



Saltmarsh deposition and its relationship to coastal forcing over the last century on the north-west coast of Ireland

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Abstract

The mesoscale (time) control of annual storm-surge activity on quasi-annual saltmarsh (tidal marsh) deposition is studied from two estuarine saltmarshes on the high-energy NW coast of Ireland. Both saltmarshes exhibit a cliffed edge where maximum sedimentary variation is expressed in the form of lamination. Sections were logged and characterised by lithofacies based on grain-size determinations. Sections dated using Cs and Pb determinations indicated deposition records of decadal to century scale (c. 0.5 cm a⁻¹). Linear multiple regression explains ($p < 0.05$) half the variation of the deposition rate by annual coastal forcing (surge frequency and magnitude) and sediment modes (coarse silt to clay). Further variability in deposition rate is partially reflected in the non-linear response between forcing and deposition that is affected by mesoscale (30, 11 and 5-year) periodicities in forcing. Increased annual surge activity appears to be associated with a coarsening of, and reduction in annual deposition. A relationship between annual deposition rate and fractal dimension of surge timing (i.e. the clustering of surge events) is identified.

Introduction

In recent years, interest has been stimulated into the study of mesoscale (decade to century scale) variation in coastal forcing and its morphological and depositional response in the littoral zone (Terwindt & Kroon 1993, Wijnberg & Terwindt 1993, Orford & Carter 1995). Attempts to establish the parameters of mesoscale change are often thwarted by the problems presented by data requirements needed to substantiate this type of scale of activity. Microscale (daily to annual scale) observations and measurements rarely cover a representative timescale to validate mesoscale observations. The keys to the problem lie in the need for resolution of data that is matched in terms of the forcing process and the coastal response, and for a data time-series that is sufficient in length to accommodate the statistical requirements of techniques by which variation is to be specified. There is also a corollary

to the latter problem, that the sample time series is defining a window of response that is representative of the parental time series from which it is drawn.

This paper will attempt to examine mesoscale variation in coastal forcing and its response within a period of 70 years for which we have specified both forcing data (annual surge statistics: Newlyn) for the South Western Approaches (east Atlantic) and coastal response (annual deposition rate) from two saltmarshes in western Ireland (Bracky Bridge and Streamstown: Figure 1). A high-resolution chronostratigraphy is presented in an attempt to define annual deposition rates which are compared with annual storm-surge data, reflecting magnitude and frequency, considered representative of atmospheric cyclonic activity. No attempts have been made in this paper to relate forcing and response on an event basis. The relationship between storm activity and deposition rate at this mesoscale will be established to identify whether such

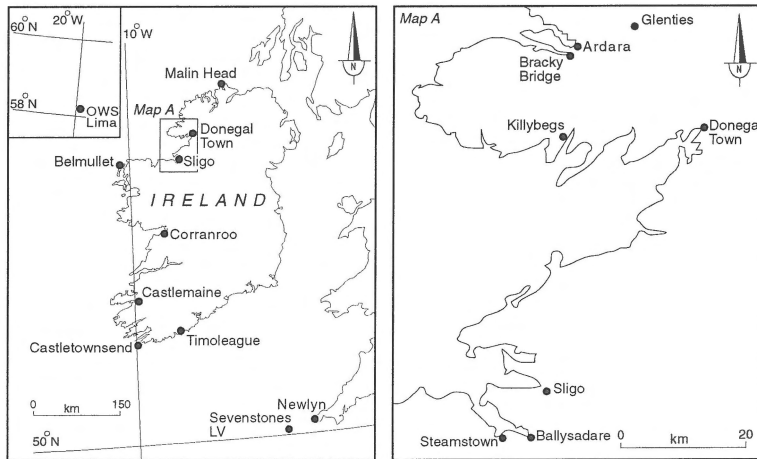


Figure 1. Location maps showing sites mentioned in the text.

changes in patterns of coastal storminess can be observed through the proxy record of coastal deposition.

Controls on saltmarsh deposition along the west coast of Ireland

Much of the west coast of Ireland is rock-controlled due to a resistant faulted and folded meta-sediment basement upon which a glaciogenic sediment cover offers a heterogeneous source of sediment for coastal evolution. The combination of resistant basement (promontories) and glacial activity has led to a highly indented coastline with a diversity of coastal forms. The inlets between the rocky promontories are often filled by narrow sandy beaches (Curtis 1991), while a high-velocity wind regime has also resulted in the development of numerous dune fields (Quigley 1991) and machair, defined as low-lying, undulating areas behind the foreshore dominated by wind-blown sand (Bassett & Curtis 1985). Despite these high-energy conditions, the degree of coastal indentation and the protection afforded by estuary-mouth coastal deposition has facilitated the development of saltmarshes (tidal marshes) in estuary heads and sheltered inlets. A survey of saltmarsh sites in Ireland (Curtis & Sheehy Skeffington 1998) identifies 162 sites along the west coast. It is important to recognise the spatial restrictions on most Irish west-coast saltmarshes, which translate into limited accommodation space for their physical development and small areal extent.

The west coast of Ireland is mesotidal with the predicted mean spring tidal ranges at stations nearest

to the sites studied being 3.5 m. Contemporary relative sea-level change for Malin Head (1960–1980), north-west Ireland, has been calculated at -2.4 mm a^{-1} (Carter 1982, locations are shown in Figure 1). This negative trend has been suggested as reflecting the final stages of glacio-isostatic effects, although subsequent unpublished work based on post-1982 analyses suggests that a positive relative mean sea-level (MSL) trend may be more realistic for the last few decades (B. Scott pers. comm.). The southern end of the western Irish seaboard is also associated with a positive rate of MSL rise; $+1.58 \text{ mm a}^{-1}$ at Castletownsend (1842–1978), based on manual tidal observations (Pugh 1982). This reflects a continuing trend of relatively low but steady rise in MSL starting in the late Holocene, as identified from Castlemaine Harbour (Carter et al. 1989).

The NW coast of Ireland is subject to a high-velocity wind regime. For instance, Belmullet received an average of 34.0 days of gale-force ($17.2\text{--}20.7 \text{ m s}^{-1}$) winds per year between 1957 and 1984 with a maximum gust for the same period (1957–1984) recorded at 48.4 m s^{-1} . Malin Head records show an average of 34.5 days per year with a maximum gust of 50.5 m s^{-1} (Rohan 1986). An analysis of wave data from Ocean Weather Ship Lima located off the west coast of Ireland identifies a high-energy environment concomitant with this wind regime (average significant wave height offshore c. 4 m). There is some suggestion of an increase in the roughness of the sea state over 1975–1988 as reflected in the increase of significant wave height (c. 4 cm a^{-1}) over this period (Carter & Draper 1988, Bacon & Carter

1991, 1993). Whether this is an indication of meso-scale variation is still unsubstantiated, though the lack of any corresponding increase in wind velocity from the Belmullet and Malin Head weather stations underlines the difficulty in ascribing wave changes to increased storminess *per se*. The incidence of high-wind events testifies to a storm-dominated coastline and to the potential of storm-generated surges entering the estuaries.

The supply of offshore sediment to the north-west coast is relatively low, given the low MSL rise over the last 2000 years. It has been suggested that the shelf has been extensively reworked such that most shelf sand is now held in coastal compartments (Carter & Wilson 1993). Extensive tidal flats are often exposed at low tide although they may be covered by a coarse gravel-rich lag. The circulation of mud and sand within the contemporary coastal zone may therefore be limited. Mud deposits *per se* are uncommon and those that do exist are usually in the form of vegetated saltmarshes infilling embayments largely sheltered from open-coast wave activity, though locally generated waves within the estuaries will have an effect on such areas.

Factors affecting the growth of saltmarshes have been the subject of numerous papers all stressing the importance of sediment supply, tidal range, organic productivity and relative sea-level rise (Randerson 1979, Pethick 1981, Krone 1987, Allen 1990a, 1990b, 1995, French 1991, 1993, French & Spencer 1992, Reed & Cahoon 1992, Cahoon & Reed 1995, Pye 1995). Clearly of great importance is the relative inundation of the site in terms of both still water level rise due to extreme tidal elevation (low-energy event) as well as still water level rise plus possible wave action (high-energy event) during storm-surges. This paper investigates primarily the influence of storm magnitude and frequency on saltmarsh growth in an area where storm incidence is high (Rohan 1986). However, other factors not already mentioned also have a strong control of saltmarsh deposition on the west coast of Ireland and are discussed below.

High rainfall, e.g. 1498 mm a⁻¹ between 1951 and 1980 at Glenties (Rohan 1986), results in a propensity for freshwater organic accumulation. Peat is a common deposit of Irish west-coast saltmarshes especially at mid- and high-marsh settings, a situation also facilitated by a limited sediment supply at many sites. High rainfall and organic content also lead to seasonal expansion and contraction of the saltmarsh (Duffy & Devoy this issue). Due to high rainfall and the

location of saltmarshes within sheltered inlets, many saltmarshes on the west coast of Ireland coincide with river outfalls increasing the influence of fresh water on saltmarsh development especially under catchment flood conditions. Correspondingly, the control of salinity on Irish west-coast saltmarsh flora is diminished, and the flora zonation of these saltmarshes less distinct than on the east coast of the British Isles (Sheehy Skeffington & Wymer 1991). Although freshwater discharge from the many rivers which outfall on the west coast is high, there seems to be little sediment transported at present, even during peak flow. Terrestrial sediment supply to the coastal zone is regarded as limited.

Methods

Analysis of depositional sequences

Monolith sediment sections were extracted from cliffed saltmarsh-edge sequences and levelled to Ordnance Datum (Malin) using differential GPS (Global Positioning System). Sections were described in detail from exposed sections and X-radiographs paying attention to sediment type and sedimentary structure using the Troels-Smith (1955) system of sediment description. Sections were dated using excess ²¹⁰Pb, ¹³⁴Cs and ¹³⁷Cs radiometric isotopes at 0.5, 1 and 2-cm intervals. Concentrations of ¹³⁴Cs and ¹³⁷Cs in the profiles reflect atmospheric nuclear fallout as a result of human activity and can be interpreted to provide dates corresponding to the initiation of atomic weapons testing (1954), the test ban treaty (1963) and the Chernobyl accident (1986) (Pennington et al. 1973, Ritchie et al. 1973, Ehlers et al. 1993). The isotope ²¹⁰Pb (half-life = 22 years) is produced in the atmosphere as a decay product of ²²²Rn and is rapidly attached to the atmospheric aerosol and deposited on all exposed surfaces (Sugai 1990). In the marine system, the isotope becomes bonded to suspended sediment particles. By extrapolating from the half-life curve of the isotope it is possible to produce an independent dated profile which validates the caesium interpretations and allows dating of earlier sediments (Sugai 1990). The samples were ashed at 550°C and the < 63 µm fraction sent to the Department of Physics, University of Bremen in Germany, where they were treated, and the concentrations of the radioisotopes of ¹³⁴Cs, ¹³⁷Cs, ²¹⁰Pb and ²¹⁴Pb were determined γ-spectrometrically using a Canberra 55%

N-type High-Purity Germanium detector. Prior to the measurements, the samples were sealed and stored until ^{226}Ra was in equilibrium with its decay daughter ^{214}Pb . Ages were calculated from excess ^{210}Pb concentrations using the 'constant initial concentration model' (CIC-model; cf. Krishnaswamy et al. 1971) and the 'constant rate of supply model' (CRS-model; Appleby & Oldfield 1978). X-radiographs of the sections suggested that bioturbation of dated sections was minimal with some disturbance by rootlets. Errors due to mixing and disturbance, as well as other errors, are reflected by the spread of excess ^{210}Pb data points and the clarity of the peaks in Cs concentrations. Errors are within acceptable limits for Bracky Bridge but are excessive for Streamstown as stated below.

Grain-size analysis was performed at 0.5-cm intervals on the section from Bracky Bridge. This sampling interval was chosen as the finest resolution possible given the limits of the dating techniques. Furthermore, the sampling of individual lamina was seen as problematic due to minor mixing at lamina boundaries by rootlets. The grain-size samples are therefore taken at 0.5-cm intervals irrespective of lithology and can be viewed as representative of mesoscale sedimentary accumulation commensurate with the dating framework. No attempt has been made to analyse the characteristics of individual events or laminae. Samples may contain several laminae or none. Detailed analysis of grain-size data from Streamstown was curtailed due to the short time duration of the sequence, making comparison with synoptic (tidal) data ineffective. Grain-size analysis was performed using the Galai Cis-1 laser particle-size analyser (Jantschik et al. 1992). Frequency counts per $4\text{-}\mu\text{m}$ size divisions were translated into 0.25ϕ size divisions. These size divisions were analysed using R-mode principal components analysis (PCA). R-mode PCA on size division in this paper is used in a hypothesis-generating mode and follows the substantial established literature (starting with Allen et al. 1972), in which grain-size data are reduced to several basic dimensions that reflect the essential textural basis of sediment structure, i.e. decomposition into constituent modes. The first three components, accounting for approximately 70% of the grain-size variation, were used as the basis for lithofacies definition using cluster analysis. The Euclidean distance was used to determine the similarity between samples, while Ward's minimum variance method was used as the linkage index to produce the clustering dendrogram for each core. Sets of similar, i.e. linked,

samples identified on the dendrogram are defined as lithofacies A to D.

This paper is concerned with establishing the degree to which conditional probabilities (colloquially referred to in sequence studies as 'memory') have been important in both the mesoscale process sequence and the depositional sequence of the saltmarsh sediment. The lithofacies by definition reflect nominal classes and measurement of memory has to be by a non-parametric technique, the simplest one being that of Markov Chain analysis (Harbaugh & Bonham-Carter 1970). The lithofacies sequences were then analysed for memory effects on a 1st-order, nth-step basis by constructing and testing a series of observed transition matrices (OTM) using Markov Chain analysis. 'Step' is defined in the sediment sequence as the 0.5-cm sediment sampling division. Matrices were constructed to indicate the frequency with which one sediment division's lithofacies type passes into the adjacent division's lithofacies type (1-step). Further transition-frequency matrices were constructed for 2-steps to 25-steps by inserting an increasing number of sediment divisions between the two divisions of interest. This enables one to study longer-term controls on conditional deposition. This approach assumes that the size divisions reflect equal time-slices, which is considered below. The analysis was performed for the whole series and for the upper and lower parts of the profile separately. Given only four lithofacies types and the possibility that the 0.5-cm-thick grain-size samples may have distortion, embedded analysis was performed where the adjacent identical lithofacies are treated as the same unit. Matrices produced were 1st-order and nth-step, i.e. only the first transition is noted regardless of the transition spacing (nth-step). Matrices from $n = 1$ to $n = 25$ steps were examined. Memory potential is indicated when the observed transitions are significantly different from the expected transitions structured from an independent event (random) model. Each OTM was transformed into an observed probability matrix (OPM) and then powered to derive its equilibrium matrix form which approximates to an independent events probability model (EPM). The difference between the OPM and EPM is tested for Markov memory potential using the maximum likelihood ratio ($-2\log_e \lambda$) method, distributed as χ^2 (Anderson & Goodman 1957) and using Krumbain's (1967) method of adjusting for any empty transition cells.

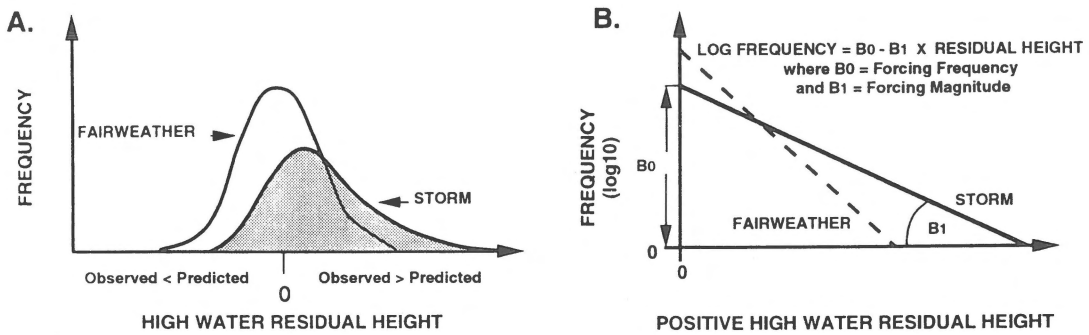


Figure 2. Characterisation of surge data: A) surge distributions of cyclonic active year and fairweather dominant year, B) use of regression to characterise the positive surges.

Analysis of tidal data

Attempts were made to relate sedimentary variables and components of storm frequency and magnitude to variations in deposition rate. Due to the limited duration of meteorological datasets along the west coast of Ireland, a record of storm-surge was extracted from a longer time series of hourly tidal measurements from Newlyn, Cornwall (1916–1992). Newlyn is the nearest long-term tidal gauging stage whose record exists into the mesoscale time frame. The use of data from Newlyn exemplifies the nature of surge generation impinging into the South Western Approaches, and as such, this is regarded as a surrogate for storm conditions to the north of this area affecting the west coast of Ireland. This premise is tested later through comparison of wave climate (significant wave height H_s) in both areas for a limited window of 1975–1988.

The methodology of surge analysis is developed in full elsewhere (Orford et al. 1992, McCloskey et al. 1996). The observed hourly values of tidal height can only be used for surge analysis after the series is detrended for the effects of relative sea-level change. The statistical MSL function was obtained by smoothing the observed annual MSL using a 19-year running term that establishes the MSL adjusted for the nodal tidal cycle (18.6 years). This MSL change function was characterised by the best-fit linear regression ($r = +0.991$) which generated a predictor equation for relative MSL rise. The predictor was used to establish the MSL increment between two adjacent years that was then linearly interpolated on an hourly basis and subtracted from all observations. The surge time-series is defined as the hourly value of detrended observed minus predicted tidal data and is the basic data series used in subsequent methods.

A number of parameters are extracted which characterise the surge data on an annual basis (one year is defined as the basic unit of temporal resolution in this mesoscale study). The frequency distribution of all surge elevations in any year is based on 4-cm intervals of surge elevation. This distribution usually realises a normal form. Years with substantial cyclonic activity register by showing a positive skew (Figure 2A). Further analysis for storm activity leading to saltmarsh deposition changes is only concerned with positive surges. A log-transform of frequency reduces the distribution of positive surge elevation to an effective straight line which can be best characterised by fitting a linear regression (Figure 2B). The two coefficients of the linear regression represent annual parameters of the number of surges (B_0 : frequency) and the range of surge generation (B_1 : magnitude). Years with extremes of surge elevation show a decrease in the slope of the regression line and a reduction in B_1 . The absolute value of B_1 grows as the surge potential for a year reduces. A final measure of extreme surge activity is undertaken by establishing for each year the number of days in which a surge at high tide (HT) exceeds the threshold set by the 1% exceedance surge level calculated for the complete time series of 77 years. The parameters B_0 and B_1 are characterising statements of the aggregate annual surge condition and can be viewed as synoptic statements of process-forcing potential, while extreme surge is a direct parameter of the inundation of extreme elevations under high-energy events. These coefficients were standardised by a z-score normalisation of the 77 values returning a mean of 0 and variance of 1. This was undertaken to ensure that the two variables when clustered for definition of surge-event-type would have the same effective measurement scale, i.e. not numerically perturbing

the clustering process. Three annual surge-event types were calculated from clustering the 77 standardised values of B0 and B1. First-order transition matrices were set up on the basis of surge-event-type change over a 1-year to 25-year step and tested for memory potential in a similar way as outlined for facies analysis.

Fractal analysis was performed on the surge data series to establish a fractal dimension describing the clustering of storm events (McCloskey et al. 1996). The box-counting or similarity dimension (D) of Hentschel & Procaccia (1983) was calculated from the following equation:

$$D = -\lim_{b \rightarrow 0} \lim_{n \rightarrow \infty} \log M_{(b)} / \log b, \quad (1)$$

where, $M_{(b)}$ is the number of time intervals that contain at least one surge event of the series. The parameter D in this study was calculated for surges which exceeded 27 cm (two standard deviations of the surge elevation distribution). The slope of $\log M_{(b)}$ against $\log b$ gives the box-counting dimension (D). This method gives no information on the number of surges within each time interval b , only the presence or absence of a surge. Essentially, D is a measure of the time-filling ability of the surges. As $D \rightarrow 1$, the time series fills 1- D space more uniformly. As $D \rightarrow 0$ then the surges are increasingly clustered towards a limit of a single observation when $D = 0$. This parameter reflects the potential for surges over a time period to show a sustained presence. The issue is somewhat complicated by the non-stationary nature of surge generation due to a seasonal reduction in surge potential. However, D can be viewed as a measure of continuing storminess over the period of measurement.

Site descriptions

Two saltmarsh sites were selected: Bracky Bridge and Streamstown (Figure 1). Their laminated sediments reflect variations in the sedimentary process. Most saltmarshes on the north-west coast of Ireland exist in sheltered locations and contain a generally non-laminated sedimentary sequence reflecting quiescent deposition as a result of a degree of protection from storms. Furthermore, the two sites were chosen because they contained a relatively substantial record of deposition. Stratigraphic investigations (Wheeler et al. 1996) defined site characteristics and the relationship between the sample site and other areas of

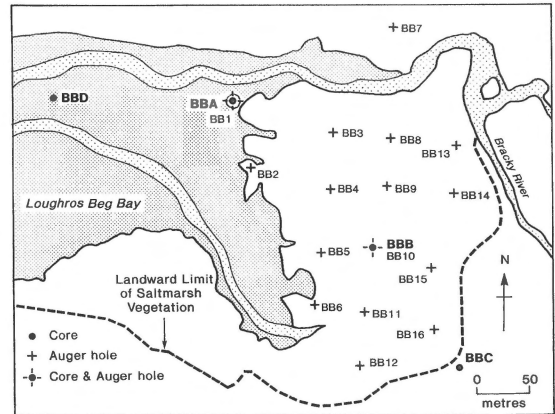


Figure 3. Site plan of Bracky Bridge showing the location of cores and auger holes used to define the stratigraphy and used for associated studies (Wheeler et al. 1996, Gallagher et al. 1996). The monolith section used in this study is at BBA adjacent to a core and auger hole. The tidal flat and river are denoted by stippling.

the saltmarsh. Sediment supply across the saltmarsh decreased from the cliffed edge, as reflected by a decreasing clastic content landwards. Maximum variation existed on cliffed-edge sites where accumulation had been influenced by wave and tidal activity under normal and storm conditions. The cliffed-edge sections were chosen for this study as they represent the greatest area of sediment accumulation on the saltmarsh, and hence potentially offer the most complete record of deposition. Furthermore, cliffed-edge sections were the most diverse lithologically being well laminated, suggesting that they are more responsive to variation in process than other areas of the saltmarsh. In this sense, cliffed-edge sections may not be any more representative of the saltmarsh than any other part of the marsh but their potential to record processes affecting the entire marsh area justifies their selection. These sections were dated and analysed for variations in grain-size characteristics. Other variables have also been studied as part of associated studies (Gallagher et al. 1996, Wheeler et al. 1996).

Bracky Bridge

Bracky Bridge, Co. Donegal, is located c. 55 km north of Donegal town, near to the village of Ardara (Figure 1). The saltmarsh is at the head of a narrow estuary (Loughros Beg), 7.5 km from the open sea. Loughros Beg narrows from 1.6 km at the mouth to 250 m at the head. The nearest predicted mean spring and neap tidal ranges are 3.5 and 1.5 m respectively, with mean high water springs at 1.70 m OD (data for Killybegs: Ad-

miralty 1995). At low tide, the intertidal areas reveal extensive sand and mudflats covered in many areas by a gravel-rich lag. The Bracky River, draining a mountainous catchment, flows into the head of the estuary and forms the easterly and northerly limit to the site (Figure 3). Concentrations of suspended sediment in the river are minimal. The saltmarsh increases in elevation landward from 1.50 to 2.56 m OD allowing increased tidal inundation at the saltmarsh edge. The saltmarsh is subject to infrequent grazing by cattle and possesses a cliffed edge of c. 70 cm height. *Juncus maritima* covers large areas of the saltmarsh, whilst saltmarsh grasses (e.g. *Puccinellia maritima*) are dominant at its more seaward localities. Back-marsh areas, only inundated by high spring tides and storm-surges, are dominated by bryophytes (mosses).

Cross-sections from Bracky Bridge (Wheeler et al. 1996) reveal a sedimentary sequence of clays, silts and organic deposits overlying a substratum of sands, gravels or bedrock. The sands and gravels represent both foreshore and slope-wash deposits. In the southern part of the site, these sands and gravels are overlain by clays grading up into organic deposits. These units represent the former outflow of the Bracky River. Elsewhere, the overlying units are of saltmarsh origin.

Sedimentation at the cliffed saltmarsh edge occurs through the 'dumping' of sediment by waves overtopping the cliff edge and during overmarsh tides. Clastic content and laminae frequency decrease landwards across the saltmarsh (Wheeler et al. 1996). At back-marsh sites, organic accumulation is dominant, with only occasional clastic laminae present. Topographic map evidence (1835, 1906 and 1952 editions) shows a change in the course of the Bracky River from the main course through the middle of the saltmarsh, and a minor outfall at the south of the saltmarsh, mapped in 1835, to the present more northerly course by 1906. The cliffed edge, however, has shown only limited readjustment since 1835, on the basis of published maps (Wheeler et al. 1996).

The sampled cliff edge section (BBA on Figure 3) consists of 70 cm of laminated organic silty clay. Organic and rootlet content decrease downwards, from 21% to 7% with some variation. Lamination consists of alterations of micaceous sandy clay and clayey silt with coarse-grained laminae between 1 and 8 mm thick irregularly spaced throughout the section. Lamina thickness increases downwards. The section rests on sandy gravel.

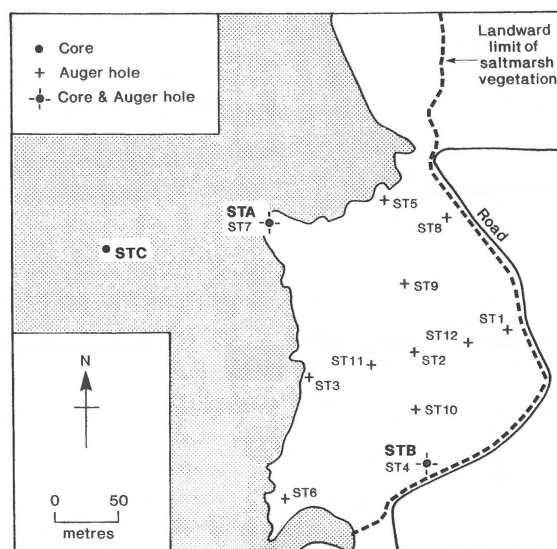


Figure 4. Site plan of Streamstown showing the location of cores and auger holes used to define the stratigraphy and used for associated studies (Wheeler et al. 1996, Gallagher et al. 1996). The monolith section used in this study is at STA adjacent to a core and auger hole. Tidal flat is denoted by stippling.

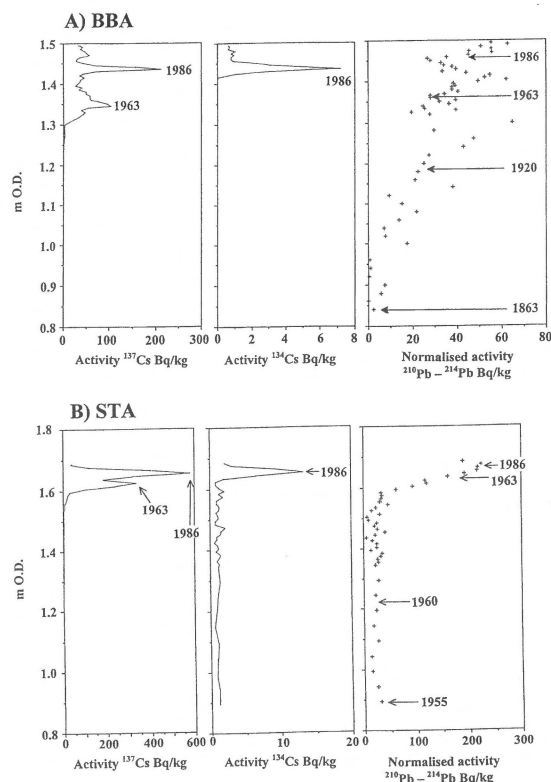


Figure 5. Radioisotope concentrations for A) Bracky Bridge and B) Streamstown.

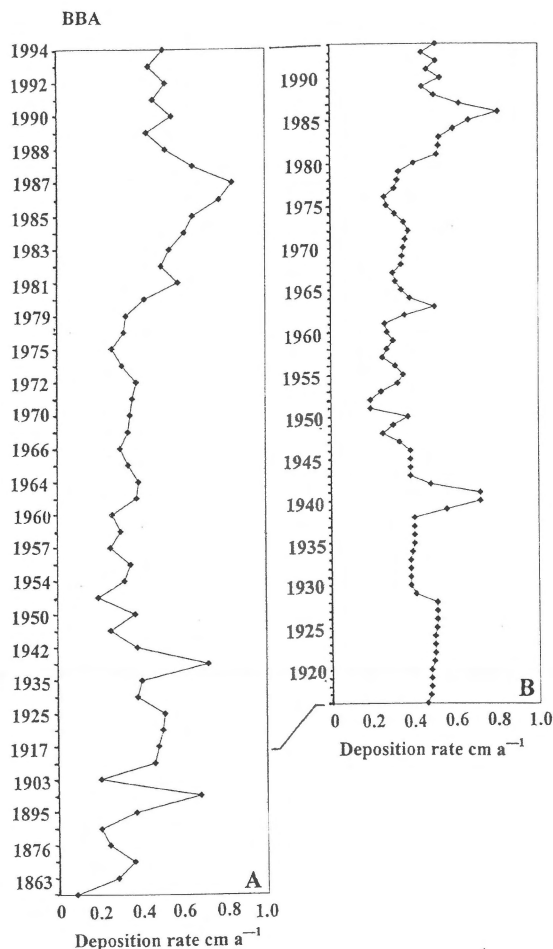


Figure 6. Deposition rates for Bracky Bridge: A) plotted against age (years AD) substituted for depth using the CRS-model, and B) plotted against linear age.

Streamstown

Streamstown, Co. Sligo, is c. 12 km from Sligo town near the village of Ballysadare on the southern side of Ballysadare Bay (Figure 1). This bay is narrowed at its mouth by a sand spit and dune system. The nearest predicted mean spring and neap tidal ranges are 3.5 and 1.5 m, respectively, with mean high water springs at 2.09 m OD (data for Oyster Island, Sligo Harbour: Admiralty 1995). At low tide the intertidal areas of the bay reveal extensive tidal flats cut by a channel. The saltmarsh is 'mature', existing between 1.07 and 2.19 m OD with highest elevations along the cliffed edge. New saltmarsh is accreting at the base of this cliff. The landward margin of the saltmarsh is bounded by a road at the supratidal limit (Figure 4). *Juncus maritima* is the predominant species although

a more diverse flora exists, in comparison with Bracky Bridge, due to a lack of grazing at Streamstown.

Cross-sections from Streamstown (Wheeler et al. 1996) show a saltmarsh sequence resting on coarser intertidal deposits. The saltmarsh sequence is generally represented by silty clay deposits grading up into clayey peat. Well-laminated sediments exist along the cliffed saltmarsh-edge and are generally coarser grained (e.g. at ST5 and ST3: Figure 4). On the northern edge of the site, the laminated sediments form a 'pseudo-chenier' with a higher saltmarsh elevation, reflecting the area of maximum deposition. Laminated deposits are restricted to the 'pseudo-chenier' with occasional laminae present at mid-marsh locations (Wheeler et al. 1996). Depositional processes on the cliffed saltmarsh edge at Streamstown are thought to be similar to those at Bracky Bridge. Topographic map evidence (1836 and 1913 editions) implies limited readjustment to the saltmarsh edge at Streamstown, probably in response to major reclamation works undertaken between map editions (Wheeler et al. 1996). Cartographic evidence post-1913 is not available.

The sampled cliff section (STA on Figure 4) consists of 80 cm organic laminated silty clay. Organic and rootlet content decrease downwards from 19% to 8% with some variation. Lamination consists of alternations of silty clay and clayey sand. Coarse-grained laminations are 2 to 10 mm thick and irregularly spaced.

Results

Chronostratigraphy

The saltmarsh-edge sequences from Bracky Bridge and Streamstown were dated using excess ²¹⁰Pb, ¹³⁷Cs and ¹³⁴Cs radioisotopes. Profiles of radioisotope concentrations are presented in Figure 5. The peak in caesium emission in 1986 due to the Chernobyl incident and the 1963 peak in ¹³⁷Cs are clearly visible in both profiles and correlate well with the independent dates derived from the excess ²¹⁰Pb determinations using the CIC-method. Excess ²¹⁰Pb dates for Bracky Bridge date the base of the section to 1863 ± 10.8 years with an average deposition of 0.50 ± 0.04 cm a⁻¹ (Figure 5A).

Deposition rates relevant to Bracky Bridge were also calculated for each sample using the CRS-model. Figure 6A shows rates plotted against depth at regular intervals with ages substituted on the y axis label.

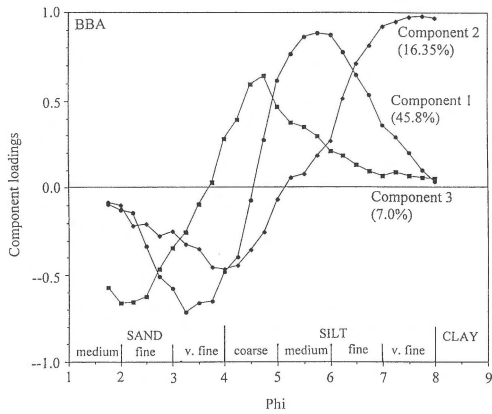


Figure 7. Principal components of the grain-size spectra from Bracky Bridge.

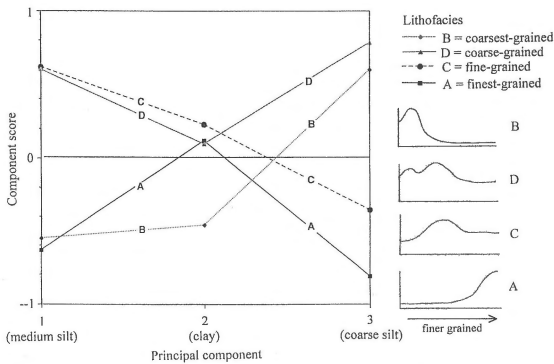


Figure 8. Component loading scores for the four lithofacies defined by cluster analysis of the principal component scores for Bracky Bridge.

Figure 6B shows the same data, truncated at 1916 commensurate with the Newlyn tide gauge time window, plotted against a regular time axis, and shows peaks in deposition rates during 1940, 1963 and 1986.

Excess ²¹⁰Pb dates for Streamstown date the base of the profile to 1955 ± 16.4 years (Figure 5B). The steepness of the best-fit line to the excess ²¹⁰Pb data below 1.60 m O.D implies rapid deposition between c. 1965 and c. 1955. Average deposition rates for this part of the profile are 7.25 ± 11.5 cm a⁻¹. Average deposition rates post-1965 are 0.24 ± 0.03 cm a⁻¹. It was not possible to calculate deposition rates using the CRS-model with the data available from Streamstown.

Lithofacies and memory

Absolute-count grain-size data from Bracky Bridge can be best described by three principal components (Figure 7). Component 1 (PC1) accounts for 45.8%

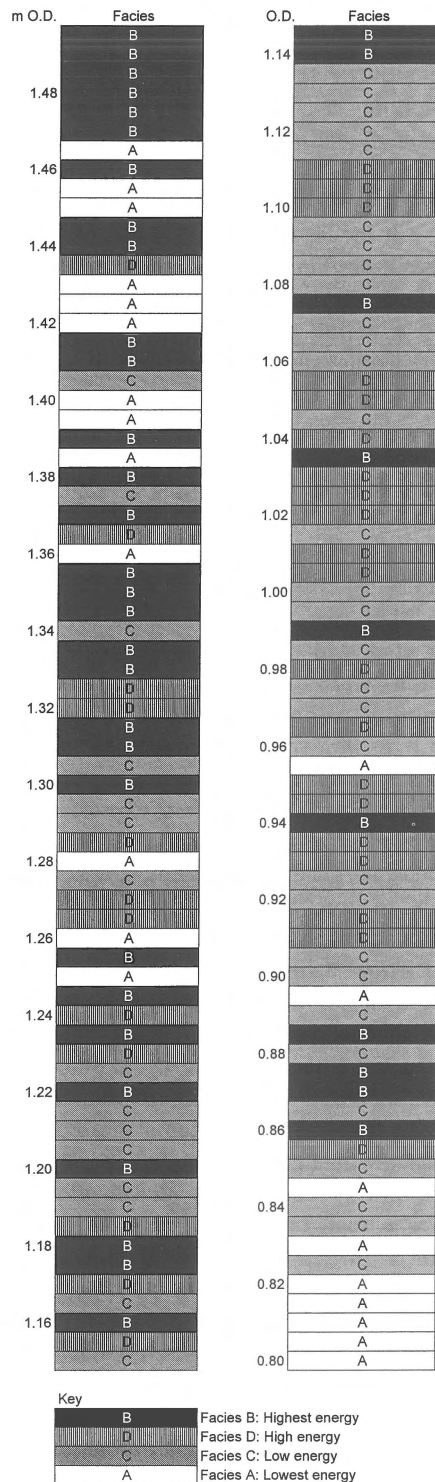


Figure 9. Bracky Bridge profile in 0.5-cm intervals ascribed to lithofacies A, B, C and D.

of the variability and describes a medium silt mode, component 2 (PC2) accounts for 16.35% of the variability and describes a fine to very fine silt mode, and component 3 (PC3) accounts for 7.0% of the variability describing a coarse silt mode. Cluster analysis of component loadings defined four lithofacies (A to D: Figure 8). Lithofacies B is the coarsest-grained lithofacies describing grain-size spectra dominated by a coarse silt mode. Lithofacies D is a coarse-grained lithofacies describing grain-size spectra with a coarse and medium silt mode and also a clay mode. Lithofacies C is a fine-grained lithofacies dominated by clay and medium silt modes with the coarse silt mode poorly represented. Lithofacies A is the finest-grained lithofacies representing grain-size spectra dominated by a clay mode. Figure 9 shows lithofacies at 0.5-cm intervals for profile BBA. As the average deposition rate at BBA is 0.5 cm a^{-1} , then each lithofacies unit can be crudely viewed as representative of a years deposition.

The lithofacies series was tested for Markovian memory effects to determine whether the lithofacies associations were a result of forcing or randomisation. Figure 10A shows the value of $-2\log_e \lambda$ for each n^{th} -step transition sequence as well as the $p = 0.05$ significance level. The 2-step and 3-step transition sequence is seen as significant expressing nonrandom memory effects. Obvious differences in lithofacies representation exist between the upper and lower halves of the profile, so the profile was split and Markovian memory effects re-analysed for both upper and lower datasets (Figure 10B). This showed no significant nonrandom memory effects in the upper half of the profile whereas for the lower half the 3-step transition sequence again shows significant non-random memory. As lithofacies often occur adjacently, Markovian memory effects were re-investigated with an embedded sequence for the upper and lower profile halves where adjacent identical lithofacies were treated as one (Figure 10C). The 1-step transition sequence is seen as significant expressing non-random memory effects for the upper profile half. This transition series relates to the significant transition of Lithofacies B (coarsest-grained) being followed immediately by Lithofacies A (finest-grained). For the lower profile half, 1-step, 2-step, 13-step, 20-step, 23-step and 25-step transitions express non-random memory effects. The 1-step and 2-step transitions relate to Lithofacies A (finest-grained) going to Lithofacies C (fine-grained) and to Lithofacies C going to Lithofacies C, respectively.

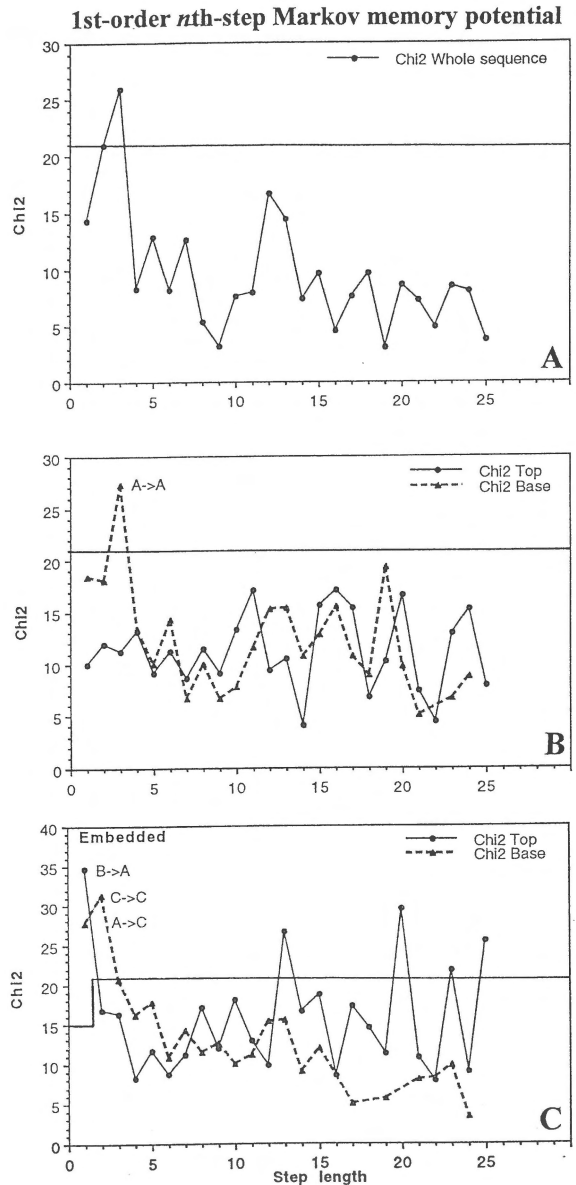


Figure 10. Markov memory effects for the Bracky Bridge profile of Figure 9 ascribed to lithofacies A, B, C and D: A) for the whole sequence, B) with the upper (1.50 to 1.15 m OD) and lower (1.15 to 0.80 m OD) halves of the sequences analysed separately, and C) for the upper and lower halves embedded.

Process forcing

Interest is centred on the extremes of storm-surge generation at high-water positions. Annual variations in B0 (frequency) and B1 (magnitude) were filtered in terms of a 5-year unweighted smoothing function, used to highlight the potential of mesoscale (sub-decadal) variation. Figure 11A shows the temporal

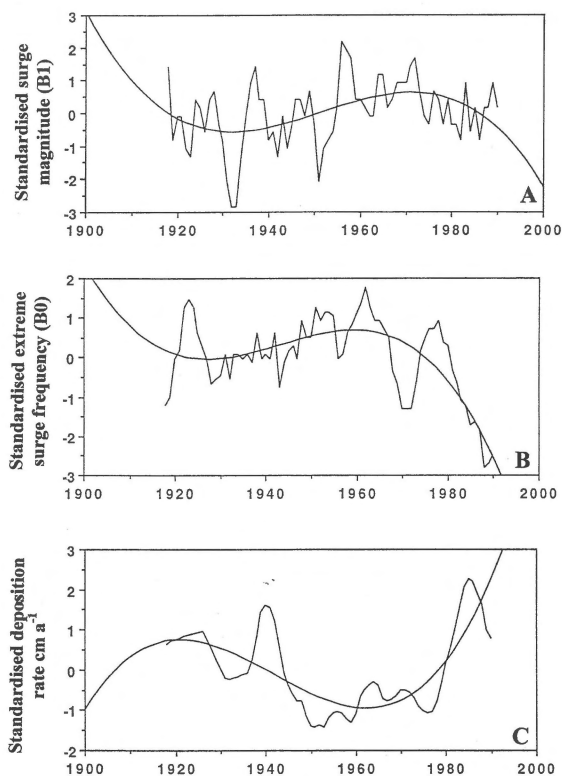


Figure 11. Nonlinear comparison of inverse association between A) standardised surge magnitude B1, B) extreme surge frequency B0, and C) standardised deposition rate for the Bracky Bridge profile. A) and B) are to be compared with C) for inverse effects.

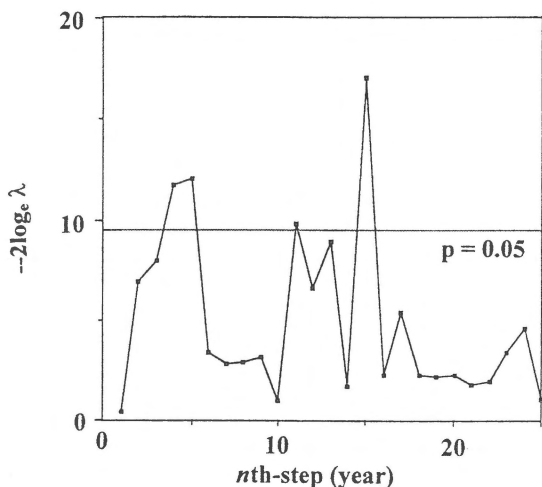


Figure 12. Significant memory of annual surge-event types recorded at high tides: Newlyn 1916–1992. Nth-steps above the $p < 0.05$ line are regarded as exhibiting non-random memory.

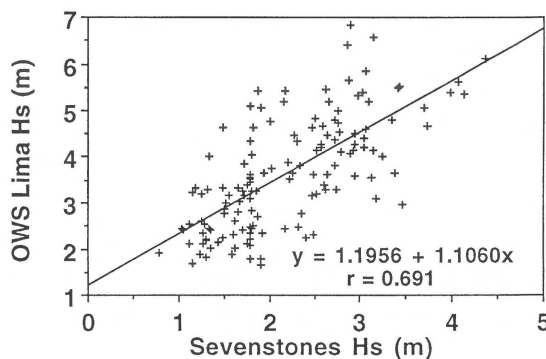


Figure 13. Comparison of sea state (monthly significant wave height) from the South-Western Approaches (Sevenstones light-house) and north-east Atlantic (OWS Lima).

variation in the standardised forcing coefficient B1. The 5-year smoothing trend picks up reduced surge activity in the mid-1930s and late 1950s. Clustering of the 77 annual values of B1 and B0 using the procedure, identified in the ‘Methods’ section, produced three basic types of annual surge generation as a function of increasing storm-surge energy. Markov Chain analysis of the transition matrices of surge events for $n = 1$ to 25 steps (years), identifies significant memory effects at 11 and 15 years (strongly influenced by reduced surge-energy conditions), while significant 4 to 5-year cycles are probably a reflection of air-pressure cyclonic periodicity, as recognised by Nue (1984) from the western Atlantic (Figure 12). The smaller cycles are superimposed as a dampened oscillation on the decadal-plus cycles (Figure 11A). The long-term trend in B1 (3rd-order polynomial) identifies minimum (1931) and maximum (1970) turning positions within the data window, denoting a decreasing surge potential in the 1980s and 1990s. Figure 11B shows the standardised annual extreme surge frequency with a 3rd-order polynomial fitted to identify the long-term trend. Its form is congruent with B1’s long-term trend as would be expected. The turning points for minimum and maximum extreme surge show a slight lead in time compared to the B1 trend. The major drop in extreme surges in the late 1980s is also notable.

Discussion

The use of Newlyn data

In order to use the coastal forcing identified from the Newlyn tide gauge in conjunction with the saltmarsh depositional rate from Bracky Bridge there is a need

to establish the representativeness of the Newlyn data for western Ireland. The analysis of Newlyn specifies coastal forcing for the South Western Approaches. Storms affecting Newlyn are likely to be part of low-atmospheric-pressure systems affecting the west coast of Ireland at approximately the same time. It is clear that on an individual storm basis there are likely to be differences between Newlyn and western Ireland in the direct value of surge given the difference between the open coast of western Ireland and the semi-open nature of the South Western Approaches. However, on an annual basis the aggregate sum of storm activity at Newlyn is likely to be similar to that experienced off western Ireland. A test of this proposition is based on the joint relationship between monthly significant wave height recorded at the Sevenstones lighthouse (Scilly Isles) and at the Ocean Weather Ship Lima (north-east Atlantic) between 1975 and 1988 (Figure 13). A significant positive correlation ($r = +0.691$, $p < 0.05$) supports the view that the wave climate of the South Western Approaches is reflective of the wave climate off the west coast of Ireland, albeit that an up-scaling is required as identified by the scale of the regression coefficients (Figure 13). The similarity of wave activity from the two sites supports the contention that annual characterisation of Newlyn storm-surge forcing can be used as a comparable estimate of annual western Ireland storm-forcing conditions.

Saltmarsh deposition

Excess ^{210}Pb dates for Bracky Bridge date the base of the section to 1863 ± 10.8 years which agrees well with map evidence (Wheeler et al. 1996). The average deposition rate for Bracky Bridge is $0.50 \pm 0.04 \text{ cm a}^{-1}$, comparable with deposition rates from other saltmarshes on the west and south-west coasts, e.g. 'Griffins', Castlemaine Harbour: 0.64 cm a^{-1} , Timoleague: 0.78 cm a^{-1} , and Corranroo: 0.28 cm a^{-1} (Duffy & Devoy this issue). The deposition rate derived from Streamstown is an order of magnitude higher and possesses a large error term ($7.25 \pm 11.5 \text{ cm a}^{-1}$). Correspondingly, the base of the section is younger (1955 ± 16.4 years). This implies that the section may have been severely eroded in approximately 1955, and that it underwent rapid accretion over an approximate 10-year period, after which, the profile was again in equilibrium with the rest of the saltmarsh, and accretion continued at the reduced rate of 0.24 cm a^{-1} . The large error term is a result of a diversity in excess ^{210}Pb concentrations possibly suggesting a de-

Table 1. Variable coefficients and significance of step-wise multiple regression linking deposition rate to surge forcing for the Bracky Bridge profile (BBA). PC1 and PC2 are principal components of grain size variation; B0 and B1 are nonstandardised multiple regression coefficients derived from the Newlyn tide gauge series (1916–1992); B0 is standardised extreme surge frequency and B1 is standardised surge magnitude.

Variable	Coefficient	Std. coefficient	F-value	Probability
Extreme surge	-0.039	-0.698	59.423	0.0001
PC1	0.081	0.394	16.702	0.001
B1	-80.236	-0.303	5.015	0.028
PC2	0.053	0.207	5.911	0.018
B0	-0.420	-0.222	2.581	0.113

gree of reworking of older material. Interestingly, a severe storm, ex-Hurricane Debbie, affected this part of the coast on 16th September 1961 and, given the error of the dates, may be responsible for this dominant erosion event.

The coarsest-grained lithofacies (Lithofacies B) on the Bracky Bridge profile is more frequent in the upper half, whereas the finest-grained lithofacies are more frequent in the lower half of the profile (Figure 9). This may reflect a geomorphological signal in the data with a higher tidal control on deposition in the lower half of the profile while the saltmarsh was at a lower elevation with respect to the tidal frame. The influence of storms may increase up-section as the saltmarsh becomes elevated within the tidal frame and possible cliff-retreat effects take place, comparable to similar findings by Allen (1996).

Markov memory potential states that there is significant memory in the lithofacies association and that these memories are not merely a random occurrence. Moreover, this implies that a forcing component is operating to produce these associations. The embedded sequence shows very significant memory in the upper half of the profile at 1-step with Lithofacies B going to Lithofacies A indicating that the depositional period producing the coarsest grain-sizes is followed by a depositional period producing the finest grain-sizes, at a rate above that expected on a random basis. It is not feasible to place a time periodicity on these embedded sequences as the unit time of each lithofacies is now variable. The lower profile half shows significant memory on 1- and 2-steps with the finest-grained lithofacies. The higher n-step transitions in the embedded sequence may reflect the much reduced size of the dataset as much as anything else.

Table 2. Statistical significance of each coefficient presented in Table 1 tested by analysis of variance. Test statistical value (F-value) and associated probability also shown.

Source	Sum of squares	DF	Mean	F-value	Probability
Regression	0.421	5	0.084	14.805	0.001
Residual	0.381	67	0.006		

Relationship between coastal forcing and coastal deposition

Given that sediment size appears to be related to deposition rate, it is likely that extreme surge frequency, surge magnitude (B1) and surge frequency (B0) are also elements in the control on deposition. A multiple regression model (Tables 1, 2) was constructed using these variables to attempt to statistically explain deposition rate. The model identifies a significant multiple correlation ($r = 0.724$, $p < 0.001$) between deposition rate and extreme surge frequency (– correlation), between clay (PC2) mode (+ correlation) and medium silt (PC1) mode (+ correlation), and between surge forcing magnitude (B1) (– correlation) and surge forcing frequency (B0) (– correlation). The power of the analysis (i.e. the standardised coefficients) identifies the extreme surge frequency (0.698) as the principal agent of explanation, with the medium silt component (0.394) and surge magnitude (0.303) as the joint second agents. The signs of the association identify increased deposition with decreased surge activity and increasing medium silt component. These results support the model of depressed deposition rate, with coarse-grained sedimentation associated with surge inundation, while confirming that the bulk of the deposition rate is associated with the enhanced deposition of clays and fine silts associated with nonsurge conditions. This joint mechanism is defined as the mesoscale process-response model for observed saltmarsh development and is supported by independent microscale (time) observations (Stumpf 1983, Reed 1988, Pethick 1992).

Given that approximately half of the statistical variation in deposition is explained by the use of these forcing variables, there is still a need to understand the basis of control of the remaining unexplained variation. Figures 11A to C, showing the generalised trend of standardised deposition rate and surge parameters over time, go some way in illustrating this issue. The multiple correlation analysis is linear in form and

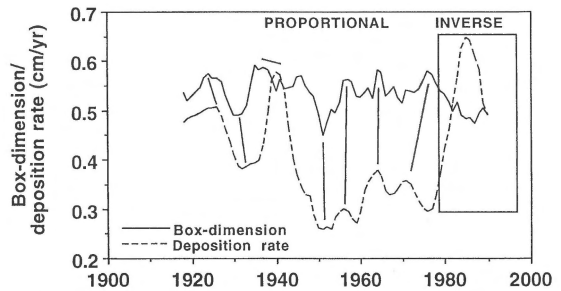


Figure 14. Non-linear association between the box-counting dimension fractal for surge > 27 cm from the Newlyn tide gauge series 1916–1992 and the deposition rate at Bracky Bridge.

probably underestimates the nonlinear inverse association that is reflected between the 3rd-order polynomial general trends of deposition and surge. It is possible that some loss of explanation in this relationship will be associated with both regional latitudinal variation in surge history between the South Western Approaches and western Ireland as well as the geomorphological filter of the net-depositional context of Bracky Bridge. The geomorphological context, in particular, controls sediment supply to the system as well as the possibility of varying deposition rates as a function of spatial variation in the saltmarsh environment over the century of identified deposition.

An interesting relationship emerges when one considers the control of storm clustering on deposition rate. The correlation between the box-counting fractal dimension (D) for surge events > 27 cm and the deposition rate (both 5-year smoothed) is not significant, indicating a lack of any *linear* relationship between both fractal and deposition variables. However, when both of these variables are co-plotted against time (Figure 14), there is substantial agreement between them of a nonlinear nature that underlines in general terms some form of positive association between fractal dimension and deposition rate. The fractal dimension indicates a variation in the clustering of surge events. The lines in Figure 14 identify distinct serial association in the sense of the two variables. It is noticeable that those years with the best clustering of surge activity (low values of D) relate to periods of depressed deposition, i.e. consistent storm activity reduces overall deposition rate. Temporal lags exist between the two datasets with peaks in the box-counting dimension occurring before peaks in deposition rate between 1916 and the 1950s, with the opposite becoming true from the 1950s to present. The out-of-phase position may reflect inaccuracies and

distortions associated with the radiometric age determinations. Although it is possible to perceive a lag between a clustering of storm occurrences and resulting suppressed deposition rates, the reverse is not tenable. Even so, the lags implied are of a duration of one year to several years. Differences in magnitude of response exist especially regarding peaks in sedimentation in the late 1930s. This seems contrary to the general trend and may be a localised effect. An apparent inverse relationship exists at the top of the profile which may be explainable in the geomorphological context of enhanced deposition rates resulting from the proximity to the saltmarsh cliff-edge. The lithofacies profile (Figure 9) shows an enrichment in coarse sediment (Lithofacies B) at the top of the profile, and increased deposition rates at the saltmarsh edge (relative to the rest of the saltmarsh) are also apparent at Streamstown with the presence of the 'pseudo-chenier'. Clearly the recognition of a clear mesoscale signal in the response sedimentation depends on the relative control that the site can exert on the regional climatic forcing signal.

Mesoscale (time) variation in coastal development

Of interest is the nature of what might be driving the various memory effects that are being observed in both forcing and deposition. If there is any association between forcing and response one would expect the memory to be identified at the same rhythmicity or at some sub-harmonic of it in the two investigated saltmarsh sequences. The length of the time window casts some doubt on the significance of the long-term embedded lithofacies cycles of 20 and 25 years. Furthermore, evidence of memory from the embedded facies analysis cannot be used directly with forcing as technically the time unit associated with the presence of any lithofacies is variable. However, it is likely that the significant 2- and 3-year steps of the regular facies analysis can be equated with the 2-steps of the embedded model. There seems little a priori reason for a subharmonic connection between deposition type and the 4 to 5-year surge cycle associated with atmospheric cyclonicity, suggesting that it is more likely that the deposition rate has been overestimated and that the lithofacies sequencing is associated in a direct one-to-one fashion with cyclonicity cycles. If this proposition is followed through it follows that higher-order memory in lithofacies (13-step) might be equated with either the 11 or 15-year rhythmicity in surge genera-

tion. The imprecision on lithofacies dating is a major limitation on further analysis.

Mesoscale analysis is principally interested in decadal scales of variation rather than the interannual scale which has just been considered. The forcing parameters show evidence of mesoscale change at a variety of scales. Surge potential offers an 11-year cycle to which it is tempting to relate sun-spot activity and the effect of ionising changes in the upper atmosphere (Huntington 1914). However, the storminess links with this latter physical change are indirect and likely to involve atmospheric changes that are beyond this immediate research area. It is certainly challenging to consider the implications of the longer-term trends identified by the polynomials (Figures 11A–C). These polynomials should only be viewed as a characterisation of trends within the time-window, and as such they identify a likelihood of atmospheric forcing periods of 30 or more years acting as an underlying control on storminess and surge generation and, indirectly, saltmarsh deposition. Storm spacing (fractal) and storm intensity (surge magnitude) appear to be variable over the mesoscale with signatures that can be recognised in the coastal deposition signal.

Conclusions

This study has identified variations in deposition rate for a saltmarsh-edge in north-west Ireland over the last century, that can be related to changes in coastal storminess. These changes identify two superimposed timescale controls on deposition: annual and decadal. The quasi-annual variation in deposition rate can be statistically explained in terms of annual frequency and magnitude of extreme water levels associated with storm-surges as recorded for the south-west British Isles. This relationship shows i) annual deposition rate varies inversely with annual level of storm-surge activity, and ii) increasing annual surge activity is associated with an increasing proportion of coarser sediment textural modes in the saltmarsh deposition. There is also mesoscale (decadal) control on deposition rate related to trends in the strength of surge generation that is linked to shifting patterns of storminess over the last century. This mesoscale regional surge-signal appears to specify a potential deposition signal that when filtered through local-scale site-specific geomorphological and sedimentary factors leads to the observed annual fluctuations in deposition.

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