ( $r = 0.0$  to  $-0.17$ ) with the minimum wind speeds, but strong and positive with the maximum wind speeds ( $r = +0.46$  to  $+0.77$ ). For F1, F2, E1 and E2 it is the monthly maximum wind speed that has the greatest influence on sedimentation, possibly indicating that episodic, e.g. storm, events best explain the responses at these seaward stations.

### Dating results

An important aspect of this study has been the radiometric dating of changes in the sediment sequences, in helping to link the microscale trends with the longer-term pattern of coastal functioning. Sampling points for dating in the marsh areas were established at Corranroo, Timoleague, and Castlemaine, using  $^{210}\text{Pb}$  and  $^{137}\text{Cs}$  techniques (Appleby & Oldfield 1978). The calculated sediment accretion rates from these sites are 2.8, 7.8 and 6.4  $\text{mm a}^{-1}$ , respectively (data in Devoy et al. 1996b). These rates are often higher than the contemporary recorded values of 3.65 and 4.76  $\text{mm a}^{-1}$  for the Castlemaine and Timoleague

mature marshes respectively, with Corranroo, the most sheltered of all the sites, recording  $< 3 \text{ mm a}^{-1}$ . These rates are also in keeping with values from neighbouring coastal sites obtained by Wheeler et al. (this issue). However there is a discrepancy with the longer-term accretion rates derived from  $^{14}\text{C}$ -dated horizons: the Castlemaine marsh sequences (at Garrane) record 1 to  $2 \text{ mm a}^{-1}$  whilst dated peats from Carrownisky produce rates between 0.3 and  $1.0 \text{ mm a}^{-1}$ .

### *Human influences*

Study of archive, map and air-photograph data shows the extensive historical impacts of people on the monitored coastal environments, indicating influences on coastal shape, e.g. from built structures, sediment distribution, vegetation and other linked environmental changes. Garrane is typical of the Castlemaine Harbour sites, and of sites elsewhere on this west coast, where the human influence is witnessed by the traces of cultivation of former reclaimed land (originally salt-marsh). Now re-occupied by the sea, the present-day marshes retain the remains of many former drainage ditches and tillage lines, known as 'lazy beds' (Figure 8). These features may have been in existence from the 1700s, or even earlier. Examination of the 1841 OS map and earlier archive materials, indicates however, that some of this cultivated land had been returned to the sea even by the early 19th century (Devoy et al. 1996b). Nevertheless, like at many sites along the west coast of Ireland, the human influence remained important during the 19th century in changing coastal shape through continued embanking and draining. In Castlemaine, renewed reclamation in the 19th century is marked by an influx of population to the coast, probably attracted by the ongoing reclamation works (Smyth et al. 1996). How much this human impact has influenced the coastal responses, via sediment redistribution and changes in coastal shape, has still to be quantified. Initial results from investigations of historical archive sources (Devoy et al. 1996b) suggest that the long-term human intervention has been a major control on coastal operation at many sites since at least the 18th century.

## **Discussion**

### *Role of hydroperiodicity and wind-wave climate on sedimentary responses: Castlemaine Harbour*

Hydroperiodicity analysis showed that only five of the responses of the marsh stations demonstrated a significant relationship. The nature of the five stations, each being located on the seaward fringe of the marshes, may indicate that it is their proximity to a sediment source that governs whether the tide plays a significant accretionary role. However, there are eight other similar stations within c. 2.0 m of marsh edges that do not have this significant positive relationship with the tidal regime, although all but one of these, Griffins no.3, is still weakly positive. Of all 26 saltmarsh responses, only five are negative (Table 1). Together these results indicate that the tidal role overall is an accretionary one, as might be expected, but it appears not to be as strong an influence as has been found elsewhere (Pethick 1981, Frey & Basan 1985, Krone 1987, Allen 1990, French 1993, Cahoon & Reed 1995, Duffy 1996).

Given the weak explanation of the tidal regime for the sedimentary responses of the marsh surfaces, it might be expected that the wind-wave activity would account for a higher proportion of the variance. To test this hypothesis the energy from incident waves around the times of high-water was modelled using wind data obtained from nearby Valencia. This analysis allowed an approximation of the degree of exposure of each of the eight harbour sites through the summing of all of their effective fetch distances (Table 3). (It should be noted that some sites show the operation of two effective fetches, due to the differing exposure of the stations upon a single transect.) Garrane and the Reenanacanna marsh stations have the greatest total effective fetches, lying approximately in the middle of the harbour and exposed to all winds except southerlies (Figure 2). The most sheltered sites, Rossbehy and the East Lonart mudflat, have the smallest effective fetches. However, absolute exposure, as gauged by the total energy supplied to each site over the first 15 months reveals a different 'energy exposure' picture (Table 3). Roscullen and Griffins, in the innermost part of the embayment, showed receipt of the greatest incident wave energy, these sites having the greatest westerly and south-westerly fetches (i.e. the directions from which the strongest winds derive).

These analyses show that wave power is a better explanatory forcing factor for sediment change than



Figure 8. Aerial photograph of Garrane, taken in 1977, demonstrating the pronounced human influence on saltmarshes within this region (see Figure 2 for location): A) ancient tillage ditches, known as 'lazy beds'; B) ditch at seaward edge that was part of an earlier sea-defence; C) sediment extraction pits created during the construction of the modern sea-defence. The transect of stations where accretionary changes have been monitored is indicated by a dashed line; scale bar at top right is 100 m. Photograph supplied by Defence Department Headquarters, Dublin.

Table 3. Total effective fetch and wind-wave power supplied, over a 15-month interval, for each Castlemaine Harbour site.

Site	Rossbehy	West-Lonart		East-Lonart		Garrane	Reenanacanna		Reen Point	Roscullen		Griffins
Stations covered	1-5	1,3,4,5	2	1-3	1	1-9	1-4	5-6	1-4	1-4	5-6	1-3
Total effective fetch (m)	9 109	19 171	3 619	18 720	7 457	24 634	23 432	11 090	16 013	20 668	16 526	18 281
Total power supplied ( $W s^{-1} m^{-1}$ )	1.34E+09	2.32E+09	5.05E+08	2.45E+09	7.68E+08	3.97E+08	3.88E+09	1.29E+09	2.73E+09	5.10E+09	4.44E+09	5.09E+09

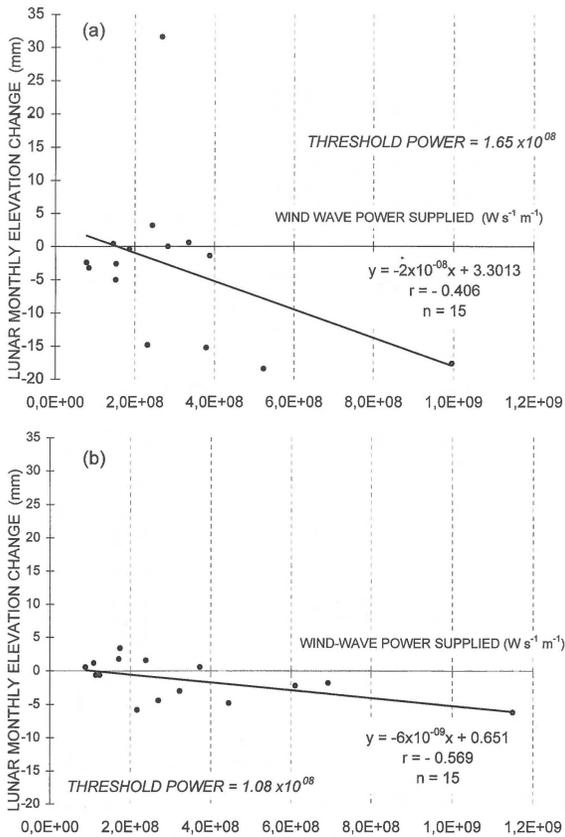


Figure 9. Plots of accretionary changes (mm) versus wind-wave power supplied ( $\text{W s}^{-1} \text{m}^{-1}$ ) for: a) the Roscullen mudflat station and b) the Roscullen degraded saltmarsh (DSM) station, over the period from 7 December 1994 to 2 June 1996. Note that two data-points are missing due to disturbance, hence  $n = 15$  instead of 17. For equations,  $y$  = elevation change,  $x$  = wind-wave power supplied,  $r$  = regression coefficient,  $E$  = exponent. See Figure 2 for location.

the tidal regime at many sites (Table 1, column g). At Roscullen maximum erosion values are recorded for Castlemaine Harbour. The two geomorphic elements with the lowest expected sediment shear strengths at Roscullen, sandy mudflat and DSM, have relatively significant negative correlations, i.e. an erosional response ( $-76 \text{ mm}$  &  $-22 \text{ mm}$ , respectively). The sediments from these areas are more easily entrained than those from the neighbouring saltmarsh surfaces and the erosion here is probably largely attributable to wind-wave action. This is especially so for the sandy mudflat station, no. 5, which experienced its greatest erosion in the first three months of the study, when strong westerly winds predominated.

The linear regression plots of wave power supplied versus elevation change of sediment surface for both the sandy mudflat and DSM are shown in Figure 9.

The mudflat environment appears to have a steeper response pattern. For the same amount of wave energy supplied (total value over a monthly monitoring interval) the sandy mudflat erodes more than twice as much as the DSM. The point where the regression intersects with the x-axis represents the threshold wave power required to push the response of that geomorphic element into an erosional regime. The threshold wave power for the DSM ( $1.08 \times 10^8 \text{ W s}^{-1} \text{m}^{-1}$ ) seems to be anomalously less than that for the mudflat ( $1.65 \times 10^8 \text{ W s}^{-1} \text{m}^{-1}$ ), given that the sediment loss recorded at the latter is at the maximum value of  $76 \text{ mm}$  for the study period. The only moderate fit of the regression lines (e.g. Figure 9b), with some large outlying residual values, may explain the apparent difference in sediment response with wave power. At this, and at other sites (Table 1), differences in sediment particle size, compaction-consolidation, station elevation and the effective cohesion of the sediments, may be as important in controlling erosion with wave power as sediment shear strength alone.

Other significant negative relationships with wind-wave power supplied have been found for the mudflat responses at Reenanacanna, Reen Point and Griffins, with that at Reenanacanna having by far the lowest threshold wave-power recorded ( $6.80 \times 10^7 \text{ W s}^{-1} \text{m}^{-1}$ ). At Griffins the negative correlation for the response of station no.2 (*Spartina* spp. dominance) is significant ( $r = -0.465$ ), the station having an even greater threshold wave power ( $2.5 \times 10^8 \text{ W s}^{-1} \text{m}^{-1}$ ) than the mudflat and DSM at Roscullen. This is attributable here probably to the binding action of the vegetation, effectively raising the critical shear strength of the surficial sediment. The marsh-edge station, no. 3 (most seaward), also demonstrates a negative relationship with the wind-wave power supplied ( $r = -0.240$ ), though the nearby mid marsh has a positive relationship ( $r = +0.352$ , Table 1). As this mid-marsh location is more protected than no. 3, the positive value found seems reasonable. Indeed, the relationship between wind-wave energy supplied and accretionary response is positive for the large majority of the marsh stations within Castlemaine Harbour (Table 1); suggesting accretion resulting from protected conditions. Alternatively, the accretion may be a manifestation of the effect described by Stumpf (1983), where Delaware (U.S.A.) marshes were found to be dependent upon storm activity for their supply of minerogenic sediment. There the net effect of larger wind-waves was to transport sediment onto the higher

marshes as opposed to physically scouring them and removing sediment.

As expected, the site most sheltered from the westerly winds, Rossbehy, has the weakest correlation with the wind-wave energy supplied (Table 1). This lack of energy may be an important explanatory factor of the only minor net gains occurring on this saltmarsh surface, i.e. significant wave action may be a prerequisite for accretion on mature Irish west coast marshes.

#### *Castlemaine Harbour energy gradients*

##### *Temporal energy gradients: accretionary responses of silt-dominated marshes*

The method used for measuring sediment accretion, although competent (see Duffy 1996), can only represent an approximation for gains or losses of sediment mass. As such, it is possible for changes in measured height of the sediment surface to occur without a transfer in sediment mass taking place. During the summer, when solstice tides are relatively small and also storm surges (meteorological forcing) are minimal, the marsh surface remains subaerially exposed for prolonged periods, possibly months. This is also generally the warmest and driest time of the year. Both these factors may lead, therefore, to the drying and contraction of the sediment and a consequent lowering of the marsh surface. At such times the marsh surface is not inundated and hence the losses may not represent actual erosion, i.e. loss of mass. The accretionary status of the marshes may thus in part be related to the ratio of inundation to subaerial exposure (Duffy 1996). Hence a substantial proportion of the variation in sediment surface elevation is probably due to seasonal variations in moisture content. However, if this ground 'breathing' pattern were removed from the cumulative elevation response, then many of the marshes would still complete the monitored time with a small net sediment gain (Figure 3), as calculated from the surface sediment datum, i.e. a real mass gain.

This interpretation is supported by the observations that: a) sediment change values are commonly irregular between stations (beyond established trends), and b) that sediment particle-size data show a landward fining. Together, these results indicate that the influx of energy, e.g. wind, waves and tides, to marsh systems is causing a real movement of sediments across marshes, producing accretionary changes. At Castlemaine, for example, many of the marsh surfaces appear to express a degree of dependence upon wind-wave activity for their gains in sediment. This was

occurring during the winter to spring period. This may suggest the operation of a seasonal energy gradient in driving marsh accretion, i.e. a critical energy threshold is necessary before sediment delivery to the marsh system can occur. Further, the sedimentary response of some of the mudflat stations has been negatively linked to the surrounding marsh surfaces (i.e. mudflat erosion and marsh accretion). Possibly the mudflat in these situations in the summer months is acting as a temporary store of sediment, which is transported up onto the saltmarsh during winter storms. Overall, the cross-matching of data sets undertaken supports the interpretation that the net gains detected on the marshes, after the 'apparent erosion' attributable to dehydration is subtracted, are real mass gains.

##### *Spatial energy gradients within Castlemaine Harbour intertidal zone*

There is also evidence for spatial, cross-marsh, energy gradients. Within Castlemaine Harbour, the erosion rates recorded on the degraded saltmarshes reflect the energy regime with respect to the local wind-wave climate; erosion increases eastward, as the fetch of the predominant westerly winds increases. This is broadly reflected in the total wind-wave power supplied to these sites (Table 3). In addition, the more sheltered mudflat of Reenanacanna demonstrates an accretionary response similar to the Garrane marshes, as it is well sheltered from the storm-wave-generating westerlies and south-westerlies. However, the overall activity on the mudflats increases up-estuary, Rossbehy mudflats being the least dynamic, to where a larger fetch exists and hence potentially larger waves may be generated (Table 1). Conversely, the exposed DSM and mudflat environments of Roscullen face directly into these storm-generating winds and their sedimentary response, i.e. erosion, evidences this. On a more localised scale, a landward fining in surficial mean grain-size has been recognised, also at the silty marshes at Timoleague and Corranroo. This may in part be explained by the deceleration of mean tidal velocities after mid tide, i.e. as the tide begins to inundate the higher mature marshes, resulting in the settling out of any fines in suspension. This trend may of course be overprinted by the wind-wave climate.

##### *Carrownisky energy gradients*

In contrast to the relatively sheltered embayment of Castlemaine, the high-energy open-coast dune and machair environment of Carrownisky is supratidal.

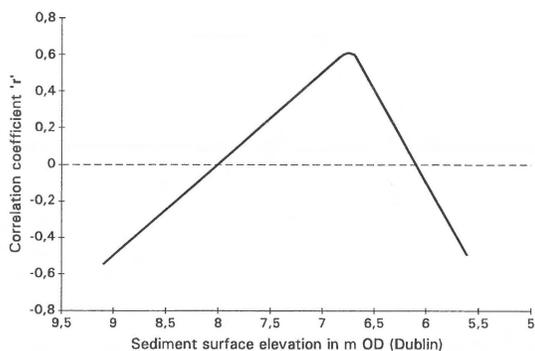


Figure 10. Model of how the relationship between wind speed and accretionary response varies with elevation of the sediment surface at Carrownisky (see text for explanation).

This site therefore, is most affected on a day-to-day basis by the wind regime. The Holocene stratigraphic record also demonstrates this (Delaney & Devoy 1995, Devoy et al. 1996a). Accretion on the dune-machair surface at Carrownisky was found to be relatively steady with only a few storm interruptions, some leading to enhanced accretion, others being sufficient to result in significant erosion. On all of the site transects accretion decreases landward, with greater distance from the inferred primary sediment source: the beach (Figure 6). Texturally the sediments are composed mainly of a medium sand, moderately well sorted, and showing little lateral variation in size (Table 2). Samples collected from the beach had a similar grain size (1.84  $\Phi$ ).

Sediment accretion was found to be much greater at the site's edge stations (no. 1s) than at the immediately adjacent landward stations, only c. 30 to 40 m to the east (Table 2). On the whole, accretion was also found to be increasing from south to north along the six edge stations, reaching a peak net gain at station F1 (226 mm) just south of the dune field. What could be interpreted from these results as an energy gradient, however, is more likely to represent the influence of a secondary sediment source from the dunes to the north of the site, increasing sediment accretion locally (e.g. transects E and F).

#### *Machair elevation as a threshold in responses at Carrownisky*

As it is not always the station closest to the beach that shows the strongest correlation between accretion and wind speed (Table 2), the relationship shown in Figure 10 is not a simple linear trend with distance or elevation, but a threshold one. The results may sug-

gest that either by exceeding a certain distance from the probable sediment source, the beach, or by falling below a particular threshold elevation, the particular influence of wind speed on machair accretion has changed. Surface sediment wetting, drying and moisture retention may also be playing a significant role in determining the rate of sediment transport.

Initial examination of the stations' elevations would suggest that elevation is not an important control on the response of the sediment surface to the wind regime, due to the range of heights associated with maximum activity (Table 2). However, stations with the strongest positive correlations with wind speed do lie within a specific height band (e.g. A3, 5.928 m; B3, 6.432 m; C2, 7.047 m; D2, 7.093 m; E1, 8.571 m; E3, 7.149 m; F1, 9.882 m and F2, 8.043 m). Station elevations for E1, F1 and F2 in this group appear as anomalous, i.e. > 8.0 m. It is possible that these stations are being influenced by an additional environmental factor in their sediment responses, possibly the proximity of the mobile sand-dunes to the north (Figure 5). As this sediment is not intertidal, it is not regularly wetted (excluding rainfall) and, therefore, is more easily entrained by the wind than the beach sands. Work based upon particle-size analyses, (Delaney & Devoy 1995) from this site independently suggested these northern dunes as a local source of sediment to the back-barrier environments.

Excluding the stations E1, F1 and F2, the other stations showing strong positive correlations lie between c. 6.0 and 7.0 m OD (Dublin). It may be, therefore, that initial residual surface elevation is a critical factor in controlling sediment responses, governing whether the wind has either an erosional or an accretional role in back-barrier sedimentation (Figure 10). These results are not conclusive and it is probable that distance from the beach-barrier, and sediment source and supply factors remain important. The results of site monitoring overall also emphasise the probable importance of variations in surface elevation in triggering accretion changes.

#### *Linking microscale to mesoscale changes: sediment dating*

Significant irregularities in the  $^{210}\text{Pb}$  and  $^{226}\text{Ra}$  profiles of all three marsh cores examined indicate significant variation in the process of sediment accumulation (Devoy et al. 1996b). However, the well-preserved nature of the  $^{137}\text{Cs}$  peaks suggests relatively little post-depositional disturbance. Irregularities

ies in the CRS and CIC dating profiles (explanation in Appleby & Oldfield 1978) for both Griffins and Timoleague are thought to be associated with the occurrence of coarser horizons (P.G. Appleby 1996, pers. comm.), and indicate that only during relatively quiescent periods, was  $^{210}\text{Pb}$  accumulation more representative of the atmospheric flux. The radionuclide data support the inferences of the wind-wave analyses on marsh accretion; that accretion is probably episodic and dependent largely upon storms.

Measurement of accretion rates at the open-coast sites also indicates that some sort of cyclical accretion and erosion process is probably in operation. At Carrownisky, stations A1, B1, C1, D2 and E1 all appear to achieve a threshold elevation after a period of continuous accretion. Similarly, map evidence of sediment cover from the 1915 survey, shows the machair surface at station C1 to be at a spot-height of 6.732 m OD (Dublin), whilst in 1995 its height is 7.489 m OD (Dublin). This equates to an accretion rate of 756 mm in 80 yr, i.e. c.  $9.5 \text{ mm a}^{-1}$ . However, the field monitoring recorded an annual rate of 60 mm  $\text{a}^{-1}$ , indicating a significant discrepancy between the modern rates and those from longer-term sources. As the sediments are sands it is unlikely that consolidation and compaction factors, or moisture losses and gains are responsible for such large differences. A possible explanation is that the sediment flux response of this coastal environment is cyclical or episodic. Accretion may be continuous, even during relatively strong storms. But when a particularly powerful, e.g. a one-in-fifty year, storm breaches the threshold of sediment stability, then erosion results, as was possibly the case at station C1 in January 1995. The build-up of sand, as shown in the stratigraphic work from these sites (Devoy et al. 1995, 1996b), is thus likely to be episodic, the sand layers resulting equally from a single event, or from numerous erosion-accretion cycles. The modern sand levels found in the Carrownisky system today though are probably dominated by aeolian transfers, rather than resulting from regular overwash mechanisms.

## Conclusions

For the low-energy silt-dominated system of Castlemaine Harbour, the influence of the tide on saltmarsh accretion, as expressed through hydroperiodicity, is surprisingly weak in comparison to similar settings elsewhere in Europe (e.g. Duffy 1996). However, the

tidal regime is still evidenced locally through a landward textural fining of the sediments. Within both end-members of the energy spectrum, machair and saltmarsh environments, storm-surge controls demonstrate strong influence on coastal sedimentation. These controls appear to be operating on a threshold-type response basis, with accretion accompanying minor to medium-scale storms, although particularly large storms may result in erosion, as evidenced by overwashing at Carrownisky. The directional aspect of this meteorological forcing has led to the development of an internal energy gradient within Castlemaine Harbour, where those sites with the longest westerly and south-westerly fetches have the largest erosional response to the wind-wave climate. Generally the lower-energy coasts, e.g. saltmarshes, have a weaker relationship with the environmental forcing factors, storms and tides, and hence are more liable to influences from localised controls.

Within Castlemaine, the removal on a more frequent basis of sediment from areas of lower critical shear strength, e.g. mudflats, may be acting as a temporary source to the longer-term sinks, namely the saltmarshes. Marshes as a whole though appear to be accreting at rates similar to those on other mid to high-latitude coasts in the North Atlantic. In western Ireland seasonality is pronounced in the accretionary response for many of the lower-energy environments, e.g. silty marshes. Episodes of sediment build-up on the marshes occur predominantly in the winter, and appear to be associated with influxes of energy, e.g. storms, to the system. Declines in surface elevation during the summer months are most likely to be attributable to marsh drying and subsequent sediment consolidation and contraction, the so-called ground 'breathing' effect.

At the open coast, results from Carrownisky also indicate a strong directional aspect of the meteorological (storm) influence upon such sites, with two major sources of sediment contributing to accretion in this coastal system. Prevailing westerly winds transport sediment from the primary source, the beach, whilst occasional northerlies can have a significant role in redistributing more mobile dune sand. Wind-speed maxima and distance from the two inferred sediment sources, and also possibly elevation, are shown to be important controls on the pattern of accretion and erosion. Sediment responses to these controls have also led to the operation of a local energy gradient.

Both the microscale and mesoscale results support an episodic mode of accretion. For the relatively low-

energy environment of Castlemaine Harbour, irregular isotope profiles ( $^{210}\text{Pb}$  and  $^{226}\text{Ra}$ ) suggest the role of storms in accretion. In the higher-energy environment of Carrownisky, the microscale net accretion rates are considerably greater (e.g.  $181 \text{ mm a}^{-1}$  at edge of machair) than the mesoscale rates ( $0.1\text{--}0.3 \text{ mm a}^{-1}$ ). However, there is considerable variation of the rates through micro- to mesoscale time as observed at both the low- and the high-energy coasts studied. This would conform best to a geological averaging of the sedimentary record (Schick et al. 1987). It is difficult therefore, to make direct links between factors acting on these coasts at different timescales. Examination of the map, photograph and other archive material shows the significant human influence on these coastal environments of western Ireland in historical times. However, it is difficult to quantify the effects on these coastal sedimentological regimes at this stage.

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