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FIELD MEASUREMENTS OF NET SEDIMENT FLUX FROM INDIVIDUAL SWASHES ON A SANDY BEACH

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Abstract

The shoreline along sandy beaches is located at a unique position on the earth's surface where marine and terrestrial processes converge. The swash zone distinguishes the landward-most reach of wave action. Field observations from this shallow and highly energetic region reveal that individual waves regularly deposit or remove hundreds of kilograms of sand per meter width of beach. Such high rates of sand movement represent several centimeters of bed-level change and far exceed the underlying pace of beach evolution. Relatively large morphological changes caused by single swashes might suggest that very rapid beach erosion or accretion is a common occurrence. The contrasting reality shown by these new observations is that beaches generally exhibit a state of dynamic equilibrium.

Key words: swash, sediment transport, morphodynamics, beachface, bed-levels

1. Introduction

The swash zone is the region of the beach that is episodically submerged and exposed by the uprush and backwash of waves arriving at the shore. Accelerating and decelerating flows at the beach face cause sediment to be transported, and the integration of this wave-by-wave sediment movement leads to morphological changes which can occur at timescales ranging from a single swash event to long term coastal erosion. The swash zone is widely recognised as the most dynamic region of beach sediment movement, characterised by strong and unsteady flows, high levels of turbulence, large sediment fluxes and the highest suspended sediment concentrations (Masselink & Puleo, 2006).

The majority of the world's sandy shorelines are presently eroding, and rates of coastal erosion are predicted to grow in coming decades as global and regional climate change results in accelerating sea-level rise and increasing coastal storminess (IPCC, 2007). Process-based coastal evolution models are increasingly being used by coastal managers to inform decision making, and can presently be applied with a reasonable degree of confidence to predict a range of morphodynamic beach changes, including the formation of sandbars (e.g., Ruessink *et al.*, 2007) and the development of rip channels (e.g., Reniers *et al.*, 2007). While these capabilities provide results of significant scientific interest, it is the changing location of the shoreline boundary in response to changing trends in sea-level and wave climate that is of principal concern to coastal planners and policy-makers. However, the physical processes occurring at this critical land-sea interface remain poorly understood. Indeed, to circumvent this problem many coastal evolution models presently neglect the existence of the swash zone. Breaking wave heights are assumed to decrease through the surf zone, becoming zero at a fixed landward position representing the shoreline, thus avoiding the very significant challenges of modelling a complex, moving and physically unresolved boundary.

Detailed research into swash zone hydrodynamics and sediment transport processes has been relatively recent, with much of the initial work in the 1980's and early 1990's tending to focus on the statistical description of the horizontal and vertical excursion of waves as they run up the beachface (e.g., Holman & Guza, 1984; Nielsen & Hanslow, 1991; Holland & Holman, 1993). In the past ten years, the focus has shifted to the identification and examination of processes that drive morphological change in this region;

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however, recent reviews stress that considerable work is still required (Butt & Russell, 2000; Elfrink & Baldock, 2002; Masselink & Puleo, 2006; Brocchini & Baldock, 2008). There is general consensus that swash zone research presently lags that of its counterparts in the adjacent surf and nearshore zones. There are (at least) two factors that have restricted progress: firstly, the inherent complexity of the physical processes to be resolved; and secondly, the considerable challenge of obtaining meaningful field observations from which new process insight can be gained. The swash zone is a notoriously hostile environment in which to undertake experimental research, characterised by energetic, turbulent, rapidly-varying, sediment-laden and aerated flows. The logistical problems are compounded by the requirement to make measurements very close to a fluctuating bed. Consequently, detailed field observations on which to base future model development are presently limited.

Based on discussions from the 1st International Workshop on Swash Zone Processes' held in 2004, Puleo & Butt (2006) suggested that in order to improve understanding and modeling of swash, there is a need to obtain measurements of swash morphology and hydrodynamics on a swash-by-swash basis to permit net sediment fluxes to be quantified and provide a suitable dataset against which to test modelling approaches. Estimates of net cross-shore sediment flux in the swash zone have been reported by a number of previous investigators by a variety of techniques. Hughes *et al.* (1997) and Masselink & Hughes (1998) made use of sediment traps to measure the total sediment load passing a point on the beachface on the uprush and backwash; however, recent measurements by Masselink *et al.* (submitted) suggest that these traps tend to underestimate total sediment load by a significant factor. Other researchers including Butt *et al.* (2004; 2005), Aagaard & Hughes (2006), Masselink *et al.* (2005) and Puleo *et al.* (2000; 2003) used collocated measurements of suspended sediment concentration and cross-shore flow velocity to estimate instantaneous sediment flux. This technique has been used to determine net cross-shore sediment flux from individual waves for comparisons with Bagnold-Type sediment transport models; however it is noted that this analysis can only provide information about suspended sediment transport and tends to underestimate the duration of backwash as the flow depth becomes too shallow for valid velocity measurements to be made.

Beach morphological change is the result of time-integrated sediment transport and consequently estimates of net sediment transport over one or many swash cycles can also be obtained from measurements of the changing beachface elevation. Measurements of morphological change have been employed by several authors to estimate net sediment transport over durations of several minutes or more (e.g., Duncan, 1964; Eliot and Clark, 1986; Holland and Puleo, 2001; Austin and Masselink, 2006; Weir *et al.*, 2006); however, as these periods contain numerous swash cycles, relating the calculated values of net sediment flux to swash hydrodynamics is not valid. Measurements of beachface morphological change at a temporal resolution sufficient to potentially resolve net sediment flux on a swash-by-swash basis have been recorded by several authors, including Waddell (1976), Sallenger & Richmond (1984), Brocchini & Baldock (2008) and Turner *et al.* (2008, submitted). Of these authors, only Brocchini & Baldock (2008) and Turner *et al.* (submitted) used their data to estimate cross-shore sediment flux and none of these studies includes corresponding measurements of swash hydrodynamics.

This paper describes recent work in which ultrasonic bed-level sensors as described by Turner *et al.* (2008, submitted) were used to make swash–by-swash measurements of the changing beach morphology throughout the high-tide swash zone during a large scale field experiment. This data was used to compute net cross-shore sediment fluxes for many thousands of swash events which provide useful new data and highlight the inherently dynamic nature of the swash zone.

2. Methodology

2.1 Study site

The data used in the present study were obtained during a field experiment at Le Truc Vert beach, France which was conducted during March and April, 2008. The experiment described here was undertaken within the structure of the multi-institutional ECORS project (Senechal *et al.*, 2008) and forms part of a large collaborative swash zone research project between the Universities of New South Wales (Australia) and Plymouth (UK). Further studies employing the techniques described here have been carried out on a steep, gravel beach at Slapton, UK and on a gravel barrier beach at prototype scale in the Delta Flume, Holland to provide comparative data for a range of sediment types, tidal ranges and wave conditions (Russell et al., 2009; Masselink et al., 2009; Williams et al., 2009).

Le Truc Vert lies on the French Atlantic coast and is part of a long, uninterrupted stretch of sandy beach to the north of the Arcachon Basin (Figure 1). The beach has a spring tidal range of 4.3 m and is exposed to a mixture of high-energy Atlantic swell and locally generated wind-waves with an average significant wave height of 1.3 m and typical storm wave heights of 5 m (De Melo Apoluceno *et al.*, 2002). The beach typically exhibits an intertidal transverse bar-rip system and a subtidal crescentic bar during large wave conditions (Castelle *et al.*, 2007), while the upper beach is relatively steep with a gradient of around 1:15. The median sediment size, D_{50} is 0.4 mm (Hibberd, 2008).

The field campaign ran over a spring-to-spring tidal cycle from 19th March to 4th April, 2008 which comprised 28 individual tidal cycles. During this time, significant offshore wave heights (H_s) and wave periods (T_p) varying from 0.9 to 4.1 m and 5 to 13 s, respectively, were measured by a Waverider buoy installed in approximately 20 m water depth.

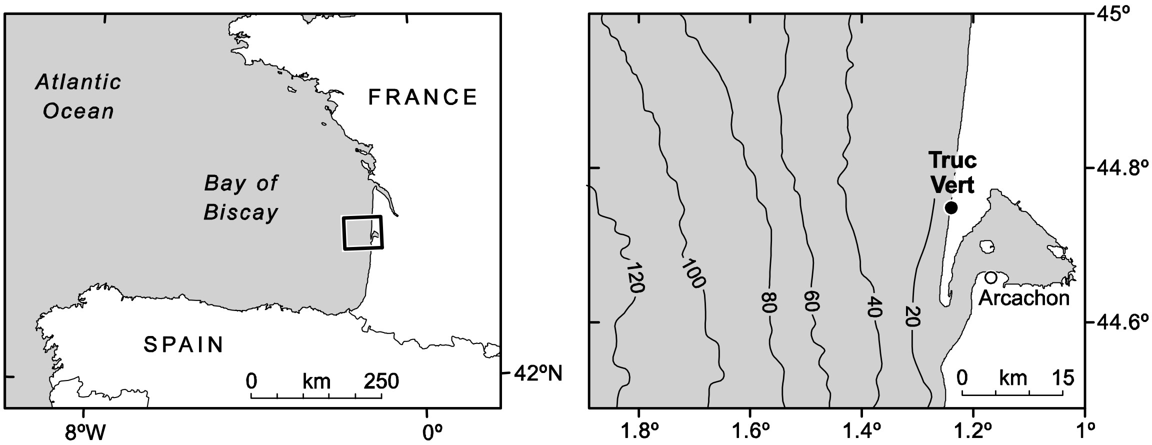

Figure 1. Location map of Truc Vert (from Masselink *et al.*, submitted).

2.1.1 Instrumentation

A total of 89 sensors were installed on the beach to measure a range of swash zone hydrodynamic and morphodynamic properties over a total of 28 tidal cycles and are described by Masselink *et al.* (submitted). The majority of the instruments were mounted on a large scaffolding rig (28 m long and 4 m wide) which was deployed extending seaward from the spring high tide swash excursion limit (Figure 2). To obtain the high-frequency bed elevation data required to resolve net cross-shore sediment flux at the timescale of individual waves, an array of 45 Massa M300/95 ultrasonic altimeters were mounted approximately 1 m above the bed and sampled at a rate of 4Hz. These sensors were described by Turner *et al.* (2008, submitted) and when mounted perpendicular to the bed use the time of flight of a reflected signal to make non-intrusive Eulerian measurements of the vertical distance to the closest target: bed-level when the bed is 'dry' and swash height when the bed is submerged. The sensors were mounted at 1.9 m spacings with a cross-shore extent of 28 m and all elevations were reduced to the local Niveau Moyen height datum (NM). In order to give some confirmation of the predominantly cross-shore nature of swash zone sediment transport at the site, three identical cross-shore lines of 15 sensors each were used. It is noted that the three lines gave essentially identical results and only the central line of sensors is used for the analysis presented here.

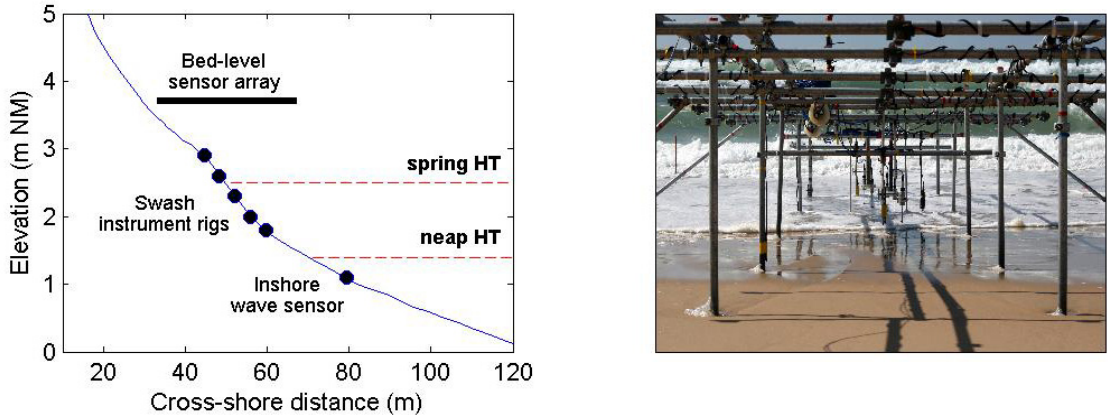

Figure 2. Beach profile at the start of the field experiment with instruments locations and photograph showing the scaffolding structure used for mounting the instruments (from Masselink *et al.*, submitted).

To complement the morphodynamic measurements made by the ultrasonic bed-level sensors, additional instrument stations were placed at five cross-shore locations along the centre of the scaffolding rig to provide concurrent measurements of swash hydrodynamics. These instrument stations were similar to those described by Masselink *et al.* (2008) and comprised electromagnetic current meters (EMCMs) to measure the swash current profile in both the long and cross-shore direction, an array of optical backscatter sensors (OBS) to estimate suspended sediment concentrations, and pressure transducers to provide water depths and information about through bed flow. These instruments were hard-wired to a bank of time-synchronised (GPS clock) computers and sampled at a rate of 4Hz.

In addition to the swash measurements described above, nearshore wave height, wave period, current velocity and water depth were measured by a self-recording acoustic Doppler velocimeter located approximately 20 m seaward (x = 80 m) of the main scaffold rig. To place the high-frequency bed-level measurements into the context of the wider beach morphology, total station surveys were completed at every low tide along 11 cross-shore transects, spaced 20 m apart alongshore, and extending seaward from the crest of the foredune to the mean low tide line.

3. Results

3.1 Measurements of swash-by-swash bed-level change

Time-series of bed/swash elevation data collected during Tide 15 (25/3/2008) at two positions on the beachface over a five-hour period spanning high tide are shown in Figure 3A. Tide 15 is representative of typical conditions during the study period with an offshore significant wave height of 2 m and a peak wave period of 9.4 s. The vertical spikes in these traces represent the raised water depth when a swash passes beneath the sensors, while between these events the bed elevation is obtained. The upper (green) trace in Figure 3A is derived from a bed-level sensor located in the upper swash zone at high tide (y = 40.4m) and documents 92 swash events that caused progressive accretion of 34 mm over a period of approximately two hours around high tide. The lower (blue) trace is derived from a sensor located seaward of the swash zone at high tide (y = 55.7 m) and represents a mixture of both swash events and inner surf zone waves. Bed-levels at this location can only be derived during the rising and falling stages of the tide as the bed was almost constantly submerged for the two hours around high tide. The data indicates net accretion of 13 mm over the total 5-hour time interval. By comparing the measured bed-levels immediately prior to successive swashes, the net bed-level change at the sensor location caused by each swash event can be calculated, and by using the full cross-shore array of sensors the morphological evolution of the beachface on a swash-by-swash time scale can be obtained. The result is shown in Figure 3B and illustrates the progressive build-up of sand leading to a net accretion of several centimeters across the upper beachface during this particular tide.

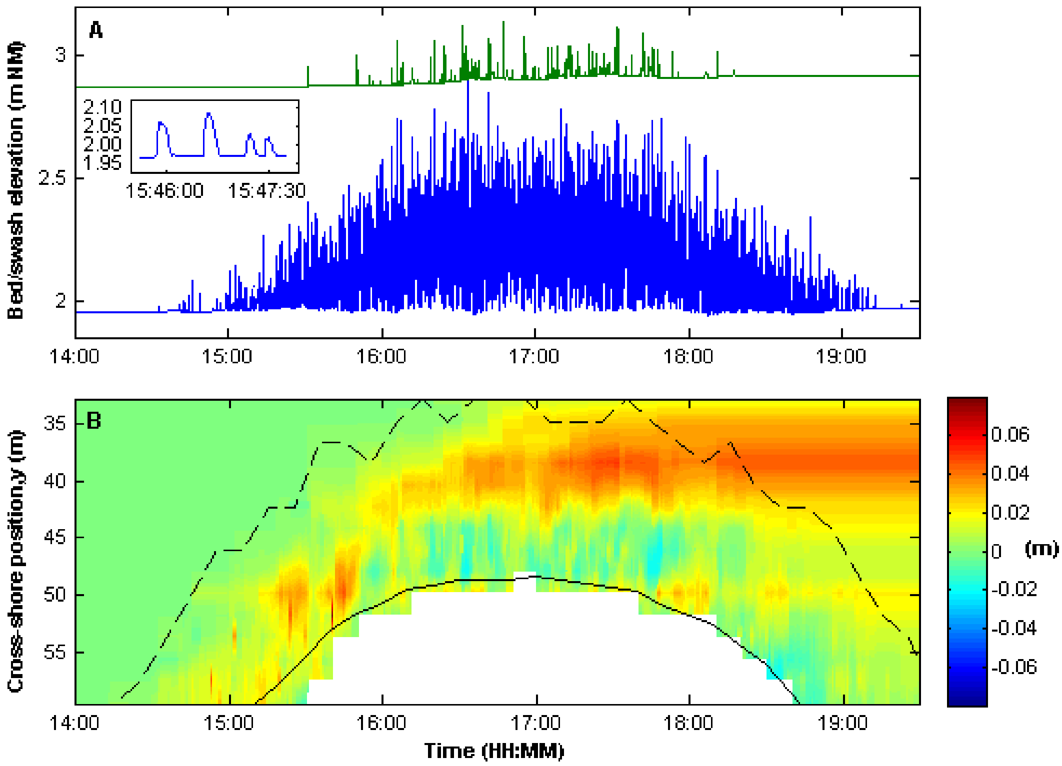

Figure 3. (A)Time-series of bed/swash elevation recorded by two bed-level sensors located at different cross-shore locations during Tide 15 (25/3/2008) with high tide occurring at approximately 17:00 hrs. The inset shows a shorter time-series of data with four swash events in which the peaks represent the raised water depth when swashes pass beneath the sensor, while the intervening periods indicate the bed elevation between swashes. (B) Change in bed-level through the swash zone during Tide 15 measured using the array of bed-level sensors (the magnitude of y increases in the offshore direction). The dashed and solid lines represent the run-up limit and the intersection of the beach and mean sea level respectively. The colour scheme represents the change in bed-level relative to the beachface morphology at the start of the time-series in meters. The net morphological change in the high tide swash zone over the tidal cycle is characterised by accretion of up to 50 mm (from Turner *et al.*, submitted).

Examination of the bed-level records throughout the 16-day field deployment revealed that large events which cause bed-level changes of 1 to 5 cm are relatively frequent, particularly in the lower swash zone. This was also observed by Waddell (1976), Sallenger & Richmond (1984), Turner *et al.* (2008) and Brocchini & Baldock (2008). If every swash had a similarly large effect and assuming that 100 or more swash events typically occur per hour, this equates to over 1 m vertical change per hour. In reality, net beachface change over tidal cycles was observed to be much lower, of the order of 10 mm per hour, while the net rate of bed-level change throughout the entire 16-day deployment period was of the order of 0.01 mm per hour. The observation of significant quantities of net sediment deposition or removal caused by the passage of single swashes suggests that the beachface should be extremely unstable. Similarly, rapid and relatively large morphological changes caused by single swashes may imply that very rapid beach erosion or accretion is a common occurrence. In the context of these field observations, the contrasting reality is that beaches demonstrate a remarkable degree of stability.

3.2 Measurements of swash-by-swash bed-level change

While measurements of bed-level change at a single point on the beach face are of interest, these changes are the result of local gradients in sediment flux and may not be fully representative of the wider beachface. Of greater interest are the net cross-shore sediment fluxes that drive these bed-level changes. To further demonstrate the extremely dynamic nature of the evolving beachface morphology, it is insightful to contrast the large quantities of sand that are episodically eroded or deposited across the beachface by individual swashes, to the net cross-shore sediment transport in this region over a complete tidal cycle. By integrating the bed-level changes over the 1.9 m x 1.9 m sensor array, the equivalent dry weight of sand (per meter width alongshore) that was deposited or removed landward of any sensor location by all swash events can be calculated. This technique was used to determine the net cross-shore sediment flux past every bed-level sensor for every recorded swash event, thus allowing both the spatial and temporal distribution of cross-shore sediment flux to be examined. The sediment volume flux Q_v past sensor i is given by

$$Q_{vi} = \frac{\Delta x}{2}\left(\Delta z_i + 2\Delta z_{i+1} + \ldots + 2\Delta z_{n-1} + \Delta z_n\right) \qquad (1)$$

where sensor n is the first sensor landward of the maximum uprush limit for each swash and Dx is the distance between adjacent bed-level sensors (Figure 3). The sediment mass flux is then obtained as

$$Q_i = (1-p)\rho_s Q_{vi} \qquad (2)$$

where ρ_s is the sediment density (ρ_s = 2650 kg m^{-3}) and p is the sediment porosity (p = 0.35).

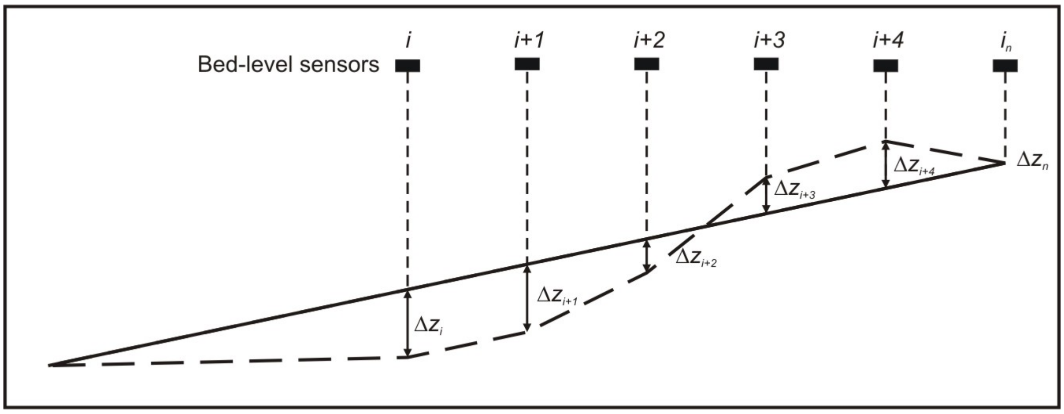

Figure 4. Definition sketch for the calculation of net cross-shore sediment flux using Equation 1. The solid black line represents the initial bed condition and the dotted red line marks the modified position of the bed after a single swash event. Sensor i_n is the first sensor landward of the maximum uprush limit

Fig 5A shows the frequency distribution of all swash-by-swash bed-level changes observed at a single point in the lower swash zone at high-tide, for the same five-hour time period depicted in Figure 3. Similarly, Figure 5B shows the corresponding frequency distribution of swash-by-swash sediment deposition or removal across the beachface landward of this location. It is noteworthy that while a considerable number of both erosive and depositional events occurred, the observed bed-level changes (Figure 5A) are essentially normally distributed between net erosion and deposition. This pattern is similarly evident in the sediment flux data (Figure 5B). This observation confirms that the beachface can experience both positive and negative bed-level changes over the timescale of individual swashes driven by large onshore and offshore sediment fluxes, but that these events very nearly balance over longer timescales, resulting in relatively little net change. This result was observed for all tides during which flux calculations could be obtained for the entire beachface. Table 1 summarises the mean and standard deviation of the swash sediment fluxes recorded at a comparable relative position within the swash zone during seven different tides with varying wave conditions and beach morphology. In all conditions the standard deviation of swash-by-swash sediment fluxes is at least an order of magnitude larger than the corresponding mean rate of sediment movement. Figure 5C further contrasts the time-series of net cross-shore sediment flux from individual swashes with the cumulative sediment flux recorded over the tidal cycle. The time-series of the net sediment flux is characterised by frequent reversals in direction. As a result, the individual net quantities of sediment transported per swash (up to 150 kg m^{-1}) are not dissimilar to the total change in beachface volume (~700 kg m^{-1}) over the entire tide. In total, more than 6000 kg m^{-1} of sediment moved on and offshore past this location over the duration of the tide. At the time-scale of successive swashes, no correlation can be identified between the quantities of onshore versus offshore-directed sediment fluxes. However, from Figure 5B it is evident that the landward and seaward movement of sediment across the beachface very nearly balanced, resulting in only minor (+11 mm) net morphological change over a 5 hour period (Figure 3B).

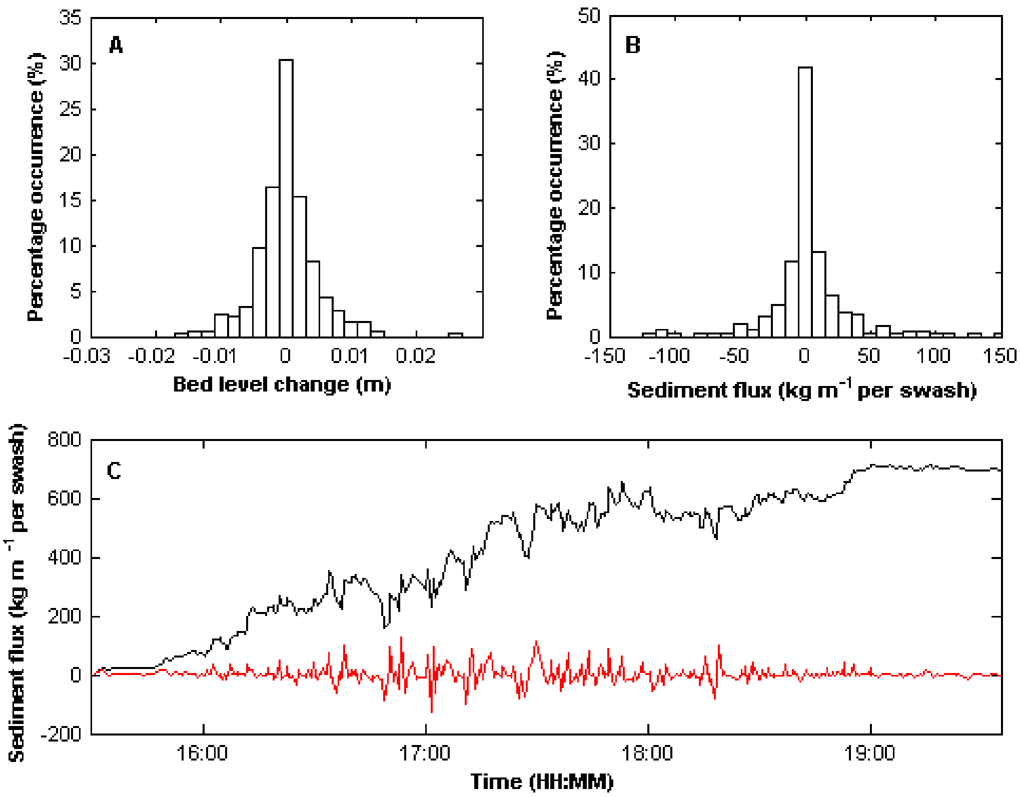

Figure 5. (A) Histogram of bed-level changes caused by individual swash events recorded at y = 48 m during Tide 15 (refer to Figure 3B). Positive values of bed-level change represent accretion. While slight accretion of 11 mm was measured at this location over the full tide, numerous individual bed-level changes with a magnitude greater than this net change were measured. (B) Histogram of net cross-shore sediment fluxes caused by individual swashes recorded at y = 48 m. The data shows an approximately normal distribution centred on a mean of 1.7 kg m^{-1} per swash, with a standard deviation of 20.7 kg m^{-1} per swash. (C) Time-series of the net sediment fluxes caused by individual swashes recorded at y = 48 m (red trace), and the cumulative sediment flux (black trace). It is evident that while there is a general trend of onshore flux (~700 kg m^{-1} over the full tide), the time-series of the net sediment fluxes caused by individual swashes shows rapidly reversing transport directions and transport rates of up to 150 kg m^{-1} per swash, which is of comparable magnitude to the flux recorded over the full tide (from Turner *et al.*, submitted).

Table 1. Summary table for seven tides during which calculation of net cross-shore sediment fluxes from individual waves was achieved. The table provides the average deepwater wave conditions (H_s – significant wave height; T_p – peak wave period) for each tide along with the mean and standard deviation of the individual sediment fluxes recorded at the sensor where the bed was submerged for 80% of the time around the time of high tide. Positive values of mean flux are directed onshore and negative values offshore.

Tide No.	Date	H_s (m)	T_p (s)	Mean Flux (kg m^{-1} per swash)	Standard Deviation (kg m^{-1} per swash)
5	20/3/08	1.26	5.8	1.2	14.2
6	21/3/08	1.45	4.8	-3.6	37.8
15	25/3/08	2.03	9.4	1.7	20.7
16	26/3/08	1.72	9.4	2.1	20.8
22	29/3/08	3.15	12.5	1.3	56.1
23	29/3/08	2.82	12.5	2.6	57.2
29	02/4/08	1.49	10.3	1.3	23.0

4. Conclusions

The concurrence of very large and rapidly reversing net sediment fluxes between consecutive swash cycles on a slowly evolving, or even stable, beachface is a remarkable example of a very dynamic equilibrium. The existing literature suggests that net beachface morphological change is generally considered to result from a small onshore or offshore bias in the net sediment transport over individual swash events (Masselink & Puleo, 2006). Swash research to date has predominantly focussed on the concept that the progressive build-up or erosion of the beachface is due to a (small) net difference between (large) uprush and backwash sediment loads. However, the field observations presented here clearly demonstrate that sediment fluxes over individual swashes can be of the same order as the total change in beachface sand volume over a full tide cycle. Considering the large net sediment fluxes caused by individual swash events, it is evident that beaches exhibit a remarkable degree of stability. It appears that rapid morphological change may be checked by some combination of negative feedback and short-term process dampening. At the present time, the form or time-scale that underpins this evident state of dynamic equilibrium at the shoreline is simply unknown. With deterministic approaches to the modelling of cross-shore sediment movement at the shoreline currently in their relative infancy, the new observations presented here suggest that an equilibrium-based approach may offer an alternative way forward.

This paper has described a large scale field experiment in which many thousands of bed-level changes and net cross-shore sediment fluxes were recorded at the timescale of individual swash events. This dataset provides considerable information about the quantities of sediment that move up and down the beachface as a result of individual swash cycles. Further work is currently underway to compare these recorded sediment fluxes with the concurrently recorded hydrodynamic data, with the aim of verifying existing models of sediment transport in the swash zone or to allow updated approaches or formulations to be developed.

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