Running title: INTERTIDAL BAR EVOLUTION ON A HIGH-ENERGY BEACH SYSTEM

Title: FIELD MEASUREMENTS OF INTERTIDAL BAR EVOLUTION ON A HIGH-ENERGY BEACH SYSTEM

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ABSTRACT

Nearshore bars play a pivotal role in coastal behaviour, helping to protect and restore beach systems particularly in post-storm conditions. Examination of bar behaviour under various forcing conditions is important to help understand the short to medium term evolution of sandy beach systems. This study carried out over a nine-week period examines, the behaviour of three intertidal bars along a high energy sandy beach system in northwest Ireland using high-frequency topographic surveys and detailed nearshore hydrodynamic modelling.

Results show that, in general, there was onshore migration for all the bars during the study period, despite the variability observed between bars, which was driven mostly by wave dominated processes. Under the prevailing conditions migration rates of up to 1.83 m day^{-1} and as low as 0.07 m day^{-1} were observed. During higher wave energy events the migration rates of the bars decelerated in their onshore route, however, under lower wave energy conditions, they quickly accelerated maintaining their shoreward migration direction. Tidal influence appears to be subordinate in these conditions, being restricted

to moderating the localised wave energy at low tides and in maintaining runnel configurations providing accommodation space for advancing slip faces.

The study highlights the intricate behavioural patterns of intertidal bar behaviour along a high energy sandy coastline and provides new insights into the relative importance of wave and tidal forcing on bar behaviour over a relatively short time period.

1. INTRODUCTION

Sand bars are common features of sandy beach systems in both intertidal (Ruessink and Terwindt 2000; Ruessink et al., 2002) and subtidal (Gelfenbaum and Brooks 2003) domains and in microtidal (Roy et al., 1994) to macrotidal (Levoy et al., 2000) regimes. They occur in swell-dominated to storm-wave conditions with changes in bar location and amplitude influencing beach and dune sediment supply regimes. Two reviews (Wijnberg and Kroon 2002; Masselink et al., 2006) have presented classification schemes for intertidal bars and three main types have been identified on the basis of morphology and environmental setting *viz. slip-face bars*, *low amplitude ridges* and *sand waves*. *Slip-face bars* have been described as having relatively large morphological amplitude; *low-amplitude ridges* are expressed as subdued topography whilst *sand waves* are labelled as 'marginal repetitive features'. Slip-face bars display a distinctively steep, landward-facing slip-face (slope usually $>30^{o}$) and low angle seaward slope (<3-6^{o}), with crest to trough heights generally over 1m. Low-amplitude ridges usually position themselves shore-parallel and group themselves into two to six bars, similar to what has been described as ridge and runnel topography. Crest to trough height does not normally exceed 1m in elevation and bar spacing is around 100m. The seaward slope of low-amplitude ridges is around 2-4^{o} and we usually find them located within the entire intertidal profile. Flat, low to medium energy beaches, with meso- or macro-tidal ranges are typical settings of this bar type. Intertidal sand waves are defined as straight or slightly sinuous, shore parallel and similar in morphology to sub-tidal sand waves. These features are the most morphologically subdued bar forms but can number from around four up to twenty. Rarely exceeding 0.5m in height their spacing is around 50m with a symmetric cross-section and slopes of 1-3^{o}. A common setting for this bar type is low energy, low inter-tidal slope but can occupy a range of tidal range environments (Masselink et al., 2006).

Formation of bars is normally associated with storm activity whereby material is eroded from beach/dune systems by wave action and moved offshore. Sediment reworking onshore during the post-storm phase typically involves initial formation of a ridge(s) over several tidal cycles. Once the ridge is formed, and providing wave energy is low to moderate, the bar stabilises or migrates onshore across the intertidal zone (Aagard et al., 2006). Bar migration occurs as long as swash action can overtop the bar crest; the ridge crest may stabilise when tides change from springs to neaps and overtopping ceases (Masselink et al., 2006). Under the latter conditions swash and backwash still operate on the seaward slope and an overall increase in elevation of the feature occurs due to accretion on the seaward edge. The bar-face may then be trimmed by currents flowing in the troughs (Anthony et al., 2005).

Circulation patterns and wave activity in the nearshore are directly influenced by the presence of bars, which in turn, dictate the patterns of sediment transport within the surf and swash zones (Jackson et al., 2007). Local tidal variability and wave climate determine the extent to which hydrodynamic conditions alter and shape nearshore bars (Wijnberg and Kroon 2002; Gelfenbaum and Brooks 2003). Traditionally, the concept of *onshore* movement of sand bars has been associated with fair-weather conditions in the aftermath of winter storms that caused initial *offshore* movement of sand (Aubrey 1979;

Thornton et al., 1996; Gallagher et al., 1998). However, the number of accounts of the mechanisms and patterns of *onshore* sediment movement in bars are surprisingly few and direct field quantification of bar movement is rare (Elgar et al., 2001; Aagard et al., 2006). Both laboratory and field studies have, however, proposed that fluid accelerations and velocities are largely responsible for driving sediment transport and, subsequently, sand bar migration across the surf zone (Osborne and Greenwood 1993; Jaffe and Rubin 1996).

Recorded migration rates of intertidal bars vary considerably from virtually static to values of around 1m day^{-1} in low to moderate wave energy conditions (Wijnberg and Kroon 2002). Rates of up to 5 m day^{-1} have been noted in higher wave energy regimes (Elgar et al., 2001; Aagard et al., 2006). As bars migrate landward they become subject to less frequent overtopping and may ultimately weld to the shoreline as the intervening runnel is in-filled (Aagard et al., 2006). Anthony et al (2004; 2005) suggested that the presence of strong trough (runnel) flows can be an important control on bar migration and Aagard et al. (2006) demonstrated that the infilling of the trough can affect bed return flows, also a key determinant in the dynamics of bar migration.

Several authors have identified diurnal tidal variation as a major control on bar behaviour. Wijnberg and Kroon (2002) contend that bars migrate more rapidly under spring tidal conditions when overtopping is more frequent. In contrast Masselink et al. (2006) suggest that neap tides produce vertical focussing of wave action within a narrow band and hence bars are more active under those conditions. Wijnberg and Kroon,

(2002) considered that high-energy waves cause an increase in set-up and consequently undertow may temporarily become dominant over the intertidal beach, resulting in bar destruction and flattening of the beach.

The beach and dunes at Five Finger Strand (Northwest Ireland) are adjacent to a tidal inlet and associated ebb-tide delta. Analysis of historical patterns of behaviour of the system (Cooper et al., 2007) indicates that periodic switches in position of the ebb channel at a multi-decadal timescale are the main driver of long-term coastal behaviour. During each of these channel switches, a new ebb delta forms at the channel terminus, drawing in sand from the adjacent beach. This causes the beach to be lowered and enables waves to penetrate to the vegetated dunes and erode them. The records in this study relate to the early stages of this reworking under conditions of abundant sediment supply and available depositional space (accommodation space) on the adjacent beach. Such conditions are rare and offer an unusual insight into bar migration.

This paper outlines field measurements of intertidal bar evolution on a high-energy beach system. The nature of the bars is described and their behaviour and morphological evolution over a 9-week period is outlined in the context of direct forcing variables (waves and tides). These observations provide an opportunity to test the existing models of intertidal bar behaviour presented by Wijnberg and Kroon, (2002) and Masselink et al. (2006) and in particular to assess the comparative role of wave conditions and tidal variation.

2. STUDY AREA

Five Finger Strand is situated on the north coast of the Inishowen Penninsula, Co. Donegal, Ireland. The beach extends for approximately 1.7km in a north-south direction between the Five Fingers Rock and Lagg Point at the narrow inlet of Trawbreaga Bay (Fig.1). The strand maintains a modally dissipative beach (Wright and Short, 1984) whose intertidal zone is 350m wide, backed by a large vegetated dune system. The beach sediment comprises carbonate-rich terrigenous sand (mean grain size 0.21 mm and largely homogenous) with a subordinate gravel component overlying a cobble/gravel base of glacial sediments. The mean spring tidal range at the site is 3.3 m. The open coast is swell wave dominated with a modal significant wave height of ca. 2.2m and period 9s. The dominant swell approach is from the W and SW and waves are fully refracted within the headland-embayment system (Jackson et al., 2005).

INSERT FIG. 1

The mesoscale (decadal) dynamics of the site is driven by tidal inlet switching and tidal delta formation and abandonment in that when the ebb channel switches, the former channel is abandoned and the sediment stored in its delta is then reworked by wave action (Cooper et al., 2007; O'Connor et al., 2011). The observations reported in this paper were made during a phase of ebb delta reworking through the formation and dominantly landward migration of a set of subtidal and intertidal bars (Fig. 1). The beach lowering associated with initial channel migration produces a large accommodation (depositional) space for later sediment accumulation and the sand being reworked from the ebb delta provides an abundant sediment supply.

3. METHODOLOGY

Profile information was gathered using DGPS along a number of fixed profile lines established on the 1.7 km stretch of beach between 1st July and 10th September 2003. A quad bike-mounted DGPS surveying system (Trimble 4400) was employed to acquire topographic information. The typical precision of an initialised kinematic survey is 10 mm + 2ppm (1 standard deviation) (Huang et al., 2002). Surveys were reduced to the national datum (Irish Ordnance Datum (OD) Poolbeg, Dublin).

Repeat topographic surveys at fixed positions enabled the chronological changes in bar morphology to be established over the 9-week period. From these data the rates of slip face movement and crest height evolution were extracted. In order to characterise the intertidal bars and their behaviour, two profiles (profile lines 1 and 3, Fig. 2) were selected for analysis, as they consistently pass through the main body of the bars and are representative of the entire beach. Profile 1 intersects Bars A and C and Profile 3 passes through Bar B.

INSERT FIG. 2

Offshore wave data were recorded by the Marine Institute M4 wave buoy (inset in Fig. 1), located in approximately 56 m water depth in the northwestern Irish shelf (54^{o} 24’, N 9^{o} 02’W) from which deep-water wave conditions (hourly significant wave height and mean wave period) for the duration of the survey period were obtained. Given the absence of directional measurements, wave direction was obtained from the hindcast Met Office UK Waters Wave Model (Golding 1983; Bradbury et al., 2004) for a grid cell coincident with the M4 buoy location, as this model presents a very good agreement with the buoy records for the study period (R = 0.85 and RMSE = 0.37 for significant wave height). The hindcast model wave direction data is provided on a 3-hour interval and was linearly interpolated to match the hourly frequency of the wave buoy data.

The offshore wave conditions (H_s – significant wave height, T_m – mean wave period; *Dir* – mean wave direction) were used to force the nearshore propagation with SWAN wave model (Booij et al., 1009, Ris et al., 1999). SWAN was implemented using a nested modelling scheme, with modelling domains composed of a 30m resolution local grid around the Five Finger Strand area, nested into a regional 100m resolution grid extending from the M4 location to the Inishowen Peninsula area (Fig. 3). Simulations were run at hourly intervals from the 1st of July to the 20th of September 2003 with the parametric data from the buoy and hindcast model applied uniformly to the offshore boundary, considering a JONSWAP spectral shape to represent the wave field and variable water levels. SWAN was run in third-generation mode, using default parameters for linear wave growth and whitecapping dissipation, JONSWAP bottom friction dissipation model following Hasselmann et al. (1973), and depth-induced breaking imposed by a scaled breaker index according to the β-kd model for surf-breaking (Salmon and Holthuijsen 2011). The wave frequency and directional space were discretized in 33 logarithmic-distributed bins from 0.03 to 1.00 Hz and 36 regular distributed bins, respectively.

The two regular bathymetric grids used for the simulations, with 100m and 30m resolutions, were compiled from high-resolution multibeam and airborne LIDAR data collected in the framework of the Joint Irish Bathymetric Survey (JIBS) and the Integrated Mapping for the Sustainable Development of Ireland's Marine Resource (INFOMAR) project. The nearshore bathymetry of the Five Finger Strand embayment, landward of 9m-depth contour, was obtained using a linear transform algorithm applied to multispectral Landsat imagery tuned with multibeam and LIDAR data from a nearby location, following the procedure described in Pacheco et al. (2015). Bathymetric data, provided in LAT (Lowest Astronomical Tide) were reduced to mean sea level (approximately +2.2m OD Poolbeg, Dublin).

INSERT FIG. 3

SWAN output variables computed included H_s, peak (T_p) and mean (T_m) wave period, as well as mean (*Dir*) and peak (*DirP*) wave direction. These were extracted at hourly intervals for a set of grid points located in the centre of the embayment and approximately 5m below mean sea level (equivalent to -2.8m OD Poolbeg, Dublin). Wave data for these locations was averaged, providing a time-series of nearshore waves in the area of incipient wave breaking for the duration of the study period.
Water levels were obtained from the astronomical tide predictions for the local tidal gauge (Malin Head). Records were subsequently reduced to OD Poolbeg, Dublin, and used to characterize water level variations and compute the daily maximum tidal range.

In order to relate intertidal bar geomorphic evolution with hydrodynamic forcing and quantify the combined influence of waves and tides in bar migration rates, the normalised wave power (Pn) was computed according to Morris *et al.* (2001):

$$Pn = P(\eta_{\text{dtr}}/\eta_{\text{str}}) \quad (1)$$

where η_{dtr} is the maximum daily tidal range, η_{str} is the maximum spring tidal range, and P is the wave power, given by:

$$P = ECg \quad (2)$$

where E is the wave energy computed according to linear wave theory:

$$E = (1/8)pgH_s^2 \quad (3)$$

and Cg is the wave group velocity, which according to the shallow water approximation is obtained by:

$$Cg = \sqrt{(gh)} \quad (4)$$

where p is the density of water and g is the acceleration due to gravity and h is the nearshore water depth.

The Pn parameter has been shown to adequately reflect the enhanced erosion potential during spring tides, restricting it for lower tidal ranges (Morris *et al.*, 2001) and applied to investigate hydrodynamic forcing and morphological change in mesotidal beaches (Loureiro et al., 2012), as well as to force equilibrium models of 3D morphological change (Stokes et al., 2015).

4. RESULTS

4.1. Bar Morphology and Type

Figure 2 shows the plan and cross-sectional morphology of the intertidal beach and bars. In plan form, the bars have discontinuous, sinuous crests with a shore-parallel orientation. The overall intertidal beach slope (MHWN-MLWN positions) averages 0.69^{o} in the south where one intertidal bar is present and 0.25^{o} in the north where there are two intertidal bars. In cross-section (Fig. 2ii and iii) the bars are strongly asymmetrical. They have gently sloping seaward faces with a consistent slope of around 0.7^{o} and a steep landward face that slopes between 3 and 15^{o} into a landward runnel. The bars are typically around 1 m in height and 150m wide. This combination of features characterises them as intertidal slip face bars (Masselink et al., 2006).

The position in the tidal frame of each bar differs. At the start of observations, the crest of Bars C and B were located below the neap high tide level (ca 2.3 m and 2.7m. respectively) and were therefore overtopped at every high tide. Bar A was located higher in the tidal frame (ca 3.0 m) and was overtopped less frequently.

4.2. Intertidal Bar Geomorphic Evolution

The geomorphic behaviour of the intertidal bars is described using topographic profiles that contain two (Profile 1) or one (Profile 3) intertidal bars. Profile 1 on the northern section of the beach shows the development of two bars (A and C) and associated runnels. The net behaviour observed during the 9 weeks of observations was of slip face landward migration by transport of sediment from the stoss side and eventual infilling of the runnel (Fig. 4i). The elevation of the leading edge of the bars showed a general increase as the bars migrated onshore across the intertidal beach. The elevation of the bar crests rose over the study period. For bar C in particular, where it was initially located below mean high water neap (and covered at every high tide), it was then positioned above that level, when it was no longer covered by every tide. Detailed examination, however, reveals differences in the evolution of the two runnel systems on this profile. The seaward runnel that separates the two bars was infilled by rapid crest migration of bar C. This was associated with gradual reduction in height of the slip face (Fig. 4iii) as the runnel shallowed and was reduced in its cross-sectional area. Eventually, the rapidly advancing slip face ridge of Bar C merged with the slowly migrating stoss side of Bar A. At this stage, the intervening runnel was totally infilled, and the two former bars merged to form a single entity.

The runnel landward of Bar A (Fig. 4ii) was initially deeper and was infilled by a slower rate of slip face advance than that of Bar C because of a larger discharge in the runnel. This migration caused a reduction in cross-sectional area of the runnel as it infilled by slip face advance and therefore a loss of competence aiding in the process of infilling and hence represented a positive feedback in the system.

During landward migration, the bars became slightly wider as the slip face advanced more rapidly than the stoss face. This suggests that cannibalisation of the stoss side is feeding the advance of the slip face and that the bar is eventually 'smeared' across the beachface. Up to the point at which the two bars merged, however, they essentially maintained their cross-sectional form as they migrated upwards and landwards. The slip face remained at a consistent angle throughout the bar migration until the point just before the bars welded.

INSERT FIG.4

Profile 3 (Fig.5) contained a single slip face ridge whose landward face migrated steadily shoreward over the study period. Its seaward face, however, remained in essentially the same position. The flat, upper surface of the bar extended landward without substantial vertical accretion. Thus the bar became wider but maintained its vertical position. The net effect was for landward infilling of the runnel as the bar extended in that direction. The bar crest remained at and/or around neap high tide levels throughout the study.

INSERT FIG.5

In contrast to Bars A and C which maintained their form as they migrated, Bar B became progressively wider. This situation is indicative of an offshore sediment supply that enabled the crest to advance without the need for cannibalisation of the bar's stoss slope. Bar B is buffered by a more extensive sediment body between itself and the channel, offering a ready sediment supply, as opposed to Bars A and C which were positioned closer to the main channel and were fronted by a much reduced sediment body (supply) width. In both cases, the slip face maintained a steep profile throughout its landward migration and did not actually weld to the subaerial beach during the study period.

4.3. Bar Migration Rates

To compute bar migration rates, bar positions were measured during each survey that took place with a time interval of 3 to 5 days. For calculation purposes, a constant rate of movement was assumed throughout inter-survey periods. The rates were obtained by comparing the total movement of each bar between surveys and then compared to the average wave height (H_s) and normalised wave power (Pn) during those 3-5 days for which the bars were migrating.

Figure 6 shows the migration rates for each of the bars based on the position of the mid-slip face point in relation to the hydrodynamic forcing variables considered. Migration rates, calculated by dividing the total displacement of mid-slip face by the number of days between surveys, varied between offshore-directed 0.38 m day^{-1} and onshore-directed 1.83 day^{-1}. The majority of movements were onshore-directed.

INSERT FIG.6

Mean wave forcing during the study period reveals a low to medium energy nearshore environment with mean H_s of 0.81m, T_m around 6 s and waves approaching from WNW (299º). Four relatively high-energy wave events (H_s > 1.5m) with W-WNW direction occurred during 10th-12th July, 1st-3rd August19th-23rd August and 6th-8th September , during which average nearshore significant wave heights were 1.78, 1.76, 1.35 and 1.5 , respectively (Fig.6ii). Maximum nearshore significant wave heights during these events reached 2.13, 2.3, 1.85 and 2 m while averaged storm normalised wave power levels were 11075, 16495, 5349 and 11869 W/m, respectively. Each of these high-energy events was accompanied by a deceleration (ascending sections of the lines in Fig. 6i) in subsequent bar migration rates on Bar C and Bar A (Fig.6). Bar A, which is closest to the shore and limited seaward by Bar C, showed less vigorous response to the variations in hydrodynamic forcing. Bar B, which is relatively sheltered by offshore subtidal sediment bodies and the tidal channel, displays slower onshore migration rate over the study period.

INSERT FIG.7

Correlation analysis of migration rates with the normalised wave power (Fig.7) reveals an apparent increase in bar migration rate with more energetic conditions and this is mostly evident at Bar C (Fig. 7iii), while no statistical significant correlation is found for Bar A and B. Furthermore, under more energetic forcing (Pn > 6000 Wm^{-1}), no clear correlation between bar migration and normalised wave power is apparent, possibly due to increased water levels (positive surge) and hence less efficient wave-seabed interaction. Other factors (e.g. position in the tidal frame, proximity to the tidal inlet etc.) may therefore be assuming greater importance as wave height is reduced.

On Bar A, which is sheltered by Bar C, results suggest a possible tidal influence on migration rates. During spring tides there is tendency for onshore migration rates to slow (Fig. 6) compared to those of neap tides for similar wave energy levels. This suggests that in those conditions, spring tides increase the flux of water through the runnel and cause more erosion of the slip face than can be countered by wave-induced deposition.

5. Discussion

The observations reported here can be compared with published observations of slip-face bar behaviour in other settings. The typical conditions under which intertidal slip-face bar formation and migration is reported relate to short-term storm recovery phases (Wijnberg and Kroon 2002; Masselink et al. 2006) when storm-eroded sediment is reworked under ensuing fair-weather conditions. The conditions reported here are similar, in that they involve sediment reworking following erosion (associated with relatively high wave energy events) but unusual because of the timescale under which the post-erosion recovery period occurs. This prolonged period in a high-energy wave climate setting increases the likelihood of occurrence of high wave conditions during the recovery phase and thus could strongly affect onshore bar migration patterns.

The bar migration rates recorded in the study area range from below close to 0 m day^{-1} up to almost 2 m day^{-1}, and thus similar to those recorded by Wijnberg and Kroon (2002) who reported observations during low to moderate wave energy associated with 1m day^{-1} migration rates. Wave energy is a dominant factor in the behaviour of the more exposed intertidal bars in the study area (especially bar C and to a lesser extent A), and appears to be more important than variations in tidal range that have been reported elsewhere (Wijnberg and Kroon 2002; Masselink et al., 2006).

The more sheltered Bar A does show a loose relationship between migration rate and tidal range. These observations, however, contrast with those of Wijnberg and Kroon (2002) who found that bars migrate onshore more rapidly during spring tides due to more frequent overtopping. After welding of Bar C to Bar A there was an acceleration in the onshore migration rate of the slip face of the newly merged bar. This may be attributed to a new influx of sediment as the bars welded and/or a period of reduced wave power which coincided with this welding phase (Fig 6ii).

For the morphological evolution of intertidal bars reported here, infilling of the runnel landward of the advancing bar crest took place through slip face progradation. Shallowing of the runnel was accomplished through deposition on its floor of the excess sediment that was not removed by shore-parallel currents in the runnels. Progressive infilling reduced the water discharge through the runnels leading to reduced efficiency. Under these conditions, a positive feedback mechanisms whereby reduced currents in the runnel facilitate more rapid progradation of the slip face, and the ultimate closure of the runnel, is considered to have occurred.

The observations presented imply that under high wave energy conditions, waves exert the primary influence on bar migration rates whilst tidal influence, although a contributing factor in helping to decelerate or accelerate bar migration patterns, appears to adopt a more subordinate role under the conditions examined in this study. During the first two successive high energy events, both bars C and A display a deceleration of their onshore migration rates and then subsequent to these higher energy events, the bars regain their accelerated onshore migration behaviour. The third high energy wave event, when normalised with tides to give a weighted wave power, actually shows a significantly lower normalised wave power than the previous two events. Bar A during this phase of lower wave forcing still shows onshore migration but at a slower rate. Migration patterns appear to be controlled by the interaction of tidal range and wave action, resulting in enhanced onshore migration. There is also a spatial dimension in that more landward and sheltered bars are less affected by incident wave energy than those in seaward positions.

The scatter of values (Fig. 7) of migration rate *vs.* normalised wave power under lower wave conditions in the study area suggests that both wave energy and tidal range play roles that are difficult to separate, but that above a certain threshold ($H_s \cong$ 1m; Pn: 2000 W/m) wave action becomes dominant, particularly in bar C which is the most exposed bar to incident waves.

As the bars migrate onshore they reach higher levels in the tidal frame and would therefore be expected to slow down due to less frequent overtopping (Wijnberg and Kroon 2002). This is not apparent in our observations and may be due to enhanced swash run-up overcoming any additional elevation reached by the migrating bars.

Most previous studies (Wijnberg & Kroon 2002; Masselink et al. 2006) have been in moderate to low wave energy environments. In those settings, tidal water levels can be demonstrated to play an important role in bar migration. In contrast, even though the tidal range is relatively large in our study area (3.8m), wave energy exerts a dominant influence on migration patterns of the seaward (and therefore more exposed) bars. This points to a different, wave-dominated domain of bar behaviour that contrasts with tide-dominance in low wave energy settings.

6. CONCLUSIONS

This study examines the short-term (9-week) behaviour of intertidal bars on a high energy coast using DGPS topographical surveys, detailed nearshore wave modelling combined with local tide levels. Several high-energy wave events were identified during this period. Over the entire study period all bars largely migrated onshore but this behaviour was not regular and was mostly related to energetic wave conditions and intervening lower energy phases. In general, higher energy events resulted in a deceleration of the onshore bar migration rates, whilst in lower wave energy periods, bars accelerated in their onshore migration. This behaviour is reflected most in the northern part of the beach where bars C and A are located. However, bar A being sheltered by the seaward-fronting Bar C, has a more muted behavioural response to this forcing. Bar B is also sheltered by the presence of offshore submerged sand bodies and is close to the inlet channel edge. This results in wave energy reduction at Bar B which is reflected in the relatively low but steady bar migration rates of Bar B over the entire study period.

In general, wave forcing is the main driver of changes in bar migration patterns at the site, helping to accelerate (low energy conditions) and decelerate (high energy) the rate of onshore migration. Tidal influence also contributes to bar behaviour at the site but has a more subordinate role compared to wave forcing (evidenced by the normalised wave power data), helping to moderate localised wave energy and maintaining runnel flushing within tidal cycles.

This short-term study provides valuable insights into post-storm beach recovery mechanisms along high-energy sandy coasts, particularly when intertidal sand bars are present and are on the process of welding back onto the beachface.

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FIGURE CAPTIONS

Figure 1. Location of Five Finger Strand within Trawbreaga Bay, Northwest Ireland. Map is based on the ordnance survey map of 1904.

Figure 2. Photo of Five Finger beach site (i), showing profile lines 1 and 3 and cross sections through each at the start of the survey (ii and iii).

Figure 3. Location of the computational grids used for wave modelling simulations, (i) 100m resolution grid and (ii) 30 m nested grid.

Figure 4. Sequential profiles of bars A and C showing (i) overall profiles of Bars A and C (ii) Zoomed view of bar C slip face and crest and (iii) zoomed view of Bar A slip face and crest.

Figure 5. Sequential profiles of bar B showing (i) overall profile, and (ii) zoomed view of Bar B slip face and crest

Figure 6. (i) Bar migration rates. Note that descending parts of the graph represent acceleration bar migration rates whilst ascending indicates deceleration of migration rates. Note that most of the migration for all bars was onshore during the study period. (ii) nearshore significant wave heights and normalised wave power. A total of four higher energy events can be observed. Note that the normalised wave power plot can at times

show reduced wave energy levels with coincident with lower tidal stages and (iii) tidal elevations during the experiment. Note periods of neap tides are highlighted.

Figure 7. Bar migration rates vs. normalised wave power for (i) Bar A, (ii) Bar B and (iii) Bar C. Note that Bar C displays the best correlation (r^2 value 0.84; P value 0.04 and therefore result is significant at $p<0.05$) in terms of forcing and response and this is likely due to its exposed location relative to other bar positions (P values not significant at $p<0.05$ and low r^2 values).

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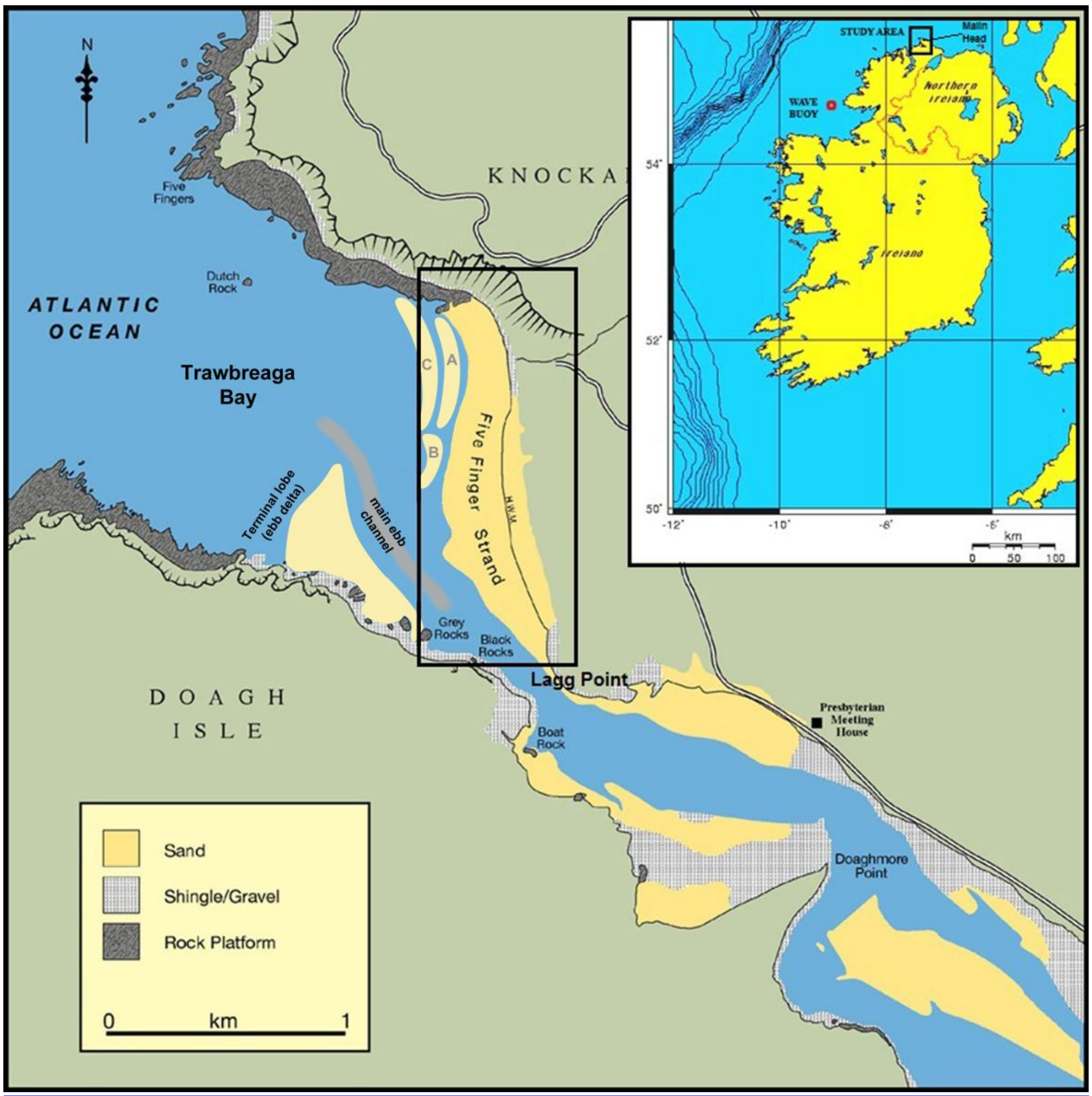
Figure1



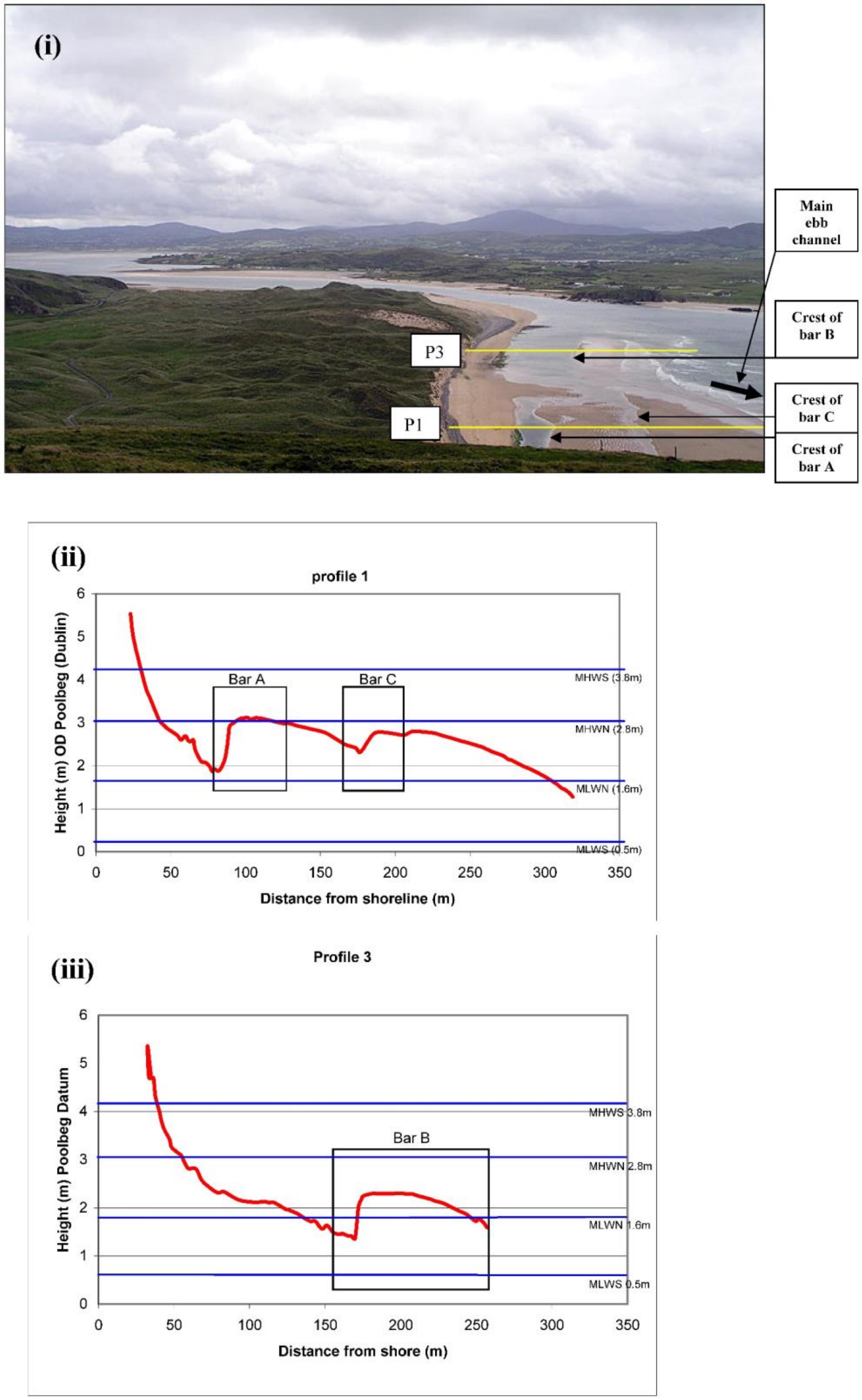
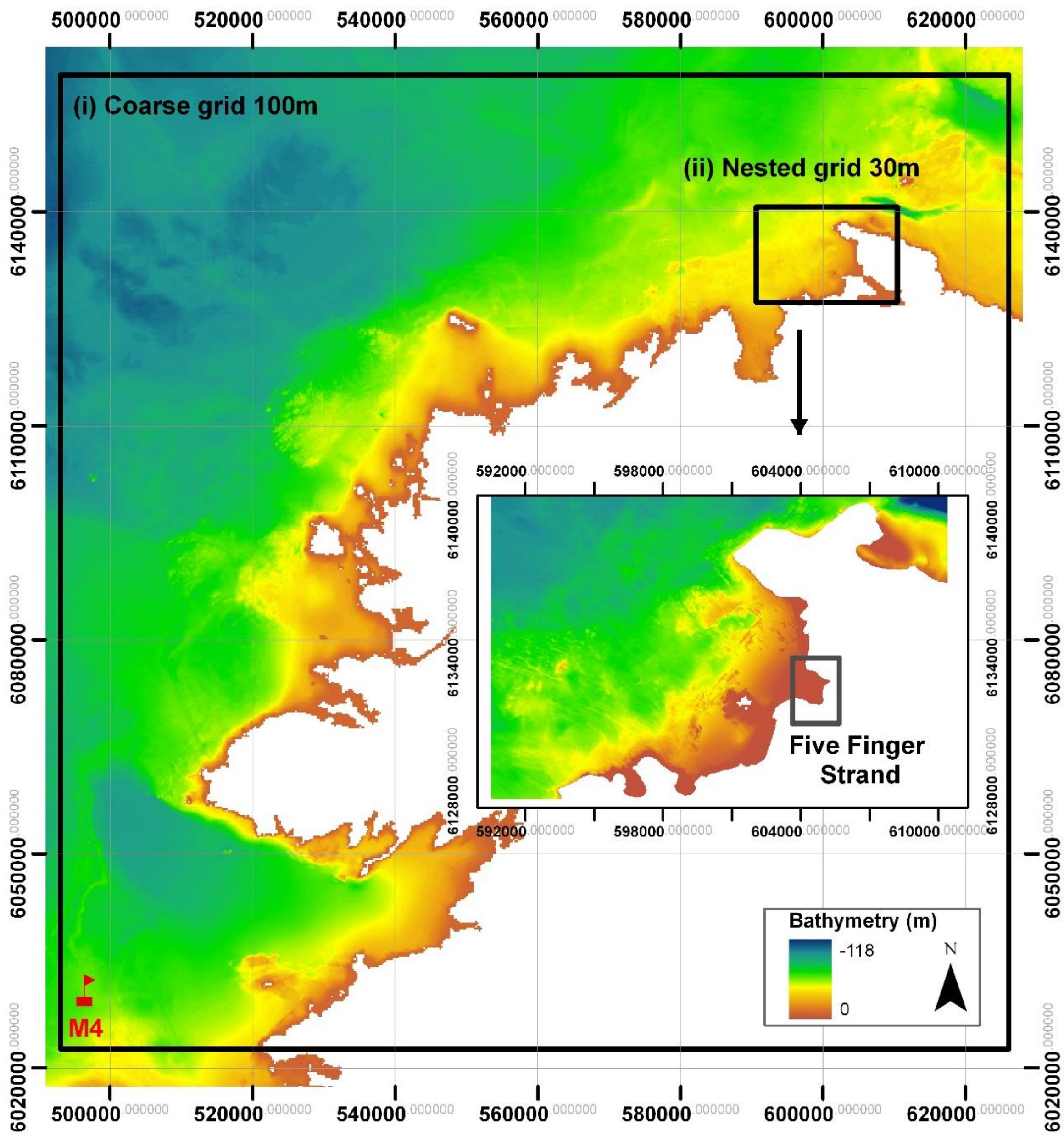

(i)
Main ebb channel
Crest of bar B
Crest of bar C
Crest of bar A
P3
P1
(ii)
profile 1
Height (m) OD Poolbeg (Dublin)
Bar A
Bar C
MHWS (3.8m)
MHWN (2.8m)
MLWN (1.6m)
MLWS (0.5m)
Distance from shoreline (m)
(iii)
Profile 3
Height (m) Poolbeg Datum
Bar B
MHWS 3.8m
MHWN 2.8m
MLWN 1.6m
MLWS 0.5m
Distance from shore (m)

FIGURE 2


(i) Coarse grid 100m
(ii) Nested grid 30m
Five Finger Strand
Bathymetry (m)
-118
0
N
M4

591
592 Fig. 3

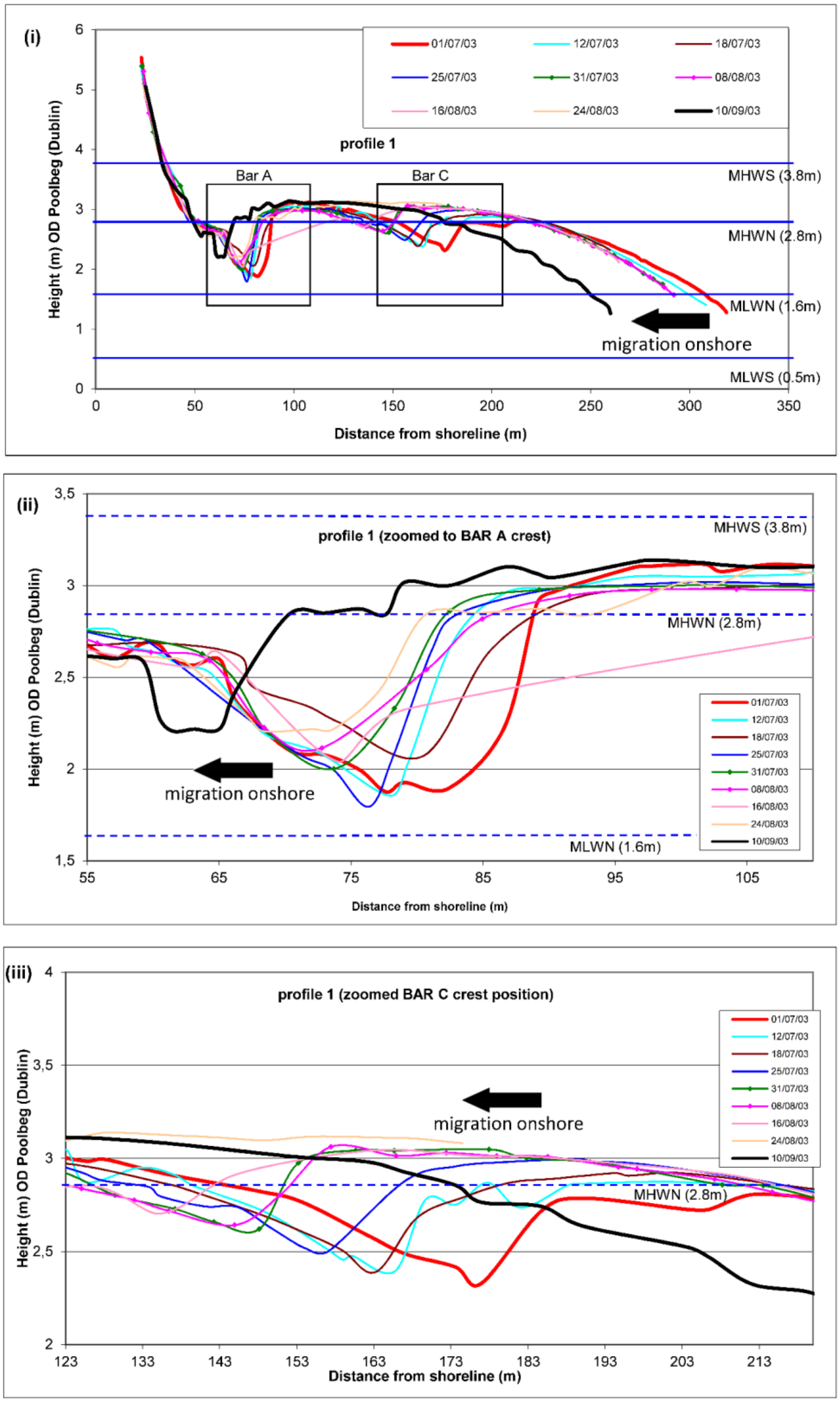

(i)
profile 1
01/07/03
12/07/03
18/07/03
25/07/03
31/07/03
08/08/03
16/08/03
24/08/03
10/09/03
Bar A
Bar C
MHWS (3.8m)
MHWN (2.8m)
MLWN (1.6m)
MLWS (0.5m)
migration onshore
Height (m) OD Poolbeg (Dublin)
Distance from shoreline (m)
(ii)
profile 1 (zoomed to BAR A crest)
MHWS (3.8m)
MHWN (2.8m)
MLWN (1.6m)
migration onshore
Height (m) OD Poolbeg (Dublin)
Distance from shoreline (m)
(iii)
profile 1 (zoomed BAR C crest position)
migration onshore
MHWN (2.8m)
Height (m) OD Poolbeg (Dublin)
Distance from shoreline (m)

FIG.4

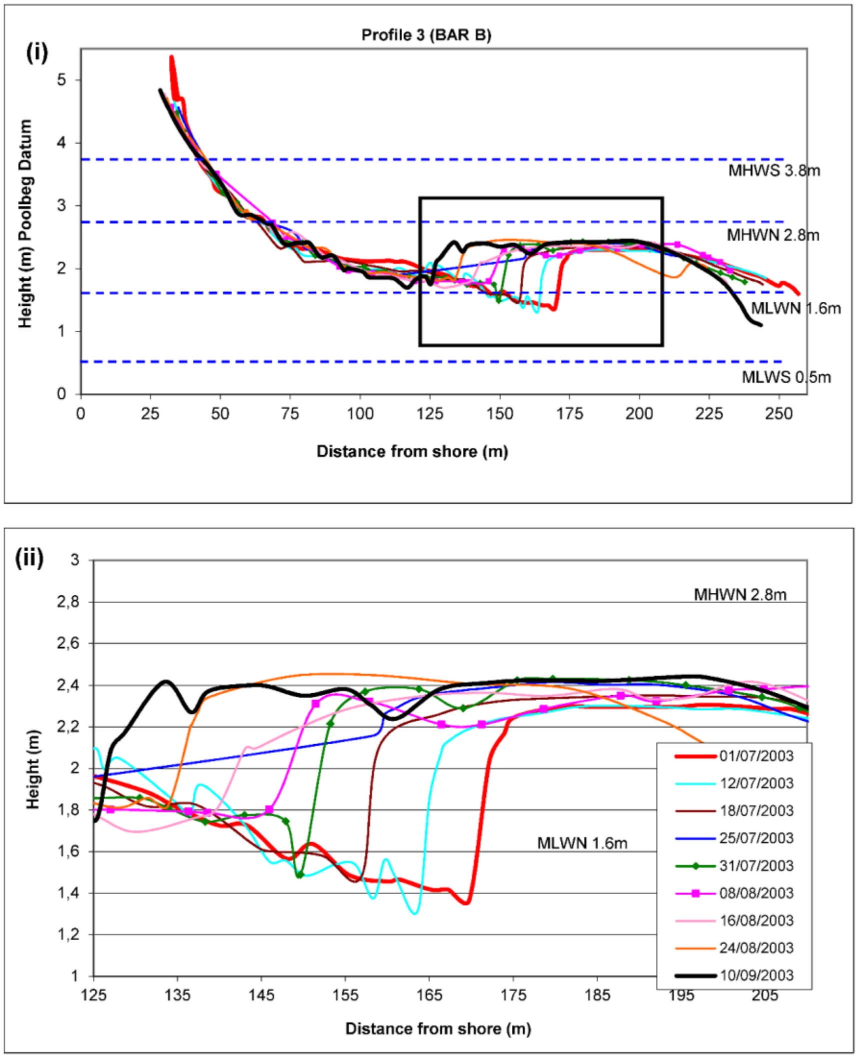

(i)
Profile 3 (BAR B)
Height (m) Poolbeg Datum
Distance from shore (m)
MHWS 3.8m
MHWN 2.8m
MLWN 1.6m
MLWS 0.5m
(ii)
Height (m)
Distance from shore (m)
MHWN 2.8m
MLWN 1.6m
01/07/2003
12/07/2003
18/07/2003
25/07/2003
31/07/2003
08/08/2003
16/08/2003
24/08/2003
10/09/2003

FIGURE 5

594

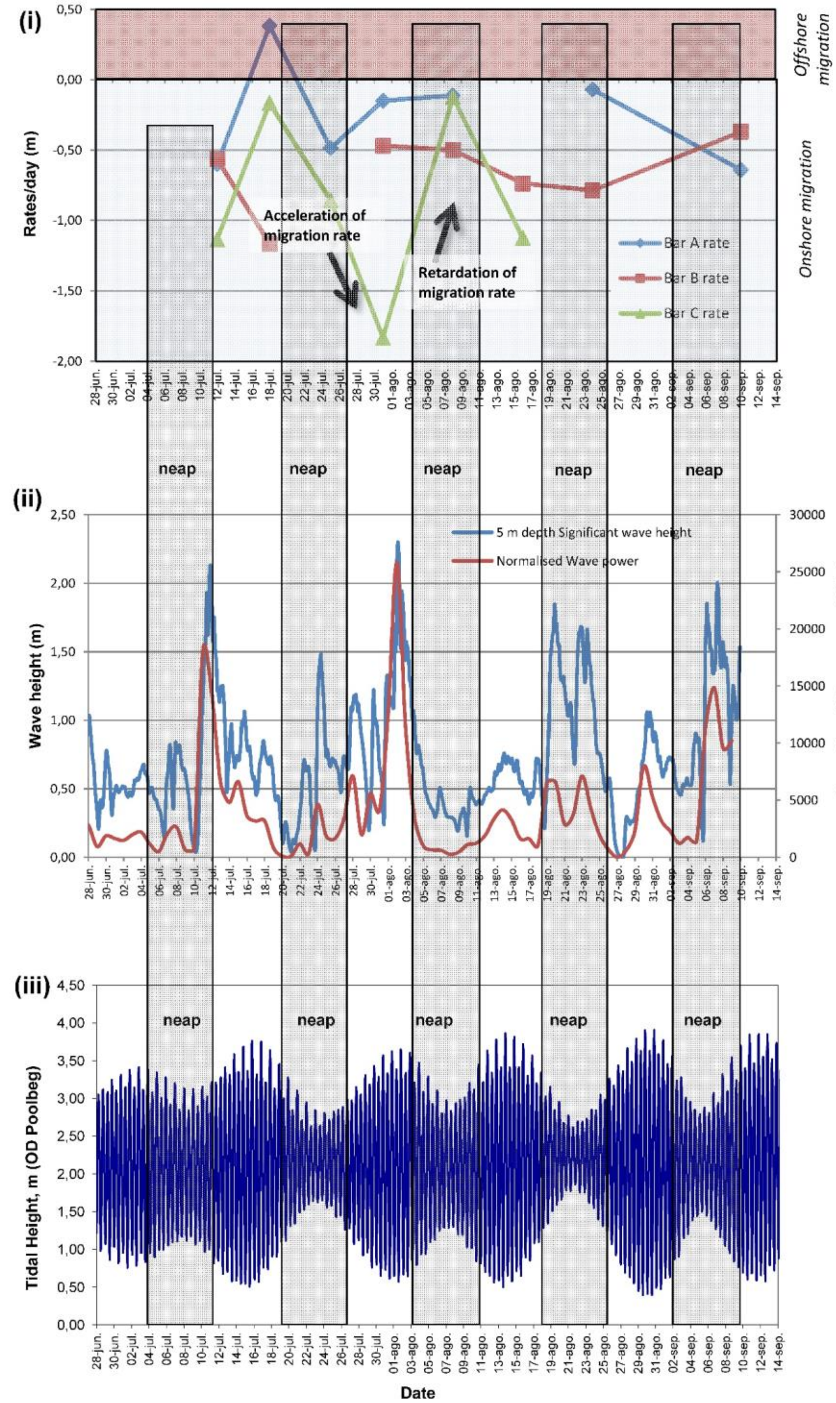

(i)
Rates/day (m)
Offshore migration
Onshore migration
Acceleration of migration rate
Retardation of migration rate
Bar A rate
Bar B rate
Bar C rate
neap
(ii)
Wave height (m)
Normalised Wave power (W/m)
5 m depth Significant wave height
Normalised Wave power
(iii)
Tidal Height, m (OD Poolbeg)
Date

FIGURE 6

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