Measuring and modelling of cross-shore sediment transport and profile evolution on natural beaches

by

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Abstract

Cross-shore sediment transport is the dominant process causing beach profile evolution. The ability to model cross-shore sediment transport allows prediction of the future beach state to be made. Due to a balance between opposing mechanisms, cross-shore sediment transport is difficult to predict. One route to make these predictions is with the development of measurement based parameterisation.

This study builds on previous parameterisations that have related cross-shore velocity moment (predictors of suspended sediment transport according to the energetics approach to sediment transport) to normalised depth (a proxy of cross-shore position), to present a new shape function parameterisation. The present parameterisation has been developed from field measurements of depth-integrated cross-shore suspended sediment transport measured during a month-long field campaign at Sennen Cove, Cornwall, UK. This parameterisation is an improvement of the previous shape function parameterisation in three key areas; i) removes the dependency on the energetics approach, and so includes all transport mechanisms, ii) incident energy (parameterised as breakpoint depth - \( h_b \)) is considered, and so allows this shape function to be used under a wide range of energy conditions, iii) the swash zone processes are considered in detail. The new shape function parameterisation is the sum of four component shape functions that represent mean and oscillatory transport in the surf- and shoaling zone and on- and offshore transport in the swash-zone. As each component shape function responds individually to energy level, the net-transport shape function responds to varying conditions. Under high-energy conditions the shape function predicts onshore transport in the shoaling zone, offshore transport in the surf zone and onshore transport in the inner swash zone, while under low energy the shape function predicts all onshore transport with a peak outside the breakpoint and in the inner surf-zone.

The shape function is implemented in a simple heuristic profile evolution model that allows the examination of beach behaviour under varying conditions to be examined over long (decadal) time-scales. Preliminary results show that the shape function model is able to replicate onshore and offshore bar migration, bar development and bar degeneration over timescale not previously modelled. Future work will use this model to investigate the response to subtleties in driving conditions, such as the varying effect of seasonality compared to random storms.
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<tr>
<td>$d_{50}$</td>
<td>Median grain size</td>
</tr>
<tr>
<td>$D_b$</td>
<td>Breaking wave dissipation (Ruessink et al., 2007)</td>
</tr>
<tr>
<td>$D_f$</td>
<td>Bottom friction (Ruessink et al., 2007)</td>
</tr>
<tr>
<td>$Dh$</td>
<td>Change in bed elevation</td>
</tr>
<tr>
<td>$dh_{sm}$</td>
<td>Smoothed profile of bed elevation change (see Section 6.1.6)</td>
</tr>
<tr>
<td>$dQ_{x=3}/dx$</td>
<td>Cross-shore gradient of sediment transport at $z = 3$ cm</td>
</tr>
<tr>
<td>$Dt$</td>
<td>Change in time, typically model time step</td>
</tr>
<tr>
<td>$du/dt$</td>
<td>Depth integrated acceleration</td>
</tr>
<tr>
<td>$du/dt$</td>
<td>Acceleration at a specific height</td>
</tr>
<tr>
<td>$Dx$</td>
<td>Change in cross-shore position, model grid-size</td>
</tr>
<tr>
<td>$dX/dt$</td>
<td>Bar migration rate (Plant et al., 1999)</td>
</tr>
<tr>
<td>$E_w$</td>
<td>Short wave energy (Ruessink et al., 2007)</td>
</tr>
<tr>
<td>$E_r$</td>
<td>Roller energy (Ruessink et al., 2007)</td>
</tr>
<tr>
<td>$G$</td>
<td>Acceleration due to gravity</td>
</tr>
<tr>
<td>$H$</td>
<td>Depth</td>
</tr>
<tr>
<td>$H_{ADCP}$</td>
<td>Wave height at ADCP</td>
</tr>
<tr>
<td>$h_t$</td>
<td>Depth below troughs (Ruessink et al., 2007)</td>
</tr>
<tr>
<td>$H$</td>
<td>Wave height</td>
</tr>
<tr>
<td>$H_h$</td>
<td>Wave height at depth $h$</td>
</tr>
</tbody>
</table>
$H/h$ Normalised wave height
$h/h_b$ Normalised depth
$H_{o,\text{rms}}$ Offshore rms wave height
$h_b$ Breakpoint depth
$H_b$ Breakpoint wave height
$H_b/h_b$ Breakpoint normalise wave height
$\hat{h}_b \times (h/h_b)$ Expression for $h$ used in swash component shape function
$h'_b$ $h_b$ at time $t$
$h_{b,t}$ Model variable for $h/h_b$ at time $t$
$h_i$ Depth at model grid cell $i$
$h_{i+1}$ Depth at model grid cell $i+1$ (i.e. seaward neighbouring cell)
$h_{i+1/2}$ Interpolated depth between model grid cell $i$ and $i+1$
$h_{i-1}$ Depth at model grid cell $i-1$ (i.e. landward neighbouring cell)
$h_{i-1/2}$ Interpolated depth between model grid cell $i$ and $i-1$
$H_o$ Offshore wave height
$H_{\text{rms}}$ rms wave height
$H_s$ Significant wave height
$H_{s,\text{rms}}/h_b$ Significant wave height normalised by $h_b$ (Aagaard et al., 2002)
$h_{\text{sm}}$ Smoothed profile (see Section 6.1.6)
$h_{\text{st}}$ Smoothed profile (see Section 6.1.6)
$h'$ Profile height at time $t$
$I$ Index of a model grid cell of interest
$IBED_{\text{conf}}, ISUS_{\text{conf}}$ Shape function of Fisher and O'Hare (1996)
$i_b$ Immersed weight bedload transport (Bailard, 1981)
$\bar{i}_{\text{bed}}$ Volumetric bedload transport rates (Fisher and O'Hare, 1996)
$i_s$ Immersed weight suspended transport (Bailard, 1981)
$\bar{i}_{\text{su}}$ Volumetric suspended transport rates (Fisher and O'Hare, 1996)
$i_t$ Immersed weight total transport (Bailard, 1981)
$L$ Wavelength
$k$ Wave number
$kh$ Relative wave number
$M_j$ $M_j$ tidal constituent
$m_{\text{cr}}$ Angle of initial yield
$m_{\text{rep}}$ Angle of repose
$n_i$ Index for grid cell
$n_{th}$ Index for grid cell
$p$ Empirical constant (Plant et al., 2001)
$p$ Maximum cross-correlation between velocity sediment concentration
(Aagaard et al., 2002)
$p$ The exponent in the migration rate (Plant et al., 1999)
$p$ Bed porosity (Ruessink et al., 2007)
$Q$ Sediment transport
$q$ Sediment transport
\( q_{\text{bed}} \)  
Bedload transport (Ruessink et al., 2007)

\( q_{\text{suc}} \)  
Suspended transport (Ruessink et al., 2007)

\( q_{\text{net}} \)  
Net transport (Ruessink et al., 2007)

\( Q(x) \)  
Transport at cross-shore position \( x \)

\( q_{t}(x,t) \)  
Transport term (Plant et al., 2001)

\( Q_d \)  
Normalised sediment flux index (Aagaard et al., 2002)

\( q_{\text{osc}} \)  
Oscillatory component of sediment transport (Aagaard et al., 2002)

\( q_{\text{mean}} \)  
Mean component of sediment transport (Aagaard et al., 2002)

\( Q_{\text{mean}} \)  
Mean component shape function

\( Q_{\text{off}} \)  
Offshore swash component shape function

\( Q_{\text{on}} \)  
Onshore swash component shape function

\( Q_{\text{osc}} \)  
Oscillatory component shape function

\( Q_s \)  
Net suspended sediment flux (Aagaard et al., 2002)

\( Q_{st} \)  
Stirring term (Plant et al., 2001)

\( r_0, r_1, r_2 \)  
Empirical constant (Plant et al., 2001)

\( R^2 \)  
Pearson correlation coefficient

\( R_{25\%} \)  
Run-up height (see Section 6.1.12)

\( R_{25\%2D} \)  
Non-dimensional run-up height (see Section 6.1.12)

\( rat \)  
Shape function transport ratio (see Section 5.5)

\( rat_1 \)  
Shape function transport ratio 1 (see Section 5.5)

\( rat_2 \)  
Shape function transport ratio 2 (see Section 5.5)

\( r_c \)  
Correlation between bed sediment load and velocity fluctuations (Plant et al., 2001)

\( \text{rms} \)  
Root mean square

\( S \)  
Wave skewness (Aagaard et al., 2002)

\( \text{SCE-UA} \)  
Shuffled Complex Evolution (SCE-UA) algorithm (Ruessink et al., 2007)

\( S_2 \)  
\( S_2 \) tidal constituent

\( \text{stepfunc} \)  
Step function for shape function closure depth (see Section 6.1.5)

\( t \)  
Time, model time step index

\( T \)  
Wave period

\( T_p \)  
Spectral peak period

\( u \)  
Cross-shore velocity

\( \bar{u} \)  
Mean cross-shore velocity

\( |u| \)  
Mean cross-shore velocity (Aagaard et al., 2002)

\( u(z) \)  
Vertical profile of \( u \) (Ruessink et al., 2007)

\( u' \)  
Cross-shore velocity variance

\( u' \)  
Cross-shore velocity skewness
\( u' \) Cross-shore velocity kurtosis
\( u_l \) Long wave component of cross-shore velocity
\( u_{rms} \) rms cross-shore velocity (Aagaard et al., 2002)
\( u_s \) Short-wave component of cross-shore velocity
\( u \) Depth dependent cross-shore velocity
\( V_1 \) Volume of sediment eroded in region 1 (see Section 5.5)
\( V_2 \) Volume of sediment eroded in region 2 (see Section 5.5)
\( V_3 \) Volume of sediment eroded in region 3 (see Section 5.5)
\( V_x \) Volume of sediment eroded in region x (see Section 5.5)
\( W \) Sediment fall velocity
\( W_s \) Sediment fall velocity
\( X \) Cross-shore position
\( X_c \) Bar crest position (Plant et al., 1999)
\( X_{eq} \) Bar equilibrium position (Plant et al., 1999)
\( y \) Along shore position
\( y \) \( y = 4.03h/T^2 \) (see Section 3.3.8)
\( y \) \( H_{rms}/h \) (Plant et al., 2001)
\( y/y_c \) y normalised by \( y_c \) (Plant et al., 2001)
\( Y_c \) Critical value of \( y \) (Plant et al., 2001)
\( Z \) Depth
\( Z_o \) A reference height above the bed (Ruessink et al., 2007)
\( \alpha \) Tidal amplitude (6-8)
\( \alpha \) Smoothing coefficient (6-8)
\( \alpha \) Bar migration rate
\( \alpha' \) is response time. (Plant et al., 1999)
\( \beta \) Beach slope
\( \beta \) The roller slope (Ruessink et al., 2007)
\( \Delta \) \( \Delta = (\rho_s - \rho)/\rho \) (Ruessink et al., 2007)
\( \Delta h/\Delta x^2 \) Gradient of bed slope
\( \Delta t \) Change in time, typically model time step
\( \epsilon \) Grain packing density
\( \epsilon_b \) Efficiency term (bedload transport) (Bailard, 1981)
\( \epsilon_r \) Efficiency term (suspended transport) (Bailard, 1981)
\( \lambda \) Sediment void ratio/porosity (Fisher and O'Hare, 1996)
\( \Gamma \) Sediment transport parameter (Aagaard et al., 2002)
\( \phi \) Angle of repose
\( \gamma_b \) Local \( H/h \) (Aagaard et al., 2002)
\( \gamma_s \) Short wave breaking index (Mariño-Tapia et al., 2007b)
\( \eta \) Surface elevation
\( \eta_s \) Set-up
\( \eta_f \) Surface elevation at time \( t \)
\( \phi \) Tidal phase
\( \theta \) Wave angle (Ruessink et al., 2007)
\( \theta(t) \)  
Time series of the dimensionless effective shear stress (Ruessink et al., 2007)

\( \theta_{cs} \)  
Slope corrected non-dimensional critical shear stress (Ruessink et al., 2007)

\( \theta_{max} \)  
Shields parameter (Aagaard et al., 2002)

\( \rho \)  
Fluid density

\( \rho_s \)  
Sediment density

\( \sigma \)  
Tidal period

\( \sigma_u^2 \)  
Velocity variance (Mariño-Tapia et al., 2007b)

\( \sigma_{\eta}^2 \)  
Surface elevation variance (Mariño-Tapia et al., 2007b)

\( \sigma_{\eta}C \)  
Sediment transport normalising parameter (Plant et al., 2001; Mariño-Tapia et al., 2007b)
Acknowledgements

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I would like to thank my supervisors Dr. Tim O’Hare, Dr. Paul Russell and Dr. Jon Miles for the support, guidance and friendship they have given me over the duration of the PhD. I have spent innumerable hours with Tim discussing this research, and his attitude and ideas have always inspired me. Paul has always had time to discuss my work, and has always been very positive. Prof. Gerd Masselink has been very helpful throughout this study, both in the field, and in front of the computer.

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Finally, I would like to thank my wife, Kathryn Tinker, for all the love and support she has given me throughout this period.
Author’s Declaration

At no time during the registration for the degree of Doctor of Philosophy has the author been registered for any other University award without prior agreement of the Graduate Committee.

This study was financed with the aid of a studentship from the Natural Environment Research Council.

Relevant scientific seminars and conferences were attended at which work was presented and several papers were prepared and submitted for publication.

Publications, presentation and conferences attended: (see page ix)

Word count of thesis: 75746

Signed

Date 29/4/2009
Plate 1 Sennen Cove, looking north.
1 Introduction

1.1 Importance of Coasts and Beaches

In the UK, the coastal regions are of vital importance; around 30 million people live within urban coastal areas and 30% of the coast (of England and Wales) is developed (Lowe et al., 2009). Economically, coastal regions are important as around 60% of the best agricultural land is 5 m or less above sea level and ~90% of our trade passes through sea ports (Lowe et al., 2009). The UK spends ~£325 million pounds every year protecting its coasts from the damaging effects of the sea (IPCC, 2007). With prediction of sea level rise of the order of one metre over the next century these pressures can only increase.

Beaches provide an important recreational resource. Many economies are supported by the draw of the beach. In the UK's Devon and Cornwall, tourism earned £2.2 billion in 2006 (South West RDA), while in the US, direct spending of $14 billion yr⁻¹ and more visitor days per year than Yosemite National Park or Disneyland make the coast the main recreation destination (Thornton et al., 2000). The economic importance of the beach system for tourism provides an impetus for understanding the complex processes that potentially threaten them.

Beaches play an important role in defending the coast by acting as a buffer between the ocean and the land. Destructive waves dissipate their energy by breaking on the beach before reaching the shoreline and damaging coastal properties (Komar, 1998; Thornton et al., 2000). As the beach is unconsolidated, it is able to adjust its shape while not being destroyed itself. Disruption of sediment supply (through interfering with longshore transport, or sand mining) reduces the ability of the beach to respond to the environment, and can lead to coastal erosion problems.

Coastal protection is generally in the form of "hard" or "soft" engineering solutions. Traditional hard defences including sea walls and groins are no longer in favour, as they can cause issues with increased beach erosion and sediment loss. Instead, soft forms of coastal protection (generally beach nourishment) are preferred. However, before any such nourishment can occur,
predicted outcomes must be considered. These changes are generally assessed with a morphological model combining hydrodynamic, sediment transport and morphological modules. Of these three, it is generally accepted that the most difficult component to model is sediment transport.

1.2 Importance of cross-shore transport

Generally, along-shore sediment transport is well studied (Komar, 1971), and simple calculations can accurately describe quantities and directions of transport (Bowen, 1969; Longuet-Higgins, 1970a; Longuet-Higgins, 1970b; Thornton, 1970; Thornton and Guza, 1986). However, cross-shore sediment transport may result from opposing mechanisms, including wave and mean flow (e.g. bed-return flow) driven transport. Small changes in either of these processes can have a large impact on the resulting net transport. Due to this sensitive dependence, it is far more difficult to predict cross-shore than long-shore sediment transport.

Modelling of cross-shore sediment transport and beach profile evolution can be achieved in a number of ways. The simplest models are based on “equilibrium” beach profiles, and ignore most of the physical processes. Although these are well studied and routinely used, they can be limited. In contrast, “process-based models” include as much of the underlying physics of the system as possible, and should theoretically provide the most realistic results. However, poor understanding of processes leads to an inability to produce long-term accurate results, partly due to a lack of high quality datasets to calibrate models but also due to the complexity of the system itself. Parametric models take another approach. By including only essential details of important processes, error multiplication is avoided, and much longer time scales may be successfully modelled. Parametric models of cross-shore sediment transport, combined with wave transformation models have recently provided good long-term predictions of profile evolution (e.g. Plant et al., 2001; Masselink, 2004; Plant et al., 2004; Mariño-Tapia et al., 2007b). Such models replace most of the model physics with a field-based parameterisation (O'Hare et al., 2006), and so are limited by these parameterisations.
1.3 The present study

1.3.1 Aims

The present study aims to develop a cross-shore suspended sediment transport parameterisation based on depth-integrated measured sediment fluxes. This will be then used to predict cross-shore morphological change and model beach profile evolution.

Following previous work (Russell and Huntley, 1999; Mariño-Tapia et al., 2007a; Mariño-Tapia et al., 2007b) it is hypothesised that there is a consistent pattern of cross-shore sediment transport, and that this pattern is a function of normalised cross-shore position and offshore wave conditions. The use of normalised cross-shore position allows the separation of the different transport regions (shoaling, surf and swash zones). The pattern varies with offshore wave energy allowing the replication of the observed offshore-directed surf-zone transport under energetic conditions and onshore-directed surf-zone transport under less energetic conditions.

The new measurements-based, cross-shore suspended sediment transport parameterisation will then be used to implement a parametric beach profile evolution model which will allow predictions of future beach profiles to be made from an existing profile and future forcing conditions. The simplicity of the model allows for long model runs (of the order of decades) and investigation of the beach system behaviour over these timescales.

1.3.2 Background

This study represents a significant extension of an approach to parameterisation and modelling of cross-shore sediment transport known as the “shape function” approach. The term “shape function” is used to describe a parameterisation of the cross-shore distribution of cross-shore sediment transport. It has had a long history (discussed in Section 2.2) with the most recent development added by Mariño-Tapia et al. (2007a), who presented a shape function to relate velocity-moments predictors of cross-shore sediment transport (described in Section 3.3.5) to
cross-shore position. Their shape function predicts offshore sediment transport in the surf zone and onshore sediment transport in the shoaling and swash zone, with a sediment convergence at the point where the waves break (breakpoint). The shape function allows onshore bar migration under lower energy conditions and offshore migration under higher energy conditions (Figure 1-1).

![Diagram showing break point bar migration](image)

**Figure 1-1** Schematic showing how a breakpoint bar responds to varying energy conditions according to the Marino-Tapia et al. (2007a) shape function. Under high energy conditions (b), waves break outside the bar leading to offshore bar migration, while lower energy conditions (c), with waves not breaking on the bar, lead to onshore bar migration. Adapted from Marino-Tapia et al. (2007a).

Although the Marino-Tapia et al. (2007a) shape function was a significant improvement on previous shape functions, there were still weaknesses. First, the shape function was based solely on velocity moments and ignored the contribution of fluid acceleration on sediment transport processes (e.g. Hoefel and Elgar, 2003). Secondly, the shape function was based largely on data collected under energetic conditions and insufficiently considers the role of low energy...
conditions. Thirdly, the Mariño-Tapia et al. (2007a) shape function included very sparse data from inside the inner surf and swash zones.

1.3.3 Approach

The present study aims to overcome the limitations of previous shape function models by developing a new cross-shore suspended sediment transport shape function based on measured sediment fluxes. By using measured depth-integrated suspended sediment fluxes, it is possible to overcome the limitations of the energetics approach, as measured fluxes include all suspended transport mechanisms (associated with acceleration as well as skewness). This is especially important in the swash zone where processes not included in the energetics approach may dominate (e.g. Masselink and Puleo, 2006). Following Jaffe et al. (1984) and Huntley and Hanes (1987), the measured fluxes are broken down into a mean and oscillatory term (with the assumption that they are linearly independent). The offshore-directed bed-return flow driven transport is the main physical process represented by the mean component, whereas onshore transport due to incident-wave skewness and flow acceleration are the main physical processes represented by the oscillatory component. As there are limited data from the swash and inner surf zone, these observations are analysed separately to increase the resolution of the measurements within this region. In the swash/inner surf zone the transport is not dominated by bed-return flow and incident wave skewness, as in the mid to outer surf and shoaling zone. Consequently, swash zone transport is parameterised separately from the mean and oscillatory components. In this region, processes such as fluid accelerations (Nielsen, 2002; Puleo et al., 2003; Calantoni and Puleo, 2006; Nielsen, 2006) and bore collapse (Jackson et al., 2004; Pritchard and Hogg, 2005) have been hypothesised to drive sediment onshore. Strong offshore transport in the outer swash/inner surf zone has been attributed to large backwashes on infragravity timescales (Russell, 1993; Butt and Russell, 1999; Masselink and Puleo, 2006). The swash/inner surf zone transport is subsequently separated into an onshore and offshore transport component due to the presence of these opposing mechanisms. The energetics approach (Bailard, 1981; refer to Section 2.1.1) does not include these mechanisms and incorrectly
predicts transport magnitude and direction in the swash zone (Masselink and Russell, 2006).
The overall shape function is then built up as the sum of four terms, each describing the cross-
shore distribution of one of the different transport contributions. This approach provides greater
insight into the underlying physical mechanisms than can be derived from parameterizations
such as that of Mariño-Tapia et al. (2007a).

1.3.4 Tied project

The present study is tied to a Natural Environment Research Council (NERC) funded project
(NERC Grant Number: NER/A/S/2003/00553) “Cross-shore Sediment Transport and Profile
Evolution on Natural Beaches (X-SHORE)”. The X-SHORE study was designed to investigate
the influence of cross-shore sediment transport on beach morphology and the specific objectives
of the project were to:

(1) Collect two unprecedented datasets of cross-shore sediment transport processes on a
planar and barred beach.

(2) Use the data collected under (1) to investigate the dependence of cross-shore sediment
transport and direction on relative surf-zone position, wave energy level, bed
morphology, sediment size, tidal stage and beach morphology.

(3) Synthesise the results of (2) into an improved suspended sediment transport shape
function.

(4) Develop a numerical model based on the shape function obtained under (3) to predict
cross-shore sediment transport and beach morphology change.

The first field campaign, conducted at Sennen Cove, UK, focused on collecting sediment
transport data with a high vertical resolution by deploying a vertical array of instruments
throughout the water column. The second campaign at Truc Vert, Gironde, France, focused
additionally on capturing the spatial variations in sediment transport with a high horizontal
resolution, over the bar trough system. Due to the three dimensional nature of the site at Truc
Vert, the data was found to be unsuitable for use in the present study, and only data from Sennen Cove is presented here.

The Principle Investigator (PI) of the X-SHORE project was Dr. Paul Russell, with Dr. Gerd Masselink and Dr. Tim O’Hare as co-investigators (Co-I). There were two postdoctoral research assistants (PDRA), Dr. Martin Austin and Dr. Tony Butt who concentrated on the first two grant objectives. This tied PhD concentrated on the last two objectives.

1.3.5 Objectives

To expand on the objectives (3) and (4) of the X-SHORE project, the specific objectives of this PhD. thesis are as follows:

1. To develop a new cross-shore suspended sediment transport “shape function” parameterisation based on depth-integrated measured fluxes.

2. To extend the usefulness of the previous shape function parameterisations by considering data from the entire nearshore zone (i.e. including the swash and inner surf regions) and from a wider range of energy levels.

3. To construct a morphological model of beach profile evolution utilising the new shape function and use it to explore the response of the modelled beach profile to relatively simple forcing scenarios (uniform wave input with and without tides and step changes in wave energy input) over timescales of weeks to months and gain a better understanding of why these responses occur.

4. To explore the behaviour of the model using the scenario of longer term (decadal) behaviour and determine whether the model can be stably run over such timescales.

1.4 Structure of thesis

Chapter 2 provides a review of the literature, focusing on the development of the shape function and other cross-shore sediment transport parameterisations and shape function based parametric
models. Descriptions of the Sennen Cove field site, instrumentation and analysis techniques are then presented in Chapter 3.

Initial time-series results are presented in Chapter 4 and the applicability of the data to the Mariño-Tapia et al. (2007a) shape function is investigated. The central part of this thesis, the development of a new measurements-based suspended-sediment transport shape function, is presented in Chapter 5 and its use in a parametric model is presented in Chapter 6. The outcomes of the study are discussed in Chapter 7 and conclusions presented in Chapter 8.
Plate 2 Daniel Buscombe, Richard Hartley and George Graham.
2 Literature Review

To put the research that follows into context, this chapter reviews relevant published literature. Specifically, it aims to:

1) Describe suspended sediment transport processes in nearshore regions and introduce the shape function approach to parameterising the cross-shore sediment transport.
2) Describe some of the shortfalls and successes of existing shape function approaches.
3) Outline what is known about the seasonal/longer-term changes that beach profiles undergo.
4) Briefly discuss morphological models for profile evolution and the time-scales on which they operate.

2.1 Cross-shore sediment transport processes

The breaking of waves is such a violent process that it completely changes the nature of the hydrodynamics, and provides a natural boundary between two very different hydrodynamic regimes: the shoaling zone before the waves break, and the surf-zone after they have broken. The sediment transport mechanisms that occur in each region are different from one another and so each will be considered in turn.

In the shoaling zone, waves are skewed and have stronger onshore velocities than offshore velocities. Although these onshore flows last for shorter periods of time than the offshore velocities, their greater intensity leads to a net onshore transport (Guza and Thornton, 1985; Huntley and Hanes, 1987; Roelvink and Stive, 1989). Observations have also shown a weak onshore transport associated with the mass transport (Osborne and Greenwood, 1992a; Osborne and Greenwood, 1992b; Russell and Huntley, 1999). These shoaling-zone onshore-transport mechanism may be opposed by a offshore transport due to bound infragravity waves (Huntley
and Hanes, 1987; Ruessink et al., 1998; Russell and Huntley, 1999), however, this region is generally dominated by the onshore mechanisms.

In the surf zone, the breaking waves lose momentum to the water column, leading to a radiation stress that pushes water towards the beach, raising the mean sea level (‘set-up’). This set-up leads to a horizontal pressure gradient that can cause a bed-return flow (undertow). The-bed return flow is an offshore-directed mean current, which can transport sediment stirred by the incident and long waves. In the surf zone, this is often the dominant transport mechanism (Guza and Thornton, 1985; Gallagher et al., 1998; Russell and Huntley, 1999). In storm events, this mechanism is exacerbated, as set-up is proportional to wave height and an additional component of wind driven setup can occur.

Observations reveal that breaking occurs at a depth related to the wave height (e.g. \( H_b/h_b = \gamma \) where \( \gamma \) is typically in the range 0.7 - 1) termed the breakpoint depth, \( h_b \). As the offshore directed bed return flow from the surf-zone converges with the onshore directed wave skewness driven transport in the shoaling zone at the breakpoint, conservation dictates sediment deposition at the breakpoint, and so bar formation.

The influences of long (infragravity) waves are an additional complication. Under some conditions, infragravity waves have been shown to transport sediment onshore (e.g. Abdelrahman and Thornton, 1987) while in other conditions, they have been observed to drive sediment offshore (e.g. Russell, 1993; Butt and Russell, 1999). Infragravity waves associated with surf beat lead to an offshore sediment transport as sediment suspended by the larger waves is transported by the offshore current under the trough of the infra-gravity wave (Larson, 1982; Shi and Larson, 1984). The formation of standing infragravity waves may lead to sediment transport towards the anti-nodes, (e.g. Aagaard and Greenwood, 1994) – this is the basis of one bar generation theory (Holman and Bowen, 1982). However, as infragravity waves often exist with a wide range of wave lengths, there is also a wide range of possible convergence positions that tend to cancel one another out. Infragravity energy increases towards the shore (such waves
shoal but do not break), and so the main contribution of infragravity waves to sediment transport is to provide additional “stirring” with sediment subsequently being transported by the mean current (Russell and Huntley, 1999).

2.1.1 The energetics approach to sediment transport

The stream flow model proposed by Bagnold (1966) and adapted by Bailard (1981) for use in the nearshore is a robust and widely used sediment transport formulation. It relates the sediment transport rate to a work rate. The energy available from the fluid motion (a function of the velocity) is multiplied by an efficiency term (to represent the available power to transport sediment). Sediment transport is divided into two distinct modes, bedload and suspended-load transport. Sediment transported in the bedload is in constant contact with the bed, through grain to grain interactions while suspended sediment is supported by the lift of the fluid.

The energetics approach assumes that the total immersed weight transport ($i_t$) is the sum of the bedload ($i_b$) and suspended load transport ($i_s$)

$$i_t = i_b + i_s$$

(2-1)

The bed load transport is further separated into a fluid term (included as $u_i'$, where $u_i$ is cross-shore velocity), and a bed slope term ($\tan \beta \tan \phi$), multiplied by an efficiency term:

$$i_b = \rho c_f \frac{e_b}{\tan \phi} \left[ \left( \frac{u_i}{\tan \phi} \right)^2 - \frac{\tan \beta}{\tan \phi} \left( \frac{u_i}{\tan \phi} \right) \right]$$

(2-2)

where $\rho$ is fluid density, $c_f$ is the drag coefficient, $e_b$ is the bedload efficiency, $\phi$ is the angle of repose, and $\beta$ is the bed gradient and $u_i$ is the total velocity. The suspended term is likewise separated into a velocity term ($u_i'$) and slope term ($\tan \beta$) multiplied by an efficiency term $e_s$. 
\[ \langle t_i \rangle = \rho \left( \frac{\varepsilon_x}{\tan \phi} \right) \left[ \frac{\langle u_i^3 \rangle}{W} - \frac{\varepsilon_x}{\tan \phi} \right] \]  

in which \( W \) is the sediment fall velocity. Combining these terms give the total load formulation.

\[ \langle t_i \rangle = \rho \left( \frac{\varepsilon_x}{\tan \phi} \right) \left[ \frac{\langle u_i^2 \rangle}{W} - \frac{\varepsilon_x}{\tan \phi} \right] + \rho \left( \frac{\varepsilon_x}{\tan \phi} \right) \left[ \frac{\langle u_i^3 \rangle}{W} - \frac{\varepsilon_x}{\tan \phi} \right] \]  

From this equation it can be seen that sediment transport is a function of the 3rd and 4th velocity moment for bedload and suspended load transport respectively. Although the Bailard (1981) model is among the "best" cross-shore sediment transport models (Schoonees and Theron, 1995), and has been successfully applied to field and modelled data (Guza and Thornton, 1985; Swain, 1987; Roelvink and Stive, 1989; Nairn and Southgate, 1993; Thornton et al., 1996; Russell and Huntley, 1999; Mariño-Tapia et al., 2007a), there are important limitations:

1. The drag coefficient is assumed to be constant.
2. There is no threshold for motion, often important in low energy conditions.
3. Breaker induced turbulence is not considered as a stirring term.
4. Instantaneous sediment concentration is considered to be directly proportional to the velocity magnitude with no allowance of phase lags. This limits the usefulness of this approach when there is known to be a phase lag, i.e. due to bed forms or fluid accelerations.

As well as these theoretical constraints, there are practical constraints, mainly that the Bailard (1981) model requires a fully non-linear wave model to provide the higher order velocity moment necessary to calculate sediment transport. This means that any implementation of the Bailard formulation may be limited by the capability of the wave model before other issues such as phase lags are considered. Tests of the Bailard (1981) model with field measurements of velocity moments have shown a general applicability to the nearshore zone. The complexity of
the models required to calculate the velocity fields for the Bailard (1981) formulation also limit timescales for which it can be applied.

2.2 Cross-shore sediment transport parameterisation – The initial shape function

During analysis of the data collected during the British Beach And Nearshore Dynamics (B-BAND) experiment (Davidson et al., 1993), consistent patterns in the hydrodynamic data were noted. The most significant of these were spatial patterns in the velocity moments (see Section 2.1). The first published study of these patterns was by Foote et al. (1994), who concentrated on three tides of data from one of the B-BAND field sites (Spurn Head). Using depth as a proxy for cross-shore position, Foote et al. (1994) investigated the flow components that contributed to the velocity moments, the form of the spatial patterns, the effectiveness of normalisation and the correspondence between the velocity moment patterns and measured suspended fluxes.

Separating the cross-shore component of velocity into a mean ($\bar{u}$), incident ($u_s$) and long ($u_L$) wave component:

$$u = \bar{u} + u_s + u_L$$  \hspace{1cm} (2-5)

led to eight non-zero components of the 3\textsuperscript{rd} velocity moment ($\langle u^3 \rangle$) associated with bed load transport (presented in Table 2-1).
Table 2-1 Velocity moment terms. Taken from Foote et al. (1994)

<table>
<thead>
<tr>
<th>Term</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$\frac{u^3}{u_s^3}$</td>
</tr>
<tr>
<td>2</td>
<td>$\frac{u_s^3}{u_L^3}$</td>
</tr>
<tr>
<td>3</td>
<td>$\frac{u_L^3}{3 u_s^2 u}$</td>
</tr>
<tr>
<td>4</td>
<td>$\frac{3 u_s^2 u}{3 u_L^2 u}$</td>
</tr>
<tr>
<td>5</td>
<td>$\frac{3 u_s^2 u}{6 u_s u_L}$</td>
</tr>
<tr>
<td>6</td>
<td>$\frac{3 u_L^2 u_s}{3 u_L^2 u}$</td>
</tr>
<tr>
<td>7</td>
<td>$\frac{u_L^2}{u_s^2 u_L}$</td>
</tr>
<tr>
<td>8</td>
<td>$\frac{u_L^2}{u_s^2 u_L}$</td>
</tr>
</tbody>
</table>

The modulus in the 4th velocity moment term ($\langle |u|^4 \rangle$), associated with suspended load transport) makes it difficult to reduce to simpler components and so Foote et al. (1994) made the assumption that the magnitude of the incident waves was greater than that of either the mean or the long wave component. This led to three suspended terms, presented in Table 2-2.

Table 2-2 Suspended flux terms. Taken from Foote et al. (1994)

<table>
<thead>
<tr>
<th>Term</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$\left( \frac{u_s^2}{u_s} \right)^{\frac{1}{2}} u_s$</td>
</tr>
<tr>
<td>2</td>
<td>$\left( \frac{u_s^2}{u_s} \right)^{\frac{1}{2}} u_L$</td>
</tr>
<tr>
<td>3</td>
<td>$\left( \frac{u_s^2}{u_s} \right)^{\frac{1}{2}} u$</td>
</tr>
</tbody>
</table>

Following the analysis of Guza and Thornton (1985), the terms were normalised by the velocity variance ($\langle u^2 \rangle^{\frac{1}{2}}$ and $\langle u' \rangle^{\frac{1}{2}}$ for the 3rd and 4th terms respectively). Each of these terms were plotted against depth, and the different spatial patterns of each velocity moment component were described and presented. The velocity moment normalisation was found to be necessary as it reduced the difference between the different tides from an order of magnitude to within a factor of 2. It was found that the normalised velocity moments were relatively insensitive to wave conditions, with tides of a breaker height of 3 and 0.7 m exhibiting similar patterns.

Separating the data inside and outside the breakpoint allowed the importance of the mechanisms within these different hydrodynamic zones to be investigated. Outside the breakpoint, the onshore-directed short-wave skewness (bedload term 2) was dominant, but terms 4 (onshore...
directed) and 8 (offshore directed) were also important. For suspended-load transport the onshore-directed incident term was dominant (term 1), as the long period (offshore directed) and mean (onshore directed) terms were weaker and tended to cancel each other out. In the surf zone different terms dominated, and the individual terms had relatively different magnitudes and/or directions. In particular, term 4 of the bedload components (transport associated with sediment stirred by the incident waves, and transported by the mean current) changed direction and dominated transport inside the breakpoint. Terms 2 and 4 were also important but, when including the weaker terms 1, 7 and 8 tend to cancel out. The suspended terms representing the mean and short wave terms were most important, but opposed one another and led to weakly offshore-directed flow.

Having identified the bedload terms 2, 4, 5 and 8 as being most important, the data from each of the terms were plotted against depth. Foote et al. (1994) found that spatial patterns in the data were better represented by plotting against the actual depth, rather than the depth normalised by breakpoint depth, as suggested by Roelvink and Stive (1989), and used in subsequent shape function studies. They suggested that this hypothesis needed further verification. Bedload transport due to incident wave skewness (Term 2) was always onshore directed, with a peak just outside the breakpoint, reducing seaward and landward. Sediment stirred by the incident waves and transported by the mean flow (Term 4) was predominantly offshore directed in the surf zone and onshore directed in the shoaling zone crossing over at approximately the breakpoint. Sediment stirred by the long waves and transported by the mean flow (Term 5) was negligible outside the breakpoint, but was offshore directed in the surf zone. Term 8 (sediment stirred by the incident waves and transported by the long waves) was always weakly offshore directed. The three suspended terms were similarly treated. The short wave term showed onshore transport peaking just outside the breakpoint, the mean term was offshore directed in the surf zone and onshore directed in the shoaling zone, and the long wave component was always offshore directed.
Having noted the importance of the various components, Foote et al (1994) examined the spatial patterns of the total velocity moments. The spatial pattern of the total bedload velocity moment showed onshore transport outside the shoaling zone, and offshore transport in the surf zone. This was replicated in the suspended velocity moment data, (both figures are presented in Figure 2-1). This pattern (termed the 'shape function') shows that the velocity moment from all the tides collapse into the same region on the graph, with little dependence on wave conditions. No attempt was made to parameterise the data into a useable equation, as would be required to drive a numerical model or to be of use in predicting cross-shore sediment transport.

Figure 2-1 Normalised velocity moments against depth. The upper panel shows the bedload components (as represented by the 3rd velocity moment), the lower panel shows the suspended component (4th velocity moment). Taken from Foote et al. (1994).
To test if the patterns were representative of the actual sediment fluxes, Foote et al. (1994) went on to qualitatively compare point measurements of suspended sediment fluxes from 10 cm above the bed to estimate the sediment flux based on the suspended velocity moment components. There was a general agreement of the mean and long wave components however the incident wave component was found to be in the wrong direction. This was attributed to the possible presence of bed forms, especially in the shoaling zone.

Finally, Foote et al. (1994) used their findings to develop a conceptual profile evolution model discussed later (Section 2.3).

Although Foote et al. (1994) produced a qualitative velocity moment shape function for sediment transport, it was only based on data from a single beach, from three tides, and so no conclusion about the universality of the shape function could be drawn.

The analysis of Foote et al. (1994) was extended by Russell and Huntley (1999). To investigate the universality of the cross-shore velocity moment patterns identified by Foote et al. (1994), three beaches from the B-BAND project were identified (including Spurn Head as used in the Foote et al. (1994) study). These beaches span a wide range of morphodynamic conditions representing a dissipative (Llangennith), a reflective, (Teignmouth) and an intermediate (Spurn Head) beach. Hydrodynamic conditions varied over the six tides studied with breaker height ranging from 0.7 – 3 m. Russell and Huntley (1999) focused on high energy condition, as the energetics model is only valid when sediment is in instantaneous response to the flow, a reasonable assumption under energetic conditions.

As with Foote et al. (1994), Russell and Huntley (1999) investigated the influence of the different components of the velocity moments. As most sediment transport models reduce to a $u^3$ dependence for high transport rates, (e.g. Dyer, 1986), and many workers have found the time-averaged $\langle u^3 \rangle$ to be the crucial velocity moment in determining the net sediment transport rate (Ribberink and Al-Salem, 1995; Wilson et al., 1995), Russell and Huntley (1999) used the 3rd velocity moment as a total load predictor. Near-bed cross-shore velocity was broken down
into the mean, short wave and long period flow as in (2-5), leading to eight potential non-zero terms (as in Table 2-1), although the two other possible (zero) terms were also included $3(u_2)\bar{u}^2$ (term 9) and $3(u_2)u^{-2}$ (term 10) both time averages of oscillatory components and so $\approx$ zero). Russell and Huntley (1999) extended the approach of Foote et al. (1994) by comparing the relative importance of the different velocity moment components. As the analysis included the data from Foote et al. (1994) it can be seen how addition of the combination of three tides from three very different beaches affects the overall patterns (Figure 2-2).

Figure 2-2 Average values of normalised velocity moments (positive values indicate onshore transport). The definition of the different velocity moment terms is given in the Table 2-1. Upper panel shows velocity moment from outside the surf-zone, lower panel shows velocity moment from inside the surf-zone. Taken from Russell and Huntley (1999).
Again the data was separated into regions inside and outside the breakpoint. Outside the breakpoint, there were no data from Llangennith, so only the single tide from Teignmouth was added. In common with the Spurn Head data, terms 2, 4 and 8 also dominate in the Teignmouth data, with the terms showing the same sign and similar magnitudes in all terms except term 2, which has a magnitude approximately half that of the Spurn Head data. Inside the surf zone the Llangennith and Teignmouth data tended to match the Spurn Head data in direction although the magnitudes were sometimes quite different. Terms 3 (long wave skewness) and 5 (stirring by long waves and transport by the mean current) were far more important in the dissipative Llangennith data. Russell and Huntley (1999) state that despite the range of conditions included in the dataset, a remarkable degree of consistency was revealed by the velocity moment data, especially in the dominance of the terms.

To look at the spatial patterns of the velocity moment, the four dominant terms (2, 4, 5 and 8) of the 3rd velocity moment normalised by the velocity variance were plotted against the normalised depth. While Foote et al. (1994) tentatively suggested that the patterns of the velocity moments were a function of depth, Russell and Huntley (1999) rejected this by using depth normalised by breakpoint depth (in line with Roelvink and Stive, 1989). The patterns suggested by Foote et al. (1994) analysis were supported by the extended dataset of Russell and Huntley (1999), and the data were parameterised with third-order polynomials, with Pearson's correlation coefficient ($R^2$) values ranging from $0.53 < R^2 < 0.81$.

Russell and Huntley (1999) plotted the 3rd velocity moment data to produce a shape function (Figure 2-3) which was parameterised with a 2nd order polynomial ($R^2 = 0.85$):

$$\frac{\left\langle u^3 \right\rangle}{\left\langle u^2 \right\rangle^{3/2}} = -0.52 \left( \frac{h}{h_b} \right)^2 + 2.27 \left( \frac{h}{h_b} \right) - 1.58$$  \hspace{1cm} (2-6)

This shape function includes onshore transport in the shoaling zone and offshore transport in the surf zone, with a convergence at approximately $h/h_b \approx 0.8$. This represents the first shape
function capable of predicting cross-shore sediment transport (via the energetic approach) from cross-shore position (via normalised depth). Having quantified the patterns, the shape function could be used to drive numerical models. The Russell and Huntley (1999) paper showed that the patterns presented by Foote et al. (1994) were not peculiar to a particular beach, but were present on a number of very different beaches, under a range of high energy conditions. However, Russell and Huntley (1999) state that sediment transport within the swash and inner surf zone is very important and is absent in their analysis.

![Figure 2-3 The Russell and Huntley (1999) velocity moment shape function: normalised total velocity moment term against normalised depth (positive values are onshore, values of h/h_b < 1 are inside the surf zone). Taken from Russell and Huntley (1999).](image)
Plant et al (2001) derived a simplified cross-shore sediment parameterisation by making assumptions about the sediment transport and hydrodynamics and simplifications of the Bagnold (1966)/Bailard (1981) bedload transport model. This was formulated as:

\[
\bar{Q} = c_2 \frac{1}{16\sqrt{2}} \frac{\rho \sqrt{g}}{\tan \phi} H_{rms}^3 h^{-3/2} \left\{ \left[ \frac{1+c_1 \sqrt{2}}{\sqrt{2}} \right] y + c_1 \left[ \frac{2}{\sqrt{\pi}} \frac{\tan \beta}{\tan \phi} + R_{cw}^{other} \right] \right\}
\]

(2-7)

where \( c_1, c_2 \) represent empirical coefficients and \( \phi, \beta, \rho, g, H_{rms} \) and \( h \) represent sediment angle of repose, beach slope, water density, acceleration due to gravity, local rms wave height and local depth respectively. \( R_{cw}^{other} \) is the correlation between bed sediment load and velocity fluctuations of the non-Gaussian (e.g. skewed) waves.

The Plant et al. (2001) model separates sediment transport into a dimensional stirring/magnitude term and a dimensionless transport term that represents the competition between opposing transport mechanisms. This is expressed as:

\[
\bar{Q}(x, t) = q(x, t)r(x, t)
\]

(2-8)

where \( q(x, t) \) is the term outside the braces in (2-7), and \( r(x, t) \) is the term inside the braces. \( r(x, t) \) was obtained empirically from the data collected in Ruessink et al. (1998). Plant et al (2001) used a parameterisation that related \( r(x, t) \) to the relative wave height, \( y = H_{rms}/h \), and beach gradient:

\[
r(\tan \beta, y) = r_0 \tan \beta + r_1 \left\{ \frac{y}{y_c} \right\} \left[ 1 - \frac{y}{y_c} \right]
\]

(2-9)

where \( r_0, r_1, p \) and \( y_c \) are empirical constants. \( y_c \) is a critical value of the relative wave height used to scale the relative wave height. It should be noted that the relative wave height varies in
an opposing manner to the relative water depth used by Russell and Huntley (1999) tending to zero in deep water and increasing towards the shoreline. Plant et al. (2001) specified values for the constants as $r_0 = 2.25$, $r_1 = 0.5$, and $\gamma_c = 0.3$, and plotted a range of $p$ values, (shown in Figure 2-4). This figure shows how the sediment transport direction changes with spatial location in an equivalent way to the shape function (e.g. Russell and Huntley, 1999). $q(x,t)$ is equivalent to the velocity moment normalising term (i.e. velocity variance, $\langle u^2 \rangle^{1/2}$). Figure 2-4 shows how, in the Plant et al. (2001) parameterisation, offshore transport occurs at values greater than $y/\gamma_c = 1$ (i.e. near shore) and onshore transport occurs further offshore (low $y/\gamma_c$ values), and tends to zero in deep water. In common with Russell and Huntley (1999), the swash zone is not included and predicted transport continues to increases towards the shoreline. The cross-over point between offshore-directed and onshore-directed transport occurs at $y/\gamma_c = 1$, which is indicative of the breakpoint. In Plant et al. (2001), the value of $\gamma_c$, which controls this location is taken as constant, although it is acknowledged that this is probably not the case in reality.

![Figure 2-4 Non-dimensional transport parameterization, $r$ (2-9) as a function of the relative wave height, $\gamma$. The function is plotted for several polynomial orders, $p$ (values of other parameters were $r_0 = 2.25$, $r_1 = 0.5$, $\gamma_c = 0.3$). Taken from Plant et al. (2001).](image)

The critical value of the relative wave height ($\gamma_c$) was investigated using inverse modelling by Plant et al. (2004) and was related to the relative wavenumber $kh$ (proportional to depth over wavelength). Allowing $\gamma_c$ to vary lets the Plant et al. (2001) parameterisation vary with wave
conditions. When \( k h \) is very low (waves are very long relative to depth i.e. low energy conditions), the analysis suggested that \( y_c \) should be very high (\( O(100) \)), whereas as \( k h \) increases (i.e. increasing wave energy conditions), \( y_c \) reduces towards the value used in Plant et al. (2001) (i.e., \( y_c = 0.3 \)). The effect this has on the parameterisation is that the under low energy conditions the relative wave height never increases enough to reach \( y_c \), and so the model always shows onshore transport (c.f. Figure 2-4).

With a typical cross-shore profile of localised wave height, \( (H_{rms}) \) increases from deep values to a peak at the breakpoint, and then decreases, nearly linearly, to zero at the shore line, see Figure 2-4), the Plant et al. (2001) parameterisation predicts onshore transport in the shoaling and swash zones as both exhibit low values of \( H/h \), whereas in the surf zone, if conditions are energetic enough, offshore transport is predicted. Although this is qualitatively correct, it makes little physical sense, as the transport mechanisms in the swash zone are very different from those in the shoaling zone but are modelled in the same manner.

Another cross-shore sediment transport parameterisation was that of Aagaard et al. (2002). During experiments on two Danish beaches, Aagaard et al. (2002) noted that one beach exhibited onshore transport in the surf zone under high energy conditions, while another showed offshore transport. These observations provided a basis for the development of a parameterisation to describe these conditions. Aagaard et al. (2002) broke down the sediment transport into a mean and oscillatory component, and observed that the two beaches both showed similar mean transport components, while the oscillatory component varied dramatically. As cross-shore sediment transport is the result of a competition between competing mechanisms, they derived a normalised sediment flux index. This parameter is non-dimensional and corrects for varying instrument heights:

\[
Q_x = \frac{q_{osc} + q_{mean}}{q_{osc} + q_{mean}} \tag{2-10}
\]

where \( q_{osc} (q_{mean}) \) is the oscillatory (mean) component of sediment transport.
Aagaard et al. (2002) developed a predictive model to describe the tendency of a beach to show onshore (skewness) or offshore (bed-return flow) dominated transport. Onshore transport is related to the correlation between the velocity and the sediment concentration, wave skewness, and the wave size, while the mean transport is a function of the mean flow. Therefore a non-dimensional parameter ($D$) was developed to relate these terms. $D$ is expected to reflect the tendency towards onshore or offshore-directed sediment flux, and is defined as:

$$D = \frac{p s u_{r m s}}{|u|}$$  \hspace{1cm} (2-11)

where $p$ denotes the maximum cross-correlation between velocity and the sediment concentration at incident wave frequencies, $s$ the wave skewness, $u_{r m s}$ and $|u|$ the root mean square and mean velocity respectively. This equation appears more conceptual than quantitative, as no evidence is presented that suggests that, for example, doubling $p$ is has the same effect as doubling $s$, or halving $|u|$. The relationship between $Q_d$ and $D$ is presented in Figure 2-5.

\begin{figure}
\centering
\includegraphics[width=\textwidth]{image.png}
\caption{Figure 2-5 Relationship between $D$ and $Q_d$. Taken from Aagaard et al. (2002).}
\end{figure}
There was a very strong relationship between $D$ and $Q_d$ (presented in Figure 2-5) however $D$ is difficult to predict in its current form. Instead, Aagaard et al. (2002) developed an empirical parameterisation for each of the constituent terms in (2-11). As $p$ is expected to be related to the bed configuration (i.e. bed ripples), it is compared to the Shields parameter, $\theta_{\text{max}}$, and a linear equation is fitted is:

$$p = 0.356 \theta_{\text{max}} - 0.130$$

with $R^2 = 0.324$. This relationship was developed from the data presented in Figure 2-6.

![Figure 2-6 Relationship between $p$ and $\theta_{\text{max}}$. Adapted from Aagaard et al. (2002).](image)

The relationship between $s$ and $H_{\text{eff}}/h_b$ is presented in Figure 2-7, and the linear relationship derived from the data is given as
\[ s = 1.332 \left( \frac{H_{rms}}{h_b} \right) + 0.004 \]  \hspace{1cm} (2-13)

with \( R^2 = 0.418 \).

The mean current was given as a function of \( \gamma \tan \beta \).

\[ |\bar{u}| = -9.26 (\gamma^2 \tan \beta) - 0.028 \]  \hspace{1cm} (2-14)

where \( \gamma \) is \( H/h \) and \( \beta \) is the beach slope (\( R^2 = 0.494 \)). This linear equation was derived from the data presented in Figure 2-8.

Figure 2-7 Relationship between \( H_{rms}/h_b \) and \( s \). Taken from Aagaard et al. (2002).
Substituting (2-12)-(2-14) into (2-11) gave a new parameter, $\Gamma$:

$$\Gamma = \frac{\theta_{\text{max}}(H_{\text{up}}/h_g)u_{\text{rms}}}{\left(\gamma_s^2 \tan\beta\right)}$$  \hspace{1cm} (2-15)

$\Gamma$ shows a weaker relationship with $Q_d$ compared to $D$. This is presented in Figure 2-9. An empirical relationship for this data was presented as:

$$Q_d = 0.0026\Gamma - 0.752$$  \hspace{1cm} (2-16)

with an $R^2$ of 0.579

Having developed a parameter to calculate the tendency of sediment transport to be onshore or offshore, Aagaard et al. (2002) then developed a parameter to give a specific sediment magnitude. This is derived from the Nielsen (1984) sediment concentration profile equations,
assuming a constant vertical mixing length. The net suspended sediment flux \( (Q_s) \) is then the product of this magnitude and (2-16).

\[
Q_s = (0.026 \Gamma - 0.752) \times 0.0015 \rho_s a' \theta_{\text{max}} \exp\left( \frac{z}{0.012 h \exp(4.781(H_s/h))} \right)
\]  

(2-17)

where \( a' = 0.6 \) is the pore space, and \( \rho_s \) is the sediment density. The resulting semi-empirical parameterisation allows onshore bar migration on gently sloping beaches and/or with large bed shear stresses, whereas there is a tendency for offshore transport on steeper beaches and/or smaller bed shear stresses. Unfortunately no evidence is given to show how well this predictor works and given that three of its four component terms are based on weak parameterisations the resulting formula is not fully supported.

Figure 2-9 The relationship between \( \Gamma \) and \( Q_s \). From Aagaard et al. (2002).
In a study at a berm fronted semi-enclosed estuary in Avoca, New South Wales, Australia, Weir et al. (2006) measured berm development during a range of hydrodynamic conditions. Two modes of berm formation were observed; mode I was associated with rapid vertical and horizontal growth of the berm, while mode 2 was associated with slower horizontal seaward growth (progradation) of the berm and the development of a neap berm. When the berm was overtopped by swash events, mode 1 predominated, while mode 2 occurred in the absence of such events. Inverting the measurements of profile accretion/erosion with the sediment continuity equation gave cross-shore profiles of sediment transport. These profiles were qualitatively constrained into 3 basic shapes (shape functions) during berm growth, although the absolute values varied greatly. The three main (and one sub-) types of shape function are presented in Figure 2-10. Type I represented onshore sediment transport across the swash zone, but stopping before the top of the berm. Type II exhibited onshore transport throughout the swash-zone, with swash events overtopping the berm, and so sediment transport does not reduce to zero at the landward end of the swash-zone. The second type is divided into two sub-types (II-a and II-b) reflecting the observational differences between small and large overtopping events. The third event (type III) shows offshore transport at the seaward end of the shape function, with onshore transport in the middle of the swash-zone, and zero transport in the upper swash-zone. This is associated with sediment being cut from the foot of the berm and deposited at the berm crest.

The conditions under which shape function occurred were linked to the state of the tide and the mode of profile accretion/erosion. These relationships informed the development of a conceptual model of the growth of berm fronting coastal lagoons, on energetic, relatively steep, intermediate-type beaches. The model described four stages; after an artificial opening of the lagoon, the berm is characterised by berm growth due to onshore sediment transport described by shape functions I/II (stage 2). This steepened the berm and lead to vertical and horizontal berm growth. After spring tide (stage 3) a neap bar formed, leading to horizontal berm growth associated with shape function I/III. As the tidal range increased after neap tide (stage 4), the
neap berm transport was onshore, while the swash event continued to overtop the berm. These processes led to horizontal and vertical bar growth. The model allows berm morphology to switch between stage 3 and 4, until the berm is artificially opened again, which returns the model to stage 1.

Although only qualitative and conceptual, the Weir et al. (2006) model provides a basis for the development of a numerical predictive model, much as the Foote et al. (1994) approach led to the development of the Fisher and O’Hare (1996) model and eventually the Maríño-Tapia et al. (2007b) model and the model presented in this thesis.

![Shape functions of Weir et al. (2006)](image)

Figure 2-10 Shape functions of Weir et al. (2006). Sediment transport was inferred from measured beach profiles (onshore sediment transport is positive). Normalised Swash Height relates the height of the swash run up to the run-up limit, and so 0 is seaward and 1 is landward. Taken from Weir et al. (2006).
Recently, Maríño-Tapia et al. (2007a) strengthened the original velocity moment shape function approach by expanding on the data included in the Russell and Huntley (1999) shape function. Data was included from 5 contrasting European beaches, increasing the number of tides from 6 to 18 over 11 years, and including some low energy data. A wide range of hydrodynamic conditions were also included (from saturated surf zone with large quantities of broad-banded surf beat to an unsaturated surf zone with sub-harmonic energy). Data was also included from the swash zone.

According to the energetics approach (2-4), sediment transport can be related to four velocity moments, relating to the suspended and bedload, process related and gravity terms. From the field observations, Maríño-Tapia et al. (2007a) developed shape functions for the terms associated with the 3rd (Figure 2-11) and 4th (Figure 2-12) velocity moments:

\[
\frac{\langle u^3 \rangle}{\langle u^2 \rangle^{3/2}} = \sin\left(2\pi h/h_b^{0.275}\right)1.9 h/h_b^{0.14} \exp\left(-0.45 h/h_b\right)
\]

for the 3rd (bed load) velocity moment, and:

\[
\frac{\langle u^4 \rangle}{\langle u^2 \rangle^{3/2}} = \sin\left(2\pi h/h_b^{0.275}\right)4 h/h_b^{0.14} \exp\left(-0.45 h/h_b\right)
\]

for the 4th (suspended load) velocity moment, where \( \langle u^2 \rangle \) represents the cross-shore velocity variance, used to normalise the sediment transport. Maríño-Tapia et al. (2007a) also investigated the structure of the slope terms, and found little cross-shore spatial relationship. Including data from the swash zone gave a pair of shape functions that predicted onshore transport in the swash and shoaling zones, with offshore transport in the surf zone. Both the 3rd and 4th velocity moment shape functions were parameterised with a function of the same form, but with higher magnitude for the 4th (suspended) velocity moment. The data showed the same
structure as seen by Russell and Huntley (1999) but with much higher resolution. The shape function was parameterised to start at the origin (no transport at the shoreline) and included a depth of closure.

\[
y = \sin (2 \pi \Phi \, 0.275) \, 1.9 \times 10^{-0.45x} 
\]

Figure 2-11 The 3rd velocity moment shape function of Maríño-Tapia et al. (2007a) (representing bedload transport). The cross-shore velocity skewness (the 3rd velocity moment) normalised by the cross-shore velocity variance is presented as a function of depth normalised by the breakpoint depth. Data points (representing 17:06 minutes (1024 seconds) time averages), are presented from a number of beaches under varying conditions. Taken from Maríño-Tapia et al. (2007a).

Although Guza and Thornton (1985) argued that the most important terms in the energetic approach are the process related terms, Maríño-Tapia et al. (2007a) deemed it important to consider the slope terms. The slope terms of the suspended and bed load terms were also plotted against normalised depth, however there was very little structure in the data, presumably this is because the slope was fairly constant. The 3rd (4th) term oscillated around a value of 1.6 (6.38) which is the theoretical value for Gaussian waves calculated by Guza and Thornton (1985).
Figure 2-12 The 4th velocity moment shape function of Marín-Tapia et al. (2007a) (representing suspended load transport). The 4th cross-shore velocity moment (skewness), normalised by cross-shore velocity variance is plotted against depth normalised by the breaker point. Taken from Marín-Tapia et al. (2007a).

Having parameterised the 3rd and 4th velocity moment terms, Marín-Tapia et al. (2007a) broke the velocity moments into the constituent terms, as in (2-5), leading to 10 potential non-zero terms, slightly different to those of Russell and Huntley (presented in Table 2-3). Marín-Tapia et al. (2007a) found the same dominant components (terms 2, 4, 5 and Russell and Huntley (1999) term 8/Marín-Tapia et al. (2007a) term 6) with the same pattern as observed by Russell and Huntley (1999). In addition, they also investigated terms 1 and 3 (the cube of the mean velocity and the cube of the long wave velocity). The mean transport term (1) had near-zero values in the shoaling zone, with strongly offshore-directed transport in the surf zone, while the long wave skewness (term 3) showed near-zero values in the shoaling zone, with increasing magnitudes in the surf-zone.
<table>
<thead>
<tr>
<th>#</th>
<th>Expression</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$\bar{u}^3$</td>
<td>Mean velocity cubed (e.g. bed-return flow current inside the surf zone).</td>
</tr>
<tr>
<td>2</td>
<td>$\langle \bar{u}_s^3 \rangle$</td>
<td>Short wave velocity cubed.</td>
</tr>
<tr>
<td>3</td>
<td>$\langle \bar{u}_L^3 \rangle$</td>
<td>Long wave velocity cubed.</td>
</tr>
<tr>
<td>4</td>
<td>$3\langle \bar{u}_s^2 \rangle \bar{u}$</td>
<td>Stirring by the short waves and transport by the mean flow.</td>
</tr>
<tr>
<td>5</td>
<td>$3\langle \bar{u}_L^2 \rangle \bar{u}$</td>
<td>Stirring by the long waves and transport by the mean flow.</td>
</tr>
<tr>
<td>6</td>
<td>$3\langle \bar{u}_s^2 \bar{u}_L \rangle$</td>
<td>Correlation of short waves variance and long wave velocity.</td>
</tr>
<tr>
<td>7</td>
<td>$3\langle \bar{u}_L^2 \bar{u}_s \rangle$</td>
<td>Correlation of long waves variance and short wave velocity $\sim 0$.</td>
</tr>
<tr>
<td>8</td>
<td>$6\langle \bar{u}_s \bar{u}_L \rangle$</td>
<td>Three way correlation $\sim 0$.</td>
</tr>
<tr>
<td>9</td>
<td>$3\langle \bar{u}_s \rangle \bar{u}^2$</td>
<td>Time average of oscillatory component $\sim 0$.</td>
</tr>
<tr>
<td>10</td>
<td>$3\langle \bar{u}_L \rangle \bar{u}^2$</td>
<td>Time average of oscillatory component $\sim 0$.</td>
</tr>
</tbody>
</table>

To test the validity of using the velocity moment shape function to predict sediment transport, Marín-Tapia *et al.* (2007a) compared its output to the point measurements of suspended sediment transport. To allow comparison between the different tides, the sediment fluxes were normalised following Plant *et al.* (2001), by

$$\sigma_u \bar{c}$$

(2-20)

This normalisation appears to work well, collapsing the point measurements of suspended fluxes for all the different tides into the same region of the graph. The pattern of the suspended sediment shows a remarkable qualitative agreement with the velocity moment shape function, with offshore transport in the surf zone and onshore transport in the swash zone and shoaling zone validating the velocity moment shape function approach.

The Marín-Tapia *et al.* (2007a) shape function provides an integrated approach (including bed return flow, and short and long wave contributions) to link sandbar migration to small scale hydrodynamic forcings. The shape function is able to capture the behaviour of bar profile
evolution, by allowing onshore and offshore bar migration. However, there are limitations to the approach. The determination of the breakpoint depth is difficult and precludes this use of the method on beaches with multiple bars. The method does not consider influence of longshore processes, and so limits the methodology to alongshore uniform beaches (i.e. beaches without alongshore rhythmic morphologies); however, one of the beaches used in this analysis had some degree of alongshore non-uniformity and did contribute positively to the shape function pattern. Other limitations are those of the energetics approach relating to the presence of bed formations (which can generate sediment suspension phase lags) and fluid accelerations, both of which exclude the use of the Mariño-Tapia et al. (2007a) approach in their presence.

2.3 Modelling profile evolution with a shape function parameterisation

Foote et al. (1994) developed a conceptual model to explain development of a macrotidal beach profile. The model was developed around the observed patterns in the data. Offshore transport in the surf-zone with onshore transport in the shoaling zone leads to a convergence point at the breakpoint and so the potential for sand bar formation. Foote et al. (1994) suggested that tidally advecting the shape function over a beach profile could lead to the typical macrotidal beach profile, a steep upper beach with a flatter low tide terrace. Foote et al. (1994) separated various possible regions of the beach that are under the influence of the swash-zone, swash/surf-zone, surf-zone and surf/shoaling zone and just the shoaling zone (Figure 2-13), although this will depend on the exact nature of the beach slope, tidal range etc.
This conceptual model was first implemented numerically by Fisher and O'Hare (1996). The velocity moment patterns were parameterised with a precursor of the Russell and Huntley (1999) shape function for the 3\textsuperscript{rd} velocity moment, as a function of the depth normalised by the breakpoint depth:

\[
I_{bed \, coeff} = \frac{\langle u^2 | u \rangle}{\langle u^2 \rangle^{3/2}} \left\{ -1.58 \left( h/h_b \right)^3 + 5.79 \left( h/h_b \right)^2 - 4.59 \left( h/h_b \right) \right\} \tag{2-21}
\]

and similar function for the 4\textsuperscript{th} velocity moment:

\[
I_{sus \, coeff} = \frac{\langle u^3 | u \rangle}{\langle u^2 \rangle^2} \left\{ -4.15 \left( h/h_b \right)^3 + 14.17 \left( h/h_b \right)^2 - 10.48 \left( h/h_b \right) \right\} \tag{2-22}
\]
The velocity moments provided by the shape functions were used to calculate the sediment transport using the energetics approach. The shape functions were unnormalised by the velocity variance calculated with a simple wave shoaling model. The bedload term as calculated from:

\[ i_{\text{bed}} = \frac{\varepsilon_b C_D \rho l_{\text{bed}} \text{coeff}}{\tan \phi} \quad (2-23) \]

where \( \varepsilon_b \) is the bedload efficiency factor, \( C_D \) is the drag coefficient, \( \rho \) is the fluid density, \( \phi \) is the angle of repose of the sediment. The suspended term was calculated from:

\[ i_{\text{sus}} = \frac{\varepsilon_s C_D \rho l_{\text{sus}} \text{coeff}}{W_s} \quad (2-24) \]

where \( \varepsilon_s \) is the suspended load efficiency factor and \( W_s \) is the sediment fall velocity. The total cross-shore immersed weight sediment transport rate was thus the sum of \( i_{\text{bed}} \) and \( i_{\text{sus}} \), and the total volumetric transport rate, \( Q \) was given by:

\[ Q = \frac{i_{\text{bed}} + i_{\text{sus}}}{(\rho_s - \rho)g} \quad (2-25) \]

where \( \rho_s \) is the sediment density, \( g \) is gravity. Each time step this expression was used to calculate a cross-shore profile of cross-shore sediment transport, the spatial derivative of which gave bed level change according to the sediment continuity equation:

\[ \frac{d\eta}{dt} = \frac{1}{\varepsilon} \frac{dQ}{dx} \quad (2-26) \]

in which \( \varepsilon \) is packing of settled grains (\( \varepsilon = 1 - \lambda \), \( \lambda \) is the void ratio), and \( \eta \) is the bed elevation. The bed level was then updated, the submerged part of the profile smoothed and the process repeated. The time step of the model was 1/100 of a tidal cycle, and the water level was adjusted after each time step to simulate the tidal signal.
Being based on the energetics approach, the model has several key assumptions. These include:

- The energetics approach is valid
- Downslope and upslope transport are equal
- Airy wave theory is appropriate (for completion of the normalisation)
- There is transmission of wave energy across bars
- Long shore transport is ignored
- Swash zone transport is ignored
- No avalanching can occur
- There is a sinusoidal monochromatic tide signal

The response of the model was tested for its sensitivity to wave and tidal range, and the results are presented in Figure 2-14. The model was restricted to four tidal cycles, after which it became unstable. These results show that the profile depth tended towards a terrace at the depth of maximum offshore flow. The region of onshore transport quickly steepened, and narrowed to become a localised transport spike. Profile change slowed with each iteration suggesting the existence of a quasi-equilibrium profile.
The introduction of a tidal range led to the formation of a pronounced high water and a suppressed low water breakpoint bar. This was attributed to the low water bars residing in both...
the on- and off-shore transport regions (at different stages of the tide). The tide acts to spread (smooth) the morphological change over the profile and so features are suppressed with increasing tidal range. The model was also tested with a range of wave heights. The greater the wave height, the faster the profile evolved and the larger the resulting features. Fisher and O'Hare (1996) state that increasing the wave height had a similar effect to reducing the tidal range. The model of Fisher and O'Hare (1996) was not able to quantitatively reproduce the profile evolution, however it did produce qualitatively realistic features including offshore bars and a low tide terrace.

The model was further developed by Fisher et al. (1997). The wave model was improved to include wave dissipation inside the breakpoint following the approach of Battjes and Janssen (1978). This stabilised the model beyond four tidal cycles, allowing the influence of the spring-neap cycle to be investigated. First, the model was driven with a monochromatic ($M_2$) tidal signal over 60 tidal cycles; in this case, the profile quickly developed to a bar at the high and low tide breakpoints. With time, there was convergence of the two bars, as the high water bar migrated offshore and the low tide breakpoint bar steepened.

Inclusion of the $S_2$ tidal constituent led to the development of four bars caused by the high- and low-water and breakpoint bar during spring and neap tides. Between springs and neaps modelled features were transient and broken down by the tidal translation. Increasing the tidal amplitudes spatially separated the morphological features. Attempts to enhance the features between neaps and springs (by enhancing efficiency factors, $e_b$ and $e_s$) failed, suggesting the dominance of tidal dynamics in the model.

Fisher et al. (1997) suggest further work to investigate the effect of varying the initial profile (e.g. from a linear profile to a equilibrium (Dean (1977) profile) or a measured profile). As all their analysis was with a 1 m wave field, they suggest testing with a more realistic variable wave field.
The model developed by Fisher and O'Hare (1996) and Fisher et al. (1997) exhibits realistic response to the forcings, and the development of the breakpoint bar and high-water berm is promising. However, the model is limited in a number of ways. Not including the swash zone is a serious drawback. The shape function used to drive the model (Figure 2-15) shows transport is increasingly offshore directed as the shoreline is approached. Assuming zero transport at the shoreline, this would lead to a sediment transport discontinuity and a major sediment divergence with associated erosion at the shoreline. This is overcome by careful smoothing of the profile in such a way as to “pin” the shoreline. The necessity of a sinusoidal tidal signal (possibly due to the coding of the model) limits this model to qualitative behavioural studies rather than being of use for real cases with measured tides, wave conditions and initial profiles. Only initial testing of the model is presented by Fisher and O'Hare (1996) and Fisher et al. (1997), and so it is difficult to ascertain the model’s behaviour with real forcing conditions.

![Figure 2-15](image)

Figure 2-15 The shape function used by Fisher and O'Hare (1996). Taken from Fisher and O'Hare (1996).
The Fisher and O'Hare (1996) and Fisher et al. (1997) model provided a proof of concept for the shape function profile evolution model, however the model was limited in terms of application. The first implementation of a (similar) shape function based model to address a specific scientific question was made by Masselink (2004). A heuristic model was developed to replicate the formation and evolution of multiple intertidal bars. The model was based around a qualitative shape function (Figure 2-17) given as

$$q = -A \sin(\pi h/h_b) \text{ for } 0 < h/h_b < 2$$  \hspace{1cm} (2-27)

where $q$ is the volumetric sediment flux and $A$ is the amplitude (set to 0.05 as a default). The development of this shape function was informed by Russell and Huntley (1999). $h_b$ is calculated by assuming $H_b/h_b = 0.4$. To stop the growth of numerical instabilities, the model profile was smoothed every hour with an 11 point moving average, and daily with a five point moving average. It should be noted that this smoothing will tend to reduce real large scale features.

![Figure 2-16 The conceptual shape function used by Masselink (2004) to drive his morphological model. Taken from Masselink (2004).](image)
Masselink (2004) initially repeated the model tests of Fisher and O'Hare (1996) and Fisher et al. (1997), focusing on constant wave conditions, \((H_b = 0.5, 2.0 \text{ m})\) with an \(M_2\) and then \(M_2/S_2\) tide. Satisfied that the model was producing realistic beach profile responses, Masselink (2004) forced the model with a year long time-series of real data. The model produced un-realistically large features. Further model runs increased the model complexity. To more accurately replicate observations of sediment transport (e.g. Russell and Huntley, 1999; Kroon and Masselink, 2002), the shape function was varied with wave energy level. This was achieved by varying the parameter \(A\) under different energy conditions. Under high energy conditions \(A\) is reduced in the shoaling zone to replicate observation of enhanced surf-zone transport (Figure 2-17). Enhanced onshore transport under low energy conditions (defined as \(H_b < 0.8 \text{ m}\)) was produced by reversing the sign of \(A\) in the surf zone under low energy conditions and setting \(A = 0\) in the shoaling zone. To reflect zero transport under very low energy conditions, \(A = 0\) when \(H_b < 0.3 \text{ m}\).

![Figure 2-17](image)

Figure 2-17 The shape function is made up of a shape term (upper panel) and an amplitude term (lower panel). In later model runs, Masselink varied the amplitude term, \(A\), to make the overall shape function more accurately represent sediment transport and morphological observations. Profiles of \(A\) are presented in the lower panel under very low energy levels \((H_b < 0.3 \text{ m black})\), low energy conditions \((0.3 < H_b < 0.8 \text{ m, red})\) and high energy conditions \((H_b > 0.8 \text{ m, blue})\).
These adaptations improved the realism of the modelled profiles, but the bars produced were rather static – showing little response to varying conditions (Figure 2-18). Also the bar features over steepened, and to avoid model instability, the default $A$ was reduced from $A = 0.05$ to $A = 0.025$. To overcome these issues, morphodynamic feedback was introduced, at both the bed and beach scale. At the bed scale the onshore sediment transport was arrested once the local gradient $\tan \beta > 0.075$, which overcame the over steepening issue. In allowing morphodynamic response at beach scales, Masselink (2004) also overcomes one of the main problems with the $h/h_b$ based parameterisations – formation of bar troughs. The surf zone was separated into multiple distinct units if troughs were present, where a trough was identified by a continuous run of 10 or more cells with a gradient of $\tan \beta < 0.0075$. Each unit had a separate $H_b$ value, which was derived by $H_b = 0.4h_b$ at the seaward end of the trough. This means that the deeper the bar, the larger the waves that are allowed to propagate over it. Surf-zone sediment transport was suppressed in the troughs, so the only sediment transport allowed over the trough is under shoaling waves or through bar migration, and so the troughs acted as effective sediment barriers. These modifications allowed the model to reproduce the complete bar trough
morphology of a multiple barred beach giving a qualitatively realistic profile (Figure 2-19). The model produced a number of features of real intertidal bar systems, including the number of bars (5), spacing (50 - 100 m) and low wave energy migration rates (10 m/month). All these adaptations are based on qualitative rather than quantitative rules. It should be noted that care must also be taken when using an $h/h_b$ based parameterisation on barred beach morphology, as two points either side of a bar, with the same depth, are predicted to have the same transport, despite the differences in wave forcings.

The adaptations to the shape function modelling approach are all conceptual in origin, and there are theoretical inconsistencies in the approach. However, as a heuristic study Masselink (2004) makes steps towards overcoming two of the key limitations of the shape function — the difficulty of using a $h/h_b$ based parameterisation in a barred beach, and the development of a bar-trough morphology.

Figure 2-19 Same as Figure 2-18, but with allowing bed and beach scale morphologic feedback. Taken from Masselink (2004).

A further example of the application of the shape function approach to a real scenario was described by Mariño-Tapia et al. (2007b) using their velocity moment shape function (Mariño-Tapia et al., 2007a). A similar approach to that of Fisher and O'Hare (1996) and Fisher et al.
(1997) was used to investigate bar migration at Duck, North Carolina. The bedload (2-19) and suspended load (2-18) shape functions relate the velocity moments to the depth normalised by the breakpoint depth and require un-normalising by the velocity variance. Mariflo-Tapia et al. (2007b) separated the variance into a mean, oscillatory and long-period component, ignoring the zero and near zero cross terms:

\[
\left( \bar{U}^2 \right) = \left( \bar{U}^2 + \left( \bar{U}_s \right)^2 + \left( \bar{U}_I \right)^2 \right) \frac{3}{1}
\]

Mariflo-Tapia et al. (2007b) included a linear wave routine to predict the mean and short wave terms but neglected the long period term. This is recognised as a limitation close to shore, however Mariflo-Tapia et al. (2007b) note that for the study of breakpoint bar migration (the focus of their study), this should not be a problem. Furthermore, the distribution of long wave variance is dependent on the type of long wave motion, making it difficult to accurately model, and the overall shape function does include infragravity terms, and so the effects of infragravity motion will, to some extent, be captured by the model. For the mean component of the velocity variance, Mariflo-Tapia et al. (2007b) used bed-return flow, following Masselink and Black (1995):

\[
\bar{u}(h) = \frac{1}{8} \left[ \frac{g \gamma_s \sqrt{h}}{h} \right] \exp \left( - \left( \gamma_s \frac{h}{H_{0,\text{rms}}} \right)^2 \right)
\]

where \( \gamma_s \) is the short wave breaker index and \( H_{0,\text{rms}} \) is the offshore rms wave height. The short wave variance was calculated by assuming a Rayleigh distribution and linear wave theory:

\[
\sigma_u^2 = \sigma_h^2 \frac{g}{h} = \frac{H_{\text{rms}}^2 g}{8 h}
\]

where \( \sigma_u^2 \) is the incident wave variance and \( \sigma_h^2 \) is the surface elevation variance. Having calculated a profile of the velocity variance, the 3rd and 4th velocity moment shape functions.
were un-normalised and inserted into (2-23) and (2-24) to give the immersed weight sediment transport, and (2-25) was used to give the volumetric sediment transport. An avalanching routine was included to limit the bed slope to be less than 28° (above which the slope “avalanches” to a slope of 22°) but maintaining sediment conservation.

Mariño-Tapia et al. (2007b) initiated the model with a time-series of rms wave height, peak period, surface (tidal) elevation and an initial profile. The model was used in two experiments; firstly to investigate whether observed bar behaviour is inherent to the system (forced system) or sensitive to initial conditions. To this end the model was initiated with a Dean (1977) profile. The second experiment was to test the model’s ability to reproduce the bar migration patterns observed for a 77-day period during the DUCK'94 experiment. A near equilibrium profile (that better represented the observed profile) was derived by running the model for 180 hrs from a Duck 16 year average profile (to avoid the need for spin up time). Both experiments were forced with time-series from DUCK'94.

The Mariño-Tapia et al. (2007b) model was unable to represent the full profile, as it cannot replicate the bar trough. To identify the bar crest, the difference between each profile and the initial profile was calculated, and the peak value taken to represent the crest, (a similar approach to Gallagher et al., 1998); this equates with the seaward edge of the low tide terrace. Results were compared to the dataset of bar location of Gallagher et al. (1998), and are presented in Figure 2-20 (experiment 1) and Figure 2-21 (experiment 2). Despite a very different initial profile in experiment 1, the model was able to replicate offshore bar migration very well. The only similarity in the Dean Profile and the original Duck profile was a similar slope at the bar location. Mariño-Tapia et al. (2007b) suggests this single characteristic is sufficient for an accurate representation of the offshore bar migration in terms of both magnitude and timing of migration events.
During experiment 2 (Figure 2-21) the model was able to explain 86% of the observed variability of the bar position, although it was unable to capture the observed full profile morphology (due to the presence of the bar trough). Onshore bar migration is over predicted, although the timing and magnitudes are reasonable. At approximately day 40, the bar apparently jumps onshore by approximately 40 m. This was shown to be the result of the method used to estimate bar location, i.e. a small perturbation of a broad bar, rather than a large movement of a well defined narrow bar. Offshore bar migration is reproduced accurately in terms of both magnitudes and timings.
Figure 2-21 Cross-shore bar crest location modelled by Mariño-Tapia et al. (2007b) in "experiment 2" and compared to the observations of Gallagher et al. (1998), and rms wave height. Taken from Mariño-Tapia et al. (2007b).

As the model was run with an averaged/modelled profile in experiment 2, the capability of the model is still questionable. To rectify this, a third experiment was run with the initial profile taken as the first measured Duck profile (Figure 2-22). During the first 10 days, the model is trying to equilibrate with the measured profile and so no meaningful sandbar is generated (double points represent "double bars"). After a spin-up period, the model is able to represent the bar migration behaviour as well as achieving a quantitative agreement.
The ability of a shape function developed under macrotidal European beaches to replicate bar migration behaviour of an unrelated microtidal North American beach into the mid-term (77 days) is remarkable, and supports the notion that the shape function is quasi-universal. The offshore bar migration is particularly well captured, partly due to the accurate reproduction of the transport mechanisms by the shape function. Onshore bar migration is less well reproduced, with only the experiment 2 accurately representing the observations. Onshore migration is caused by the sediment convergence point \((h/h_s \approx 1)\) moving onshore of the bar location. The bar crest is then subject to erosion, while the "bar trough" (the low tide terrace) is accreted. As the shape of the Mariño-Tapia et al. (2007b) shape function remains constant with energy conditions, its ability to reproduce both onshore and offshore migration accurately must be
biased in one direction. This will limit the Mariño-Tapia et al. (2007b) model to use with the medium term.

The Mariño-Tapia shape function model represents a very advanced implementation of such a simple model. Many of the limitations of the Fisher and O'Hare (1996) and Fisher et al. (1997) model have been overcome or improved upon. The shape function parameterisation was rigorously tested and found to accurately predict many behaviours observed in the field. There are still limitations in the velocity moment shape function approach, predominantly due to its dependence on the energetics approach. As well as being inapplicable in the swash zone where non-energetics mechanisms dominate, there are questions raised about it accuracy under low energy conditions (e.g. Russell and Huntley, 1999). Although Mariño-Tapia demonstrated that the velocity moment data collected under low energy conditions showed similar patterns to high-energy data, little attempt was made to confirm how the low-energy suspended sediment behaviour differed from the high energy data.

The ability of a processed based model (IBW PAN model, developed by Institute of Hydro-Engineering of the Polish Academy of Science) at modelling profile evolution was compared to a shape function model (PLYMPROF, developed by University of Plymouth) by O'Hare et al. (2006). As the two field sites were modelled without field observations, the focus of the study was to compare the modelled behaviour rather than the absolute profile evolution. The IBW PAN model incorporates a quasi-three-dimensional hydrodynamic model (Szmytkiewicz, 2002) with a quasi-phase resolving sediment transport sub-model (Kaczmarek and Ostrowski, 2002), and a smoothed bed update scheme. The model replicates onshore transport due to wave asymmetry in the shoaling zone and offshore directed bed-return flow driven sediment transport in the surf-zone. At the breakpoint the near bed transport maybe offshore directed, with onshore transport higher in the water column. Provided the breakpoint remains in one location for long enough, this sediment convergence may allow a bar to develop.
The PLYMPROF model combines a simple wave transformation model with a sediment flux parameterisation and bed updating scheme. For the model runs presented in the paper, the wave transformation model of Thornton and Guza (1983) was implemented with a parameterised wave breaking coefficient (Raubenheimer et al., 1996; Ruessink et al., 2003). The sediment transport was calculated from a parameterisation based on that of Plant et al. (2001). This parameter is the product of a term that represented the sediment magnitude (related to depth and wave height) and the other giving the shape of the cross-shore bedload sediment transport profile. This shape function includes a term for wave and bed slope driven transport, and is a function of \( H_{ref}/h \). Multiplying this term by a sediment transport multiplier (O(10)) takes into account suspended sediment transport. The directional component of the shape function is a sinusoidal function, allowing onshore transport in the shoaling zone, offshore transport in the surf zone and onshore transport in the swash zone (Plant et al. (2001) used a quadratic equation which led to offshore swash transport, and continuous shoreline erosion). The active region of sediment transport was extended above the still water level to the run-up limit. As the shape function predicts onshore transport throughout the shoaling zone, out to the seaward boundary of the model, a closure scheme is implemented to ensure sediment continuity (i.e. otherwise the shape function predicts onshore transport at the boundary). The bed was updated at every time-step, and a 5-point linear smoothing was applied to the sediment flux gradient.

As there was insufficient survey data to validate the models, the study compared the model behaviour relative to one another. The models were initialised with three types of morphology (linear, barred and stepped), and forced with uniform and non-uniform conditions. The highly detailed processed-based IBW PAN model tended to exhibit all onshore-directed sediment transport. In the surf-zone there was minimal offshore-directed sediment fluxes associated with bed return flow, resulting in near-zero net onshore sediment transport. Conversely the PLYMPROF model (when run with default settings), produced significant offshore directed sediment transport in the inner surf-zone. Although the sediment transport patterns of the
PLYMPROF model typically occurred closer to shore than the IBW PAN model, the resulting profiles did not appear to be significantly different between the two models.

Alteration of a single parameter in the PLYMPROF model stretched the sediment transport pattern laterally and better matched that of the IBW PAN model. However, this adaptation also enhanced the offshore surf-zone transport. It was not possible to ascertain which of the two models were more realistic, however, the uncertainty and sensitivity of the model coefficients in the PLYMPROF model was noted as being a potentially serious drawback, requiring model validation with observational data. Further work with the PLYMPROF model examining storm events suggested that the morphological evolution cannot be simply related to the presence/absence of storms, but relates to the details of the forcing waves, and how/where they break on the existing profile. This suggests that the feedback between the previous morphology and waves/sediment transport patterns may exert a major control on the morphological development.

2.4 Long term bar migration

Bar behaviour has long been of interest to the coastal research community. Observations of bar behaviour are made by a number of methods including periodic direct physical profile measurement (e.g. Larson and Kraus, 1994), acoustic surveys (e.g. Ruessink and Kroon, 1994), instantaneous point measurements of bed elevation change along a profile line, and video analysis (e.g. Shand, 2003). Some datasets span decades and so allow the long term behaviour to be analysed (e.g. Wijnberg and Terwindt, 1995). One complicating issue is that of alongshore variability. While some locations exhibit bars that are alongshore uniform, other sites exhibit alongshore variability (e.g. crescentic bars). Complex Empirical Orthogonal Functions (CEOF) have been used to separate the alongshore uniform and variable components of beach morphology. Ruessink et al. (2000) showed that 85% of the profile variability at Egmont aan Zee (The Netherlands) was due to the along shore non-uniformity, while 10% of the variability was due to the along shore uniform component. Furthermore the non-uniform component was
associated with alongshore migration, which was shown to dominate the cross-shore bar crest position in the short term. Conversely, on analysing two years of video imagery from Duck North Carolina, Lippmann and Holman (1990) attributed 74.6% of variability to cross-shore bar migration (only ~14% was due to alongshore migration of 3-d bars) and Plant et al. (1999) ascribed 50%-90% of the bathymetric variability to the alongshore uniform bar migration (also Duck).

Beaches typically follow patterns dominated by the seasons. A early study showed the existence of a summer/winter profile cycle in California, USA (Shepard and Inman, 1950). During the winter a barred profile formed while the lower energy in the summer led to the development of a summer berm profile. On analysing 11 years of data from Duck, NC, Larson and Kraus (1994) calculated four seasonally averaged profiles for comparison. The summer profiles were shown to have the maximum amount of sediment stored at the shoreline, and the greatest depth at the offshore end of the profile. The winter profile showed the greatest inshore depth out of all the profiles, with sediment deposited further offshore. The spring and autumn profiles were intermediate between the summer and winter extremes, and were very similar to one another. Other beaches show a complex cycle of bar generation, migration and decay, in a process termed Net Offshore Migration (NOM – see below).

Profile evolution has been shown, in some cases, to be dominated by the sequence of high energy conditions. When extreme wave events at Duck, North Carolina were coincident with a reduced outer bar, there was an episodic transition from a 1 to a 2 bar system (Lippmann et al., 1993). The most dramatic change was observed when two such events occurred within 10 days, when the only bar migrated offshore and a new inner bar was formed. This was demonstrated by Lee et al. (1998), by showing that when 2 storms occurred within a short period (39 days), the profile changed extensively (the outer bar migrated offshore and increased in volume), as the first storm destabilised the profile, and the second storm hit before the profile had a chance to recover. The intervening periods between such energetic conditions lasted up to 4 years, during which time there was a net onshore transport from beyond the outer bar to the shoreline.
Net Offshore Migration (NOM) describes a type of bar behaviour that has been observed at Duck, North Carolina (Lippmann et al., 1993), The Netherlands (Ruessink and Kroon, 1994) (e.g. Terschelling and Holland coasts), and at Wanganui, New Zealand (Shand et al., 1999; Shand and Bailey, 1999), all of which are multi-barred beaches. A conceptual model of NOM, presented by Ruessink and Terwindt (2000) breaks the lifecycle of a bar in to 3 phases: i) genesis (Phase 1), ii) offshore migration (Phase 2) and iii) decay (Phase 3). A bar generated close to the shore migrates on and offshore in response to breaking/non-breaking or on seasonal cycles of energy, however the bar exhibits little net migration. If the average breaking conditions increase in intensity (e.g. the protective outer bar decays) the inner bar migrates offshore into deeper water (i.e. its crest depth increases) and so shifts to Phase 2. Once a bar enters Phase 2, it cannot migrate onshore to re-enter Phase 1 as the onshore currents at the bar depth are insufficient. A bar in Phase 2 migrates on- and offshore in response to local conditions, however, each offshore migration is slightly greater than the onshore phase, and so the bar edges ever further offshore. As the bar migrates into deeper water, the sediment transport associated with the bed return flow weakens, and is eventually cancelled by the onshore flux associated with short wave skewness, and so the bar stops and enters Phase 3. This outer bar is now subject to onshore sediment transport which causes erosion and ultimately decay, and eventually triggers the inner bar to migrate offshore into Phase 2.

Bar migrations can be seen as the result of processes that occur on difference timescales. Bars respond to a range of time scales including the storm/calm seasonal/annual and multi-year cycle. Observations of bar behaviour over 3.4 years have been broken down into different timescales (weekly, seasonal and multi-annual) by van Enckevort and Ruessink (2003). The results illustrate that the multi-annual component is net offshore directed while the weekly and seasonal have no net migration (Figure 2-23). The different behaviour seen at different beaches can be related to the relationship between strengths of these different signals. On sites that exhibit NOM, the net time-averaged signal is significant, while on beaches that exhibit a strong seasonal cycle, the seasonal time cycles dominate.
As discussed in Section 1.2, quantitative models of beach profiles typically fall into three categories, simple equilibrium models, parametric models, and process-based models, with realism and computational expense increasing through the classes, while feasible modelling timescales decrease. Comparisons of the performance of six of state of the art process-based models at modelling profile evolution and bar behaviour over timescales ranging from weeks to seasons have been under taken by van Rijn et al., (2003). Models were able to represent inner and outer bar behaviour over a storm cycle, but not the complete profile evolution. Post storm onshore bar migration can be modelled if complex wave sub-models are included, but not beach recovery (because 3d morphology is not included). Over seasonal cycles, bar-crest location/migration could not be modelled with default model parameters, but required
significant tuning, and complete profile morphology was not possible even with tuning. It was concluded that such models were still in their infancy, and were best used as tools to qualitatively compare one coastal management approach to another. Although more complex models (e.g. Rakha et al., 1997; Kobayashi and Johnson, 2001) have shown promise at modelling onshore migrations over short time scales, when trying to run over longer timescales they are computationally prohibitive, and error multiplication becomes an issue.

In order to investigate bar behaviour on longer scales, attention focuses on parametric models, such as those discussed in Section 2.3. Modelling long term (multi-annual) bar behaviour tends to be limited to parametric models. Plant et al. (1999) presented a heuristic model of bar-crest location and migration. This model was based around the tendency of a bar to migrate towards the breakpoint. The basis of the model is given as

$$\frac{dX_c}{dt} = -\alpha(t)[X_c - X_{eq}(t)]$$  

(2-31)

where \(X_c\) is the bar crest position, \(X_{eq}\) is the bar equilibrium position (a function of the wave height), \(dX_c/dt\) is the bar migration rate, and \(\alpha(t)\) is the response time. As \(X_c\) approaches \(X_{eq}\), the rate of migration decreases. The term \(\alpha(t)\) relates migration rate to the energy level. It is a power function, and so is predominately controlled by the exponent \(p\). As \(p\) has a physical meaning there has been a range of suggested values (Bagnold (1963) suggested \(p = 3\) or 4, Komar and Inman (1970) suggested \(p = 2.5\)) and so, it was fitted to the observed relationship between wave height and beach response rate. The model sensitivity to \(p\) is illustrated in Figure 2-24, which shows different bar migration patterns with different values of \(p\).
The variable migration rate tended to shift the average bar position offshore towards the equilibrium position associated with the largest waves. Under lower energy conditions, the bar migration is slower and so the bar takes longer to reach the low energy equilibrium position. This allows the model to predict aspects of NOM, as bars initiated at the shore migrate offshore. However, there are no mechanisms within the model to allow automatic bar initiation or shielding by the outer bar.

Figure 2-25 presents modelled bar position compared to observations from a 16 year dataset from Duck, North Carolina, USA. As bar response time was greater than the forcing timescales, bars initiated at the shoreline often took many years to reach an equilibrium position. Once in a
near equilibrium location, the bar exhibits the characteristic rapid offshore migration to a winter bar position with slow onshore migration due to summer conditions.

Figure 2-25 The bar crest location, as modelled by the Plant et al. (1999) model is compared to observed location. Taken from Plant et al. (1999).

This model was able to capture 80% of the bar location and 70% of the bar migration rates, however, the model was optimised with the data that it was tested against. Although the model shows several aspects of NOM, many mechanisms integral to NOM (i.e. bar generation and decay) are not included, and there is no potential to include them. This is not a profile model and thus cannot produce the full profile behaviour. However, as a point model of bar crest location, it provides a heuristic tool to help understand long term bar behaviour.

Most process-based models are not applicable to the study of long term bar migration as they are too computationally expensive. However, in a recent study, Ruessink et al. (2007) presented a coupled wave-averaged, cross-shore process model that allowed bar behaviour to be predicted on timescales of weeks, which was subsequently used by Ruessink and Kuriyama (2008) with runs up to 540 days. The model was developed and tested to hindcast observed bar behaviour from three beaches (Duck, North Carolina, USA, Hasaki, Kashima Coast, Japan and Egmont, Netherlands) which included storm and calm conditions. The observations from the 3 field sites all show an averaged change in profile at least a factor of 2-4 times greater than the rms difference, implying that sediment was predominantly redistributed along the cross-shore
profile. The processes affecting bar behaviour represented in the model included near-bed velocity skewness, bound-infragravity waves, undertow and boundary layer streaming.

Being a process-based model, most physical mechanisms are replicated to a good theoretical level, so in contrast to the model of Plant et al. (1999), a range of phenomena are modelled. This allows a wide range of behaviour to be replicated as the whole profile is modelled rather than just the bar crest position. The Ruessink et al. (2007) model is a wave-averaged model. It calculates the cross-shore distribution of the wave statistics, and resulting sediment transport, rather than calculating the effects of individual waves. This allows model time steps of $dt \approx 1$ hr, rather than $dt \approx 0.1$ s typical of wave-resolving models.

For a full description of the theoretical basis of the model and how it is implemented refer to Ruessink et al. (2007); here the outline the model is briefly described. The model balances wave dissipation across the cross-shore as:

$$\frac{\partial}{\partial x} \left( E_w c_g \cos \theta \right) = -D_b - D_f$$  \hspace{1cm} (2-32)

where $E_w$ is the short wave energy, $c_g$ is the group velocity, $\theta$ is the wave angle and $D_b$ and $D_f$ are the breaking wave dissipation and bottom friction respectively. The breaking wave dissipation is modelled following Battjes and Janssen (1978), and is fed into a balance for roller energy (see Nairn et al., 1990; Stive and De Vriend, 1994). Set-up is calculated, but the effects of the mean shear stress at the bed due to cross-shore set-up and of the cross-shore winds on the cross-shore set-up pattern are ignored.

Currents are calculated with the quasi-3D model of Reniers et al. (2004), that separates the water column into 3 layers, i) the wave-boundary layer, ii) from the boundary layer to the bottom of the wave trough, and iii) above the wave troughs. Onshore mass flux in the upper layer is balanced by a bed return flow in the lower layers given as:
\[ \bar{u} = -\frac{E_w + 2E_r \cos \theta}{\rho ch_i} \]  

(2-33)

where \( \bar{u} \) is the mean cross-shore velocity, \( E_r \) is roller energy, the \( \rho \) is water density, \( c \) is phase celerity, and \( h_i \) is the depth below the troughs.

The bedload and suspended sediment transport are calculated separately, with the net transport being the sum of the two. The basis of the bedload transport flux is that of Ribberink (1998) and van Rijn (1995), given as:

\[ q_{\text{bed}}(t) = 9.1 \beta \left[ \theta'(t) - \theta_{\text{cr}} \right] \left( \frac{\theta'(t)}{\theta'(t)} \right) \sqrt{\Delta g d_{50}} \]  

(2-34)

with \( q_{\text{bed}}(t) = 0 \) if \( |\theta'(t)| \leq \theta_{\text{cr}}, \beta = 0.1 \) (Nairn et al., 1990; Reniers and Battjes, 1997) is the roller slope, \( \theta'(t) \) is time series of the dimensionless effective shear stress, \( \theta_{\text{cr}} \) is the slope corrected value of the non-dimensional critical shear stress, \( \Delta = (\rho_s - \rho) / \rho \) (where \( \rho_s \) is the sediment density), \( g \) is acceleration due to gravity, and \( d_{50} \) is median grain size. Suspended sediment transport was given as

\[ q_{s, e} = \frac{\int_{Z_s}^{h} c(z) u(z) dz}{\rho_s} \]  

(2-35)

where \( q_{s, e} \) is the suspended sediment transport, \( c(z) \) and \( u(z) \) is the vertical profile of sediment concentration and cross-shore velocity, which are integrated from \( Z_s \) (a reference height above the bed) to the water surface, \( h \). Finally, the total sediment transport \( (q_{\text{net}} = q_{\text{bed}} + q_{s, e}) \) is used to calculate the bed level changes through continuity:

\[ \frac{\partial x(x, t)}{\partial t} = \frac{1}{1 - \rho} \frac{\partial q_{\text{net}}(x, t)}{\partial x} \]  

(2-36)
where $p = 0.4$ is the assumed bed porosity. The model is only solved for the wet domain, and the last wet grid cell is taken as the first grid point with a non-dimensional wave period exceeds $T_p \sqrt{g/h} > 40$ (e.g. for a period of $T_p = 7$ s, the last wet cell is $h > 0.30$ m).

The model has several parameters (not described above) that are either set to values presented in the literature or are optimised using the Shuffled Complex Evolution (SCE-UA) algorithm (Duan et al., 1993).

The model does not consider a spectrum of grain sizes, thus apparent large changes in $d_{50}$ caused by slight changes in a bimodal grain-size distribution are not captured. This was shown to be important during the Duck94 experiment (Stauble and Cialone, 1996) as it explains fine sediment being removed from the shoreline during storms. The Ruessink et al. (2007) model showed unrealistic shoreline behaviour (over-steepening at the shoreline) which was attributed to this. To counter this, a fixed bed routine was implemented which did not allow erosion below the original profile, in the region above the low tide mark. Deposition followed by erosion down to this layer was however allowed.

With the free parameters fitted by the SCE-UA algorithm, the temporal cross-shore profile evolution agrees well with the observations. This is reflected in the good model skill varying from 0.50 (Egmont) to 0.88 (Duck). The model was capable of predicting the combined on/offshore events at Duck and Hasaki, and the prolonged onshore and offshore events of the outer bar at Duck and Egmont. The Egmont inner bar behaviour was not well modelled, and this is reflected in the difference of model skill between the inner bar (-0.25) and the outer bar (0.82). This is attributed to the increased alongshore variability in this region.

Under energetic conditions, the net transport across the bar is offshore directed, predominantly due to the suspended sediment transport, although the offshore-directed bedload transport peaks just seaward of the bar. Shoaling zone transport is onshore directed, driven by wave skewness. These processes lead to a sediment convergence and cause the bar to move seawards, with
considerable steepening of the seaward bar flank. The surf-zone also expands seawards as the model is coupled between the hydrodynamics and morphology. Under lower energy (weakly- to non-breaking) conditions the onshore migration is due to net skewness-induced onshore-directed transport that peaks near the bar crest. When breaking and non breaking conditions alternate over the bar between high and low tide, the bar remains static, i.e. the relaxation time of the bar is greater than the tidal period. Under very low (non breaking) energy conditions, the bar remains static as the sediment transport rates are so low.

These results show that the Ruessink et al. (2007) model was able to realistically reproduce aspects of the cross-shore bar behaviour (offshore and onshore migration) without resorting to computationally expensive wave-resolving Boussinesq models. This allowed much longer model runs (e.g. >100 days at Duck). However, these runs are still insufficient to capture the bar behaviour of decadal time scales on which Net Offshore Migration operate. The models of Ruessink et al. (2007) and Plant et al. (1999) can be considered as opposite ends of a spectrum of model complexity and so modelled timescales. Neither model is able to predict the full profile evolution over the decadal timescales as required to fully model NOM.

2.5 Summary

This chapter summarises material from the published literature that is relevant to the present study. Initially, a brief background to the processes that occur in the nearshore including a description of the energetics model for sediment transport is given. This is followed by an overview of cross-shore sediment transport parameterisations and their implementation in profile evolution models. An outline to long-term bar migration is then followed by a comparison of two long-term bar-migration models.

Early cross-shore sediment transport shape function parameterisations presented by Foote et al. (1994), Russell and Huntley (1999) and extended by Mariño-Tapia et al. (2007b), relate normalised velocity moments (from field measurements - proxies for sediment transport) to $h/h_b$ (a proxy for cross-shore position, where $h$ represents water depth and $h_b$ represents the
breakpoint depth). As the velocity moments are normalised by cross-shore velocity variance, a single equation is able describe the pattern of cross-shore transport under a wide range of energy conditions. The potential use of the shape function approach with a model for nearshore profile evolution was outlined by Foote et al. (1994) and a proof of concept implementation was undertaken by Fisher and O’Hare (1996) (also Fisher et al., 1997). Mariño-Tapia et al. (2007a) developed an improved shape function model and used it to successfully describe bar migration at Duck, North Carolina, over a 77-day period (Mariño-Tapia et al., 2007b). A similar approach was taken by Plant et al. (2001) but related cross-shore sediment transport to normalised wave height ($H/h$, where $H$ represents wave height). This parameter decreased seaward and landward from a peak in the surf-zone. In the Plant et al. (2001) parameterisation, offshore transport occurred at high values of $H/h$ and so there was offshore transport at the surf-zone $H/h$ peak and onshore transport in the shoaling and swash zone either side. Under low energy conditions, $H/h$ values did not reach high enough values for an offshore transport region to occur, and so the parameterised sediment transport was always onshore directed. A different approach was taken by Aagaard et al. (2002), who developed a function describing sediment transport direction from velocity skewness, velocity/sediment concentration cross-correlation mean and rms cross-shore velocity. As each of these values were not readily available, they were in turn derived from weak empirical relationships to other parameters, which rendered the overall parameterisation somewhat unreliable.

Long term bar behaviour, including Net Offshore Migration (NOM), is described with special consideration given to long-term empirical bar behaviour models. Two contrasting approaches are compared – a 1D processed-based model of Ruessink et al. (2007), and an abstracted model of Plant et al. (1999). The two models work at opposite ends of the spectrum of modelling approaches (bottom-up vs. top-down), while both extending into the long-term (Ruessink and Kuriyama (2008) ~500 days, Plant et al. (1999) ~10 yrs). However, the Plant et al. (1999) model does not include enough mechanisms to replicate full profile evolution and so cannot
replicate full bar migration, while the Ruessink model runs still do not extend long enough to explore the decadal time scales associated with NOM.

Currently, there is no measurements-based cross-shore sediment transport shape function parameterisation. Such a parameterisation should combine the approach of Plant et al. (1999) by reflecting the different sediment transport patterns that occur with changing energy levels, with that of Mariño-Tapia et al. (2007a) by being based predominantly on measurements. Modelling long-term bar migration/behaviour and profile evolution with such a parameterisation should improve on the Mariño-Tapia et al. (2007b) model by using measured sediment fluxes and allowing response to varying energy levels.
Plate 3 Martin Austin, Peter Ganderton (front), Gerd Masselink, Tim O'Hare, Daniel Buscombe.
\[ h_{SM,j} = \alpha h_{j-1} + (1-2\alpha)h_j + \alpha h_{j+1} \quad (6-8) \]

where \( 0 < \alpha < 1 \). When \( \alpha = 1/3 \) each of the weightings are equal (i.e. the same as an un-weighted mean). The 3-point weighted mean is only effective at removing grid-scale oscillations when \( \alpha = 1/4 \), i.e. the weighting discussed above. Jensen et al. (1999) suggested this routine was effective at damping oscillations of the order of the grid-size, but did not specify the number of times this should be iterated. Johnson et al. (2002) suggested that there was little benefit in iterating this more than once.

This technique has been reduced to a simple weighting. Having calculated \( h_{SM} \) from (6-8), \( dh \) can be calculated as

\[
dh = h - h_{SM,j} \\
= (0h_{j-1} + h_j + 0h_{j+1}) - (\alpha h_{j-1} + (1-2\alpha)h_j + \alpha h_{j+1}) \\
= h_{j-1}(-\alpha) + h_j(2\alpha) + h_{j+1}(-\alpha) \\
\]

which is then smoothed using (6-8). This is best calculated as a matrix operation, e.g.

\[
dh_{SM} = \begin{bmatrix} \alpha & 2\alpha h_{j-1} & -\alpha h_j \\
(1-2\alpha) & -\alpha h_{j-1} & 2\alpha h_j \\
\alpha & -\alpha h_j & -\alpha h_{j+1} \end{bmatrix} \\
\]

\[
= \begin{bmatrix} -\alpha^2 h_{j-2} & 2\alpha^2 h_{j-1} & -\alpha^2 h_j \\
(2\alpha^2 - \alpha)h_{j-1} & (-4\alpha^2 + 2\alpha)h_j & (2\alpha^2 - \alpha)h_{j+1} \\
-\alpha^2 h_j & 2\alpha^2 h_{j+1} & -\alpha^2 h_{j+2} \end{bmatrix} \\
\]

\[
= \begin{bmatrix} -\alpha^2 h_{j-2} & (4\alpha^2 - \alpha)h_{j-1} & (6\alpha^2 - 2\alpha)h_j & (4\alpha^2 - \alpha)h_{j+1} \\
-\alpha^2 h_j & -\alpha^2 h_{j+1} & -\alpha^2 h_{j+2} \end{bmatrix} \\
\]

Adding (6-8) and (6-10) gives the first iteration of \( h \).
3 Field sites, instrumentation and basic data analysis

In this chapter the field site and instrumentation are presented. The basic data analysis techniques are introduced, along with underlying time-series analysis theory. Although two field campaigns were undertaken during the X-SHORE project, only the Sennen dataset is suitable for the purpose of this study. For completeness, the details of the Truc Vert campaign are included here, but none of the data from this site are used in the later analysis.

![Figure 3-1 Location of the two field sites. Taken from Tinker et al. (2006).](image)

3.1 Field Site

3.1.1 Sennen Cove (50°5'N 5°42'W)

Sennen Cove is a 2-km long embayed beach with rocky headlands at each end. It faces north-west into the North Atlantic Ocean (see Figure 3-1) and is exposed to both swell and locally
generated windsea. It is a macrotidal beach with a mean spring range of 5.3 m, an average significant wave height of 1.4 m and median grain size \( d_{50} \approx 0.7 \) mm. Sampling at Sennen started on the 5th of May, 2005 and continued over 39 tides until the 25th May, 2005.

During the campaign a wide range of the hydrodynamic conditions were experienced (Figure 3-2). The field campaign began during spring tide, and continued through neaps until the next spring tide. Wave conditions were dropping in the first period at the beginning of the experiment, and remained generally calm \( (H_{sig} < 0.5 \) m, \( h_b < 1 \) m) throughout the second period, with periods of \( T \approx 7 \) s until the 19\(^{th}\) of May, when a storm occurred (the third period). Wave heights peaked at \( H_{sig} = 1.5 \) m \((h_b = 2 \) m), with \( T \approx 10 \) s. Although the wave height dropped beyond the peak to the storm (21\(^{st}\) May), it remained high. In fact the lowest post-storm wave heights were always higher than the pre-storm wave heights. This is particularly evident in the value of \( h_b \) shown in the lower panel (the procedure for determining \( h_b \) is described in Section 3.3.8). A second more intense storm occurred on the 25\(^{th}\) May, with wave heights of \( H_{sig} = 2.5 \) m, \( h_b > 2.5 \) m and \( T \approx 12 \) s.

In general, the beach was characterised by two distinct regions, consisting of a steep upper section (beach slope, \( \tan \beta \approx 0.06 \)), separated from the gentler lower section (\( \tan \beta \approx 0.03 \)) by a distinct break in slope (Figure 3-3). There were often beach cusps and an escarpment in the upper section of the beach. The profile evolution of the beach is presented in Figure 3-4, showing the development of a low tide terrace at \( x \approx 90 \) m and a high-water berm at \( x \approx 35 \) m, both of which were wiped out by the first storm on 19\(^{th}\) May, returning the profile to its original state.
Figure 3-2 Time-series of conditions at Sennen, tidal surface elevation (m), offshore significant wave height (m) and spectral period (s) are presented in the upper three panels. The lower panel gives a time-series of breakpoint depth (bold dotted lines) and energy categories (grey patch), with the vertical lines show the range of normalised depth recorded for each tide.

Figure 3-3 Example profile from Sennen, including rig positions. The data from this study was predominantly from the main rig at x = 105 m.
Figure 3-4 Conditions observed during the two field campaigns. The upper panels show morphology change with respect to the initial profile line. The x axis is distance from the top of the beach; dark colours indicate erosion and light colours deposition. The white line indicates the position of the main rig. The lower panels show significant wave height measured in 16 m water depth.

In order to assess the morphological characteristics of the site during the experimental period, values of dimensionless fall velocity, relative tidal range, beach slope and surf scaling parameter (Figure 3-5) were calculated from the data obtained from the lower instrumentation rig and used
to determine the beach classification according to the model of Masselink and Short (1993) (see Figure 3-6). The beach changed in response to the hydrodynamic conditions such that at the very start of the measurement period, the wave height dropped from $H_{sig} \approx 1\, \text{m}$ to $H_{sig} \approx 0.5\, \text{m}$ and the beach state responded by changing from low tide bar/rip morphology to a reflective low tide terrace morphology. This state persisted for approximately one week, and then the wave height increased to $H_{sig} \approx 2\, \text{m}$, with the beach responding by shifting to the barred shallow trough/near dissipative state. These changes in morphology traced out an envelope of beach state, when plotted on the Masselink and Short (1993) classification scheme (Figure 3-6).

![Figure 3-5](image)

Figure 3-5 The dimensionless fall velocity ($\Omega$), relative tidal range ($RTR$), beach slope ($\tan \beta$) and surf scaling parameter ($\alpha$) calculated during the field work. The dotted horizontal lines indicate boundary values of the Masselink and Short (1993) beach classification model.
3.1.2 Truc Vert (44°45′N 1°15′W)

The Aquitaine Coast is a 230-km long high-energy meso-macrotidal straight coast between the Gironde estuary and the Adour estuary (see Figure 3-1). The spring mean tidal range is approximately 4.5 m with mean annual significant wave height of 1.4 m. Truc Vert is a low sandy beach with aeolian foredunes, a relatively broad intertidal region (around 200 m), and a median grain size of 0.35 mm. There are two different sandbar patterns in the nearshore zone; crescentic bars in the sub-tidal zone (mean wavelength of approximately 700 m), and intertidal bars in the dissipative zone, while the upper beach face is steep. The intertidal bars are regularly broken into rip channels, especially after long periods of fair weather, leading to bars of a mean wavelength of 400 m (Butel et al., 2002; Sénéchal et al., 2002; Castelle et al., 2006).
Sampling at Truc Vert occurred over 31 tides, from 8th – 23rd of May, 2006. During the Truc Vert experiment, conditions ranged from very low energy ($H_{\text{avg}} \approx 0.5 \text{ m}, T \approx 9 \text{ sec}$) during the first 10 days, followed by a storm event that peaked at $H_{\text{avg}} \approx 5 \text{ m} (T \approx 11 \text{ sec})$. Wave measurements were provided by the French Navy (Ardhuin et al., 2007), using a calibrated model output for a point in 55 m of water ($44^\circ 39'\text{N} 1^\circ 27'\text{W}$). Wave conditions observed at the beach were often quite different especially in the very low-energy conditions. Surveys of the beach profile were taken every low tide, and full 3-dimensional beach surveys were undertaken every daylight low tide.

Initially, the beach had very regular bars in the alongshore direction (Figure 3-4). The site chosen for the instrumentation was in the middle of a bar measuring approximately 250 m in the longshore direction and 60 m in the cross-shore direction. The trough-to-crest bar height was approximately 10 cm and width of the trough was approximately 20 m. Initially the upper beach, landward of the trough, was planar in form, and had a slope ($\tan \beta$) increasing from 0.075 to 0.025. However, as the wave energy decreased and remained low a berm started to form, which increased in height with each tide. At its peak, the berm had a cross section area of over 8 m$^2$. On 19 May, the berm was flattened in a single tide, and the beach was returned to a near planar state.

In the first period, Truc Vert remained classified as an intermediate beach, but as $H_{\text{avg}}$ fell and RTR increased, the classification shifted from barred-shallow trough to a low tide bar rip beach. In the calm second period, the RTR increased, and $\Omega$ hovered around the boundary between the reflective low tide terrace and intermediate low tide bar rip state. At the end of Period 2, $H_{\text{avg}}$ increased, RTR decreased, and Truc Vert entered the barred–shallow trough state as Period 3 began. During Period 3 the beach state remained classified as barred–shallow trough state, although during the two peak energy storms, the beach entered the barred (dissipative) state. Again as the beach state changed over the course of the campaign, current beach state moved around on the Masselink and Short classification scheme, leading to an envelope of beach state, presented in Figure 3-7.
3.2 Instrumentation

The data used in this analysis were obtained from an instrumentation rig which was essentially the same during both field campaign (Figure 3-8). A cross-shore array of instrument rigs was installed with the main rig situated at approximately mean sea level (MSL). As the tide floods over the instruments, measurements are made from swash, surf and shoaling zones so that the measurement approach gives quasi-spatial data of cross-shore processes using depth as a proxy for distance. The coverage of measurements in the different zones depends on the tide and wave conditions such that under high energy conditions, only limited amounts of data from beyond the breakpoint can be obtained.
During the Sennen field study three main instrumentation rigs were deployed in a cross-shore array, as shown in Figure 3-8. The main rig (Figure 3-9) included a vertical array of six discus electromagnetic current meters (EMCMs – Valeport discus) at 3, 6, 9, 13, 19 and 29 cm above bed. An acoustic Doppler velocimeter (ADV) at 13 cm above the bed measured the velocity at high frequencies to allow estimates of turbulent kinetic energy (TKE) to be made. A vertical stack of 13 miniature optical backscatter sensors (MOBSs – developed in-house), measured the vertical profile of suspended-sediment concentration (SSC) at -2, -1, 0, 1, 2, 3, 5, 6, 9, 13 and 19 cm above bed. A pair of miniature pressure transducers (PT – Druck) was deployed at bed level and at 2 cm below the bed to measure instantaneous water depth. Continuous bed-level change was measured by a fixed altimeter and ripple parameters (wavelength, height, migration rates) were measured by a swinging altimeter. All these instruments were cabled to the field.
base station with the EMCMs, MOBSs and PTs being logged synchronously at 4 Hz and the ADV was logged at 32 Hz. The seaward and landward auxiliary rigs (SLOTS) were self logging, with an EMCM, optical back-scatter sensors (OBS), PT and a Global Positioning System (GPS) receiver to provide a timestamp to allow synchronicity. Every low tide the beach profile along three transects was surveyed with a total station, and the depth of disturbance was recorded. A camera system was installed capturing hourly images of the field site. A bathymetric survey was undertaken during the study, and several 3D total beach GPS surveys were undertaken. Offshore wave conditions were measured at Sennen with an Acoustic Döppler Current Profiler (ADCP – RDI) deployed in 16 m of water. Grain-size distributions were estimated using a camera based auto-correlation method (Rubin, 2004) and samples were taken to calibrate this method. Weather observations were taken at 15-minute intervals.

Figure 3-9 The main and seaward instrumentation rig used throughout the experimental period. The main rig was wired to the field station, whilst the auxiliary rigs were self-contained.

The experimental set-up at Truc Vert was essentially the same as at Sennen. One significant difference was that one of the ripple profiles was on a separate rig in the bar trough. In addition to the main rig located at the bar-crest, there were four auxiliary self logging rigs. These were again positioned along a cross-shore profile, with one offshore to the main rig and three onshore. The self logging equipment systems (Vectors - Nortek) included an ADV, OBS and a PT. In addition, some of the vector rigs included an altimeter. Bathymetry was provided by SHOM (Service Hydrographique et Océanographique de la Marine). Beach morphological
change was measured daily, with three profile lines measured with a Total Station every low tide. Three-dimensional differential GPS beach surveys were also undertaken every daylight low tide.

The main data used in this study came from the main rig (from the Sennen campaign; Truc Vert data is not used in the analysis presented in this thesis due to alongshore non-uniformity and instrumentation error), as depth integrated fluxes from the vertical arrays of EMCMs and MOBSs were vital. The PT and ADCP were the other main sources of data, giving surface level, and wave measurements. The data from the auxiliary rigs at Sennen were of a lower quality and so were not extensively used, although they gave some important boundary/offshore conditions. Although not used in analysis for this thesis, the other data was used in several studies. Altimeter data at Sennen was used in an investigation of the effect of OBS instrument height by Austin and Masselink (2008). Data from the Ripple profiler at both Sennen and Truc Vert was used by from Austin et al. (submitted) and Masselink (2007a). Sediment grain size distribution was investigated by Gallagher et al. (2006) and Masselink et al. (2007b; 2008b)

3.3 Analysis techniques (Data Processing and Methodology)

3.3.1 Introduction

Throughout the course of this study, the Mathworks programme Matlab has been used for all data analysis.

Statistical analysis of the surface elevation, velocity and SSC data has been undertaken during this study. For the statistical analysis of the near-shore data to be valid, it must not be aliased and must be assumed to be a result of a stochastic random process, which depends upon stationarity, ergodicity and similarity to a Gaussian process.
3.3.2 Aliasing

When a signal is sampled at a frequency that is too low to capture the full behaviour of the signal a false signal can be observed. When the highest frequency signal of interest has a period of 1 second, a sampling rate less than 2 samples per seconds will miss this signal, and the observed frequency will be lower than in reality. This error is known as aliasing, and an example is given in Figure 3-10.

Figure 3-10 An example of aliasing. The upper panel shows a raw signal, which, if sampled at a rate below the Nyquist frequency, leads to an erroneous interpretation.

To avoid aliasing the data, the period between the samples should be at most, half the period of the highest frequency signal of interest. For example, to observe a signal with a 10 second period, the sampling period would have to be less than or equal to 5 seconds, although generally a sampling rate of 10 to 20 faster than this is used. For a given sampling rate, the highest frequency signal that can be observed, is called the Nyquist frequency and is defined as:
where $dt$ is the sampling period (in seconds). The sampling period used for the majority of the data in this study was 4 Hz, and so no signal with a period $< 0.5$ s is resolved. Given that the typical period of the waves observed during this study was $T \approx 7$ s, this assumption is reasonable and so aliasing is ruled out as a possible source of error.

### 3.3.3 Time-series as a stochastic random process

To allow valid statistical properties to be derived from a time-series, the data series is assumed to be a subset of a linear Gaussian stochastic process. While a deterministic process can be defined by a mathematic expression, a stochastic process varies randomly, with particular outcomes being defined by some probability distribution. This assumes that the observed processes satisfy the conditions of stationarity and ergodicity.

#### Stationarity

The statistical properties of a time-series must be assumed to be constant (stationary) with time to allow the application of statistical techniques to a dataset. As hydrodynamic conditions are time dependent the stationarity of the system is dependent on the timescale being considered.

Variations of sea level (due to the tide) and offshore wave conditions can introduce non-stationarity into measurements, so the choice of sampling period must reflect the time-scales of these variations. These processes work on timescales that can be assumed to be constant for durations of the order of 1 hour, and so signal stationarity can be assumed for short durations.

While stationarity is improved with decreasing the sample period, statistical rigor is weakened because a smaller sample period contains fewer measurements; consequently the optimum sampling period is a trade-off between the two. In regions with small tidal range, it is acceptable to assume stationarity over longer time scales and so sampling periods can be increased.
however in macrotidal environments shorter timescales must be used. Sample periods of 17:04 min (giving 4096 \(2^{12}\) samples at 4 Hz) are common in macrotidal beach studies where low frequency signals are important (e.g. Foote et al., 1994; Butt and Russell, 1999; Mariño-Tapia et al., 2007a; Mariño-Tapia et al., 2007b). In the present study less emphasis is placed on the low frequency oscillations, and so to improve stationarity and the number of samples, a 10 min sampling period was used. This period increases stationarity over 17:04 sample periods, while still giving considerable confidence in the statistical parameters by capturing a significant number of waves (i.e. one hundred 6 s waves). A sampling period of 10 minutes with a sampling rate of 4 Hz represents 2400 samples; however this is increased to 2401 to allow the mean value to be represented on the original time-series, without introducing a time offset.

**Ergodicity**

Representing the average conditions with a sample mean is invalid without ergodicity. Ergodic theory allows the statistics of a sub-sample to be up-scaled to the whole population. Any analysis requiring statistics of a flow must assume ergodicity as measurements cannot include the complete history and future of the flow. The present study makes the assumption of ergodicity.

**Linear Gaussian Process**

Describing a data set as being a linear Gaussian process assumes that all data points with a sub-sample are independent of each other. This condition is satisfied in ocean waves by assuming that a random sea has a Gaussian distribution made up of the linear addition of an infinite number of waves, given as

\[
\eta(t) = \sum_{n=1}^{\infty} a_n \cos(\sigma_n t + \phi_n)
\]  

(3-2)

where \(a_n\) is amplitude, \(\sigma_n\) is frequency, and \(\phi_n\) is phase angle of freely propagating independent waves.
As waves shoal and break, non-linear interactions occur as energy is transferred from the spectral peak to higher and lower frequencies. As non-linear wave components fix some phase angles, waves are not always independent or linear. However, it is possible to express ocean waves as the sum of a series of sinusoidal waves, thereby allowing techniques such as spectral analysis to be employed, although these waveforms should not be seen as a physical reality.

### 3.3.4 Water depth and wave height

To obtain a mean sea level over a 10-minute period, 10 minutes of the surface elevation record were averaged. This averages out the effect of waves. By calculating a mean of the first 2401 data points (~10 minutes), and storing the result as the 1201 point, and then the mean of the elevations in range 2-2402 and storing it as 1202, and so on until the last 2401 points, a running mean can be calculated (e.g. Figure 3-11).

*Figure 3-11 Schematic of how a filter window is used to calculated a running mean. The top line shows the raw data "\(\cdot\)", with a filter ("\(\cdot\)\) sequentially moving along the dataset, and calculating a statistic (e.g. average, standard deviation), with the result allocated to the centre of the window ("\(\times\)").*
This can be considered as

\[ y(n) = f(n-1200)x(n-1200) + f(n-1199)x(n-1199) + \ldots + f(n)x(n) + \ldots \quad (3-3) \]

\[ + f(n+1199)x(n+1199) + f(n+1200)x(n+1200) \]

\[ f = [1 \ 1 \ \ldots \ 1 \ \ldots \ 1] / 2401 \]

where \( f \) is a filter window (of width 2401), \( x \) is an unfiltered time-series (i.e. surface elevation), and \( y \) is the filtered time-series, \( n \) is the current point, and the equation is applied recursively through the dataset. The filter window is of an odd number so that the result is not offset; hence the actual mean is from a period of 10 minutes and 0.25 second. Calculating the running mean with a filter is considerably more efficient (computationally) than calculating recursively.

Wave height is a measure of how far the surface oscillates about the mean water level. This is typically calculated from the standard deviation, where the significant wave height \( H_{\text{sig}} \) is given as:

\[ H_{\text{sig}} = 4\sigma \quad (3-4) \]

and \( \sigma \) is the standard deviation of the surface elevation.

Having established that a time-series of a running mean can be calculated by a filter, this method can be extended to calculate a time-series of variance. This is important to efficiently derive a standard deviation, and so significant wave height. As variance can be expressed as

\[ \text{var}(x) = \bar{x}^2 - \bar{x}^2 \quad (3-5) \]

where \( x \) is a time-series, the filtering technique can be utilised. The values in a time-series are squared, and filtered with as described above (3-3), and from this the squared filtered time-series is subtracted. This again gives substantial increases in computational efficiency over calculating the running variance recursively.
As the calculated running mean and variance are centred in time, the first and last 5 minutes (1200) cannot be calculated in this manner. This leads to problems when trying to analysis data from the swash zone, hence swash zone data is analysed separately with a smaller window.

3.3.5 Velocity moments

Velocity moments give a statistical description of a sample of the velocity record, with the first moment representing the mean, second moment the variance, third the skewness and fourth the kurtosis. The $n^{th}$ velocity moment is defined as

$$\langle u^n \rangle$$

(3-6)

where $()$ indicates time averaging. According to the energetics approach (Bailard, 1981) velocity moments predict sediment transport, with the 3rd (4th) velocity moment predicting bedload (suspended) transport. Normalising the 3rd and 4th velocity moment by the second velocity moment (variance) removes sensitivity to wave height. Following Maríño-Tapia et al. (2007a) the 3rd and 4th velocity moment are normalised as

$$\langle u^3 \rangle/\langle u^2 \rangle^{3/2}$$

(3-7)

$$\langle u^4 \rangle/\langle u^2 \rangle^2$$

(3-8)

Although theoretically the 3rd velocity moment represents bed load transport, it has been used to represent total sediment transport (Dyer, 1986; Ribberink and Al-Salem, 1995; Wilson et al., 1995; Russell and Huntley, 1999).

3.3.6 Sediment flux estimation

Unlike other studies that have used point measurements of suspended sediment transport, or a vertical array of velocity measurements with a point measurement of sediment concentration,
the present study calculated a depth profile of suspended sediment transport from the product of a vertical array of velocity and sediment concentration measurements. The bed level was calculated from the vertical array of MOBSs (buried sensors gave a distinctively saturated signal) and this was used as a common reference to which the velocity and suspended sediment concentration measurements were interpolated. The velocity and sediment concentration data were interpolated to a range of heights from 1 - 15 cm above the bed in steps of 1 cm. Sediment concentration measurements below 1 cm are affected by inaccuracy of the bed-level elevation, and so sediment transport below 1 cm is not included. As the lowest EMCM is nominally at 3 cm above the bed, velocity is assumed to be constant below this level. The interpolated arrays of velocity and suspended sediment concentration are multiplied to give an instantaneous, bed-level corrected, vertical profile of suspended sediment transport. This was then broken down into 10-minute (2401 sample) sections for further analysis and averaging. A de-spiking routine was used on these 10-minute sections, with rejected data (i.e. upper values saturated, drop-out values etc.) checked to confirm rejections, before the data was used in the bulk analysis.

As this method uses a measured vertical profile (rather than a point measurement) of suspended sediment concentration, no assumptions are made about the form of the vertical profile. As sediment concentration profiles tend to be very depth dependent (much more so than velocity profiles (i.e. Austin and Masselink, 2008), the absolute height of the sensor relative to the bed is vital. Unlike many other studies, this is measured and corrected for in the present approach. However, there are still limitations in the present study. Sediment suspended above 15 cm and below 1 cm is not included in the calculations leading to possible under estimation of concentration rate. In order to quantify these errors, a logarithmic curve was fitted to the sediment concentration profile and was extrapolated from 1 cm to the surface, or if lower, a height of near-zero concentration ($c_s = 0.01 \text{ kgm}^{-3}$). This profile was integrated and compared to the measured integrated flux (presented with two standard errors about the mean in Figure 3-12).
Figure 3-12 The percentage of the theoretical (fitted) sediment concentration that is in the measured profiles. Values below 100% suggest sediment that is higher than 15 cm above the bed, and so not included in the measurements. a) 2 standard errors about the mean percentage, with the raw data points, plotted by tide. The horizontal line represents the average of mean percentages b) the time-series of $h_b$ for comparison, c) the percentages plotted against $h_b$. Note there are 10 points (out of 583) above 150% that are not included in the figure, but are included in the error bars.
All tides show generally the same trends in these percentages, with an average percentage of \(~56\%\). There is little trend in the percentages with time (upper panel) or energy (lower panel). This suggests that, although the estimates have an error associated with them, there is no definite trend in this error.

One of the strengths of the present approach is that the sediment concentrations profiles are measured rather than assumed. Following this approach the measured sediment concentrations have not been extrapolated above the lower 15 cm, but are accepted as the sediment fluxes for this region.

3.3.7 Quality control techniques

The raw data was quality checked as follows: The suspended-sediment data was rejected if it showed any visual signs of contamination by daylight (i.e. upper sensors showing higher concentration than lower sensors during daylight hours, see Figure 3-13). Noisy data due to the instruments being very near the surface were also rejected by using the water-depth \( (h) \) time-series to ensure that velocity and suspended data were only considered for analysis when the instruments were covered by 0.5 cm of water.

Figure 3-13 Example of a concentration profile that includes daylight contamination, visible as the surface values are higher than the lower sensors.

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There are two main assumptions in the suspended sediment transport quality control routine. The first is based on the fact that the suspended sediment concentration is expected to be higher nearer the bed. Although sediment transported in sediment vortices may drop sediment above the instruments which would propagate downwards though the profile as a peak, time averaging the vertical sediment concentration profiles removes these peaks. Any averaged measurement of suspended sediment that is greater than the measurement below by a specific threshold is assumed to be erroneous and is flagged (red circle, Figure 3-14a). When the profile is interpolated from being based on instrument heights to being height relative to bed the flagged data are treated as missing data (i.e. the erroneous point is not used in the interpolated profile, e.g. black line in Figure 3-14a). As suspended sediment profiles approximate a log linear profile, this threshold is based on the log values of suspended sediment. This part of the quality control routine was developed to correct for sediment concentration peaks which can be caused by large particles passing close to the sensors.

The other common data quality issue is drop-outs where the sensor records near-zero values. Such drop-outs are most likely to be caused by instrumentation error. As the sediment concentration profile is depth integrated, the effect these drop-outs have depends on the nature of the suspended sediment concentration profile at that time, and the height that the drop-outs occur at. Assuming a classical log-linear profile, a drop-out higher in the water column has less effect that a drop-out lower in the profile (compare the effect of a drop-out at \( h = 2 \) cm with one at \( h = 13 \) cm in Figure 3-14b). Where the values of suspended sediment are less than 0.0001 kg m\(^{-3}\) the values are removed, and again, interpolating to bed-related frame of reference ignores these points (e.g. the black line in Figure 3-14b).
Figure 3-14 Examples of the sediment concentration error-trapping routines. The upper panel shows how spikes in suspended sediment transport (red circle) are ignored when the profile is interpolated (grey patch). The middle panel shows the relative effect of drop-out for a sensor near the bed or higher in the water column (nearer the bed, the bigger the error). The upper sensor is allowed to drop-out as this still gives a better representation of the sediment concentration profile (illustrated in the lower panel). The sediment concentration profile should extend to the blue line, however, the upper sensor records a drop-out (red circle). Therefore the measured sediment profile follows the black diagonal line (i.e. the pale grey patch). If the upper sensor was ignored, the profile would stop at $z = 14$ cm (the dark grey patch), however, accepting the drop-out value, increases the measured profile to include the dark and grey patch – closer to the actual profile (dark and while grey and white patch). This is further described in the text.
The uppermost sensor is generally subjected to the lowest sediment concentration and so is most likely to break this minimum concentration threshold. However, to interpolate a complete sediment concentration profile onto the bed referenced frame (without extrapolating) the upper measurement cannot be removed. This is illustrated in Figure 3-14c. The correct upper sediment concentration is given as the black circle, but the sensor has recorded a drop-out value (red circle). If the drop-out is ignored (as with any sensor other than the upper one), the interpolated profile is truncated to \( h = 14 \) (i.e. the dark grey patch). Allowing the upper value to be a drop-out value, the profile is extended to \( h = 15 \), and includes both the dark and light grey patch. Although this is less than the actual profile (which would also include the while patch), it is more accurate than a truncated profile. One issue with this technique is that when a sensor measures a very low \( (c \leq 0.0001 \text{ kg m}^{-3}) \) “real” sediment concentration, it will be treated as a drop-out. However, on a typical tide (6 hrs, \(~86400\) samples), typically 10 measurements per sensor will record a concentration that will erroneously be treated as a drop-out (i.e. \( 0 < c \leq 0.0001 \text{ kg m}^{-3} \)), accounting for \(< 0.01\%\) of the record.

### 3.3.8 Breakpoint depth

In common with the parameterisation of Mariño-Tapia et al (2007a) the breakpoint depth \((h_b)\) is a key term in the present study. However, it is often difficult to define and can be sensitive to the method of estimation. For the purpose of this study an objective method for determining \(h_b\) was used in which the offshore wave height \(H_o\) measured at the ADCP at Sennen was shoaled linearly into shallow water until it exceeded a specific breaker criterion (Battjes and Janssen, 1978):

\[
H = 0.14L \tanh(kh)
\]  

(3-9)

The offshore waves were shoaled using the linear wave shoaling equation (conservation of energy flux) which states that:
\[ H^2 C_g = \text{const} \]  

(3-10)

where \( H \) is the local wave height and \( C_g \) is the group velocity given as:

\[ C_g = \frac{L}{2T} \left( 1 + \frac{2kh}{\sinh(2kh)} \right) \]  

(3-11)

where \( L \) is local wavelength, \( T \) is wave period, \( k \) is local wave number, and \( h \) is local depth. A cross-shore profile \( kh \) (and so \( k \), \( L \)) which included the ADCP location was calculated from \( h \) and \( T \) using the method of Hunt (1979):

\[
(kh^2) = y^2 + \left( \frac{1}{1 + 0.666y + 0.355y^2 + 0.161y^3 + 0.0632y^4 + 0.0218y^5 + 0.00654y^6} \right)
\]  

(3-12)

where

\[
y = \frac{\sigma^2 h}{g} = \frac{4\pi^2 h}{gT^2} = 4.03 \frac{h}{T^2}
\]  

(3-13)

Rearranging the shoaling equation gives

\[ H_h = \sqrt{\frac{H_{ADCP}^2 C_{G_{ADCP}}}{C_g_h}} \]  

(3-14)

where \( H_{ADCP} \) and \( C_{G_{ADCP}} \) are the wave height and group velocity at the ADCP, and \( H_h \) and \( C_g_h \) is the wave height and group velocity at any the local depth \( h \). This equation, with the cross-shore profile of \( C_g \) (calculated in (3-11)), and values of \( H \) and \( C_g \) from the ADCP, gives a cross-shore profile of the shoaling wave heights for the initial cross-shore profile of depths.
Given the cross-shore profile of $h$ and $kh$, a theoretical cross-shore profile of broken wave heights is calculated. The breakpoint is taken to be located where the cross-shore profile of the shoaling wave heights meets the cross-shore profile of broken waves' heights.

Figure 3-15 Example of the model used to calculate $h_b$. The wave height and bed profile are represented with black lines (solid and dashed respectively). Profiles of broken and unbroken waves are given as green and blue lines, with their cross-over point giving the breakpoint (red line). The breakpoint depth can be taken as the depth where this occurs.

To test this model, $h_a$ was independently estimated by plotting local depth against local wave height for each of the tides. The gradient $\partial H / \partial h$ is at first negative due to shoaling and then becomes positive in the saturated surf zone (e.g. Guza and Thornton, 1985) with the change in
gradient giving an estimate of the position of the breaking zone and so $h_b$. There was strong correlation between the $h_b$ calculated by the two methods (Figure 3-16).

There was little variation of $h_b$ over each tide (error of $<15\%$ between tidally variable and $h_b$ calculated from the tidally averaged conditions), so for simplicity a tidally averaged $h_b$ was used.

![Figure 3-16](image)

Figure 3-16 To increase confidence in the breakpoint model, breakpoints estimated from the raw data are compared to the modelled values. The left panel gives sample plots of wave height vs. depth, used to observe the breakpoint, with an example high and low energy tide highlighted. The right panel gives the plot of the observed vs. modelled $h_b$ values, with a 1:1 line for comparison. The circled points in the right-hand panel relate to the example high and low tides highlighted in the left-hand panel.
3.3.9 Separation of energy categories

To allow comparison of tides with similar energy conditions, the dataset was subdivided into two energy categories based on $h_b$. Tides with $h_b$ between 0.5 and 0.85 m were categorised as being low energy, while those with $h_b$ between 1.8 and 2.1 m were classed as high energy (see Figure 3-2). These arbitrary bands were chosen based on the condition observed during the Sennen fieldwork. Defining such specific ranges for the analysis ensured least scatter due to varying energy levels within each category. There was very little data from intermediate energy levels and it was spread over a wide energy band so it was not used for the bulk analysis.

3.3.10 Sediment transport components

Cross-shore sediment transport, $cu$, is the product of $c$ and $u$, where $c$ and $u$ can each be broken into a mean and oscillatory component, following Huntley and Hanes (1987):

$$c = \bar{c} + \ddot{c}$$

$$u = \bar{u} + \ddot{u}$$

Here, $\bar{c}(\bar{u})$ is the mean suspended concentration (velocity) and $\ddot{c}(\ddot{u})$ is the oscillatory component of suspended sediment concentration (velocity). Following this approach, time averaged sediment transport $\langle cu \rangle$ (angled brackets denote time averaging) can also be separated into a mean and oscillatory component:

$$\langle cu \rangle = \langle \bar{c}\bar{u} \rangle + \langle \ddot{c}\ddot{u} \rangle$$

3.3.11 Bulk analysis

Measured sediment fluxes have an inherent scatter, requiring large amounts of data to elucidate underlying structures. Only a limited number of time-averaged data-points were retrievable for
any tide resulting in insufficient data to draw conclusions on the behaviour of the fluxes from individual tides. This was overcome by grouping similar tides.

### 3.3.12 Bin averaging

To evaluate the underlying structure within the noisy data typical of this study, a technique of plotting bin averages with error bars was developed. Firstly, two independent variables are plotted on a scatter plot. The data points are ranked with respect to the x value, and the first 30 points are treated as a sub-sample. The mean and standard error are calculated (with respect to x and y) for this sub-sample. This process is then repeated for the next 30 points until all the data is binned. For each bin, the mean value of x is plotted against the mean value of y, with error bars of two standard errors in the x and y direction. This method gives 95% confidence that the mean of the data lies within the error bars.

### 3.3.13 Fitting statistics

In order to evaluate goodness of fit of a non-linear curve, the following technique was used. The dependent measured variable was plotted against the dependent modelled variable, and a correlation analysis performed. Values of the correlation coefficient (r) the coefficient of determination ($R^2$) and p-value were calculated. The correlation coefficient indicates the strength and direction of the correlation between two random samples, x and y. The coefficient of determination is the fraction of the variance of y, that is accounted for by a linear fit of x and y. The p-value is the probability of getting a correlation as large as the observed value by random chance, when the true correlation is zero. Typically, the correlation is accepted if the p-value < 0.05, as there is less that 5% chance the relationship has occurred by chance alone.

### 3.3.14 Units of parametric equations

Throughout this study, empirical relationships are established to relate one variable to another, often in the form of power functions. In such relationships, the use of SI units (Système
International d'Unités) is assumed, and thus the numerical constants are not valid for non SI units.

**3.3.15 Special treatment of the swash zone**

Swash and inner surf zone data are intermittent and so the analysis techniques used for the shoaling and surf zone were modified for this region. To allow for measurements further shoreward into the swash zone, averaging periods were reduced from 10 to 3 minutes. The start and end times of each record were extended as far as was practical, in order to include swash events not included in the shoaling/surf-zone analysis. This shorter period increased the uncertainty of the measurements, and therefore the technique is restricted to depths of $h/h_b < 0.4$, the approximate location where the data from swash/inner surf and surf/shoaling zone converge. Measurements were still time-averaged and depth-integrated for the bottom 15 cm, again assuming the velocity is constant below the bottom sensor.
Plate 4 Instrument rigs from the Black Hut.
4 Spatial distribution of sediment transport: the energetics model and measured fluxes

The shape function approach is based on idea that i) velocity moments are offshore directed in the surf-zone and onshore directed in the shoaling zone, ii) these patterns can be predicted and iii) these patterns accurately represent sediment transport. As a first step in the data analysis these assumptions are tested with the Sennen data. Two typical tides (one low energy and one high energy) are closely examined to provide a descriptive frame-work within which further results can be understood. The Mariño-Tapia (2007a) shape function is then tested with the velocity moments measured during the Sennen field work and their dependence on the energy level and instrument height is investigated.

4.1 Summary of conditions

Table 4-1 provides an overview of the typical wave height, period, maximum tidal height (relative to the main rig) and breakpoint depth for each tide during the field work. Significant wave heights and periods are taken from the ADCP. Tidal elevation is taken from the main rig while breakpoint depth is modelled using the method described in Section 3.3.8.
Table 4-1 Overview of conditions during the Sennen field campaign.

<table>
<thead>
<tr>
<th>Tide</th>
<th>High tide depth</th>
<th>$h_b$ (m)</th>
<th>$H_w$ (m)</th>
<th>$T_p$ (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>09</td>
<td>2.0</td>
<td>0.8</td>
<td>0.4</td>
<td>4.9</td>
</tr>
<tr>
<td>10</td>
<td>2.0</td>
<td>0.7</td>
<td>0.3</td>
<td>5.6</td>
</tr>
<tr>
<td>11</td>
<td>2.0</td>
<td>0.6</td>
<td>0.3</td>
<td>5.9</td>
</tr>
<tr>
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To investigate how the hydrodynamic conditions vary over the tide and with energy level, two typical tides (#25, $h_b = 0.6$ m and #37, $h_b = 2.0$ m) are taken as examples. Initially the complete tides are considered, with time-series from these tides being presented in Figure 4-1 and Figure 4-8. Each figure includes the tidal elevation curve normalized by the breakpoint depth, cross-shore velocity measured 10 cm above bed (instantaneous and with a 10-minute running mean), and the instantaneous cross-shore velocity cubed, $u^3$, with the normalised 3rd velocity moment, $(u^3)/(u^2)^{3/2}$. In the upper panel a horizontal dotted line indicates $h/h_b = 1$ (i.e. the breakpoint) and delineates between the shoaling and surf zone.
Figure 4-1 Overview of conditions during Tide 25. The upper panel gives depth normalised by the breakpoint depth (black line). The breakpoint, separating the shoaling zone from the surf zone is highlighted with the red line. The middle panel gives instantaneous cross-shore velocity (black), and the 10-minute time-average (red line). The lower panel gives instantaneous and normalised (by \((u^3)^{1/3}\)) 10-minute time-averaged (red line) cross-shore velocity skewness \((3^{rd} velocity moment). The sub-sections of data considered below are highlighted (with grey) in all panels. Rotate this figure clockwise 90° to view.
Under low energy conditions (Figure 4-1), the velocity moment time-series suggests offshore transport in the surf-zone on the rising (i.e. 23:00 – 23:45) and falling tide (02:15- 03:30), near zero velocity moment at the breakpoint (23:45 and 02:10) and predominantly onshore-directed velocity moments in the shoaling zone (23:45 – 02:10). There is apparent pulsing (~45 minute period) in the shoaling zone velocity time-series (not apparent in Figure 4-1) which translates into the velocity moment time-series. Data from the highlighted sections (surf zone (A), breakpoint (B) and shoaling zone (C)) are shown in more detail in Figure 4-2-Figure 4-7.

Figure 4-2 presents a time-series of low energy surf-zone data (section A in Figure 4-1). This data includes surface elevation, instantaneous and time averaged cross-shore velocity ($u$ and $\langle u \rangle$), variance ($u'^2$ and $\langle u'^2 \rangle$), skewness ($u''$ and $\langle u'' \rangle$), kurtosis, ($u'''$ and $\langle u''' \rangle$) and acceleration ($du/dt$ and $\langle du/dt \rangle$). The surface elevation time-series shows the profiles of the waves have a particular saw-tooth shape. The time-series of $u$ reveals a mean offshore current associated with a bed return flow. The offshore-directed mean current leads to the offshore velocity moment observed in Figure 4-1.

Figure 4-3 presents the associated time-series of suspended sediment concentration and transport for the same period as presented in Figure 4-2. For comparison, cross-shore velocity and acceleration (from 1 cm above bed) are also included. The suspended sediment transport is presented as the instantaneous depth integrated flux and the 10-minute time average, which is further broken down into the mean and oscillatory component.

The mean flux is onshore directed in contrast with the velocity moment predictors. The phase between the sediment concentration and velocity is critical to the direction and magnitude of sediment transport. In this region, large suspension events tend to be caused by wave crests and occur around the time of peak onshore flow. This leads to net onshore transport, although some events start just before flow reversal (e.g. 02:53:07). Often the onshore flow velocities associated with these suspension events are much weaker than the offshore flows (compare 02:53:05 and 02:53:25), suggesting another suspension mechanism not included in the
energetics approach. This helps to explain why the velocity moment approach fails to predict onshore transport in the surf-zone under low energy conditions.

At the breakpoint (Figure 4-4, section B in Figure 4-1), the low energy waves have a less saw-toothed shape. The mean cross-shore velocity has dropped to approximately zero, possibly suggesting that the bed-return flow doesn't extend to the breakpoint under low energy conditions. The instantaneous velocity record shows similar crest and trough magnitudes (large backwashes are absent). This and the fact that \( \langle u \rangle = 0 \), leads to near-zero velocity moments, which is consistent with the observed velocity moment reversal at the breakpoint in Figure 4-1 and in the Marín-Tapia et al. (2007a) shape function.

The peak sediment concentration events are higher at the breakpoint (Figure 4-5), more frequent and persist for longer. These events appear to be caused by the stronger onshore velocities that occur under the wave crests. This leads to frequent onshore-transport events, and gives a mean onshore-directed transport. There is also evidence of acceleration driven suspension, with sediment suspension events coinciding with acceleration peaks and near-zero velocity (e.g. 23:44:35, 23:44:39); this transport mechanism not included in the energetics approach.

The surface elevation time-series (Figure 4-6) from the low energy shoaling zone (Figure 4-1 C) show the waves have a more symmetrical form (implying unbroken waves), consistent with the shoaling zone location. The velocity moment time-series is slightly positive, as the time-series of \( u \) shows similar trough and crest magnitudes with \( \langle u \rangle \gtrsim 0 \).

The suspension events in the shoaling zone (Figure 4-7, section A in Figure 4-1) are of a lower magnitude than at the breakpoint, but often last longer. The initial peak in suspension is timed with the onshore phase of the wave, leading to a strong onshore transport event. As the sediment remains in suspension, it is subsequently transported on- and offshore with little net transport. The initial onshore transport peak causes the mean transport to be weakly onshore directed.
Figure 4.2 Low-energy surf-zone hydrodynamic data. The upper panel gives instantaneous surface elevation relative to the bed (m). The middle four panels give instantaneous (blue) and time-averaged (red) cross-shore velocity, velocity variance, velocity skewness and velocity kurtosis. The lower panel gives instantaneous (blue) and time-averaged (red) cross-shore velocity acceleration.
Figure 4-3 Low-energy surf-zone sediment-transport data. The upper panel gives instantaneous cross-shore suspended-sediment transport (black). Also included is the 10-minute time average (red), the mean (blue) and oscillatory (green) component of the of the sediment transport, all of which are increased by a factor of 10 for clarity. The lower three panels give instantaneous (black) and 10-minute averaged (red) depth-integrated sediment concentration (second panel), near-bed velocity (third panel) and acceleration.
Figure 4.4 Low-energy breakpoint hydrodynamic data. The upper panel gives instantaneous surface elevation relative to the bed (m). The middle four panels give instantaneous (blue) and time-averaged (red) cross-shore velocity, velocity variance, velocity skewness and velocity kurtosis. The lower panel gives instantaneous (blue) and time-averaged (red) cross-shore velocity acceleration.
Figure 4-5 Low energy breakpoint sediment-transport data. The upper panel gives instantaneous cross-shore suspended-sediment transport (black). Also included is the 10-minute time average (red), the mean (blue) and oscillatory (green) component of the of the sediment transport, all of which are increased by a factor of 10 for clarity. The lower three panels give instantaneous (black) and 10-minute averaged (red) depth-integrated sediment concentration (second panel), near-bed velocity (third panel) and acceleration.
Figure 4-6 Low-energy shoaling-zone hydrodynamic data. The upper panel gives instantaneous surface elevation relative to the bed (m). The middle four panels give instantaneous (blue) and time-averaged (red) cross-shore velocity, velocity variance, velocity skewness and velocity kurtosis. The lower panel gives instantaneous (blue) and time-averaged (red) cross-shore velocity acceleration.
Figure 4-7 Low-energy shoaling-zone sediment-transport data. The upper panel gives instantaneous cross-shore suspended-sediment transport (black). Also included is the 10-minute time average (red), the mean (blue) and oscillatory (green) component of the of the sediment transport, all of which are increased by a factor of 10 for clarity. The lower three panels give instantaneous (black) and 10-minute averaged (red) depth-integrated sediment concentration (second panel), near-bed velocity (third panel) and acceleration.
Under high energy conditions (Figure 4-8), there is limited data outside the breakpoint as the breakpoint depth is large relative to the depth over the instruments. This lack of high energy shoaling zone data was exacerbated by the fact that the larger values occurred during neap tides. The pattern observed under low energy conditions is also apparent under high energy condition with offshore-directed velocity moment within the surf-zone, onshore-directed velocity moment within the shoaling zone crossing over at approximately the breakpoint. As most of the data was from inside the breakpoint there is more data from within the swash-zone allowing a closer investigation within this region. There is a suggestion of reducing velocity moment in the shallowest portion of this time-series. Four data subsets (from within the inner surf zone/swash-zone (A), surf zone (B), breakpoint (C), and the shoaling zone (D)) are further examined in Figures 4-9 - Figure 4-16.
Figure 4-8 Overview of conditions during Tide 37. The upper panel gives depth normalised by the breakpoint depth (solid line). The breakpoint, separating the shoaling zone from the surf zone is highlighted with the red line. The middle panel gives instantaneous cross-shore velocity (black), and 10-minute time-averaged (red line). The lower panel gives instantaneous (black line) and normalised (by $\langle u^3 \rangle^{3/2}$) 10-minute time averaged (red line) cross-shore velocity skewness ($3^{rd}$ velocity moment). The sub-sections of data considered below are highlighted (with grey) in all panels. Rotate this figure clockwise 90° to view.
Data from **inner surf-zone** is present in Figure 4-9 (section A in Figure 4-8). The waves exhibit strong asymmetry, with strong onshore-directed accelerations on the leading face of the bores. The mean cross-shore velocity is strongly offshore directed, with large backwashes dominating the weak onshore uprushes. This is reflected in the time-series of $\langle u' \rangle$ from which positive values are almost absent.

Figure 4-10 presents the high energy inner-surf zone data. Although the largest sediment suspension events are caused by the onshore phase of the waves, the strong offshore-directed mean velocity reduces the influence of these events. The mean current transports the mean sediment concentration offshore and leads to the resulting offshore sediment transport. This is the first observational evidence presented in this study of the oscillatory component of suspended flux visibly transporting sediment in the opposite direction to the mean component. In these conditions the mean component dominates over the oscillatory component.

**Mid surf-zone** data (section B in Figure 4-8) is similar to that from the inner surf-zone (Figure 4-11). The waves have a much greater wave height and are still very asymmetric. The amplitude of the cross-shore velocity is much stronger than in the inner surf-zone, while the $\langle u \rangle$ is still negative; it is weaker than the inner surf-zone data. The onshore velocity of the wave is much weaker than the offshore magnitude, and this is reflected in the velocity moment time-series, which is suggestive of offshore-directed transport.

Again the strong offshore-directed bed-return flow dominates the suspended-sediment transport (Figure 4-12). Most sediment suspension events occur in phase with the wave crest (e.g. 03:27:45), perhaps due to fluid acceleration or bore turbulence, however as $\langle u \rangle$ is so strongly offshore directed, the onshore flows are near zero and so the oscillatory transport component is greatly reduced.
Figure 4-9 High-energy inner surf-zone hydrodynamic data. The upper panel gives instantaneous surface elevation relative to the bed (m). The middle four panels give instantaneous (blue) and time-averaged (red) cross-shore velocity, velocity variance, velocity skewness and velocity kurtosis. The lower panel gives instantaneous (blue) and time-averaged (red) cross-shore velocity acceleration.
Figure 4-10 High-energy inner surf-zone sediment transport data. The upper panel gives instantaneous cross-shore suspended-sediment transport (black). Also included is the 10-minute time average (red), the mean (blue) and oscillatory (green) component of the sediment transport, all of which are increased by a factor of 10 for clarity. The lower three panels give instantaneous (black) and 10-minute averaged (red) depth-integrated sediment concentration (second panel), near-bed velocity (third panel) and acceleration.
Figure 4-11 High-energy mid surf-zone hydrodynamic data. The upper panel gives instantaneous surface elevation relative to the bed (m). The middle four panels give instantaneous (blue) and time-averaged (red) cross-shore velocity, velocity variance, velocity skewness and velocity kurtosis. The lower panel gives instantaneous (blue) and time-averaged (red) cross-shore velocity acceleration.
Figure 4-12 High-energy mid surf-zone sediment-transport data. The upper panel gives instantaneous cross-shore suspended-sediment transport (black). Also included is the 10-minute time average (red), the mean (blue) and oscillatory (green) component of the of the sediment transport, all of which are increased by a factor of 10 for clarity. The lower three panels give instantaneous (black) and 10-minute averaged (red) depth-integrated sediment concentration (second panel), near-bed velocity (third panel) and acceleration.
Figure 4-13 High-energy breakpoint hydrodynamic data. The upper panel gives instantaneous surface elevation relative to the bed (m). The middle four panels give instantaneous (blue) and time-averaged (red) cross-shore velocity, velocity variance, velocity skewness and velocity kurtosis. The lower panel gives instantaneous (blue) and time-averaged (red) cross-shore velocity acceleration.
Figure 4-14 High-energy breakpoint sediment-transport data. The upper panel gives instantaneous cross-shore suspended-sediment transport (black). Also included is the 10-minute time average (red), the mean (blue) and oscillatory (green) component of the of the sediment transport, all of which are increased by a factor of 10 for clarity. The lower three panels give instantaneous (black) and 10-minute averaged (red) depth-integrated sediment concentration (second panel), near-bed velocity (third panel) and acceleration.
Figure 4-15 High-energy shoaling-zone hydrodynamic data. The upper panel gives instantaneous surface elevation relative to the bed (m). The middle four panels give instantaneous (blue) and time-averaged (red) cross-shore velocity, velocity variance, velocity skewness and velocity kurtosis. The lower panel gives instantaneous (blue) and time-averaged (red) cross-shore velocity acceleration.
Figure 4-16 High-energy shoaling-zone sediment-transport data. The upper panel gives instantaneous cross-shore suspended-sediment transport (black). Also included is the 10-minute time average (red), the mean (blue) and oscillatory (green) component of the sediment transport, all of which are increased by a factor of 10 for clarity. The lower three panels give instantaneous (black) and 10-minute averaged (red) depth-integrated sediment concentration (second panel), near-bed velocity (third panel) and acceleration.
Waves from the breakpoint (Figure 4-13, section C in Figure 4-8) show less asymmetry than within the surf-zone, which is reflected in the acceleration time-series. The mean cross-shore velocity is still offshore directed \((\langle u \rangle < 0)\), as in the low energy breakpoint data. The troughs and crests in \(u\) are of equal magnitude and so the \(\langle u'^2 \rangle\) velocity moment is near zero, consistent with the Mariño-Tapia et al. (2007a) shape function.

The near-zero flow leads to a near-zero mean sediment flux component under high energy conditions at the breakpoint. The suspension events shown in Figure 4-14 are of a greater magnitude and last longer than in previous examples. This is probably due to the largest waves breaking here. The sediment suspension events often appear to be initiated by the peak offshore velocity, and are sustained through the flow reversal and then peak with the onshore velocity peak. The suspended concentration often increases at the leading face of the wave, suggesting acceleration plays an important role (e.g. \(t = 04:35:35\)). As the mean flow is offshore directed it balances the onshore oscillatory transport leading to a near-zero net transport.

Although the high energy measurements from outside the breakpoint (Figure 4-15, section D in Figure 4-8) show waves that are much less asymmetric than in the surf-zone, there is still a definite asymmetry. This is probably related to the proximity of the breakpoint. The mean cross-shore velocity is near zero, with apparent wave grouping. These wave groups (e.g. 05:40:00) exhibit stronger skewness than the waves between (e.g. 05:39:00 and 05:40:35). The magnitudes of the onshore and offshore stroke of the wave are similar, although the enhanced skewness in the wave group follows through to the \(u'^3\) time-series, and leads to a slightly onshore mean skewness value \(\langle u'^3 \rangle\).

In the shoaling zone (Figure 4-16) transport events appear to be caused solely by the peak onshore velocity (with acceleration playing only a minor role), and so the oscillatory transport component is exclusively onshore directed. The weak mean flow leads to a negligible mean transport component, which is dominated by the oscillatory component.
In both tides a general qualitative pattern emerges with respect to the velocity moments. The surf zone is generally associated with negative (offshore) values for the velocity moments, the shoaling zone with weak positive (onshore) values, with the zero velocity moments occurring generally around the breakpoint location. Although the running mean of the velocity moment does not extend to the swash zone, the raw values of $u'$ appear to become positive again in this region.

Under low energy conditions, the measured net sediment flux tend to be all onshore directed, which is at odds with the observations of the velocity moment time-series. This is generally due to the offshore-directed mean flow being weaker than the onshore-directed oscillatory transport component. In the surf zone this is particularly noticeable (Figure 4-2-Figure 4-3) as the net flux is onshore directed whereas the velocity moments predict offshore transport.

The net transport observed under high energy conditions is generally in agreement with that suggested by the velocity moments (consistent with earlier studies). In the surf zone the bed-return flow driven mean transport component dominates over the oscillatory transport, leading to a net offshore-directed transport, whereas in the shoaling zone the mean component is weaker and so the oscillatory flux leads to a net onshore-directed flow.

Net sediment transport within the shoaling and surf zone appears to be the result of the competition between two opposing transport components, the onshore-directed oscillatory component and the offshore-directed mean component. Any parameterisation of suspended sediment transport should include both of these components, and describe their behaviour. The swash zone was not included within this analysis; however, the concept of a “mean” transport component is difficult within the swash zone as there is no continuous time-series of velocity or sediment suspension. Instead, the swash zone is treated as a special case, and analysed separately.
4.2 Investigation of swash zone fluxes

As the energetics approach is known to be inaccurate in the swash-zone (Masselink and Russell, 2006), particular attention must be taken in this region. The sediment transport mechanisms were investigated as part of a separate collaborative study (Butt et al., in press). The analysis and plotting for this collaboration were undertaken by the author of this thesis, and so many of the figures in this section are adapted from those in the paper. Specifically, Figure 4-17 to Figure 4-22 are equivalent to Figure 8 to Figure 10 in the paper, and Figure 4-23 and Figure 4-24 are equivalent to Figure 11 and 12 in the paper. This section investigates these swash zone processes from high and low energy tides (tide 35, \( h_b \approx 1.8 \) m and tide 8, and \( h_b \approx 0.8 \) m), including their cross-shore distribution and response to energy level. As this analysis was completed as part of a collaboration, the processing techniques used are slightly different to those presented earlier in this thesis. In particular, the instantaneous sediment flux time-series was closely inspected to investigate the swash mechanisms. Figure 4-17 presents high energy time-series of depth-integrated suspended sediment transport (\( cu \)), suspended sediment concentration (\( c \)) and near-bed velocity measured at \( z = 3 \) cm (\( u_{bed} \)) against time, for \( 0 > h/h_b > 0.65 \). Five-minute averages of net sediment transport \( \langle cu \rangle \) are also shown for comparison. Moving through the surf zone towards the shoreline (moving from later to earlier times in Figure 4-17), large values of \( c \) start to coincide with large backwashes in the velocity time-series, leading to an offshore transport. Moving progressively through the swash zone, these large negative values of \( u \) become less frequent and the velocity record becomes predominantly onshore directed. As sediment transport is critically dependent on the phase lag between \( c \) and \( u \) (Osborne and Rooker, 1999), the shift from offshore to onshore transport is due to a shift in balance between the number of onshore and offshore events and also the fact that \( c \) suspension events occur during the onshore phase of the waves.

A sub-section (highlighted with a grey box in Figure 4-17; \( 19 < t < 22.6 \) min) encompassing the outer surf/swash-zone is investigated in Figure 4-18. The record is predominantly comprised of
offshore-directed transport events. Suspension events occur between the offshore phase of one wave and the onshore phase at the beginning of the next wave, in agreement with previous studies (e.g. Butt and Russell, 1999; Osborne and Rooker, 1999; Puleo et al., 2000). The increases in $c$ only appear to occur once the velocity has exceeded $\approx 1 \text{ m s}^{-1}$ (shown in Figure 4-18). In the four large backwashes (at $t \approx 19.2, 20.3, 20.7$ and $22.1$ min, marked with * in Figure 4-18) the values of $c$ only increase once this apparent threshold is met. The backwashes that do not exceed this threshold have much smaller or insignificant suspension events.

The other highlighted section in Figure 4-17 ($7 < t < 11$ min), centred in the inner to mid swash-zone is presented in Figure 4-19. In this section the major suspension events occur in phase with the onshore velocities, which peak at or above the apparent velocity threshold. The offshore velocities are generally not measured (occur below the lowest sensor), with the exception of the backwash associated with the event at $t \approx 9.6$ min, however, as sediment suspension events (measured down to 1 cm above the bed) do not occur during troughs in the surface elevation record, it is assumed that the offshore transport below the lowest EMCM is negligible in this region. The two main suspension events ($t \approx 8.0$ and $9.6$ min) coincide with the highest onshore velocities, which are in excess of the apparent velocity threshold. Due to the skewed nature of bores, these data do not discriminate between velocity and acceleration as the suspension mechanism.

Under low energy conditions the sediment transport throughout the swash zone is onshore directed (Figure 4-20). The large backwashes that dominated the outer swash zone transport under high energy are absent. The magnitude of transport events increases towards the shore (earlier times), peaking at $t \approx 5$ min. Onshore sediment transport events are more frequent than offshore events and have a large magnitude. The two highlighted subsections of data in Figure 4-20 are investigated in Figure 4-21 and Figure 4-22.
Figure 4-17 High-energy time-series showing surface elevation, cross-shore velocity (at 1 cm above bed, dashed red lines shows apparent threshold of motion), suspended-sediment concentration, and suspended-sediment transport. The red line with circles in the lower two panel shows 5-minute averages, the grey areas correspond to the ‘inner’ and ‘outer’ expanded time-series in Figure 4-18 and Figure 4-19.
Figure 4-18 High-energy swash/surf transition zone time-series of surface elevation (upper panel), near-bed velocity (with apparent sediment-suspension thresholds), instantaneous and time-averaged suspended-sediment concentration, and instantaneous and time-averaged suspended-sediment transport (lower panel).
Figure 4-19 High-energy inner- to mid-swash zone time-series of surface elevation (upper panel), near-bed velocity (with apparent sediment-suspension thresholds), instantaneous and time-averaged suspended-sediment concentration, and instantaneous and time-averaged suspended-sediment transport (lower panel).
The low energy outer swash-zone (Figure 4-21) is subject to predominantly onshore transport, with onshore events occurring more frequently, and typically having greater magnitude. The suspension threshold observed under higher energy is not so evident here, as different suspension events occur at different velocity values. However, the three largest velocity peaks did exceed the threshold ($t \approx 5.75, 6.2$ and $6.9$ min, all by onshore velocity), with two of these events leading to the two main transport events ($t \approx 6.2$ and $6.9$ min). The other event ($t \approx 5.75$) led to significantly less sediment transport, possibly due to the smaller depth of water. The offshore velocities do suspend sediment, however, as the suspension occurs near the peak offshore velocity (only the peak values of offshore velocity appear to be sufficient to suspend sediment), the velocity quickly reverses, and so net transport is limited (e.g. $t \approx 6.5$ min).

The inner-swash zone shows exclusively onshore-directed transport (Figure 4-22). As the offshore velocity is typically half that of the onshore velocity the apparent threshold of $1 \text{ m s}^{-1}$ is only exceeded beneath the wave crests (uprushes). Therefore the four main suspension events ($t \approx 0.5, 1.3, 1.9$ and $2.6$ min) occur in phase with the onshore transport. Some of the smaller suspension events occur under apparently near-zero velocity magnitude (e.g. $t \approx 1$ min), however in these cases the wave that suspended material had was probably passed below the lowest EMCM ($z = 3$ cm).

Under both tides, the inner swash zone was dominated by onshore-directed transport, while the transport regime of the outer swash/inner surf zone had a strong energy dependence. Under high energy conditions strong infragravity backwashes caused strong offshore-directed net transport. This component was absent under low energy conditions.
Figure 4-20 Low-energy time-series showing surface elevation, cross-shore velocity (at 1 cm above bed, dashed red lines show apparent threshold of motion), suspended sediment concentration, and suspended sediment transport. The red line with circles in the lower two panel shows 5-minute averages, the grey areas correspond to the ‘inner’ and ‘outer’ expanded time-series in Figure 4-21 and Figure 4-22.
Figure 4-21 Low-energy swash/surf transition zone time-series of surface elevation (upper panel), near-bed velocity (with apparent sediment-suspension thresholds), instantaneous and time-averaged suspended-sediment concentration, and instantaneous and time-averaged suspended-sediment transport (lower panel).
Figure 4-22 Low-energy inner to mid swash-zone time-series of surface elevation (upper panel), near-bed velocity (with apparent sediment-suspension thresholds), instantaneous and time-averaged suspended-sediment concentration, and instantaneous and time-averaged suspended-sediment transport (lower panel).
4.3 Structure of individual events

Having identified the relationship between transport direction, energy levels and swash/inner surf zone position, it is instructive to investigate how sediment is transported within individual waves. To do this, individual transport events (similar to the offshore events in Figure 4-18 and the onshore events in Figure 4-19) were closely examined. For each event, the depth and time dependent profiles of suspended concentration ($c_i$), cross-shore velocity ($u_c$), and cross-shore suspended sediment transport ($cu_c$) are presented.

Seven similar offshore-directed outer swash/inner surf zone events were identified for further analysis. These events were ensemble averaged to provide contour plots of $c_i$, $u_c$, $cu_c$, acceleration, $du_c/dt$, and vertical shear, $du_c/dz$ as well as time-series of depth-integrated flux, $cu$. The process was repeated for nine onshore-directed inner/mid swash transport events. To qualify as an onshore (offshore) sediment transport event, the depth- and time-integrated flux of the onshore (offshore) component of the event had to be 1.5 times greater than the offshore (onshore) component. Events were selected to have the same length so that they did not need to be stretched by interpolation as in other studies (e.g. Masselink et al., 2005). For this reason, events were stipulated as being between 5 seconds before and after the local minimum depth for the offshore events, and 2 s before and 5 s after the local minimum depth for the onshore events. Another criterion for choosing events was that the velocity peaked with a magnitude greater than 1 ms$^{-1}$. These offshore ('outer') and onshore ('inner') ensemble-averaged events are presented in Figure 4-23 and Figure 4-24 respectively. For an overview of the ensemble-averaged data, Table 4-2 presents the mean and spread of $u_c$, $c_i$ and $cu_c$. Peak velocities are also included to show the relative strength of the wave stirring, highlighting the mismatch between mean transport for the onshore event (11.8 kg m$^{-2}$s$^{-1}$) compared to the offshore event (-3.6 kg m$^{-2}$s$^{-1}$) despite similar peak velocities, (1.68 ms$^{-1}$ vs. -1.24 ms$^{-1}$).
## Table 4-2 Mean ensemble-averaged values and mean standard error.

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<thead>
<tr>
<th></th>
<th>Offshore (N = 7)</th>
<th></th>
<th>Onshore (N = 9)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$u_z$ (m s⁻¹)</td>
<td>$c_z$ (kg m⁻³)</td>
<td>$c_{uz}$ (kg m⁻² s⁻¹)</td>
<td>$u_z$ (m s⁻¹)</td>
</tr>
<tr>
<td>Mean</td>
<td>-0.24</td>
<td>8.4</td>
<td>-3.6</td>
<td>0.17</td>
</tr>
<tr>
<td>Mean standard</td>
<td>0.12</td>
<td>3.5</td>
<td>3.5</td>
<td>0.06</td>
</tr>
<tr>
<td>error</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peak velocity</td>
<td>-1.24</td>
<td></td>
<td>1.68</td>
<td></td>
</tr>
</tbody>
</table>

In the outer ensemble (Figure 4-2), the near bed velocity is strongly offshore directed due to the backwash undercutting the incoming bore (visible by the sharp increase in water depth) for $0 < t < 1.5$ s. The velocities higher in the water increase sharply to a maximum $\approx 1.2$ s after bore arrival; this lag is consistent with bore turbulence having a lower average velocity. Just after the arrival of the bore the vertical inhomogeneity in velocity leads to a strong shear between depths of $8 < z < 12$ cm with flow reversal ($u_z < 0$ occurring below $u_z > 0$) persisting for $\approx 1$ s. This velocity shear has intensity 4 times greater than that in the boundary layer. The highest values of $c_z$ occur where the backwash undercuts the bore and the highest velocity gradients occur, however the peak in $c$ close to the bed occurs $\approx 0.6$ s after the peak higher in the water column. There is no obvious direct relationship between $c_z$ and $du/dt$. The large offshore transport event at $t \approx 1$ s is due to peak sediment concentrations coinciding with strong offshore velocities where the backwashes undercut the bores. This is in contrast to the onshore event at $t \approx 1.5$ s where the weaker onshore transport is due to lower sediment concentrations and lower velocity strengths over a greater portion of the water column.
Figure 4-23 Ensemble-averaged event from outer-swash/inner-surf zone. The upper panel gives the depth-integrated suspended-sediment transport, the lower panels gives sediment transport, sediment concentration, cross-shore velocity, cross-shore shear, and acceleration. The local minimum depth corresponds to $t = 0$. 
Figure 4-24 Ensemble-averaged events from mid- to inner-swash zone. The local minimum depth corresponds to \( t = 0 \). Similar to Figure 4-23.
In the onshore inner ensemble average (Figure 4-24) the velocity is weakly offshore directed until \( t \approx 0.5 \) s after the arrival of the bore. The flow then accelerates at all heights to a peak at \( t \approx 1.5 \) s after the bore arrival, after which it decelerates. There is a degree of shear in the mid water column but the boundary-layer shear is about twice as strong. There is no flow reversal above the bed as the onshore flow close to the bed is not undercut, and so the onshore flow is much stronger. Peak values of \( c_z \) again coincide with the largest gradients of \( u_z \), although this time acceleration dominates over shear (there is no apparent relationship between \( c_z \) and vertical shear). Peak near-bed values of \( c_z \) occur \( \approx 0.3 \) s before the shear peaks, during or just after the peak acceleration. As maximum acceleration leads maximum velocity, the current observations support the idea that the entrainment of suspended sediment is associated with acceleration.

### 4.4 Energetics approach applied to the Sennen Cove data

All the data from all the tides considered in this study are presented in Figure 4-25 and compared to the Maríño-Tapia (2007a) shape function. In each case the depth is normalised by the breakpoint depth (see Section 3.3.8), and the 3rd velocity moment is normalised by the velocity variance from a height of 10 cm above bed. The raw data are also presented as bin-averages with two standard errors about the mean (in both the x and y direction), giving 95% confidence that the mean of a subset resides within the region bound by the error bars.
Figure 4-25 Normalised velocity moments plotted against normalised depth for all the tides, to allow comparison with the Mariño-Tapia shape function.

The general pattern of the data qualitatively fits the shape function. The surf-zone data \((h/h_b < 1)\) is strongly offshore directed with all the bin averages being significantly different from zero. The shape function appropriately models the behaviour of the data within the surf zone, but over predicts the magnitudes so the measured values are significantly different from the modelled values. The values become less negative towards the breakpoint, and hint at positive values in the shoaling zone. The convergence depth of the data is outside the breakpoint \((1 \leq h/h_b \leq 1.35)\), whereas it is fixed at \(h/h_b = 1\) in the Mariño-Tapia shape function. The bulk of the shoaling zone data, however, is not statistically different from zero. The shape function tends to over predict the velocity moment at all depths, especially in the shoaling zone.

This initial analysis suggests that the Sennen velocity moment data generally support the Mariño-Tapia et al. (2007a) shape function, however the shape function over-predicts the magnitudes, especially within the shoaling zone. This analysis has been performed using the cross-shore velocity record from 10 cm above bed in line with previous studies (e.g. Russell and Huntley, 1999; Mariño-Tapia et al., 2007a). These studies used data from a single point
measurement of velocity, and so no investigation of the vertical variability of the data was possible. The shape function hypothesis must assume that the shape function is relatively insensitive to the instrument height – if the bed changed by 2 cm, the shape function pattern is assumed to remain. However there has never been any data to test this assumption.

4.5 Elevation dependence of the Mariño-Tapia et al. (2007a) shape function

To test the assumption of insensitivity to bed elevation, the velocity moment shape function obtained at different heights above the bed was examined. The normalised velocity moment from 15 different heights above the bed was plotted against normalised depth and presented in Figure 4-26 - Figure 4-28, with the appropriate $R^2$ and rms values shown in Table 4-3.

Table 4-3 Correlation coefficients for varying velocity measurement heights. All values are significant at the 1% level.

<table>
<thead>
<tr>
<th>$z$ (cm above bed)</th>
<th>$R^2$</th>
<th>rms</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.19</td>
<td>0.73</td>
</tr>
<tr>
<td>2</td>
<td>0.20</td>
<td>0.71</td>
</tr>
<tr>
<td>3</td>
<td>0.22</td>
<td>0.70</td>
</tr>
<tr>
<td>4</td>
<td>0.24</td>
<td>0.68</td>
</tr>
<tr>
<td>5</td>
<td>0.25</td>
<td>0.67</td>
</tr>
<tr>
<td>6</td>
<td>0.31</td>
<td>0.62</td>
</tr>
<tr>
<td>7</td>
<td>0.41</td>
<td>0.56</td>
</tr>
<tr>
<td>8</td>
<td>0.47</td>
<td>0.52</td>
</tr>
<tr>
<td>9</td>
<td>0.48</td>
<td>0.53</td>
</tr>
<tr>
<td>10</td>
<td>0.45</td>
<td>0.57</td>
</tr>
<tr>
<td>11</td>
<td>0.37</td>
<td>0.62</td>
</tr>
<tr>
<td>12</td>
<td>0.34</td>
<td>0.65</td>
</tr>
<tr>
<td>13</td>
<td>0.33</td>
<td>0.66</td>
</tr>
<tr>
<td>14</td>
<td>0.31</td>
<td>0.66</td>
</tr>
<tr>
<td>15</td>
<td>0.29</td>
<td>0.67</td>
</tr>
</tbody>
</table>

Qualitatively the same pattern is apparent in the data from all heights, but there are systematic changes in the pattern with instrument height. To illustrate this pattern, the average velocity moment for each bin, (the centre of each y error bar) is plotted against height in Figure 4-29, with each bin represented by a different colour. The value from most bins exhibit a slight relationship with height, however the outer three shoaling zone bins and the inner surf zone bin have a distinct depth dependent behaviour.
Figure 4-26 Velocity moment shape function for heights 1 – 6 cm above bed.
Figure 4-27 Velocity moment shape function for heights 7 – 12 cm above bed.
Figure 4-28 Velocity moment shape function for heights 13 – 15 cm above bed.

The outer three bins are slightly negative near the bed and at higher elevations but have a positive peak at $z \approx 8$ cm, an example of this (the outer most bin) is highlighted in Figure 4-29. As the shoaling zone data are so low relative to the shape function, this peak in velocity moment is apparently the main reason for the improved correlation at 8-9 cm.
Figure 4-29 The pattern of velocity moments measurement varies with height above the bed. To illustrate this, each bin average (from Figure 4-26-Figure 4-28) has been colour coded in the upper left panel. The average normalised velocity moment (with two standard errors) for each bin is plotted with height above bed in the mid panels. For example, the normalised velocity moment of the outer most bin (bold) is generally slightly offshore directed, but has an onshore-directed peak centred on ≈ 7 cm, this value is much lower than the value predicted by the Mariño-Tapia shape function, as shown by the dotted line of the same colour. The lowest panel shows the $R^2$ and rms for the data at a given height above bed to the Mariño-Tapia (2007a) shape function.
At the other end of the cross-shore profile, the surf-zone bins generally increase in magnitude towards the shape function predicted values with elevation above bed. This leads to the higher correlation at higher elevations. The first bin (highlighted in Figure 4-29) goes against this trend, by decreasing in magnitude with elevation.

These results suggest that although there is subtle variation with elevation in the energetics shape function approach, there is no systematic relationship with height. Previous studies using $z = 10 \text{ cm}$ have, perhaps fortuitously, used data from the optimum elevation. These results suggest that there is some sensitivity to instrument height, which is another source of error when bed-level change is not taken into consideration.

### 4.6 Energy dependence in the Mariño-Tapia et al. (2007a) shape function

In the previous section, sediment transport was found to be sensitive to energy level, for example, offshore surf-zone transport was found to be absent under low-energy conditions. The next stage in the analysis is to investigate whether this energy dependence translates into the shape function patterns of velocity moments in the cross-shore direction. Russell and Huntley (1999) describe their shape function as being a high energy parameterisation, so the pattern might be expected to be very different under low and high energy conditions. The data in Figure 4-30 and Figure 4-31 are segregated into low and high energy categories (see Section 3.3.9), with fitting statistics given in Table 4-4. The most obvious difference in the data is the difference in the horizontal spread, with the high energy data compressed below $h/h_b = 1.5$, whereas the low energy data extends to $h/h_b \approx 3.5$. While the maximum height of water over the rig varies by a factor of three ($0.8 \leq \max (h) \leq 2.4 \text{ m}$), $h_b$ varies by a factor of $\approx 5$ ($0.55 \leq h_b \leq 2.7 \text{ m}$). Under low energy conditions, the maximum depth is greater than $h_b$ and so the data extends well into the shoaling zone, whereas under high energy, $h_b$ is generally similar to the depth over the instruments and so little data is recorded in the shoaling zone.
Figure 4-30 The influence of wave energy is investigated by segregating the high-energy tides from the low-energy tides, and plotting the normalised velocity moments against the normalised depths.

Table 4-4 Correlation coefficients for shape function.

<table>
<thead>
<tr>
<th></th>
<th>Low Energy</th>
<th>High Energy</th>
<th>Total Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R^2$</td>
<td>0.1996</td>
<td>0.4499</td>
<td>0.4385</td>
</tr>
<tr>
<td>$R$</td>
<td>0.4468</td>
<td>0.6707</td>
<td>0.6622</td>
</tr>
<tr>
<td>Rms</td>
<td>0.6275</td>
<td>0.4963</td>
<td>0.5685</td>
</tr>
</tbody>
</table>
The general pattern of the data is reproduced under both energy conditions, however within the surf zone, the data separates. Under high energy conditions, the data fits the Mariño-Tapia et al. (2007a) shape function reasonably well, while under low energy conditions, the observed normalised velocity moments have half the magnitude of the high energy data. This could be caused by the normalisation technique not removing all the energy dependence.
4.7 Comparison of Mariño-Tapia (2007a) shape function to measured fluxes

Having found a strong pattern in the velocity moment data that is relatively insensitive to energy conditions and which may potentially be used to predict sediment fluxes, the next step is to ascertain whether the same pattern actually exists within the measured fluxes. While the velocity moments are normalised by wave variance to compress the pattern of the data to allow comparison, there is no generally accepted normalising term for suspended sediment transport. Mariño-Tapia et al. (2007a) used the product of the time-average sediment concentration and the standard deviation of the cross-shore velocity record (equation (2-20)). However, this is not a useful quantity as it requires measurements of cross-shore profiles of \( u \) and \( c \) to enable its determination and a key aspect of the shape function approach is to remove the need for knowledge of these quantities. As the low- and high-energy categories are narrow (i.e. large amounts of data with small ranges of \( h_s \)), any pattern occurring within each energy category should be apparent without the need of normalisation.

Figure 4-32 presents the relationship of the un-normalised 3\(^{rd} \) velocity moment with the measured time-averaged depth-integrated suspended sediment transport. A linear (although not necessarily a 1:1) fit is expected if velocity moments do serve as a proxy for sediment flux as is commonly supposed. The data from the high energy conditions (upper panel) show an apparent linear relationship, with strong offshore transport predicted by the energetics approach correlating with strong offshore measured fluxes, although due to the intercept, predicted weak offshore-directed fluxes correspond to measured weak onshore-directed fluxes.

Under low energy conditions (middle panel) no relationship is apparent. Although both on and offshore fluxes are predicted with the energetics approach, there are very few measurements of offshore-directed sediment flux. This has immediate and serious implications for the Mariño-Tapia (2007a) shape function approach, as even though the low-energy surf-zone offshore-directed velocity moments were smaller than predicted with the shape function, their
magnitudes were still significantly different from zero. Interestingly, the magnitudes of the low energy velocity moment predicted fluxes have a quasi-linear relationship with the measured fluxes if only magnitudes (i.e. not the directions) are compared (not shown).

![Graph showing sediment fluxes under different energy levels](image)

**Figure 4-32** Measured suspended sediment fluxes compared to sediment transport predicted by the 3rd velocity moment, under low, high and all energy levels.

As the 3rd velocity moment theoretically represents the bedload transport rather than the suspended transport, the apparent lack of relationship could simply be the result of plotting the wrong velocity moment. To confirm that this isn’t the case, the measured fluxes are plotted against the 4th velocity moment in Figure 4-33. The resulting figure is very similar to that of the
3rd velocity moment, although under low energy pattern is less complex. As with Figure 4-32, the combined figure shows a weak relationship, which hides the breakdown under low energy.

![Graph showing measured suspended-sediment fluxes compared to sediment transport predicted by the 4th velocity moment.](image)

Figure 4-33 Measured suspended-sediment fluxes compared to sediment transport predicted by the 4th velocity moment, under low, high and all energy levels.

Having ascertained the complexity of the relationship between the predicted (velocity moment) fluxes and the measured fluxes, the ability of the Mariño-Tapia shape function to predict the cross-shore profile of measured suspended sediment fluxes is examined. Figure 4-34 presents 10-minute time-averaged depth-integrated suspended-sediment transport against depth normalised by breakpoint depth. The data are presented separated into un-normalised low and
high energy and normalised (with $\sigma_e C$) total energy. The total energy data must be normalised to allow the low and high energy data to be objectively compared.

Figure 4-34 Spatial patterns of cross-shore suspended-sediment transport for unnormalised high (left) and low (centre) energy tides, and total energy normalised by suspended flux normalisation suggested by Mariño-Tapia et al. (2007a). Note the total energy (right-hand) panels are plotted by combining the raw data from the low and high energy, and recalculating the bin averages. For this reason, the error bars will not be located in exactly the same position as under low and high energy.

Although the Mariño-Tapia shape function qualitatively fits the high energy data (left panel, Figure 4-34), the low energy data (centre panel, Figure 4-34) has a completely different structure. The low energy data is all onshore directed (as suggested by Figure 4-32). This is a crucial point which prevents the velocity moment based shape function from being used under low energy conditions. However, the low energy data does show a strong (different) pattern which supports the idea that a cross-shore transport parameterisation can be defined. The different patterns of the low- and high-energy data suggest that any suspended sediment transport shape function must be energy dependent. To combine the low- and high-energy data, the datasets must be normalised to remove the differences in absolute magnitude (allowing the relative directions to be compared). This combined normalised datasets (right panel, Figure 4-34) hides energy dependences and a relatively coherent structure appears, masking the differences between low and high energy conditions. Figure 4-34 illustrates how an apparent generic relationship can hide fundamental differences that are apparent when a third parameter is investigated (i.e. energy level).
4.8 Summary

Sediment transport mechanisms show a dependence on cross-shore location (swash, surf or shoaling zone), and an energy dependence. The shoaling zone shows predominantly onshore-directed velocity moment and sediment transport under high- and low-energy conditions. The surf-zone velocity moments show offshore transport under all energy conditions, whereas offshore-directed sediment transport is only observed under high energy conditions. In the swash zone, two distinct transport components were observed. In the inner surf-zone, onshore transport was observed under all energy conditions, whereas offshore transport in the outer swash-zone was only observed under high energy conditions. This was attributed to the dependence of the offshore swash transport on large (infragravity) backwashes, which tended to be absent under low energy conditions. The swash zone transport mechanisms were further investigated and vertical profiles of ensemble event averages were produced.

These results strongly suggest the transport components that should be included in an accurate sediment transport parameterisation (oscillatory, mean, onshore and offshore swash component). Importantly, the analysis suggests that there are distinct differences between the measured sediment fluxes and those suggested by the observed velocity moment and the energetics approach.
Plate 5 Wave approaching, main rig.
5 A new shape function from observations of suspended sediment transport

In the previous chapter, it was shown that velocity moment based shape functions are not applicable to low energy conditions. Further analyses into the measured sediment fluxes suggested the main transport mechanisms of sediment transport in the swash, surf and shoaling zones. This chapter presents a new parameterisation of the spatial patterns of measured cross-shore suspended sediment transport, incorporating the influence of energy level on these patterns. After observing the relative importance of the mean and oscillatory components of sediment transport, the shoaling- and surf-zone data are separated following the procedures outlined in Section 3.3.10. The swash zone data is treated separately, with the onshore and offshore components split in line with Section 4.2. The work presented in this chapter, and subsequent discussion, forms part of a paper currently under consideration for publication in the journal "Continental Shelf Research" (Tinker et al., 2009). In particular, Figure 5-1, Figure 5-2 and Figure 5-3 are equivalent to Figure 5 of the paper; Figure 5-4, Figure 6; Figure 5-5, Figure 7; Figure 5-7, Figure 8; Figure 5-8, Figure 9; Figure 5-10 is equivalent to Figure 10. The present author was the lead author of this paper and completed the bulk of the data analysis in it.

5.1 Parameterisation approach

Observations of the spatial distributions of the four sediment transport components were used to gain information to develop a cross-shore suspended-sediment transport parameterisation. This shape function is a heuristic model with an emphasis on capturing the behaviour of the fluxes; consequently, the shape function approach used here to parameterise cross-shore suspended sediment transport is best described as a behaviour-orientated (e.g. De Vriend et al., 1993; Masselink, 2004) rather than a statistical model.

Two component shape functions are defined for the mean and oscillatory transport, the sum of which gives the surf/shoaling function $Q_{sh}$, with another two functions for the onshore and offshore transport in the inner-surf zone which combine to give the swash/surf zone function.
Addition of $Q_{inh}$ and $Q_{sw}$ leads to the total shape function, $Q_{tot}$. It is noted here that all empirical relationships within this thesis assume the use of SI units (see Section 3.3.14).

Component shape functions describing observations under specific conditions allow the flux patterns to be predicted under similar conditions. However, as wave energy conditions form a continuum, simply defining a single low and high energy shape function has limited predictive value. A shape function that can be interpolated/extrapolated from known wave energy levels allows prediction of cross-shore sediment transport for a wide range of conditions, and leads to a more universal and widely-applicable model. To this end, the data were fitted with a set of curves that replicate the observed behaviours. The curves fitted were the product of a shape term and an amplitude term and have the generic form,

$$Q(x) = a(x)^b \exp(-cx^d)$$

(5-1)

$Q(x)$ denotes a transport component as a function of normalised depth, $x$ ($x = h/h_b$). The amplitude term ($a$) and coefficients ($b$, $c$, $d$ and $e$) were fitted with the Gauss-Newton nonlinear curve fitting method. Equation (5-1) is fixed at the origin (zero transport at the shoreline), increases to a maximum magnitude and then decreases with $x$ towards zero transport in deep water. For each transport component, the coefficients $b$, $c$ and $d$ are independent of wave energy, with only the amplitude term, $a$, changing. In other words, the shape of the curve remains unchanged with only the magnitude of the peak varying with wave energy. The functions for $Q_{sw}$ are slightly more complicated to derive but ultimately can be expressed in the form of equation (5-1) with $e$ being a function of $h_b$ ($e = 1$ for the shoaling surf zone functions). Describing $a$ as a function of $h_b$ allows the shape function approach to be applied to a continuum of wave-energy conditions. The three known amplitudes ($h_b = 0$, low energy, high energy) are fitted with a power function and the limited data available from wave energy conditions outside the high and low energy categories used to lend support to the proposed amplitude function.
5.2 Surf/shoaling zone results

Having separated \((cu)\) into an oscillatory and mean term, and the tides into low and high energy conditions, the four data subsets were related to the depth normalised by the breakpoint depth \(h/h_b\). Unlike the shape function of Maríño-Tapia (2007a), where the sediment transport term (velocity moment) was normalised by the cross-shore velocity variance, the present sediment transport term was not normalised for energy conditions because the data were already separated into two relatively narrow energy categories. Despite the large amount of scatter in the data, there is a clear underlying structure highlighted by the bin-averages (Figure 5-1). The patterns support the observations of Russell and Huntley (1999) and Maríño-Tapia et al. (2007a) with a total flux function under high energy conditions (Figure 5-2) showing offshore transport in the surf zone, a convergence point near the breakpoint and onshore transport in the shoaling zone. Under low energy (Figure 5-3) conditions, the surf zone was compressed such that the instruments were not in the surf zone for a very long time, resulting in relatively little data from this region. The low-energy total fluxes support expectations of an onshore transport peak just outside the surf zone, and negligible transport associated with bed-return flow.

Being able to separate the transport into a mean and oscillatory component offers new insight into the distribution of the underlying transport mechanisms. The same pattern of the oscillatory component was observed under all energy conditions, with only the magnitude changing. The data also support the assumption that the form of the mean transport is independent of energy level, with only its magnitude varying with \(h_b\). Under low energy conditions the mean component, though small compared to the oscillatory component, was offshore directed and significantly different from zero. Under high energy conditions, the observations suggest that, while the mean flow dominated in the inner surf zone, the oscillatory component dominated in the shoaling zone.

The mean component was consistently offshore directed, with an absolute magnitude decreasing seaward. Assuming that the mean flux is zero at the shore, this is indicative of an apparent
offshore-directed peak in the surf zone, although the data were of insufficient resolution to ascertain its exact position. The observed flux gradient implies that the peak is asymmetric, with the magnitude increasing quickly from the shore, and then decreasing slowly. The oscillatory flux was positive, increasing from zero in deep water to a peak just outside the breaker zone, and then decreasing shoreward. All the binned data showed averages that were significantly different from zero.

Figure 5-1 Plot of suspended sediment transport mechanisms separated by energy conditions as a function of depth normalised by breakpoint depth across the surf/shoaling zone. Cross-shore suspended sediment transport is the 10-minute time-average of the depth-integrated flux of the bottom 15 cm. The raw data is presented with error bars of two standard errors about the mean, for bin averages of 30 data points. The oscillatory, mean and surf/shoaling shape functions (described later) are included for comparison.
Figure 5-2 Low energy shape function data as presented in Figure 5-1, with scales optimised to show the detail.
Mean, oscillatory component shape functions and the total net suspended-sediment transport shape function are included on all panels for comparison.

Fitting the 10-minute averaged data to Equation (5-1) results in the following shape functions

$$Q_{\text{mean}} = a_{\text{mean}} \left(\frac{h}{h_b}\right)^4 \exp\left(-9.4 \frac{h}{h_b}^{0.75}\right)$$

(5-2)
Figure 5-3 High energy shape function data as presented in Figure 5-1, with scales optimised to show the
detail. Mean, oscillatory component shape functions and the total net suspended-sediment transport shape
function are included on all panels for comparison.

for the mean transport mechanism and

\[
Q_{\text{osc}} = a_{\text{ osc}} \left( \frac{h}{h_b} \right)^{3.5} \exp \left( -4.2 \frac{h}{h_b}^{1.05} \right)
\]  

(5-3)
for the oscillatory component (Figure 5-1), where $a_{\text{mean}}$ is -50 (-460) for low (high) energy conditions and $a_{\text{osc}}$ is 2 (4) for low (high) energy conditions.

Under low and high energy conditions, the RMSE of the oscillatory, mean and total surf/shoaling function was always less than the scatter of the data. The confidence is always stronger under low energy conditions due to the fact that there are more data here. Under high energy conditions, the confidence in the oscillatory component is weaker, but when combined with the mean term (giving the total surf/shoaling shape function) the confidence is as strong as the low energy equivalent.

Suitable amplitude functions to capture the change in behaviour from low to high energy conditions are

$$a_{\text{mean}} = -120 h_b^2$$

$$a_{\text{osc}} = 2.75 h_b^2$$

These are chosen to have the same general mathematical form for convenience.

Substituting Equations (5-4) and (5-5) into Equations (5-2) and (5-3) gives equations for the shape functions that are scaled by $h_b$, rather than having separate functions for separate wave heights. The resulting functions are presented in Figure 5-4 and are

$$Q_{\text{mean}} = (-120 h_b^2) (h/h_b)^{4.3} \exp(-h/h_b^{0.75})$$

(5-6)

$$Q_{\text{osc}} = (2.75 h_b^{0.6}) (h/h_b)^{3.5} \exp(-4.2 h/h_b^{1.05})$$

(5-7)
Figure S4 The shape function family of curves, oscillatory, mean and total surf/shoaling transport functions (the sum of the mean and oscillatory terms), left, centre and right panel respectively. Breakpoint depth increases up the plot, the dashed line indicates the local zero transport. The scale bars are included for the sediment fluxes of each shape function about their zero lines. The measured function lines are plotted in bold with a breakpoint depth of $h_b = 0.7$ m and $h_b = 1.9$ m.
A key feature of the two shape functions is that both the mean and oscillatory sediment fluxes increase with $h_b$, but that the offshore-directed mean flux increases faster than the onshore-directed oscillatory fluxes. Consequently, the net surf-zone transport changes from onshore- to offshore-directed at around $h_b = 1.7$ m (representing an offshore significant wave height of around $H_{1/3} = 0.8$ m). This change in sediment transport direction, which is observed in the present data, is not reproduced by the previous shape function of Marino-Tapia et al. (2007a).

5.3 Swash/inner surf zone results

Following the analysis described in Section 4.3, the swash/inner surf data were separated into an onshore and offshore component. The onshore transport within the swash zone occurred under all conditions, but was confined to very shallow water, while offshore transport tended to occur only under more energetic conditions and took place further offshore in the inner surf zone.

![Figure 5-5 Proposed swash/surf zone functions plotted against absolute depth with the bin averages showing two standard errors about the mean for the swash/inner surf data. The total adjustment function (black) is the sum of the onshore and offshore functions (grey). A limited number of data points lie outside of the $y$ limits under high energy conditions; however these are included in the bin averages.](image)

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The relationship between the swash suspended sediment data and $h/h_b$ varied in behaviour with energy level, implying that the swash data did not simply depend on the normalised depth. Re-plotting this swash data against the depth ($h$ rather than $h/h_b$) produced a pattern that maintained the cross-shore position of the peak and spatial extent of the onshore transport component under varying energy levels (Figure 5-5). The spatial patterns of the shape functions for this region are therefore a function of absolute depth rather than normalised depth in the current parameterisation.

The swash/inner surf zone functions were used to extend the surf/shoaling zone functions further towards the shoreline. Although the mean and oscillatory terms are insignificant inside the inner surf zone they must be removed from the swash/inner surf zone data, before this can be parameterised. This ensures that sediment transport is not included in more than one term and allows the combined shape function to be the sum of the surf/shoaling shape function and the swash/surf shape function.

Separating the swash/surf mechanisms into an onshore and offshore component was not as simple as separating the mean and oscillatory component in the surf/shoaling zone. The data suggest that the offshore mechanism is absent from the swash/inner surf zone under low energy conditions. This is consistent with the notion that the offshore transport in the swash zone is primarily driven by infragravity backwashes, which tend not to occur under low energy conditions. Assuming the pattern of the sediment flux is consistent in all wave energies with only the magnitude varying, the patterns of onshore swash/inner surf zone sediment transport observed under low energy conditions can be applied to the high energy conditions.

At low energy levels the amplitude of the offshore component was set to zero reflecting the absence of offshore-directed transport due to infragravity backwashes under these conditions. The form of onshore term was then determined from the low energy data. Once this has been established the high energy data were used to obtain the offshore transport component and the amplitude for both terms by assuming that the transport at high energy levels could be modelled
as a linear combination of the already established onshore component (scaled for increased energy level) and an offshore component with similar mathematical form.

The onshore amplitude \( a_{on} \) was fitted with a power function but this method was unsuitable for the offshore component. Instead, a function that smoothly switches from zero (for low \( h_b \)) to a straight line (for high \( h_b \)) was developed and this was tested against the calculated amplitudes of the individual data.

The resulting equations for the inner surf/swash zone functions are

\[
Q_{on} = a_{on} (h)^{1.1} \exp(-31(h)^{1.1})
\]  

(5-8)

for the onshore swash/inner surf function and

\[
Q_{off} = a_{off} (h)^{1.1} \exp(-5.7(h)^{1.1})
\]  

(5-9)

for the offshore swash/inner surf function where

\[
a_{on} = 3.5h_b^{0.8} \quad a_{on} = 3.5h_b^{0.8}
\]  

(5-10)

\[
a_{off} = -3h_b + 4 \quad \text{for } h_b > 2.15
\]

\[
= -1.25(h_b - 0.75)^2 \quad \text{for } 0.75 > h_b \geq 2.15
\]

\[
= 0 \quad \text{for } h_b \leq 0.75
\]  

(5-11)

describe the amplitude functions. Although there is little data in the swash/inner surf zone, the RMSE of the data and the functions is less than the scatter inherent in the data and so these functions fit within one standard error of the mean.

To confirm the form of the shallow water amplitude functions, the data from each shallow water tide was fitted to the sum of the onshore and offshore function, using a Newton-Gaussian non-linear fitting technique. This outputted the amplitude that best fitted the data for both the
onshore and offshore components. Plotting these amplitudes against the breakpoint depth shows how the data compares to the amplitude functions (Figure 5-6). Although there is an insufficient data to conclusively confirm the amplitude functions, the data does not invalidate them. Similar analysis was performed with the mean and oscillatory functions and they are presented for comparison.

Figure 5-6 Amplitude functions of the four component shape functions, plotted with the amplitude fitted to each tide. The amplitude functions were derived by fitting power functions to the black asterisks (high and low energy amplitudes) and constraining to the origin. The red dots are the best fit amplitudes for each individual tide. These are only shown for comparison, as there is insufficient data in each tide to make confident estimates of amplitudes, and this technique does not allow error-bounds to be calculated.
Figure 5-7 Profiles of cross-shore suspended sediment-transport (time-averaged depth-integrated flux over the bottom 15 cm) predicted by the proposed shape function under varying energy levels for the onshore swash/inner surf zone shape function (left panel), the offshore swash/inner surf shape function (middle panel) and the swash/inner surf zone shape function (right panel). Each panel shows the predicted flux profile under a breakpoint depth given by the local zero line (dashed). The flux for each profile is relative to that zero line. Energy levels vary from $h_b = 0$ to 2.5 m at 0.1 m intervals. The scales quantify the strength of the transport about the zero line. The profiles fitted to the data (at $h_b = 0.7$ m and 1.9 m) are indicated with a bold line.
As the swash/surf zone functions are related to absolute depth, when incorporated into the main shape function, their area of influence narrows towards \( h/h_b = 0 \) with increasing energy. The swash zone increases (decreases) in width relative to the surf zone as wave energy condition decreases (increases) and this is visible in the range of \( h/h_b \) affected by the onshore swash/inner surf component (Figure 5-7).

### 5.4 Combined swash/surf/shoaling zone transport function

The total shape function \( Q_{tot} \) is the sum of \( Q_{ssh} \) and \( Q_{sw} \). However, as the swash functions are functions of \( h \) rather than \( h/h_b \), they cannot be directly combined. Substituting \( h_b \times (h/h_b) \) for \( h \) into Equations (5-8) and (5-9) and rearranging into the form of Equation (5-1) gives

\[
Q_{on} = 3.5 h_b^{-1.9} \left(h/h_b\right)^{-1} \exp\left(-31 \left(h/h_b\right)^{-1}\right) \tag{5-12}
\]

for the onshore swash/inner surf function and

\[
Q_{off} = a_{off} h_b^{1.1} \left(h/h_b\right)^{1.1} \exp\left(-5.7 \left(h/h_b\right)^{1.1}\right) \tag{5-13}
\]

for the offshore swash/inner surf function, where \( a_{off} \) is given in Equation (5-11).

Having the four shape function terms in the same form allows them to be easily presented and combined simply to give \( Q_{tot} \)

\[
Q_{tot} = Q_{ssh} + Q_{mean} + Q_{on} + Q_{off} \tag{5-14}
\]

The form of the sediment fluxes predicted by the equations is presented in Figure 5-8 and the coefficients used for each term are given in Table 5-1.
Table 5-1 Coefficients for shape function terms, where $Q = a(h/b)^2\exp(-c(h/b)^4)$.

<table>
<thead>
<tr>
<th></th>
<th>$a$</th>
<th>$b$</th>
<th>$c$</th>
<th>$d$</th>
<th>$e$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q_{\text{mean}}$</td>
<td>$-120h_b^2$</td>
<td>4.3</td>
<td>9.4</td>
<td>0.75</td>
<td>1</td>
</tr>
<tr>
<td>$Q_{\text{swash}}$</td>
<td>$2.75h_b^{0.6}$</td>
<td>3.5</td>
<td>4.2</td>
<td>1.05</td>
<td>1</td>
</tr>
<tr>
<td>$Q_{\text{on}}$</td>
<td>$3.5h_b^{1.9}$</td>
<td>1.1</td>
<td>31</td>
<td>1.1</td>
<td>$h_b^{1.1}$</td>
</tr>
<tr>
<td>$Q_{\text{off}}$</td>
<td>$a_{\text{off}}h_b^{1.1}$</td>
<td>1.1</td>
<td>5.7</td>
<td>1.1</td>
<td>$h_b^{1.1}$</td>
</tr>
</tbody>
</table>

The magnitudes of the fluxes observed in the swash/inner surf zone were larger than those observed in the outer surf zone and shoaling zone. Combining the surf/shoaling zone function and the swash/surf zone function (Figure 5-8) shows that the swash functions strongly influenced the overall sediment transport shape function. Under low energy conditions, the shape function adopts a double peak profile (shown in the total shape function for $h_b = 0.7$ m; Figure 5-8), whereas under moderate energy conditions the swash/surf zone functions lead to onshore transport in the swash zone and offshore transport in the surf zone, bringing the present shape function in line with the shape function of Maríño-Tapia (2007a).

It is difficult to validate the shape function against individual tides, as there is insufficient data within each tide to outweigh the inherent scatter in suspended sediment transport measurements. However, two example tides (low and high energy) that show good agreement with the shape function are presented in Figure 5-9.
Figure 5.4 Profiles of cross-shore suspended-sediment transport (time-averaged depth-integrated flux over the bottom 15 cm) predicted by the proposed shape function under varying energy levels for the surf/shoaling zone shape function (left panel), the swash/surf shape function (middle panel) and the total transport function (right panel). Each panel shows the predicted flux profile under a breakpoint depth given by the local zero line (dashed). The flux for each profile is relative to that zero line. Energy levels vary from $h_s = 0$ to 2.5 m at 0.1 m intervals. The scales quantify the strength of the transport about the zero lines. The profiles fitted to the data (at $h_s = 0.7$ m and 1.9 m) are indicated with a bold line.
Figure 5-9 A cross-shore sediment-transport data from a low- and high-energy tide compared to the shape function.

As the proposed parameters are functions of the two variables $h/h_b$ and $h_b$ (proxies for cross-shore position and energy level respectively), it is possible to plot the functions as surfaces (Figure 5-10a). To highlight the detail of the sediment transport in the swash zone, the $x$-axis $(h/h_b)$ is presented on a logarithmic scale. Under very low energy conditions, there is no net offshore transport (the oscillatory component dominates over the mean component), hence the zero contour line (the bold black line in Figure 5-10a) does not extend down to the $h_b = 0$ line, but has a minimum at $h/h_b \approx 0.3$ and $h_b \approx 0.85$ m. At this energy level, sediment transport has two distinct onshore transport regions, separated by a point of no transport. As the energy level increases, the location of zero transport becomes an offshore transport region. The zero transport line between the surf zone and the shoaling zone was at $h/h_b = 1$ in the Marino-Tapia (2007a) shape function, whereas in the present study it quickly increases from $h/h_b \approx 0.3$ at
$h_b \approx 0.85 \text{ m to } h/h_b \approx 0.95 \text{ at } h_b = 2.5 \text{ m}. \text{ The zero contour does not meet the origin as the normalised depth decreases, but moves onshore with increasing energy due to onshore transport in the swash zone. The strongly negative values of transport associated with offshore swash component transport at high energy levels (high } h_b \text{) show the influence of the swash/inner surf zone functions at very low values of } h/h_b.$

![Figure 5-10](image)

Figure 5-10 Total flux function ($Q_{on}$, upper panel) and the spatial derivative (lower panel) plotted in spatial energy space $h/h_b - h_b$. Total suspended-sediment transport is given with the colourscale values (hot tones denote onshore transport with colder tones denoting offshore transport), delineated with numbered contours (bold contours indicate zero transport). The spatial derivative illustrates regions of accretion (positive, hot tones) and erosion (negative, cold tones). The limits of the greyscale axis are held to delineate regions of strong accretion and erosion, such as berm, bar and bar trough formation regions; however values off this scale are shown with the numbered contours.

Morphological change is related to the spatial derivative of sediment transport. Figure 5-10b presents a surface plot of $d(cu)/d(h/h_b)$, where positive (negative) values denote accretion (erosion). Although the relative position of the zero-flux contour varies with $h/h_b$, the depositional region remains fairly stable (centred at $h/h_b \approx 0.5$ and expanding with $h_b$). The

176
presence of the accretionary (bar forming) region within the surf zone is in agreement with Masselink et al. (2007b) who observed and described the formation of an inner surf zone bar on Sennen beach during the same field campaign.

Regions of bar and berm formation are clearly delineated in Figure 5-10b. The berm depositional zone is caused by the sediment convergence due to the onshore transport in the swash and surf zones decreasing in magnitude with distance onshore \( \frac{d(cu)}{d(h/h_b)} > 0 \) where \( x \) increases away from the shore. In this parameterisation, increasing wave energy reduces the relative swash width with respect to \( h/h_b \) leading to an intensification of this convergence. Further offshore, there is a region of erosion that could lead to the formation of a bar trough. This erosion is caused by weakening of the mean offshore-directed transport, combined with a strengthening of the onshore transport in the swash zone, with distance onshore (i.e. \( \frac{d(cu)}{d(h/h_b)} < 0 \)). Under more energetic conditions, this divergence is enhanced by the weakening of the offshore swash component with distance onshore. The bed change in this erosional region is more intense than the two main depositional regions. The bed change in the main bar-forming region is due to the strengthening of the mean offshore-directed transport combined with the weakening of the onshore oscillatory transport with distance onshore (i.e. \( \frac{d(cu)}{d(h/h_b)} > 0 \)).

### 5.5 Sediment budget due to shape function

Having presented a shape function parameterisation for cross-shore sediment transport, the values of sediment eroded from one region and accreted in another are investigated. This provides an insight into the possible form that a profile developed with the shape function may take. Initially the regions of the shape function are classified, and then the transport rates between these regions are quantified.

Under most conditions the shape functions lead to six regions dependent on the erosion/deposition and transport direction (see Figure 5-13). These regions are separated by points of no cross-shore sediment flux (e.g. A, C, E and G), or zero cross-shore gradient of flux.
(e.g. B, D and F). These regions can be paired up in terms of flux direction or accretion/erosion depending on the context. To describe the origins of the resultant regions, an example shape function produced under conditions of $h_b = 1.5$ m is considered. For clarity, the component forcings are described in turn, progressively in the offshore direction, starting at the shoreline, at point A, and finishing at the depth of closure, at G. Thus when the flux is described as increasing, its magnitude is increasing with distance from the shore line.

Figure 5-11 An illustration of the shape function Regions. The upper panel shows a typical high-energy shape function, with the inner part of the profile colour green. The central left panel shows Regions 1-3 (relating to the green section in the upper panel), while the central right panel shows Regions 4-6. The lower panel shows the low-energy shape function Regions.
Table 5-2 Sediment transport direction and accretion/erosion for shape function regions.

<table>
<thead>
<tr>
<th>Region</th>
<th>Flux Direction</th>
<th>Accretion/Erosion</th>
<th>Low energy region</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Onshore</td>
<td>Accretion</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>Erosion</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>Offshore</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>Accretion</td>
<td>5</td>
</tr>
<tr>
<td>5</td>
<td>Onshore</td>
<td>Erosion</td>
<td>6</td>
</tr>
</tbody>
</table>

Region 1 extends from the shoreline to the inner swash zone (the point of maximum onshore transport, B) and is accretionary due to the convergence of onshore swash component increasing across the region, to its maximum at point B. Region 1 is responsible for berm formation. Region 2 extends from point B, to the mid swash zone, point C, and has onshore-directed erosion which feeds the accretion in region 1. Onshore-directed transport decreases across region 2, primarily due to a decrease in the onshore swash component but also due to an increase on the offshore swash component, until the two components balance at point C, resulting in zero sediment flux. In Regions 1 and 2 the swash components produce over ~98% of the onshore and offshore flux (Figure 5-12), however the mean and oscillatory components become increasingly dominant across region 3. Region 3 is offshore-directed erosional, extending from C, to the maximum offshore transport point D with sediment transported to region 4. Offshore transport is primarily due to the offshore swash flux, although the driving forces in Region 3 increasingly become the result of surf zone processes. The mean (oscillatory) component accounts for ~2% (~0%) of the offshore (onshore) transport at C, compared to ~25% (~94%) at D. Region 2 and 3 are responsible for the development of the bar trough. Region 4 is fed sediment from Region 3 which is deposited, as part of the main breakpoint bar creation region centred on point D (the combination of Regions 4 and 5). Offshore transport in Region 4 is increasingly due to the mean flow (~25% at D and ~93% at E). The accretional nature of Region 4 is due to the sediment flux becoming decreasingly offshore directed as the oscillatory component peaks beyond the mean component peak. Point E occurs where the oscillatory component matches the magnitude of the mean component. E is a point of zero flux, and so sediment transported offshore in Region 3 and 4 cannot move into region 5. The increasing
dominance of the oscillatory over the mean component in Region 5 means that it is a region of onshore transport, while the increasing nature of the transport magnitude leads to accretion, with sediment supplied from Region 6. Region 5 extends to the point of maximum onshore shoaling zone transport, Point F. Region 6 extends from F to the depth of closure, G. Here the decreasing oscillatory component leads to decreasing onshore-directed transport, which feeds region 5.

Figure 5-12 How the onshore, offshore and transport is composed as a function of $h/h_b$ at $h_b = 1.5$ m. The upper panel shows the percentage of the onshore transport is that is made up of the mean and offshore swash component. The middle panel shows the percentage of the offshore transport is that is made up of the oscillatory and onshore swash component. The lower panel shows the multiplier between magnitudes of the on and offshore component, i.e. at $h_b = 0.2$, offshore transport components are ~11 times greater than onshore components.

Under low energy, ($h_b < 0.85$ m), the shape function always predicts onshore transport. Under these conditions, the shape function is still divided up by the same method, wherever the gradient or the flux is zero. However in such cases, the flux is never zero, and so Regions 3 and 4 do not exist. Despite these regions not existing, the same pattern of erosion/accretion is present (Table 5-2).
Spatially integrating the deposition in these regions gives the total deposition and erosion within each region. These values allow a quantitative analysis of the localised suspended sediment budget, and how it changes with wave energy. Figure 5-13 presents the gradient of the shape function under four energy levels \((h_b = 0.5, h_b = 1.0, h_b = 1.5\text{ and } h_b = 2.0)\) against horizontal distance (assuming a linear beach of gradient \(\tan \beta = 0.02\)). Each of the four regions defined above are delineated with vertical lines, and the gradient has been integrated with respect to horizontal distance to give total erosion or deposition within each region (due to suspended fluxes). These values are also presented \((1 \times 10^5 \times \text{m}^3/\text{m}^2/\text{s} \approx 0.01 \times \text{mm/s})\) as in Table 5-3.

Figure 5-13 The gradient of the proposed shape function (with swash adjustment) is plotted against cross-shore distance assuming a linear bed (gradient 1:20; gradient = blue, shape function is grey). The gradient is important for bed-level change, with a positive gradient indicating deposition and negative gradient erosion. The spatial domain is divided into transport regions (by vertical grey lines), with the deposition within each zone integrated.
Except under low energy levels (i.e. $h_b = 0.5$ m), each region is bounded by zero transport on one side (i.e. Regions 2 and 3 are bounded by Point C). This should make predicting sediment transport between the regions simple. However, as the regions of deposition and erosion are linked on the beach, the origin and destination of these morphological regions is of interest.

Region 1, linked to berm formation, and region 6, linked to bar degeneration, are relatively simple cases, as the reference source or sink of sand can only by from the neighbouring region (the shape function assumes no sediment is lost to the dry beach, or beyond the closure depth).

The bar trough (Regions 2 and 3) and crest generation (Regions 4 and 5) zones are more complicated, as there is more than one destination/origin for the eroded/deposited sediment. These regions raise two questions, "Where is the sediment eroded in the trough deposited?" and "What is the origin of sediment deposited on the bar?"

Under energetic conditions, the trough is the source of sediment that is transported on and offshore. There is a known point of zero transport in the trough (Point C) that segregates these destinations, however, the amount of sediment eroded either side of this point varies with energy, and is not known. If, like a sinusoidal curve, the maximum gradient of the shape function coincided with the point of zero flux, the volume of sediment transported onshore and offshore from the trough would be equal. As the sediment deposited in Region 1 only comes from the trough, it is easy to quantify how much sediment it transported onshore from the trough. The relationship between total volume of sediment eroded from the trough to that deposited in the berm region (transported from Regions 2 and 3 to Region 1) answers the first question.
This is formalised with a ratio, termed $rat_1$, which is described as:

$$rat_1 = \frac{-(V_2 + V_3)}{V_1}$$

(5-15)

where $V_x$ describes volume of sediment deposited in region $x$ ($V_x < 0$ denotes erosion). When $1 < rat_1 < 2$, most of the sediment eroded from the trough is transported onshore to supply berm formation in Region 1 (the volume of sediment deposited in the berm is more than half of the sediment eroded, and so more sediment is transported onshore). When the sediment deposited in the berm region is less than half of the amount eroded, the sediment is predominantly deposited in the bar. This occurs when $rat_1 > 2$. When the volume of sediment deposited in the berm is exactly half the amount eroded from the trough, the eroded sediment is equally distributed between the berm and bar, ($rat_1 = 2$). Under low energy conditions $V_3$ is zero (region 3 and 4 do not occur when there is no offshore transport) and so $rat_1$ becomes $-V_2/V_1$. As there is no point of zero transport separating Region 2 and 5, not all the sediment deposited in Region 1 is from Region 2 – resulting in $rat_2 < 1$. When the volume of sediment eroded in the bar is the same as that deposited in the berm, $rat_1 = 1$. This occurs when the there is no offshore transport, but when surf-zone transport reduces to zero. These relationships are presented in Table 5-4.

Sediment deposited in the bar from offshore can be quantified (as region 6 is the only possible source). Onshore deposition in the bar can only be from the trough, but as sediment is transported onshore and offshore from the trough, this is not known. The approach taken to ascertain the origin of sediment deposited in the bar is similar to $rat_1$. A ratio between the volume of sediment deposited in the bar (Region 4 and 5) and the amount of sediment eroded offshore of the bar (Region 6) is developed as:

$$rat_2 = \frac{-(V_4 + V_5)}{V_6}$$

(5-16)
Table 5-4 The sediment transport behaviour associated with different values of $\text{rat}_1$ and $\text{rat}_2$.

\[
\text{rat}_1 = \frac{-(V_2 + V_3)}{V_1} \quad \text{Where does trough sediment go?}
\]

\[
\text{rat}_2 = \frac{-(V_4 + V_5)}{V_6} \quad \text{Where does the bar sediment come from?}
\]

<table>
<thead>
<tr>
<th>$\text{rat}_1$</th>
<th>Sediment from Region 6 directly to Region 1, as Regions 2-5 are absent.</th>
<th>Sediment from Region 6 directly to Region 1, as Regions 2-5 are absent.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0 &lt; \text{rat}_1 &lt; 1$</td>
<td>When no offshore transport, Region 2 is a “passing through” region, not solely a sediment source.</td>
<td>Sediment eroded in Region 6 is deposited in Region 5, and also Region 1.</td>
</tr>
<tr>
<td>1</td>
<td>As no offshore sediment transport, sediment eroded in Region 2 is the sole supply for Region 1.</td>
<td>Sediment deposited in Region 5 is exclusively from Region 6.</td>
</tr>
<tr>
<td>$1 &lt; \text{rat}_1 &lt; 2$</td>
<td>Sediment eroded from trough Region predominantly transported onshore.</td>
<td>Bar developed predominantly from sediment eroded further offshore, in Region 6.</td>
</tr>
<tr>
<td>2</td>
<td>Eroded sediment equally transport onshore and offshore.</td>
<td>Bar developed equally from onshore (Region 3) and offshore (Region 6).</td>
</tr>
<tr>
<td>$\text{rat}_1 &gt; 2$</td>
<td>Eroded sediment transported predominantly offshore.</td>
<td>Bar developed predominantly from sediment eroded from the trough region (Region 3).</td>
</tr>
</tbody>
</table>

When the volume of sediment eroded from Region 6 is half deposited in the bar, the bar is developed equally from onshore and offshore sediment. This occurs when $\text{rat}_2 = 2$. When the sediment eroded in Region 6 is less than half the sediment deposited in the bar, the bar is developed from trough eroded sediment transported offshore ($\text{rat}_2 > 2$), when it is more than half, the bar is predominantly formed from sediment eroded in Region 6 ($1 < \text{rat}_2 < 2$). Under lower energy, when the there is no offshore sediment transport and surf-zone transport reduces to a point of zero flux, the bar cannot be developed from trough eroded sediment (there is no offshore transport), and so the volume of sediment deposited on the bar is equal to that eroded from Region 6, and so $\text{rat}_2 = 1$. At still lower energy, sediment transport is never zero in the surf-zone, and so some sediment eroded in Region 6 is transported beyond the bar region. When this occurs, the volume of sediment eroded in Region 6 is larger than the volume of sediment.
deposited in the bar and so $rat_2 < 1$. The implication of values of for $rat_1$ and $rat_2$ on sediment transport behaviour are summarised in Table 5-4.

These ratios (with the regional depositions from which they were derived) have been established for a range of breakpoint depths, and are presented in Figure 5-14. Under very low energy conditions ($h_b < 0.2 \text{ m}$) $rat_1$ and $rat_2 = 0$, as there is only one erosion (accretion) region, with all sediment eroded in Region 6 transported to Region 1. When $0.2 < h_b < 0.85$, there are two onshore transport peaks, separated by a trough. This leads to four erosion/accretion regions, with the middle two regions not separated by a point of zero transport. Under these conditions, sediment eroded in Region 6 can be transported throughout the nearshore and be deposited in the swash-zone in Region 1. As the trough between the two onshore peaks deepens $rat_1$ and $rat_2$ increase. At $h_b \approx 0.85 \text{ m}$ this trough reaches zero transport, and acts a sediment barrier separating shoreward berm formation from seaward breakpoint bar crest formation; this point occurs when $rat_1 = rat_2 = 1$. Increasing energy conditions ($h_b > 0.85 \text{ m}$) leads to an offshore transport region that introduces the final two regions, (3 and 4). As energy increases ($h_b > 0.85 \text{ m}$), $rat_1$ and $rat_2$ increase above 1, which is because the existence of Regions 3 and 4 means that offshore transport from the trough to bar crest is present, thus not all sediment is transported onshore. When $rat_1$ and $rat_2$ are greater than 2, sediment eroded from Regions 2 and 3 is subject primarily to offshore transport and deposition is Region 4 and 5.
Figure 5-14 Analysis of the sediment budget as a function of breakpoint depth. The upper panel is rat₁ against breakpoint depth, where rat₁ is given the destination of sediment eroded from the trough (rat₁ > 1 leads to predominantly offshore). The lower panel gives rat₂ against breakpoint depth, being the origin of sediment deposited on the bar (rat₂ > 1 leads to predominantly from the trough). The ratios of the Mariño-Tapia et al. (2007a) shape function are also presented (red line).

5.6 Summary

The cross-shore sediment transport has been broken into a mean and oscillatory component and the swash/inner surf zone data into an onshore and offshore component. The spatial patterns of these components were investigated and four individual shape function parameterisations were developed which combine to form a total shape function. Significantly, this is the first such parameterisation to be based on measured sediment fluxes and thus overcomes the problems associated with previous velocity moment based functions. Each component shape function is the product of a shape and magnitude term. The shape term give the transport direction and the
shape of the cross-shore transport profile. The magnitude term is a function of the incident energy (in terms of $h_b$) that scales the shape term with energy levels. In this way, the sediment transport does not need normalising (c.f. Mariño-Tapia et al., 2007a). As the amplitude function of each component shape function has a different relationship with $h_b$, the resultant shape function can respond to varying energy levels by changing its shape so that while profile high energy sediment transport are predicted similarly to the Mariño-Tapia et al. (2007a) shape function, under low energy, all onshore transport is predicted. Special treatment of the swash zone provides more realistic swash component shape functions, with a net onshore transport in the inner surf-zone, and onshore transport in the outer surf-zone under high energy conditions and onshore transport in the swash-zone under low energy conditions.

Upon classifying the various region and points of the shape function in terms of erosion, accretion onshore and off transport, the resulting erosion/accretion patterns are analysed. It is noted that under low energy conditions the bar is developed predominantly from sediment sources further offshore, while under high energy conditions sediment scoured from the trough region is the dominant source. This is contrast to the Mariño-Tapia et al. (2007a) shape function, where the bar development is exclusively from the trough region.
Plate 6 Surveying and downloading data in the sun.

18:40 17th May, 2005
6 Sediment flux shape function model: description and behaviour

In the previous chapter field observations of suspended-sediment transport were used to develop an energy-dependent shape function parameterisation and the implications of this shape function in terms of sediment budget and profile change were explored. However, to fully investigate beach response the shape function should be used within a numerical model to allow morphological feedback to occur. Here, such a model is presented as a proof of concept, with the aim of showing the profile behaviour that the shape function model can produce. Although the shape function is based on measured fluxes, it is adapted (see Section 6.1.13) and so the model is described as a qualitative behavioural model. Initial tests investigate profile response to simplified representative forcing conditions with later tests increasing the level of complexity and realism.

6.1 Model Description

This model solves the sediment continuity equation

\[ \frac{\partial h}{\partial t} = -\frac{1}{\varepsilon} \frac{\partial Q}{\partial x} \] (6-1)

where \( \varepsilon \) is the grain packing density \( (\varepsilon = (1 - \lambda) \) and \( \lambda \) is porosity), using an explicit finite difference scheme that is centred in space and uses forward differencing in time, with the shape function parameterising sediment transport.

6.1.1 Model notation

To allow description of the model scheme a standard notation will be used. To denote an instantaneous quantity of a time varying parameter (e.g. \( h_b \)) at particular time, \( t \), a superscripted \( t \) will be used, \( h_b^t \), with the next (future) point being described as \( h_b^{t+1} \) and the previous (past)
time step value $h_b^{k,t}$. The first (last) value in a time-series is given as $h_b^1$ ($h_b^{end}$). The time index increases from $t^1$ at the beginning of the model run to $t^{end}$ at the end. To describe a spatially-varying quantity (e.g. $h'$) at a particular point, $x$, a subscripted $x$ is used, thus a particular point along the initial profile can be given as $h'_x$, with $h'_{x+1}$ ($h'_{x-1}$) describing the adjacent cell to the left/landward (right/seaward). The spatial index begins at zero at an arbitrary point on the dry beach, and increases in the seaward direction. The spatial and temporal indexes are dimensionless and describe the number of time steps/cells from the temporal and spatial origin.

6.1.2 Finite difference scheme

Rearranging the sediment continuity equation (6-1) in finite differencing form gives,

$$\frac{h^{t+1} - h^t}{\Delta t} = -\frac{1}{\varepsilon} \frac{\partial Q}{\partial x}$$

(6-2)

where $\Delta t$ is the model time step. This can be simplified as

$$h^{t+1} = h^t + \Delta h^t$$

$$\Delta h^t = -\frac{\Delta t}{\varepsilon} \frac{\partial Q'}{\partial x}$$

(6-3)

and so the future profile is the addition of the current profile and a function of the shape function.

6.1.3 The basic model

The model has a regular spaced grid in the cross-shore direction ($x$), with a corresponding profile elevation grid ($h$). The co-ordinate system is positive offshore in the horizontal and positive downwards from the mean water level. The model run is started with an initial profile and is forced from a time-series of breakpoint depth ($h_b$) and mean surface elevation ($\eta$) and simple parameters (phase ($\phi$), amplitude ($a$) and period ($\sigma$) of the $M_2$ and $S_2$ tidal components (denoted with an $M_2$ and $S_2$ subscript)) are generally used to simulate the tide.
Each time step, the normalised water depth ($hh_b'$, i.e. $h/h_b$, calculated as $h'/h_b'$) is calculated by dividing the profile depth (adjusted for $\eta$) by the breakpoint depth, $h_b'$, with negative (dry) values being set to zero. Instantaneous suspended sediment transport ($Q_{sf}$) is derived from the shape function using $h_b'$ and $hh_b'$. The instantaneous suspended sediment transport is modified to account for down slope transport to stop the formation of unrealistic beach slopes. Sediment transport is modified by

$$Q' = Q \frac{\tan \phi - \tan \beta}{\tan \phi} = Q \left(1 - \frac{\tan \beta}{\tan \phi}\right) \quad (6-4)$$

where $\phi$ is the angle of repose ($-35^\circ$) and $\beta$ is the beach slope (positive when the beach slopes down seawards) (Roelvink et al., 2007). It can be seen that when $1 - \tan \beta/\tan \phi > 1$ ($\tan \beta/\tan \phi < 0$), the sediment transport is enhanced by slope transport, and when $1 - \tan \beta/\tan \phi < 1$ ($\tan \beta/\tan \phi > 0$) sediment transport is reduced by the bed slope. Whether the slope enhances or reduces sediment transport is dependent on both the slope and direction of transport, so this method must be adapted (otherwise it will be only controlled by the magnitude of $\beta$). This is illustrated in Table 6-1.

<table>
<thead>
<tr>
<th>Positive slope ($\tan \beta &gt; 0$)</th>
<th>Offshore transport $Q &lt; 0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Downwards seawards</td>
<td>Transport should be reduced</td>
</tr>
<tr>
<td></td>
<td>Should be $\tan \beta/\tan \phi &gt; 0$</td>
</tr>
<tr>
<td></td>
<td>Correct $\tan \beta &gt; 0$</td>
</tr>
<tr>
<td>Negative slope ($\tan \beta &lt; 0$)</td>
<td>Transport should be enhanced</td>
</tr>
<tr>
<td>Upwards seawards</td>
<td>Should be $\tan \beta/\tan \phi &lt; 0$</td>
</tr>
<tr>
<td></td>
<td>Correct $\tan \beta &lt; 0$</td>
</tr>
</tbody>
</table>

Table 6-1 Bed slope influences sediment transport by either enhancing down-slope transport or reducing up-slope transport. As the enhancement/reduction is described as $1 - \beta/\phi$, it is a function of the slope direction rather than the both transport and slope direction. This illustrates that when the transport is offshore directed the function $1 - \beta/\phi$ does not work, and needs to be reversed.
From Table 6-1 it is apparent that by multiplying the $\beta$ by the sign of the sediment transport, suitable adaptation can be achieved. This factor ($Q_s$) is a function of the beach slope ($\beta$) and the angle of repose ($\phi$), and is calculated as

$$Q_s = \frac{\tan \phi - sfs' \tan \beta'}{\tan \phi} = 1 - \frac{sfs' \tan \beta'}{\tan \phi}$$  \hspace{1cm} (6-5)

where $sfs$ is a term to correct for the sign of the shape function, i.e. offshore transport is enhanced by beach slope, whereas onshore transport is reduced. This approach is similar to the scheme used in the XBEACH model (Roelvink et al., 2007). The product of $Q_s f$ and $Q_s g$ give an instantaneous spatial distribution of suspended sediment transport ($\mathcal{Q}$). The profile elevation change, $dh'$, is calculated as the product of the spatial gradient of $\mathcal{Q}'$ ($d\mathcal{Q}/dx$) and $-\Delta t/\mathcal{E}$. The future profile is the sum of $dh'$ and $h'$. The updated profile is then used to drive the next iteration of the model.

### 6.1.4 Model stability

Explicit numerical schemes can lead to instabilities if the time step is too large for the spatial step. This is the basis of the Courant-Fredrics-Levy criteria (CFL limit) which relates the time it takes information travelling at a given speed, to cross the grid cell compared to the time step. This is expressed via the Courant number ($Cu$) (Roelvink, 2006) as

$$Cu = u \frac{dt}{dx}$$  \hspace{1cm} (6-6)

where $u$ is a representative velocity in the model (often taken as the shallow water wave speed in hydrodynamic models), $\Delta t$ and $\Delta x$ are the time step and cell width. The CFL criteria states that explicit models cannot be stable when $Cu > 1$. As the current model is not a coupled processed-based model, there is no hydrodynamics component to provide a typical velocity and so it is difficult to apply this method. Trial and error has shown a threshold of $\Delta t = 600$ s is
stable with a grid size of $\Delta x = 1$ m. Even when the Courant number is below unity, explicit models can become unstable when the model is shocked. In the current model this can occur whenever the profile becomes sharp, typically originating in Region 2 due to the offshore swash transport term. Once numerical instabilities start to form, untreated, they grow with each model iteration. The generally accepted method for removing these instabilities is with smoothing.

### 6.1.5 Depth of closure

As the shape function is asymptotic, sediment flux tends toward, but never becomes zero at large depths. To reduce the model edge effects, the profile is extended to a depth where sediment flux is negligible. This is ensured by introducing a depth of closure at $h/h_b = 4$. This is achieved by multiplying the shape function by a step function that is one at $h/h_b < 3$ (and so does not change the shape function sediment flux predictions within this range), 0 at $h/h_b > 4$ (so sediment flux is zero in deep water), and smoothly translates between the two following a cosine curve. This step function is given as:

$$
\text{stepfunc} = \begin{cases} 
0 & h/h_b > 4 \\
1 & h/h_b < 3 \\
-1/2 (\cos((h/h_b - 3)\pi)+1) - 1 & 3 < h/h_b \leq 4
\end{cases}
$$

One of the concerns about introducing a depth of closure is that the sediment flux gradient would be modified at the boundary, and so a numerical feature would occur. As the sediment flux at $h/h_b = 3$ is less than 1% of the peak value when $h_b > 0.1$ m (and lower under more energetic conditions), this closure depth is deep enough to stop this happening. Although a deeper depth of closure would have further reduced the likelihood of a numerical feature, it increases the size of the domain and so processing time.

### 6.1.6 Smoothing

A frequent problem with process-based coastal morphological models is the appearance of high wave-number spatial oscillations in the simulated bed levels with time (Johnson and Zyserman, 2002). The most common way of removing these oscillations is by smoothing or filtering the
profile. However, this is no trivial matter as smoothing can have several drawbacks. Smoothing can cause erroneous sediment transport, especially at regions of strong gradients of beach slope (the second derivative of profile elevation). Various solutions to the smoothing will be investigated here, with increasing complexity.

A 2-point averaging is the simplest form of smoothing, but shifts the profile half a grid cell each time step (Figure 6-1). To overcome this, an odd number of cells must be used in the smoothing; i.e. replace a value with the average of it and its two neighbouring points. This is illustrated in Figure 6-1.

Figure 6-1 The upper panel show that using a 2-point forward or backwards averaging scheme leads to a horizontal shift in the profile, as the initial profile (blue) is shifted in the second profile (red) one time step later. The lower panel shows the same initial profile, but with a three point averaging scheme, showing the profile is not horizontally offset.
Figure 6-2 This is an example of why short wavelength numerical oscillations cannot be removed with a simple unweighted mean, but require a weighting. a) An example dataset with 2-point wavelength numerical oscillations (bold black) is presented with the result of a 3-point unweighted mean (red). Below this the steps of how the unweighted mean are calculated are illustrated. b) The effect of increasing the smoothing window is illustrated from 3-point (red) to 5-points (blue). The raw data (black) is also presented for comparison. This shows that increasing the filter window does reduce the oscillations, but doesn’t remove them. c) The example in a) is continued, with the data being smoothed with a weighting of [1 2 1]. The raw data is presented (bold black) with a 3-point unweighted mean (red) and with a weighted mean (black). The workings are presented below. This shows that weighting is required to effectively remove numerical oscillations.
Numerical oscillations tend to have a wavelength of approximately two grid points, and so smoothing must effectively remove oscillations at this length scale. Consider the example presented in Figure 6-2a. Consider first, the point \( t = 23 \). As the maxima (minima) have a value of 1 (-1), a straight 3-point (un-weighted) mean (illustrated in Figure 6-1, and as the red line in Figure 6-2a) gives \((1-1+1)/3 = 1/3\), rather than 0 (the average of the time-series). Similarly, for point \( t = 24 \), a 3 point mean gives \((-1 +1 -1)/3 = -1/3\). A five point average does better (giving \((1-1+1-1+1)/5 = 1/5\) and \((-1+1-1+1-1)/5 = -1/5\); illustrated as the blue line in Figure 6-2b) however, is still not able to remove the oscillations. In fact, it is not possible to remove this oscillation with this type of smoothing no matter how many points are used. This issue is overcome by using a weighted mean, where each point is given a different weighting.

The effectiveness of weighted means at removing noise is illustrated in Figure 6-2c, with the previous example of Figure 6-2a continued. A simple weighting of \([1 2 1]\) effectively removes this signal completely, as this is equivalent to doing the average of a forward and backward 2-point average (with a weighting of \([1 0 0]\) and \([0 1 1]\) respectively). In a 3-point smoothing with a weighting of \([1 2 1]\), the current point has twice the weighting of the surrounding points, and so can cancel out both values completely. The value at \( t = 23 \) is 1, while the adjacent points \((t = 22, 24)\) have a value of -1. While a non-weighted 3-point mean gives a value of \((1-1-1)/3 = -1/3\), giving the central point a double weighting allows it to cancel out both the adjacent points, so \((-1 + 2*1 -1)/3 = 0\), giving the mean of the data series. In this example, this weighting completely removes the numerical oscillations. When the sum of the odd indexes of a weighting (i.e. first, third, fifth, seventh... value) equal the sum of the even indexes, the weighting will have some skill at removing single point numerical oscillations (as in Figure 6-2b), such example weightings are presented in Table 6-2.
Table 6-2 Example weightings for 3 – 9 point weighted smoothing that have been optimised to remove single point numerical oscillations.

<table>
<thead>
<tr>
<th>Weighting</th>
<th>Example Weighting</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 point</td>
<td>[1 2 1]</td>
</tr>
<tr>
<td>5 point</td>
<td>[1 3 4 3 1]</td>
</tr>
<tr>
<td>7 point</td>
<td>[1 3 4 6 4 3 2]</td>
</tr>
<tr>
<td>7 point</td>
<td>[1 2 5 8 5 2 1]</td>
</tr>
<tr>
<td>7 point</td>
<td>[1 1 5 0 5 1 1]</td>
</tr>
<tr>
<td>9 point</td>
<td>[2 3 4 7 8 7 4 3 2]</td>
</tr>
<tr>
<td>9 point</td>
<td>[1 3 4 7 1 0 7 4 3 1]</td>
</tr>
<tr>
<td>9 point</td>
<td>[1 2 4 8 1 0 8 4 2 1]</td>
</tr>
</tbody>
</table>

Figure 6-3 Smoothing a profile with a simple [1 2 1] weighting can lead to erroneous erosion (accretion) at convex (concave) features, implying a non-existent numerical sediment flux. This is illustrated by smoothing an example profile (blue) with a [1 2 1] weighting (black). The red profile is an intermediate step to demonstrate how this weighting can be calculated.
Simply optimising the weighting to remove single cell oscillations (as in Table 6-2) can lead to adverse effects on larger features. This is visible in the lower panel of Figure 6-1; however it will be investigated graphically in Figure 6-3. A 3-point averaging with [1 2 1] weighting can be calculated by averaging the average of a 2-point forward averaging and 2-point backward averaging. Averaging $h_{i-1}$ and $h_i$ (equivalent to a weighting of [1 1 0]) gives $h_{i+1/2}$, averaging $h_i$ and $h_{i+1}$ (equivalent to a weighting of [0 1 1]) gives $h_{i-1/2}$, and averaging $h_{i-1/2}$ and $h_{i+1/2}$ gives the equivalent of a [1 2 1] weighted 3-point average. This is presented in Figure 6-3, with the blue line showing the initial profile to be smoothed, and the red line showing average of $h_{i-1/2}$ and $h_{i+1/2}$, the average of which is plotted in black (the weighted [1 2 1] mean). Simple [1 2 1] weighted means tend to erode convex and fill concave features. In fact these smoothing techniques tend to act strongly in any regions where the slope of the slope (magnitude of $\Delta h/\Delta x^2$) is greatest. The shape of the profile suggested in Figure 6-3 is a commonly occurring feature in beach profiles (e.g. seaward of the terrace, seaward of the berm), and so the resulting effect of the smoothing on this type of morphology is important. The smoothing simulates erroneous down slope transport, which over time may dominate the real, parameterised transport.

A filtering technique that overcomes this issue was suggested by Jensen et al. (1999), and is illustrated in Figure 6-4. A profile with large scale morphology overlaid with single cell oscillations ($h$, upper panel blue) is smoothed ($h_{sm}$, upper panel red). This smoothed profile is then subtracted from the initial profile to give a profile of the difference ($dh$, middle panel, blue) which includes the numerical instabilities, and a small proportion of the large morphological features. This profile ($dh$) is then smoothed ($dh_{sm}$, middle panel red) to remove the numerical noise (but leaving the portion of the large scale morphology) and added to the smoothed profile ($h_{sm}$) to give a smoothed profile that suppresses single cell oscillations without overtly suppressing larger scale morphology.
Figure 6-4 The method of Jensen et al. (1999) allows small scale oscillations (numerical noise) to be removed from the profile without affecting the larger morphological features. The upper panel presents a noisy profile (blue, $h$) with the first stage of smoothing (with a $[1 2 1]$ weighting; red, $h_{sm}$). The red smoothed profile removes some sediment from the underlying profile. The middle panel shows the difference between $h$ and $h_{sm}$, ($dh$, blue), which is smoothed (red, $dh_{sm}$), and represents the sediment erroneously removed from the profile by the smoothing in the upper panel. The lower panel adds the sediment ($dh_{sm}$) back to the smoothed profile ($h_{sm}$), to give a smoothed profile that doesn’t affect the larger scale morphological features (cyan). These are presented with the original profile ($h$, blue) and the first stage smoothed profile ($h_{sm}$, red) for comparison.

Jensen et al. (1999) suggest that the smoothing be undertaken with a three point weighted mean and formalised this as
where 0 < \alpha < 1. When \alpha = 1/3 each of the weightings are equal (i.e. the same as an un-weighted mean). The 3-point weighted mean is only effective at removing grid-scale oscillations when \alpha = 1/4, i.e. the weighting discussed above. Jensen et al. (1999) suggested this routine was effective at damping oscillations of the order of the grid-size, but did not specify the number of times this should be iterated. Johnson et al. (2002) suggested that there was little benefit in iterating this more than once.

This technique has been reduced to a simple weighting. Having calculated \( h_{SM} \) from (6-8), \( dh \) can be calculated as

\[
dh = h - h_{SM},
\]

\[
= (0h_{-1} + h_{0} + 0h_{+1}) - (\alpha h_{-1} + (1 - 2\alpha)h_{0} + \alpha h_{+1})
\]

\[
= h_{-1}(-\alpha) + h_{0}(2\alpha) + h_{+1}(-\alpha)
\]

which is then smoothed using (6-8). This is best calculated as a matrix operation, e.g.

\[
dh_{SM} = \begin{bmatrix}
\alpha & -\alpha h_{-2} & 2\alpha h_{-1} & -\alpha h_{0} \\
(1 - 2\alpha) & -\alpha h_{-1} & 2\alpha h_{0} & -\alpha h_{+1} \\
\alpha & -\alpha h_{0} & 2\alpha h_{+1} & -\alpha h_{+2}
\end{bmatrix}
\]

\[
= \begin{bmatrix}
-\alpha^2 h_{-2} & 2\alpha^2 h_{-1} & -\alpha^2 h_{0} \\
(2\alpha^2 - \alpha)h_{-1} & (4\alpha^2 + 2\alpha)h_{0} & (2\alpha^2 - \alpha)h_{+1} \\
-\alpha^2 h_{0} & 2\alpha^2 h_{+1} & -\alpha^2 h_{+2}
\end{bmatrix}
\]

\[
= \begin{bmatrix}
-\alpha^2 h_{-2} & (4\alpha^2 - \alpha)h_{-1} & (-6\alpha^2 + 2\alpha)h_{0} & (4\alpha^2 - \alpha)h_{+1} & -\alpha^2 h_{+2}
\end{bmatrix}
\]

Adding (6-8) and (6-10) gives the first iteration of \( h \).
\[ h = h_{SM} + dh_{SM} \]

\[ = [\alpha h_{n-1} + (1 - 2\alpha)h_i + \alpha h_{n+1}] + \\
\left[ -\alpha^2 h_{n-2} \quad (4\alpha^2 - \alpha) h_{n-1} \quad (-6\alpha^2 + 2\alpha) h_i \quad (4\alpha^2 - \alpha) h_{n+1} \quad -\alpha^2 h_{n+2} \right] \]  

(6-11)

\[ = [\alpha^2 h_{n-2} \quad 4\alpha^2 h_{n-1} \quad (1 - 6\alpha^2) h_i \quad 4\alpha^2 h_{n+1} \quad -\alpha^2 h_{n+2}] \]

As this technique is built up as the application of a 3-point weighting, and having established that a 3-point weighting of \([1 \ 2 \ 1]\) (equivalent to \(\alpha = 0.25\)) is required to remove numerical oscillations, (6-11) can be simplified to a 5-point smoothing with:

\[ \text{weighting} = [-1 \ 4 \ 10 \ 4 \ -1] \]  

(6-12)

which is presented in the time and frequency domain in figure

![Figure 6-5](image-url)  

Figure 6-5 The window given in (6-12) presented in the time and frequency domain.

In this implementation of the shape function model, this 5-point weighted mean, with the weighting presented in (6-12) is used as the smoothing routine.

### 6.1.7 Calculating gradients

Profile change is caused primarily by spatial gradients in the suspended sediment transport. There are various ways of numerically deriving gradients, each with their own drawbacks. The
most common methods are those of forward, backwards and centred differences. Forward and backward differencing calculates a gradient from two adjacent points, and ascribes this gradient to one of the points, (depending on whether a forward or backwards scheme is used). Figure 6-5 illustrates how inaccurate this technique is.

By considering both adjacent points, the gradients can be calculated by the centred-difference technique. Centred-differencing is more accurate than the forwards/backwards technique, as illustrated in Figure 6-5. However a centred-difference gradient is still only an approximation for the real gradient, and can lead to issues at boundaries/discontinuities. An example of this is calculating the gradient at the shoreline (Figure 6-6). The shape function only calculates a sediment flux within the submerged part of the profile (including the run-up limit) so the dry beach leads to a zero flux. In this example, the first wet grid cell ($x = 4$) experiences weak offshore-directed transport (the shoreline profile is steep enough that the onshore nose of the shape function is missed i.e. it is in Region 3 close to point C on the shape function; see Section 5.4). Grid points further offshore ($x > 5$) experience stronger offshore-directed transport, but there is little change in transport magnitude beyond this point. When the gradient of the flux is calculated with a centred difference (i.e. Panel 3 in Figure 6-6) the first dry grid cell (i.e. $x = 3$) is shown to have a sediment transport accretion/erosion (i.e. $\frac{dQ}{dx} \neq 0$). This is because, although $Q_{x-3} = 0$, $(Q_{x-1} - Q_{x+2}) \neq 0$. This means that although there is no sediment transport occurring on the dry beach, the beach will accrete/erode. In this case as the first wet grid point experiences offshore-directed transport the shoreline will erode, and becomes a wet grid cell. Depending on whether the first wet grid cell experiences onshore or offshore transport, the shoreline will either erode or accrete, however as point B on the shape function is unstable (i.e. the profile tends to erode or accrete away from this depth), the first wet grid point generally experiences offshore-directed transport, and so the shoreline tends to erode. This is the major drawback of using centred-difference gradient, as under high energy conditions, the shoreline tends to cut back extensively.
Figure 6-5 Forward-, backward- and centred-differencing techniques are simple ways of calculating gradient, however, do introduce errors. To illustrate these limitations, the estimation of the gradient of a curve (green) at $x = 6$ is presented (sampled with a resolution of $dx = 2$). The left panel illustrates the gradient approximated by forward (blue) and backward (red) differencing, by including the tangents calculated by these methods. The central panel shows how these estimations are improved by using a centred difference. Here the point either side of the central point (black dotted line), are used to calculate the gradient at the central point (black solid line). The right-hand panel shows how the estimation can be further improved by fitting a cubic spline (e.g. pchip (blue) or spline (red)), and differentiating algebraically.

Another technique for calculating the sediment flux gradient is to fit a mathematical equation to profile and differentiate it algebraically. Two curve fitting techniques within the Matlab environment are ideal for this purpose, the cubic spline interpolation (spline) and the piecewise cubic Hermite interpolating polynomial (pchip), both of which will be illustrated in the example in Figure 6-7. These functions fit a cubic polynomial between each point on a profile, in such a way that the resulting profile is smooth. As the coefficients are known for the cubic polynomial between each point of the profile, they can be differentiated to give an analytical solution. The resulting solution from pchip and spline are different and each has different benefits. Spline provides a smoother fit which a continuous in both the first and second derivative, however it tends to oscillate and overshoot if the data is not smooth. In terms of the model, the spline technique leads to profile change above the water line (on the dry beach), which leads to a
similar problem as with the centred-difference, thus invalidating the technique. Figure 6-7 shows an example sediment flux profile (upper panel) that must be differentiated to calculate the bed level change (middle panel), however the integral of the bed level change must equal zero (lower panel), such that sediment is conserved. The oscillation and overshooting due to the spline technique (red line) is visible between $0 < x < 8$ (especially $2 < x < 6$), and $11 < x < 16$, however the integral is zero, (the cumulative integral is presented in the lower panel).

![Sediment Flux Profiles](image)

Figure 6-6 Illustration of how a centred difference approach to calculating sediment flux gradients can lead to bed level change above the still water level. The upper panel shows the initial profile, with the shoreline between $3 < x < 5$. The second panel show the sediment fluxes, with zero flux for the dry grid points ($x \leq 3$). The third panel shows the gradient of the sediment flux (as calculated by a centred difference routine). N.B. the sediment transport gradient is negative, even though the grid point is dry - this leads to erosion. The lower panel shows how sediment flux gradient causes the profile to change. Note the erosion at $x = 3$ lowers the grid-point to below MSL, which then becomes an active part of the profile.
Figure 6-7 Illustration of effects of the spline and pchip technique of calculating sediment flux gradients. The upper panel shows how the spline (red) and pchip (blue) fit an example cross-shore profile of sediment transport. Note how the spline technique overshoots the flux at points of extreme gradient change (e.g. $x = 3, 5$). The pchip routine does not overshoot, and instead maintains the regions of zero gradient (e.g. $x < 3$). The second panel shows the gradient of the spline and pchip curves fitted to the upper panel. The dashed lines show the continuous gradient while the solid line shows the gradients sampled at the grid points (i.e. as used by the model). As the model does not include sub-grid-scale fluxes, gradient (and so erosion/accretion) between the grid points are lost. As the pchip routine fits most of the curve between the grid-points, the dashed and solid lines are different. The lower panel shows the cumulatively integrated sediment gradient as an indication of sediment conservation. As the sediment transport profile in the upper panel starts and finishes at 0, the integrated gradient should be zero. The spline curve is similar to the initial sediment transport profile suggesting the method conserves sediment, whereas the pchip routine does not finish at zero, suggesting sediment is not conserved in this example.
As the pchip technique does not allow oscillation along flat portions of flux profile, all the smoothing is pushed into the region of change (i.e. between $3 < x < 5$ and $12 < x < 15$), and so there is zero gradient at $x = 3, 5, 12, 15$. This property of the pchip technique means that the sediment flux gradient is zero at the shoreline and the dry beach - a requirement for a gradient calculating technique.

In the second panel of Figure 6-7, the gradient of the flux (as calculated by pchip) is presented. Pchip fits a continuous line through the discrete grid-cell points of modelled sediment flux, and so calculates a continuous sediment flux gradient (blue dashed line). However, the model only considers the flux gradients at the discrete grid points — in effect intermediate sediment flux and sediment flux gradients are assumed to be linear between these points (i.e. solid blue line). The difference between what the sediment transport flux that the pchip routine calculates (blue dashed line) and the sediment flux gradient that is "seen" by the model is, by definition zero at grid cells. However, when the gradients are integrated over the profile (for sediment conservation, the profile integrated sediment flux gradient must equal 0), there is an important difference between the continuous and discrete flux gradients. As much of the flux gradient is compressed into regions of maximum flux change (i.e. $3 < x < 5$), a lot of the sediment erosion/accretion may be compressed between grid points, and so is missed by the model (it become a sub-grid process). For example, between $3 < x < 4$, the large flux gradient occurs over one grid cell. The continuous pchip (dashed blue) calculates twice the flux gradient at $x = 3.5$ compared to the linear interpolation of the gradients at $x = 3$ and $x = 4$. The area under the solid, discrete flux gradient can be seen to be a significant less than that under the dashed continuous line; this introduces an error into the amount of sediment eroded in this region. The amount of sediment eroded by the continuous pchip routine is balanced by the amount of sediment deposited at $12 < x < 15$ (i.e. the areas under the blue dashed line in both regions is equal), while the discrete pchip routine suggests an imbalance that does not conserve sediment. This is shown in the cumulative integral in the lower panel.
Of the two analytical techniques to calculate (sediment flux) gradient, one does not conserve sediment (pchip), while the other leads to profile change above the water level (spline). As it is easier to ensure sediment conservation than to stop dry profile change, the pchip technique is favoured over the spline technique to calculate sediment concentration gradient.

To illustrate the difference between how the centred difference and pchip technique behave with respect to shoreline cutback, Figure 6-8 and Figure 6-9 present modelled shoreline output. With a centred difference technique (Figure 6-8), the shoreline cuts back even under moderate energy conditions ($h_b = 1$ m). Initially sediment is accreted between the run-up limit (R) and point B, and sediment eroded between B and D. However, once the second wet point is in the offshore transport region (Regions 3 and 4), the first point (irrespective of whether it is subject to onshore- or offshore-directed transport) is subject to a sediment divergence (zero transport at the first dry cell, and offshore-directed transport at the 2nd wet cell) and so erodes. This is repeated until the 1st wet cell is in an offshore transport directed region and so the shoreline is eroded. This is apparent in Figure 6-8, in that the shoreline is cut back in stages. This behaviour is represented in Table 6-3.

**Table 6-3** Sequence of events associated with numerical shoreline cutback under a centred difference scheme. This described the sediment transport and profile change in the shoreline cells as illustrated in Figure 6-8.

<table>
<thead>
<tr>
<th>Shoreline Cell</th>
<th>1st wet cell</th>
<th>2nd wet cell</th>
<th>Profile accretion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shoreline Cell</td>
<td>1st wet cell</td>
<td>2nd wet cell</td>
<td>Profile accretion</td>
</tr>
<tr>
<td>1</td>
<td>No transport</td>
<td>Onshore transport</td>
<td>Onshore transport</td>
</tr>
<tr>
<td>2</td>
<td>No transport</td>
<td>Onshore transport</td>
<td>No transport</td>
</tr>
<tr>
<td>3</td>
<td>No transport</td>
<td>Onshore transport</td>
<td>Offshore transport</td>
</tr>
<tr>
<td>4</td>
<td>No transport</td>
<td>No transport</td>
<td>Offshore transport</td>
</tr>
<tr>
<td>5</td>
<td>No transport</td>
<td>Offshore transport</td>
<td>Offshore transport</td>
</tr>
</tbody>
</table>
Figure 6-8 Calculating the sediment transport gradient with centred differencing technique leads to numerical shoreline cutback. This is shown in a run with waves of $h_b = 1$ m on a linear beach. The profiles are coloured so the earlier (later) profiles are blue (red), with the shape function Region and Points highlighted. The profile accretes above B and even one point above point R (the run-up limit). This is because the flux is zero at the first two grid cells above R, and onshore directed in the first below it (assuming it is between R and B). This leads to a sediment convergence at the first point above R. There is erosion between B and D, and this steepens the upper profile. Once the profile is so steep that the first wet point is below B, the first dry grid cell experiences a sediment divergence and so is eroded. This initiates a period of continuous shoreline cutback (assuming the $h_s = \text{constant}$).

In contrast to the centred difference technique (Figure 6-8), under the same condition the pchip technique (Figure 6-9) does not lead to the shoreline cutting back. Here, sediment is accreted above point B, until an equilibrium is reached. Once this occurs, the shoreline tends to stabilise.
Figure 6-9 The shoreline is not subject to numerical cutback when sediment flux gradients are calculated with a pchip routine. This figure is similar to Figure 6-8, although the pchip is used rather than centred differencing. When the profile steepen such that there is an apparent (three point) divergence centred at the first dry grid cell, the centred difference technique would calculate a divergence and erode the dry beach, whereas the pchip routine returns a zero flux gradient as there is zero flux, so stopping numerical cut-back.

In this model, the default method for calculating gradients (both of sediment transport and beach slope) is the pchip technique, as the method protects against the shoreline cut-back, although there are sediment conservation issues.

### 6.1.8 Sediment conservation

As the pchip technique does not necessarily conserve sediment, a technique to ensure sediment conservation is required. Maríno-Tapia et al. (2007b) encountered a similar issue due to their smoothing technique. Maríno-Tapia et al. (2007b) theoretically calculated the sediment volume change between time-steps ($dV$), where $dV > 0$ denotes an increase in profile volume. If the
profile volume had decreased (increased), $dV$ was distributed over (removed from) the wet part of the profile. A similar approach is taken in the present model, however $dV$ is measured as

$$dV' = \int h' \, dx - \int h'^{-0} \, dx$$

(6-13)

where $h'^{-0}$ is the initial profile, and $h'$ is the current profile. When there are large changes in profile volume, the cumulative effect of continuously adding sediment over the whole (wet) profile can dominate the profile change. This is particularly obvious beyond the depth of closure ($h/h_s > 4$) where no other processes change profile elevation. The validity of the model for long term studies will depend on the rate at which sediment added or removed from the profile and will be a key objective in initial model tests.

6.1.9  *Avalanching routine*

To ensure that the modelled profile does not become steeper than is realistic, an avalanching routine adapted from the on the XBeach model (Roelvink et al., 2007) is implemented. When the profile gradient become greater than a critical value:

$$\left| \frac{\partial h}{\partial x} \right| > m_{cr}$$

(6-14)

where $m_{cr}$ is the angle of initial yield ($28^\circ$), sediment slumps down the slope until the maximum bed gradient is equal to the angle of repose. The volume of sediment above the avalanching routine is equal to that below the avalanche, (this is confirmed by checking the integrated profile doesn’t change during the routine). The routine is called iteratively; avalanching to restore the gradient of one section of the bed can steepen the adjacent section beyond $m_{cr}$, leading to a cascading effect. The extent of vertical bed movement above the slope is given as:

$$\Delta z = \min \left( \left( \left| \frac{\partial z}{\partial x} \right| - m_{rep} \right) \Delta x, 0.005 \right), \frac{\partial z}{\partial x} > 0$$

(6-15)
\[ \Delta z = \max \left( -\left( \frac{\partial z}{\partial x} - m_{\text{rep}} \right) \Delta x, -0.005 \right), \frac{\partial z}{\partial x} < 0 \]  

(6-16)

where \( m_{\text{rep}} \) is the angle of repose (28°). In the XBeach model, the avalanching routine only restores the profile to \( m_{\text{cr}} \). The methodology used here restores it to the angle of repose following Mariño-Tapia et al. (2007b), and so reduces the number of times that the routine is called (essentially when avalanching occurs in the model, sediment is moved downslope to ensure that the resulting profile is well below the critical value).

### 6.1.10 Equilibrium profile

Having noted that under continuous high-energy conditions, the shoreline continuously cuts-back, the ability of the model to form equilibrium beach profiles is questioned. The shape function suggests that an equilibrium profile should occur (e.g. panel C in Figure 6-10) when the morphology is horizontal between Points A and B (as a berm), C and F (the terrace) and F and G (outer shoaling zone), and near-vertical at approximately Points B and F. The sediment fluxes are zero across horizontal regions of this profile, so profile evolution is subdued in this region. In the vertical section, as Point A and D converge, they become one grid point apart.

However the avalanching routine means that the vertical sections will collapse (e.g. panel D in Figure 6-10) moving the shoreline landward. Under constant condition (in terms of \( h_b \)), a new equilibrium profile begins to form, until it too collapses. Hence while the pchip routine stops the shoreline cutting back for numerical reasons, the avalanching routine allows the profile to cut back due to physical reasons.
Figure 6-10 Illustration of the effect of the avalanching scheme, and how it limits the development of an equilibrium profile. From an initially linear profile (a), the shape function starts to develop a featured morphology (b). Under constant conditions, the profile develops towards an equilibrium profile (c, dominated by vertical and horizontal sections). However the avalanching routine collapses the vertical sections and allowing the profile to continue developing.

6.1.11 Wave set-up

According to Guza and Thornton (1982), wave set-up is a function of the offshore wave significant wave height, $H_{\text{sys}}$, and causes the mean sea-level to rise at the shore line by approximately $h_M$: 

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\[ \bar{\eta}_M = 0.17H_{sig, o} \]  \hspace{1cm} (6-17)

As the model is driven exclusively by \( h_b \), it is beneficial to describe the set-up in terms of \( h_b \). Using the wave model described in Section 3.3.8, the relationship between \( H_{sig, o} \) and \( h_b \) was examined where \( H_{sig, o} \) is specified at \( h = 10 \) m (Figure 6-11). The influence of \( T \) decreases with increasing period but above a period of \( T = 5 \) s, all the curves start to behave similarly, and all curves collapse towards the \( T = 20 \) s curve. For simplicity, this relationship is captured at \( T = 8 \) s, as:

\[ H_{sig, o} = 0.45h_b^{1.23} \]  \hspace{1cm} (6-18)

As discussed in Section 3.3.14, the coefficients in this parameterisation are only valid with SI units. Although this does not accurately represent the relationship over the whole range of reasonable periods (5 s < 15 s), it represents the middle of this region. The error introduced by this is investigated by considering a breakpoint depth of 1 m. \( h_b = 1 \) m can be produced by a range of offshore conditions, with \( T = 5 \) s/\( H_{sig, o} \approx 0.34 \) m and \( T = 20 \) s/\( H_{sig, o} \approx 0.49 \) m at opposite ends of the scale. Although these conditions both produce the same breakpoint depth (\( h_b = 1 \) m), they cause different set-up values (~6 cm and ~8 cm respectively). The difference between these two values can be considered as the error introduced by the simplification presented in (6-18). On a typical beach slope of \( \tan \beta \approx 0.02 \), this error is equivalent to a difference in the horizontal displacement of the shoreline by ~1 m, a similar magnitude to the horizontal resolution of the model, and considered within a reasonable limit.

Substituting equation (6-18) into (6-17) gives

\[ \bar{\eta}_M = 0.0765h_b^{1.23} \]  \hspace{1cm} (6-19)
which is added onto the instantaneous water level across the profile to allow for wave set-up. Adjusting the water level rather than allowing a spatially varying water level is a simplification that is not thought to introduce any significant errors.

![Figure 6-11 The relationship between $h_b$ and $H_{sig,r}$ at different values of $T$. $T$ ranges from 1 s (blue) to 20 s (red) in steps of 1 s. At higher periods the lines collapse towards single line, suggesting that the influence of period reduces with increasing period. A power fit is applied to the line associated with a period of $T = 8$ s and this is shown as the dashed line. This is considered to be a reasonable representation of $5 \, s < T < 20 \, s$, as the difference of set-up with $h_b = 1$ m varies from 6 cm to 8 cm over this range.](image)

### 6.1.12 Model run-up

The narrow accretionary zone at the shoreline (Region 1) caused by the onshore swash-zone transport, acts as a defence for the shoreline. Without this region, the shoreline is subject to continuous cut-back (the shoreline would be subject to continuous erosion). Region 1 is very narrow, and as it is a function of normalised depth, as the profile gradient at the shoreline increases, this region narrows further. Once the shoreline accretionary zone is narrower than the typical grid spacing of the model (i.e. it is sub-grid size) it is not captured by the model, and so
is effectively removed, allowing continuous shoreline cutback. This is overcome by introducing a run-up function into the model, which stretches Region 1 from the water level to a point further up the beach.

Wave run-up is calculated in a number of ways, but due to the simplicity of this model (i.e. no wave sub-model) the run-up limit is calculated following Hunt (1959), who proposed the run-up limit ($R_{2\%}$):

$$R_{2\%} = 8H_{seg,m} \tan \beta$$  \hspace{1cm} (6-20)

where only 2% of run-up heights exceed $R_{2\%}$. Substituting equation (6-18) into (6-20) gives the run-up height, $R_{2\%}$ (note that the constant has the units of m$^{0.13}$):

$$R_{2\%} = 3.6h_{b}^{1.23} \tan \beta$$  \hspace{1cm} (6-21)

Whereas $hh_{b}'$ (the modelled representation of $h/h_{b}$ at time $t$) is generally set to zero when $h < 0$, the run-up function sets $hh_{b}'$ to zero at the run-up limit, and stretches it from there to the maximum onshore swash transport, extending the transport region. This is stretched with:

$$hh_{b}' = \text{swpk} \left( \frac{h_{b} \times hh_{b}' - R_{2\%}}{h_{b} \times \text{swpk} - R_{2\%}} \right)^{2} \quad R_{2\%} < hh_{b}' < \text{swpk}$$

$$= hh_{b}' \quad hh_{b}' \geq \text{swpk}$$  \hspace{1cm} (6-22)

where swpk is the numerically calculated location that corresponds with the peak onshore value of swash transport (in terms of $hh_{b}'$). For simplicity, when using this expression the values of $h_{b}$ used is taken as 1 m (although $R_{2\%}$ is calculated from the variable $h_{b}$). The assumption has negligible affect on the results. This scaling is represented in Figure 6-12, the upper panel shows how scaling the $h/h_{b}$ values allows what would be negative $h/h_{b}$ (i.e. dry beach) on the x axis to be considered within the run-up limit, and so are compressed to be considered positive, wet values. The discontinuity between the curved and straight part of the line corresponds to the peak onshore swash peak – as this point has zero flux gradient, the discontinuity does not
transfer through to the predicted flux pattern. The lower panel of Figure 6-12 show how the run-up routine modifies the shape function. The blue profile shows the original pattern of sediment transport predicted by the shape function, with zero transport above the MSL, and the green profile which shows positive transport from the run-up limit (at \( h/h_0 = -0.1 \)), to the onshore swash peak, where it seamlessly joins the original shape function.

![Figure 6-12](image)

**Figure 6-12** An example of the effect of the run-up limit routine with \( h_0 = 1.5 \) m. The upper panel shows how \( h/h_0 \) is scaled between the run-up limit and the peak onshore swash-zone transport. The lower panel shows the resulting shape function (green) compared to the unscaled shape function (blue).

### 6.1.13 Removal of the offshore swash transport component

Preliminary model runs showed that the modelled profile tends to have an unrealistically shallow terrace. This is illustrated in Figure 6-13, which shows the profile produced with \( h_0 = 1 \) m (black, from the initial (blue) profile). Under these conditions the terrace produces a bar at a depth of \( h/h_0 \approx 0.3 \), rather than the expected depth of \( h/h_0 \approx 1 \). In Section 5.5 it was noted that the terrace is formed from point D on the shape function profile. This is because part of the profile that is shallower (deeper) than D, in Region 3 (4) is subject to erosion (accretion)
that drives the profile towards the depth associated with D. Stable point D is the position of maximum offshore-directed sediment transport, so moving the position of this trough will affect the depth of the terrace. It is the offshore swash component that dominates the offshore-directed sediment transport at high energy conditions, and as it is dependent on \( h \) rather than \( h_b \), it becomes increasingly close to the shoreline with increasing energy levels. Removing this component of the shape function would move the offshore flux maximum to deeper water and so lower the terrace depth. The overall shape function shape would remain similar (onshore transport in inner swash zone, offshore transport in the surf-zone, and offshore transport in the shoaling zone; see Figure 6-14). The offshore swash component is the least supported of the transport components. The shape function model would reduce to a surf-zone model but with a limited swash component at the swash nose to protect against beach cut-back. The model runs presented in this thesis are all with the offshore component removed, with the exception of the run presented in Figure 6-13.

Figure 6-13 Near-equilibrium profile developed with (black) and without the offshore swash component shape function, from a linear profile (blue).
Figure 6-14 The shape function response under increasing energy, without the offshore swash component shape function.

This adaptation of the shape function for the purpose of the model allows the development of a more realistic profile. This is illustrated in Figure 6-13, showing the profile that is developed under 1 month, $h_b = 1$ m, with (black line) and without (red line) the offshore swash component. This profile is more consistent with observations of low tide terrace often observed on macrotidal beaches in the UK.
Figure 6-15 Illustrating how the (logged) absolute depth of the Points (and so Regions) on the shape function expand and contract with $h_b$ with and without the offshore swash term. Points D and F (segregating Regions 3 from 4 and 5 from 6 respectively) are highlighted, as Point D is the depth that bars tend to form at, while Point F is the point beyond which bar degeneration occurs.

As the swash components are scaled by $h$ (depth rather the normalised depth, $h/h_b$), the stable point D (and so the terrace depth) does not vary much with $h_b$, in fact it reduces with $h_b$ at higher energy levels. By plotting the depth of the shape function Points as a function of $h_b$ (Figure 6-15), it can be seen how the terrace depth (point D) changes with increasing energy. The bold cyan solid line (representing the depth of D from a shape function including all 4 components) shows that the terrace depth increases with energy level up to an energy level of $h_b \approx 1.25$ m, at which point it starts to decrease. When the offshore swash transport component is removed
(bold dotted cyan line), the terrace depth continues to increase with $h_b$. The overall outcome for this is that the terrace depth will increase with energy level to a depth of approximately $h \approx 1$ m with $h_b = 2.5$ m when the offshore swash component is ignored, as opposed to a depth of $h \approx 0.25$ m when it is included. The other effect of ignoring the offshore swash component is that the swash depositional region (Region 1, between Point A (off scale in Figure 6-15) and Point B) does not compress with energy level ($h_b < 1$ m), but remains at a depth of $h \approx 0.4-0.5$ m. This decreases the chance that the shoreline will be continuously eroded numerically (e.g. Figure 6-8).

### 6.1.14 Bar degeneration

Figure 6-15 also shows that bar degeneration is theoretically possible with a model driven by the shape function, and illuminates the conditions under which it can occur. The bold lines on Figure 6-15 representing D and F correspond to the stable depth of bar formation, and the depth beyond which a bar is subject to onshore erosion. Under energetic conditions a bar forms at depth illustrated by line D, for a specific value of $h_b$. As the energy level drops, the shape function compresses and so, although the bar may remain in the same depth of water, it is now in a region associated with seaward region. If the energy level drops sufficiently, and rapidly enough, the bar may find itself in Region 6, where it will be subject to onshore erosion which may degenerate the bar. For example, a bar formed under $h_b = 2.5$ m, will occur at a depth of $h_{Dhb-2.5m} \approx 1.08$ m (denoted with an “a” on Figure 6-15). If the energy level drops suddenly (i.e. before the bar has time to respond) to be $h_b \approx 1$ m, the bar is now on beyond Point F (the bold red line), in Region 6, and degenerates (point “b” on Figure 6-15).

### 6.1.15 Model adaptations summary

Generally, the model runs presented here use the following settings:

- Depth of closure at $h/h_b = 4$, (starts at $h/h_b = 3$)

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• The profile is smoothed every 10 time steps with a weighted \([-1 4 10 4 -1]\) mean (an adaptation of the Jensen et al. (1999) filter).

• Gradients of sediment flux and bed slope are calculated with the pchip technique.

• The avalanche routine is run every 10 time steps.

• The offshore swash component is excluded from the shape function.

• Wave set-up is included.

• The active profile is extended to the run-up limit. This stretches the depositional onshore swash region (Region 1) without moving the peak onshore transport (point B).

6.2 Initial model results

6.2.1 Response to constant wave

Initial model tests focused on the models response to simple forcings. The model was run for a three month period with a range of constant breakpoint depth \((h_b = 0.5, 1.0, 1.5, 2.0, 2.5 \text{ m})\), with the default model settings, (see Section 6.1.15). The bed profile was initiated as a linear beach, with 1 m grid spacing and a 10-minute time step. The results are presented in Figure 6-16.

As the energy level increases, the active region of the profile expands (due to scaling of \(h_b\), e.g. the lower and upper profiles in Figure 6-16 extend to approximately the same normalised depth \(- h/h_b = 3\)) and the features increase in volume (due to the amplitude terms in the shape function). The lower-energy profiles tend to exhibit shoreline accretion from offshore erosion, while the higher energy profiles show predominantly accretion from landward erosion and offshore transport.
Figure 6-16 The modelled profile response to simple forcings. The model was run with a series of 5×3 month tests, with a range of breakpoint depths ($h_b = 0.5, 1.0, 1.5, 2.0$ and $2.5$ m) and no tide. Each profile is offset by 3 m for clarity, and is presented with the original profile (grey dashed line) and mean sea level (red). The profiles increase in energy up the figure, ($h_b = 0.5$ m at the bottom, and $h_b = 2.5$ m at the top).

Under high energy conditions, the shoreline shows extensive cut-back. The pchip routine ensures that this is not an artefact of the numerical scheme, but is a real prediction. In this case it is due to the avalanching scheme – the model steepens up the profile near the shoreline, until it
collapses (and cuts back), transports that sediment away, and then repeats the process. This illustrates why the model will never form equilibrium (e.g. Figure 6-10). However, these forcing conditions are very unrealistic (constant wave conditions, no tides). Under low energy conditions, sediment is returned to the shoreline, and so high energy conditions must remove this store prior to cutting back. Under constant high energy conditions as present here, it is considered acceptable for the model to continuously cut back. It should also be noted that initially under high energy conditions sediment was accreted at the shoreline (prior to collapsing), as expected from the shape function (not shown).

The development of an exaggerated the berm under zero tidal amplitude (Figure 6-16, e.g. \( h_b = 1.5 \) m) is a numerical artefact of the pchip technique. However, this behaviour is suppressed by the presence of a tide (e.g. Figure 6-17), and does not grow in amplitude with time. This is illustrated in Figure 6-9 which shows the development of a bermed profile, with each subsequent profile represented by a different colour, moving from the cold colours (blue) towards the hot colours (red) with time. The berm \((496 < x < 502 \) m) is seen to develop with time (dark blue lines) and then stabilise (the following profiles compress down to a single profile (dark red)), suggesting the berm reaches equilibrium with the forcing conditions.

### 6.2.2 Response to a monochromatic \( M_2 \) tide

The model (with default setting) was run with constant breakpoint depth \((h_b = 1.5 \) m, representing medium to high energy conditions) and a range of \( M_2 \) tidal ranges \((M_2 = 0, 0.25, 0.5, 0.75 1.0, 1.5 \) m) for a period of 1 month (Figure 6-17). The tide acts to smooth the profile, as any deposition at a particular breakpoint may be subjected to erosion at a different tidal level. When a tide is present the dominant features form at locations related to the high and low water level. This is because the tide “stands” at these the levels for significant periods of time allowing a feature to form, while the features between are subdued by the tidal smoothing effect. With this in mind the profile formed by a monochromatic tide can be thought of as the product of two shape functions linked to the high and low water mark.
Figure 6-17 The modelled profile response to simple forcings. The model was run with a series of 6x3 month tests, with constant breakpoint depths (hb = 1.5 m) and range of monochromatic tides (M2 = 0, 0.25, 0.5, 0.75, 1.0, 1.5 m). Each profile is offset by 3 m for clarity, and presented with the original profile (grey dashed line) and mean sea level (red). The profile increase in tidal range up the figure, (M2 = 0 m at the bottom, and M2 = 1.5 m at the top).

As the tide increases, the morphological features widen as the two sets of features separate. Initially the shoreline is further cut back (M2 = 0.25 m), but otherwise the profile changes little.
As the tidal range increases, the terrace depth drops, and a second step feature forms onshore of the main terrace. The depths of these terraces diverge with increasing energy, and become less extreme (i.e. the gradient of the terrace formed \( M_2 = 0 \) m is near horizontal, with terraces becoming relatively steeper with increasing \( h_b \)). This is because tidal smoothing spreads the deposited sediment over a wider area, and so more sediment (and hence time) is required to develop a feature to the same extent. Under increasing energy condition, the location of the outer terrace crest (outer edge of the terrace) initially remains static, then starts to move offshore with an increasing rate, while the inner terrace crest on formation initially moves offshore, before slowing (on the \( M_2 = 0.75 \) m profile at \( x = 560 \) m), and then moving onshore. The shoreline berm feature (when present) moves onshore with energy level.

### 6.2.3 Response to a bichromatic \( M_2/S_2 \) tide

To show the response to a bichromatic tide, the model was run with the default settings, from a linear profile, for three months with a constant energy level (\( h_b = 1.5 \) m), and tide conditions (\( M_2 = 1.0 \) m). Six model tests were run with increasing \( S_2 \) tidal amplitude, (\( S_2 = 0, 0.125, 0.25, 0.375, 0.5, 0.75 \) m), to simulate the spring-neap cycles. As the tide become more bichromatic, the morphology becomes wider, depressed and increasing complex (Figure 6-18). Initially the berm migrates onshore and increases in volume. The two terrace crests deepen and the terraces steepen, as the morphology is generally subdued. At \( S_2 = 0.5 \) m, the spring and neap tidal stand have separated enough for secondary features to be isolated, and distinct spring and neap morphology is visible (e.g. \( S_2 = 0.5 \) m, \( x = 440, 470, 550, 600 \) m). The neap features are inferior to the spring features as they are subjected to tidal smoothing for much of the spring neap cycle; however they form sufficiently during the neap tidal stands to last through the intermediate and springs portions of the tide. The increasing \( S_2 \) amplitude reduces the time that the tide spends at any point and so the morphology takes longer to form, and hence is less developed. This also increases the stability of the model, and further protects against shoreline cutback.
Figure 6-18 The modelled profile response to simple forcings. The model was run with a series of 6×3 month
tests, with a constant breakpoint depths (h₃ = 1.5 m), M₂ amplitude of M₂ = 1.0 m and a range of S₂ tide
amplitude (S₂ = 0, 0.125, 0.25, 0.375, 0.5, 0.75 m), leading to an increasingly bichromatic tide. Each profile is
offset by 3 m for clarity, and is presented with the original profile (grey dashed line) and mean sea level (red).
The profile increase in tidal range up the figure, (S₂ = 0 m at the bottom, and S₂ = 0.75 m at the top).
6.2.4  Profile response to changing energy levels

The previous sections have focused on the form a linear profile will tend towards under constant conditions. This section will look at how the profile responds to changing conditions. This will suggest how quickly various profiles respond to changing conditions, and give an idea of how the profile will behave under real conditions. The section will also show whether the model can lead to bar migration and whether the model will allow bars erosion/decay – previous models have had difficulty doing this. The sensitivity of the developing profile on the initial profile will also be shown. To simulate changing conditions, the model was run with the default settings, from a linear profile, with no tide, and a range of breakpoint depths ($h_b = 0.5, 1.0, 1.5, 2.0, 2.5$ m), for one month, forming an initial profile. The model was then run for a second month under a different energy level, giving 20 model runs, (Table 6-4).

Table 6-4 Energy level combinations for the model runs presented in Section 6.2.4. The first number represents the initial energy level and the second number the subsequent energy level. For example, run 3 1 refers to an energy level of $h_b = 1.5$ m (3/2) dropping to $h_b = 0.5$ m (1/2).

<table>
<thead>
<tr>
<th>$h_b$ in period 2</th>
<th>$h_b$ in period 1</th>
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<tbody>
<tr>
<td></td>
<td>0.5 m</td>
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<td>0.5 m</td>
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<td>1.0 m</td>
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<td>1.5 m</td>
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<td>2.0 m</td>
<td>1 4</td>
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<tr>
<td>2.5 m</td>
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For each model run, the initial profile and final profile are presented in Figure 6-19, and the absolute profile change in Figure 6-20 (both laid out in the same order as in Table 6-4). Profiles subjected to high energy (e.g. $h_b > 2.0$ m) all tended towards the same end profile no matter what the initial profile was, as the sediment flux magnitudes allowed the profile to quickly respond to the new conditions. Under low energy conditions, the amount of profile change depended on the initial profile. When the start profile was relatively low energy, there was
significant profile change, whereas when the initial profile was from high energy conditions, there was very little profile change (e.g. run 5_1). This is because the initial profile is so flat along the terrace that the flux gradients are small and so there is little change. Also the feature is so large that it time it would take for the low energy shape function to move that volume of sediment is considerable.

Figure 6-19 This figure shows how profiles respond to changing conditions. Each test case was run for 1 month with the initial energy level, and 1 month with the current energy level. The x axis gives the previous energy level, and the y axis gives the present energy level, e.g. Run 2_4 had $h_b = 1$ m, which was followed by $h_b = 2$ m. The initial profile for each combination is given as a dotted line, with the new profile in solid black. Each combination is presented with its run number, as referred to in the text and Table 6-4. The figure is separated into 3 morphological regimes, offshore bar migration (green), onshore bar migration (red) and bar degeneration (cyan).

It can be seen that when the energy level increases slightly (e.g. $dh_b = 0.5$ m), the profile quickly responds, with a generally offshore migration of the terrace crest, and deepening of the terrace
(e.g. Figure 6-20, runs 1_2, 2_3, 3_4, 4_5). When the energy level slightly decreases (e.g. \( d\theta_b \approx -0.5 \) m) however, the profile change is far less (e.g. Figure 6-20, runs 2_1, 3_2, 4_3, 5_4), with the terrace crest migrating slightly onshore, and the terrace slightly shoaling. These results suggest two regions of onshore and offshore migration, shown as the red and green regions respectively.

Figure 6-20 This figure is similar to Figure 6-19, showing how much profiles change as to varying conditions. The x axis gives the previous energy level, and the y axis gives the present energy level, e.g. Run 2_4 had \( h_b = 1 \) m, which was followed by \( h_b = 2 \) m. The total profile change is given for each combination where positive values are accretion and negative values are erosion. The volumes are scaled relative to one another, but are not given as absolute values. Each combination is presented with its run number, as referred to in the text and Table 6-4. The figure is separated into 3 morphological regimes, offshore bar migration (green), onshore bar migration (red) and bar degeneration (cyan).

When a bar forms under very high energy levels, and the energy drops by a large amount, (e.g. runs 3_1, 4_1, 5_1, 5_2), the bar can be subjected to bar degradation. As a bar formed under
high energy has a relatively deep terrace, if the energy level drops sufficiently, the terrace may be in the shoaling erosional region (Region 6) of the low energy shape function. When this happens the terrace is subjected to offshore erosion rather than migrating onshore. This balance is sensitive to the initial and final energy levels. If the final energy level is too low there is not enough transport to make sufficient impact on the profile, whereas if the final energy level is too high, the bar will be just in the onshore accretion region (Region 5). As a bar forms at point D, and the bar must be within Region 6 to degenerate, it is possible to predict conditions that will lead to bar degeneration. From Figure 6-21 (a simplification of Figure 6-15, showing the depth that point D and F occur) it can be seen that when a bar form under, for example, \( h_b = 2.5 \) m it will be in a depth of approximately \( h = 1.1 \) m, while, for this depth to be in Region 6 (i.e. beyond Point F), the energy level will have to fall below \( h_b < 1.2 \) m (i.e. when \( h_b = 1.2 \) m, Point D is in 1.1 m water). This leads to a region of Figure 6-19 where bar degeneration occur (shaded cyan).

![Figure 6-21 The depths of Point D & F, under a range of breakpoint depths. This is an adaptation of Figure 6-15. This figure allows conditions under which bar degeneration can occur, e.g. a bar forming under \( h_b = 1.5 \) m has a depth of \( h \approx 0.5 \) m (line D), and a bar with a depth of \( h = 0.5 \) m will degenerate when \( h_b < 0.6 \) m (line F).](image-url)
6.2.5 Initial model results summary

Initial tests have focused on how the shape function model responds to simple forcings, treating each situation discretely. These insights into how the model responds to unrealistic conditions have shown that the model is able to reproduce sensible behaviour (offshore bar migration under increasing energy conditions, onshore bar migration under low energy conditions, bar degeneration after substantial energy reductions etc.).

6.3 Modelling long term behaviour of nearshore bars

The simplicity and efficiency of the shape function model allows timescale to be investigated beyond those of process-based models. These initial longer term tests will form the basis for further work that is beyond the scope of this thesis.

The first step is to develop a method for producing realistic forcing conditions. The system developed allows complete control and manipulation of the time-series of breakpoint depth, and so subtle differences can be examined.

6.3.1 Storm/calm wave time-series derivation

In order to investigate beach response to subtle changes in the hydrodynamic forcing regime, a program was developed to produce a random storm time-series. This program allowed control over the characteristics of the storm and calm durations, the overall energy level and the seasonal variations. The program models $h_b$ as a series of "storm events", where a storm event is the combination of a single calm and storm period. For a particular time of the year, the duration of the calm and storm events, and their $h_b$ value is randomly chosen between user defined limits. These limits can vary seasonally to allow investigation of the transitions between summer and winter profiles. The annually integrated energy can also be controlled, in which case the $h_b$ time-series is scaled to match a predefined energy value.
6.4 Applicability to long term modelling

To test the applicability of the model to long-term profile behaviour, a set of five runs were completed, with a near sinusoidal annual variation of breakpoint depths. This simulates energetic conditions during the winter and calm conditions during the summer. The $h_b$ time-series used to force the five model runs (Figure 6-22, labelled ‘a’ – ‘e’) exhibit the same seasonality but have increasing energy levels (annually integrated). The model (with default settings) was run with a mean spring range of 1.5 m and a mean neap range of 0.5 m. The energy level time-series was designed so that the mean value of $h_b$ for the middle run was $h_b \approx 0.85$ m, the level where Point C, D and E coexist (see Section 5.5; i.e. there is no offshore transport, but the onshore transport in the swash/inner surf and shoaling zones are separated by a point of zero transport), so theoretically this leads to all onshore transport during the summer, and two regions of onshore transport, separated by a region of no transport in the spring and autumn, and offshore surf-zone transport in the winter. For the other runs, this time-series is shifted to lower (‘a’ and ‘b’) and higher (‘d’ and ‘e’) energy levels. The breakpoint depth is restrained from becoming negative, and so for run ‘a’, the $h_b$ time-series is cut off in mid summer (visible in Figure 6-22).

![Figure 6-22 Time-series of $h_b$ used to force the long term behaviour model tests.](image)

First, to examine the model stability and applicability to long term modelling, run ‘c’ is examined.
Having run the model for 10-years with the pchip routine (Section 6.1.7), it is possible to ascertain the effect that the pchip routine has on the profile in terms of conservation of sediment. As the pchip method does not necessarily conserve sediment, the sediment conservation routine (Section 6.1.8) would have been active. This maintains a constant volume of sediment by calculating the difference in the current profile with the initial profile. The difference is then accounted for by adding or removing the appropriate depth of sediment over the entire wet profile. In the case where there is serious increase or loss of sediment, the profile exhibits accretion/erosion beyond the depth of closure. If this rate of change is high enough, and/or the model is run for long enough, this numerical artefact can lead to features that dominate the real profile change. Figure 6-23 presents the extent of this issue. The upper panel shows a time-series of the sediment volume, which remains constant. The second panel shows a time-series of four deep water elevation cells, which show no visible change (to precision of $5 \times 10^{-13}$ m) over the 10-year run. To confirm that these cells are not the exceptions, the difference between the first and last profile is examined in the lower two panels (at two y scales). Again the outer profile, beyond the depth of closure remains unchanged. This analysis confirms that although small adjustments are required to the model profile elevation to ensure sediment conservation, these are clearly insignificant even over long timescales and have no negative impact on the overall model results.

6.4.1 Long term results

Having established that the scale of the sediment conservation adjustments is not an issue even over the long timescale, the resulting modelled profiles for the intermediate conditions (run 'c') are examined. A series of the profiles are presented in Figure 6-24, each offset for clarity. The profile does tend towards a steady state (quasi-equilibrium) profile, although this is different from a profile that develops from the mean energy level (not shown). There is a well developed berm at $h \approx -1.0 - -1.2$ m, which is consistent with the water level from the spring high tide ($h = -0.75$ m) combined with the maximum energy level ($h_b = 2.2$ m) setup and run-up. The foot of this structure extends to a depth of $h = 3.5 - 3.7$ m, which is consistent with point D.
Figure 6-23 Model diagnostics of run ‘c’. The upper panels shows a time-series of integrated sediment volume (within a 1 m strip of the beach, hence m³), scaled to illustrate the very small changes with no net change. The second panel shows a time-series of the offshore grid cells. A systematic increase or decrease would highlight a profile change due to the smoothing routine continuity issues. The lowest two panels show the difference between the initial and final profile. The bottom panel is scaled to show very small scale features. The effect of the depth of closure is shown to be negligible (<5 × 10⁻⁹ mm after 10 years) while the possible continuity issues of the smoothing routine are not visible.
Figure 6-24 The development of the profile during run 'e'. Each profile is offset by 2 m for clarity.

The profiles presented in Figure 6-24 clearly show how the terrace develops, with the high/low, spring/neap features merging to form one dominant feature. Figure 6-24 however, does not clearly show the subtle spatial patterns that occur over time. These are better illustrated in Figure 6-25, which plots accretion (compared to the initial profile) as colour, for a range of cross-shore positions, and time. A time-series of $h_b$ is also plotted to show how the patterns relate to the different energy levels.
Figure 6-25 The forcings (left-hand panel time-series of \( h_b \)) and morphological response during run 'c' (right panel). The right-hand panel shows the profile change relative to the initial profile, with positive values indicating accretion and negative numbers showing erosion. The landward boundary of the domain is at \( x = 0 \) m.

The surface plot shows the accretion of the terrace, erosion further offshore, suggesting the terrace was derived from offshore material. That the profile converges on a quasi-equilibrium state is also evident, however the subtle seasonal profile oscillation between a summer and winter is also visible. The profile shows a spin up period of approximately ~3-5 years, after which the annual profile oscillation is slight, but regular.

### 6.5 Response to seasonal cycles of energy levels

The patterns of bar behaviour from run 'c' is interesting in isolation, but is more informative when considered in the context of the full range of energy conditions tested in the current series ('a' – 'e'), presented in Figures 6-26 – Figure 6-30. The figures present the time-series of the breakpoint depth (lower panel), surface plots of the resulting morphology and morphology change relative to the initial profile (second and third panel from the bottom) and example profiles throughout the model run.
Figure 6-26 Run 'a’. The left (lower) panel shows a forcing time-series of $h_b$. The second panel shows the profile response (relative to the initial linear profile, positive values represent accretion, the landward boundary of the domain is at $x = 0$ m). The third panel shows the absolute profiles. The fourth (upper) panel shows example profiles taken from the dotted line in the first three panels. The MSL of these profiles are given with the dotted line in the upper panel. Rotate this figure clockwise 90° to view.
Figure 6-27 Run ‘b’. The left (lower) panel shows a forcing time-series of $h_b$. The second panel shows the profile response (relative to the initial linear profile, positive values represent accretion, the landward boundary of the domain is at $x = 0$ m). The third panel shows the absolute profiles. The fourth (upper) panel shows example profiles taken from the dotted line in the first three panels. The MSL of these profiles are given with the dotted line in the upper panel. Rotate this figure clockwise 90° to view.
Figure 6-28 Run 'c'. The left (lower) panel shows a forcing time-series of $h_b$. The second panel shows the profile response (relative to the initial linear profile, positive values represent accretion, the landward boundary of the domain is at $x = 0 \text{ m}$). The third panel shows the absolute profiles. The fourth (upper) panel shows example profiles taken from the dotted line in the first three panels. The MSL of these profiles are given with the dotted line in the upper panel. Rotate this figure clockwise $90^\circ$ to view.
Figure 6-29 Run 'd'. The left (lower) panel shows a forcing time-series of $h_p$. The second panel shows the profile response (relative to the initial linear profile, positive values represent accretion, the landward boundary of the domain is at $x = 0$ m). The third panel shows the absolute profiles. The fourth (upper) panel shows example profiles taken from the dotted line in the first three panels. The MSL of these profiles are given with the dotted line in the upper panel. Rotate this figure clockwise 90° to view.
Figure 6-30 Run 'e'. The left (lower) panel shows a forcing time-series of $h_b$. The second panel shows the profile response (relative to the initial linear profile, positive values represent accretion, the landward boundary of the domain is at $x = 0$ m). The third panel shows the absolute profiles. The fourth (upper) panel shows example profiles taken from the dotted line in the first three panels. The MSL of these profiles are given with the dotted line in the upper panel. Rotate this figure clockwise 90° to view.
Under the lower energy conditions (Figure 6-26 - Figure 6-28, runs ‘a’ – ‘c’), the model produces a strongly bermed profile, which shows little seasonal response. As the energy level is predominantly in the range appropriate for berm formation, it is likely that the more energetic winter conditions are insufficient to produce the typical winter response. In run ‘c’, during the winter the seaward edge of the terrace is slightly removed, but there is no significant change.

As the energy level increases, the time that it take to form a quasi-equilibrium profile increases, in run ‘a’ a fairly consistent profile is visible at $t = 1.5$ yrs; run ‘b’, $t \approx 2$ yrs; run ‘c’, $t \approx 2.5$ yrs; run ‘d’, $t \approx 3.5$ yrs and run ‘e’, $t \approx 5$ yrs. Increasing the energy level also leads to more profile seasonality; as the energy level increases, the winter conditions have more of a chance to affect the profile. This is most visible in run ‘e’, which shows a strong seasonality, with bar migration of $dx > 150$ m, and very different seasonal profiles. As run ‘e’ shows the most interesting behaviour, it will be further analysed.

Closer examination of the profile of run ‘e’ (Figure 6-31) shows that while the summer and winter profiles are clearly very distinct, the spring and autumn profiles are very similar. However, the summer and winter profiles are not simply the end points, with the spring and autumn phases lying between them. There is a complex cycle of bar generation, offshore migration and degeneration, and this is reflected in the complexity of the profile evolution. There is a phase lag of ~60 days between the peak winter/summer morphologies, and the peak winter/summer forcing conditions, which is clearly illustrated in Figure 6-31. As the energy level reaches a threshold level ($-h_b \approx 0.8 - 1.2$ m), the bar starts to move offshore, and continues offshore until after the energy level peaks. The bar then remains static until the energy level drops below a separate threshold ($-h_b \approx 1.2-1.4$ m), when the bar starts to migrate onshore again.
Figure 6-31 Analysis of the relationship between the forcing and morphological response of run 'e'. The upper panel is a section of the absolute morphology (second panel of Figure 6-30), scaled to highlight the bar crest. A representative contour (bold white) and a time-series of $h_b$ (dotted white line) show the morphological response relative to $h_b$. The panels below show example profiles that correspond to the minimum (summer), maximum (winter), and mean (spring and autumn) energy levels in terms of the seasons (left-hand panel) and bar morphology (morphology maximum profiles; profile of the maximum offshore bar position, maximum onshore bar position, and intermediate profiles, right-hand panel). The lower two panels correlate the time-series of bar migration (the highlighted contour in the upper panel) and $h_b$ (these time series are presented in the second from bottom panel). The correlation is given in the bottom panel.
Figure 6-32 After allowing the model to spin-up, the last 6 years were averaged to give averages of that month from previous years. These profiles are presented with dotted lines representing two standard errors about the mean. Each profile is offset by 4 m for clarity.

As the morphology in Figure 6-30 shows a distinct temporal rhythm, the last 6 years are averaged, so that each profile is an ensemble average of six years (e.g. Figure 6-31). These profiles are presented with two standard errors around the mean profile in Figure 6-32, with the
solstice and equinox profiles highlighted and with each profile offset to allow the forms of the profile to be clearly seen. Averaging the profiles removes the inter-annual variability, and so allows the underlying processes to be investigated with more rigour. To show how the profiles change relative to one another, the active part of the profiles ($165 \leq x \leq 310$) was plotted with no offset (Figure 6-33). The location of profile features were visually recorded through time. The bar crest positions were noted as the maximum positive residual from the initial profile, an adaptation of the method suggested by Holman and Bowen (1982), however other topographic features were noted by change in gradient. The patterns of these feature migrations are presented in Figure 6-34.

The profile associated with the most seaward migration of the bar is termed the “peak winter” profile (February). The peak winter profile has a very steep seaward edge of the bar. After the peak winter profile has formed and starts to break down, the foot of the bar ($x \approx 300$ m) remains constant as sediment is removed from the seaward edge of the profile and deposited at the berm at the landward end of the terrace ($190 \leq x \leq 250$ m). As the process continues and the energy levels reduce (during spring), the depth to which the profile erodes also reduces. The upper portion of the bar continues to erode and so migrates onshore, while the outer part of the bar is stranded (dropping energy means that the shape function cannot penetrate deep enough to affect the deeper part of the bar). This divides the bar in two (e.g. June, $x \approx 235$ m, 270 m). The summer low energy conditions compress the shape function, and so the outer stranded bar is in the onshore erosional region (Region 6) of the shape function and so subjected to decay. Over the summer, the outer stranded bar remains relatively constant (it is to deep to be eroded), but becomes more prominent as the sediment from the crest of the bar is eroded (compare $255 \leq x \leq 295$ m, June to July), meanwhile the inner portion of the bar remains relatively static at $x \approx 240$ m (May – August). As the shape function expands with increasing energy (as winter approaches) Region 6 of the shape function deepens, and the outer stranded bar crest is subjected to increasing erosion, and so deepens with time (e.g. August ($z \approx -2.25$ m), September
(z ≈ -3 m), October (z ≈ -4 m), November (z ≈ -5 m)), eventually being completely decayed, e.g. November/December.

Figure 6-33 The active region (165 < x < 310 m) of the monthly averaged profiles presented with no offset, highlighting the relative profile change.

While the bar is migrating offshore in the autumn, separating into a decaying outer bar, and an inner bar that migrates onshore during the spring, the berm follows a separate evolution cycle. During the autumn, the berm migrates shoreward, cutting back the shoreline and widening the
terrace (October, $x \approx 220$ m; January, 180 m). The crest of the berm remains relatively static throughout the winter and spring, however as energy levels decrease in spring, sediment is accreted at the foot of the berm, such that the elevation at $x \approx 220$, rises from $z \approx -0.6$ m to $z \approx 0.6$ m from February to July. This builds the berm out and it becomes indistinguishable from the onshore migrating bar by late summer (e.g. August). At this point, the profile is described as the “peak summer” profile. As the energy level increases, the berm/bar feature diverges into an onshore migrating berm and offshore migration bar.

![Diagram](image)

**Figure 6-34** The location of the features in the averaged morphological time-series were visually estimated, and plotted in the upper panel. The berm is red, the bar is blue and the outer decaying bar is green. The lower panel presents a time series of $h_b$ for comparison.

Plotting the location of the yearly averaged bar/berm crest location clearly shows the complex migration pattern. Figure 6-34 shows that the annual cycles of the berm and bar are out of phase by 180°. At the start of this time series (note, Figure 6-34 does not start in January) the bar (blue) and berm (red) are joined. During autumn the energy levels increases and the bar and
berm separate, until they reach their maximum separation in February (e.g. Figure 6-33). The bar and berm converge as the energy levels drop, with the outer bar dividing into the stranded (green) bar, and the onshore migrating inner bar (blue). The stranded bar follows the inner (blue) bar, albeit at a greater depth. At the end of the summer, it decays as it migrates offshore.

6.6 Summary

The shape function presented in the previous chapter was implemented into a numerical model. Routines to calculate gradients, smoothing, sediment conservation and avalanching were developed to maintain the stability and realism of the modelled profile. The offshore swash component was excluded to improve the realism of the modelled terrace.

Initial model runs with constant tide and wave conditions showed that the model was stable. The model behaviour for a range of constant energy levels and tidal regimes was investigated, and resulting profiles were presented. The model response to varying energy levels was investigated by running the profile developed under one energy level with a different energy level. This showed that the model was capable of replicating off- and onshore bar migration, and bar decay. The conditions under which these behaviours occur were also described.

Having shown that the bar migration model is capable of producing these common behaviour, and appears to be stable, the applicability to long term time scales was investigated. The model was run with a series of 10-year forcings, each containing the same seasonality (amplitude of the seasonal cycle of $h_b$) but with a different integrated energy level between each run. The model runs showed that the model was stable, conserved sediment, and did not introduce any numerical features (often a problem with standard smoothing techniques).

The model runs showed bar formation, offshore migration during the winter and onshore migration during the summer. There was a distinct spin-up period, after which the profile settled into a regular behaviour. The most energetic run showed more complex behaviour, so was further analysed. The profile was shown to go through a four stage morphology (where the
winter and summer morphologies were at two extremes, with the autumn and spring profile between, but distinctly different). There was a phase lag of ~60 days between the forcing and the morphologic response. After the spin-up period, there was little inter-annual variability, so to further investigate bar behaviour, the inter-annual mean profile (excluding spin-up) for each month was calculated. This showed the morphology exhibited a 2-bar system (the inner bar oscillated between a summer berm and winter inner bar — not separated by a trough). The outer bar split into two bars at the end of the winter, with the outer part decaying, and the inner part migrating onshore to meet an inner bar feature.

The simulation of profile morphology over decadal time scales is novel. Other long term studies of bar behaviour have parameterised individual aspects of bar behaviour. Plant et al. (1999) modelled bar crest position and migration rates over a similar timescale, but no attempt to replicate the full morphology was made. The current approach provides a means to investigate the long term behaviour of bar migration while retaining details of profile evolution.

Although based on measured fluxes, the shape function model is considered a heuristic model, as it has not been validated with a long term dataset, and the implemented shape function (i.e. excluding the offshore swash component) is different from the shape function presented in the previous chapter.
Plate 7 Stormy seas.

7 Discussion

In this chapter, the results of the previous three chapters will be discussed in the context of the published literature. After outlining the limitations of the study, the results from the Chapter 4 are briefly discussed. This is followed by an in-depth discussion of the new suspended sediment transport shape function parameterisation. The implementation of the shape function in a numerical model, and the resulting long term model runs are then discussed, followed by suggestion for further work.

7.1 Limitations

As with other studies, there were limitations to the method of measuring suspended sediment transport. These included i) varying instrument elevation with respect to the bed ii) not measuring sediment transport above 15 cm above the bed, or below 1 cm above the bed, iii) assuming a constant velocity below 3 cm above the bed, and iv) the influence of measurement errors such as bubbles and light saturation. A processing technique (described in Section 3.3.6-3.3.7) reduced the error introduced by iv). Here, the implications of i) - iii) are discussed.

Measurements were used from a vertical array of co-located MOBSs and EMCMs and were interpolated onto a bed-level corrected reference. This procedure was designed to remove the influence of varying bed levels and allow direct measurement of the profile of sediment transport without reliance on assumed values. As the sediment concentration profile is predominantly a function of depth (sediment concentration generally shows a near inverse-logarithmic profile with height above the bed) changes in instrument height relative to the bed can lead to significant errors in the measurements. Even measuring instrument heights at the beginning and end to the tide does not sufficiently resolve this issue, as bed levels change throughout the tide. Austin and Masselink (2008) calculated this effect could lead to errors in measurements of suspended sediment transport of ~30-40%. They presented a technique to
correct for the varying bed level, and we have adopted their methodology (outlined in Section 3.3.6 and 3.3.7).

The interpolated sediment flux measurements ranged from 1 to 15 cm above the bed, and so sediment transport within the lowest 1 cm and above the 15 cm was not included in the depth integration. As sediment concentrations generally decrease with height above the bed, the peak sediment concentration is expected to be below 15 cm. However, depending on the sediment concentration profile above 15 cm, the portion of total suspended sediment within the lower 15 cm (and thus measured) is unknown. To give an estimate of the quantity of unaccounted sediment concentration, a logarithmic profile was fitted to the data, and extrapolated to a height where the concentration has fallen to a near-zero concentration ($c_z = 0.01$ kg m$^{-3}$). Comparing the integral of this fitted, extrapolated profile to the measured profile, suggests that this error may be $O(50\%)$, a similar value to that quoted by Masselink et al. (2008a) for the same dataset.

Although a few studies have measured the suspended sediment transport with multiple co-located OBS and current meters in a vertical profile (e.g. Beach and Sternberg, 1992; Miller, 1999; Masselink et al., 2007a), most studies have relied on a single OBS at a nominal height above the bed, combined with either co-located (e.g. Saulter et al., 2003; Miles and Russell, 2004) or vertically separated (e.g. Osborne and Greenwood, 1992a; Aagaard and Greenwood, 1995; Ruessink et al., 1998) current meters. The method employed here is an improvement on the methods of these previous studies, and is in line with Masselink et al. (2008a) and Austin and Masselink (2008), and as such, is an advance on previous studies.

Another source of error was from the vertical array of EMCMs. As EMCMs rely on an electromagnetic field around the sensors, interference, and consequently measurement errors, can occur if they are located too close to the bed. For this reason, the EMCMs were not deployed in the lowest 3 cm above the bed, and were reset to this height at the beginning of each tide. Velocity below the lowest EMCM was treated as constant, possibly leading to an overestimate of the near-bed velocities. However, in this study, the absolute values of sediment
transport are less important than their relative spatial distribution, and as there appears to be little trend in these errors (e.g. Figure 3-12) there is confidence in the observed gradients.

Due to all these sources of error it is difficult to give error-bounds for the sediment transport data. Using the same instrumentation, data and processing techniques, Masselink et al. (2008a) suggested a conservative estimate of 50% error. As the error-bounds are not precisely known, and sediment transport data has a large inherent scatter, the limited data from each tide was not analysed in isolation. Instead, the approach taken in this study was to combine data from tides of similar energy conditions (in terms of $h_b$) into large ensembles that were then analysed together, giving increased confidence in the observed results.

### 7.2 Analysis of velocity moment and suspended sediment time series

Initial results from the velocity moment time-series showed patterns that were in general agreement with the literature (Russell and Huntley, 1999; Mariño-Tapia et al., 2007a), with positive (onshore-directed) velocity moments outside the breakpoint, and negative (offshore-directed) velocity moments inside. These patterns were generally the same under both high and low energy conditions. The observed suspended sediment transport showed a different pattern. In the shoaling zone the observations showed predominantly onshore-directed transport under all energy conditions. This is in agreement with the velocity moment observations, and the Mariño-Tapia et al. (2007a) velocity moment shape function. The surf-zone measurements show offshore, mean-flow dominated transport under high-energy conditions, again in agreement with the velocity moment observations and Mariño-Tapia et al. (2007a) velocity moment shape function. However, under low energy conditions, the surf-zone sediment transport is onshore directed, in complete contrast with the velocity moment observations and Mariño-Tapia et al. (2007a) shape function. This is a key observation, illustrating that the velocity moment shape function approach is inappropriate under low energy conditions.

Closer inspection of the surf-zone time-series shows why the relationship between velocity moment and sediment transport breaks down. Under low energy, large sediment suspension
events occurred in phase with peak onshore flows, leading to a strong onshore-directed oscillatory transport component. The mean velocity (Figure 4-3) was weak (offshore directed), and so the mean transport component was negligible, thus the net sediment transport is oscillatory/onshore dominated. In contrast, under high energy conditions (Figure 4-12) the mean velocity is strongly offshore directed, which leads to a strong (offshore-directed) mean transport dominating over the oscillatory component and giving a net offshore directed flux. So the breakdown between the velocity moment and suspended sediment transport is related to the weak offshore-directed mean component of sediment transport. The change in net surf-zone transport with energy illustrated the value of separating the sediment transport mechanism into the mean and oscillatory components (following Huntley and Hanes, 1987). The net cross-shore suspended sediment transport is a competition between these components, so it is sensible to treat them separately. The disagreement of the velocity moment and measured sediment transport in the surf-zone informs the development of a shape function for each component.

7.3 Swash-zone transport patterns

The swash-zone contains sediment transport processes that do not occur within the surf- and shoaling zone (Butt et al., 2004), and so different mechanism dominate. Breaking swash-zone data into a mean and oscillatory component is not valid in the swash-zone as the data is not continuous (i.e. drying between bores). For this reason, the approach taken for the surf- and shoaling zone is not directly applicable to the swash zone. This leads to careful consideration of the swash-zone.

Observations of time-series show separation of mechanisms between the inner and outer swash zone. The inner swash zone is dominated by onshore transport due to sediment suspended during the accelerating onshore phase of the bore. The offshore velocities do not exceed the apparent velocity threshold of $\approx 1 \text{ m s}^{-1}$, and so there are few offshore directed transport events in the inner swash-zone. In the outer swash-zone, the predominant sediment direction is energy dependent. Under low energy, the sediment transport is still predominantly onshore-directed.
coinciding with the peak onshore velocity. Under high energy conditions infragravity backwashes (IGB) occur. These lead to large peak offshore velocities (in excess of the apparent threshold), that persist for relatively long periods. IGBs cause sediment suspension, which is subsequently transported offshore in large quantities. Under high energy, IGBs dominate the outer swash-zone transport, leading to net offshore directed transport. IGBs were not observed under low energy conditions, while the onshore swash-zone mechanisms were observed throughout the swash-zone under all energy conditions (albeit dominated by IGB when and where present). Therefore, general cross-shore patterns within the swash-zone were: 1) under low energy conditions, onshore directed throughout the swash-zone, 2) under high energy conditions, offshore transport in the outer swash-zone, due to IGBs, onshore transport in the inner surf-zone, leading to a sediment divergence in the mid swash-zone.

Further investigation into the swash-zone mechanisms was undertaken by looking at vertical profiles of the sediment transport within swash bores. These cross-sections suggest there were several mechanisms involved in swash zone sediment transport, and their dominance varied throughout the wave cycle. Looking at the phase between the near-bed velocity and near-bed sediment concentration helped isolate the acting mechanisms. Being in-phase suggested that near-bed velocity shear was directly driving sediment suspension, whereas being out of phase suggested that other mechanisms such as bore turbulence (e.g. Butt et al, 2004; Puleo et al, 2000), acceleration (e.g. Calantoni and Puleo, 2006; Nielsen, 2002; 2006; Puleo et al, 2003) or in-exfiltration (e.g. Nielsen, 1998; Turner and Masselink, 1998) were playing a role in suspending sediment.

In the outer swash-zone this suggested that an important suspension mechanism could be turbulence vortices, generated by the backwash undercutting the uprush ($t = 0.3-1.3$ s, Figure 4-23), reaching the bed. Initially the depth-averaged suspended-sediment transport was offshore because large near-bed peaks in suspended sediment concentration coincided with large peaks in offshore near-bed velocity. As the near-bed velocity dropped the depth-integrated suspended-sediment transport changed to be offshore directed. This was due to a lower concentration of
sediment spread throughout a larger proportion part of the water column that was subjected to the onshore velocity associated with the arrival of the bore front.

In the inner swash-zone, the velocity of the bore suspends and then transports sediment onshore. Without a backwash providing strong offshore velocities, the sediment transport is onshore throughout the water column, and so the net transport is strongly onshore directed throughout the duration of the bore uprush. With this data it was difficult to discriminate between the likely dominant suspension mechanism, namely bore-turbulence and acceleration (Nielsen, 2002; Puleo et al., 2003; Nielsen, 2006), because both occur at during the same period of the wave cycle (e.g. Puleo et al., 2003).

### 7.4 The velocity moment shape function

The velocity moments measured at Sennen provided the first independent test of the Marínó-Tapia et al. (2007a) shape function (Tinker et al., 2006) and showed that the patterns observed on a range of beaches across Europe were consistent with observations at Sennen Cove — a beach not included in the initial analysis. Plotting all the data (from both high and low energy conditions; Figure 4-25) suggested that the existing shape function slightly over-predicted the velocity moments in the surf-zone (by a factor of 1-1.2), whereas the near-zero velocity moments observed in the shoaling zone are strongly over predicted. Upon separating the velocity moment into energy levels, it can be seen the over prediction is exclusively from low energy data; a condition under which the energetics approach is likely to break down (see Section 2.1.1). Conversely, under high energy conditions, the shape function gives a good prediction of the velocity moments. This is expected as the Marínó-Tapia et al. (2007a) shape function is predominantly a high-energy parameterisation, the energetics approach is often invalidated under low energy conditions.

It was possible to investigate the vertical dependence of the velocity moment shape function with the vertical array of EMCMs. Previous studies have been from a point source of data at an arbitrary height above the bed, with no account taken of bed-level changes. With a vertical
profile of velocity moments, it is apparent how the cross-shore spatial pattern of velocity moment varies with height above the bed. There is a small change in the observed velocity moment with height. As the shape function was derived from data measured at a nominal height of $z \approx 10$ cm above the bed, it is not surprising that the fit of the data to the Mariño-Tapia et al. (2007a) shape function is best at approximately this height, (the $R^2$, and rms values suggest measurement from $h = 8$ cm and $h = 9$ cm best fit the Mariño-Tapia et al. (2007a) shape function). The innermost measurements show the shape function over estimates the velocity moments by an increasing margin with height. The next four data bins (in the cross-shore direction) show overestimates that decrease with height. The near-zero data in the outer bins are overestimated (in the onshore direction) by the shape function, but show a definite peak at $6 \text{ cm} \leq h \leq 10 \text{ cm}$. For a particular bin, the variability for each height is generally greater than the variability between heights, however there are exception to this (e.g. the outer three bins), and these exceptions suggest that velocity moment measurements are significantly depth dependent, a factor that should be considered in velocity moment shape functions such as that of Mariño-Tapia et al. (2007a).

7.5 The sediment transport – velocity moment relationship

Having shown that the velocity moment data from the Sennen field campaign is in broad agreement with the Mariño-Tapia et al. (2007a) shape function, the ability of an energetics based shape function to predict the measured fluxes is investigated. The energetics approach calculates sediment transport from velocity moments, and so a simple relationship is expected in the observed data. As the velocity moment patterns in the time-series and shape functions vary with wave energy, the comparison of velocity moments and measured sediment transport was done for the individual energy levels. Under high energy, conditions there was a fairly linear relationship, supporting a velocity moment based shape function. Under low energy conditions, the linearity of the relationship completely breaks down. Although the velocity moments predict onshore and offshore-directed transport, the measured fluxes are almost exclusively onshore directed, with 95% confidence that the bin averages are positively different from zero. No
simple relationship is apparent in the data. This is in line with theoretical limitations of the energetic based sediment transport model as it assumes sediment responds instantly to velocities (i.e. there is no threshold of motion), which is often not true under low energy conditions. Also the investigation of the time-series showed increased importance of acceleration as a suspension mechanism under low energy conditions (Figure 4-14). This analysis was also repeated with the combined dataset, which showed a fairly linear relationship. This is a cautionary tale – it would be easy to assume that the velocity moments provide a good proxy for sediment transport under all conditions, when the scale of the high energy data simply hides the poor relationship of the low energy data. Despite having followed Russell and Huntley’s (1999) assumptions that the 3rd velocity moment gives a good description of the suspended sediment flux (the 4th velocity moment being the theoretical predictor of suspended sediment transport) it was instructive to test the relationship between the velocity kurtosis and suspended sediment transport. This showed the same relationship as with the 3rd velocity moment (i.e. good fit under high energy conditions, poor fit under low energy conditions, and the good high energy relationship masking the poor low energy relationship when the datasets are not separated). This analysis supports the careful qualification of the Russell and Huntley (1999) velocity moment shape function as being a “high energy flux”.

The sediment transport – velocity moment plots suggest that the velocity moment shape function will not correctly predict the pattern of the observed sediment transport; this is confirmed by plotting the unnormalised, energy segregated sediment transport against $h/h_n$. The high energy data is compatible with the Marıño-Tapia et al. (2007a) shape function, however the low energy data is strongly incompatible with it. A tentative normalisation of the low and high energy data (following Marıño-Tapia et al. (2007a) and Plant et al. (2001)) allows the combination of the low and high energy data, again suggesting the inappropriateness of velocity moments as a proxy for predicting suspended sediment in any conditions other than high energy.
7.6 Cross-shore suspended-sediment transport parameterisation

The first cross-shore suspended sediment transport parameterisation based on measured depth-integrated fluxes was developed during the study for this thesis, and has been presented by Tinker et al. (2009). Previous parameterisations have been developed from point measurements of sediment transport and/or the application of the energetics concept to predict sediment transport (e.g. Russell and Huntley, 1999; Plant et al., 2001; Aagaard et al., 2002; Weir et al., 2006; Mariño-Tapia et al., 2007a), or have been purely conceptual (Masselink, 2004; O’Hare et al., 2006). While these models have advanced understanding of cross-shore sediment flux parameterisations, the results presented here are based entirely on field measurements and both support previous parameterisations and extend their scope.

Field-measurements velocity moments parameterisations (Foote et al., 1994; Russell and Huntley, 1999; Mariño-Tapia et al., 2007a) only include sediment transport mechanisms described by the energetics approach to sediment transport (Bailard, 1981). As the new shape function is based on measured fluxes, this approach includes all sediment transport mechanisms in operation. This is particularly important in the swash zone, as velocity moments predict exclusively offshore transport, despite measurements showing of net onshore transport (Masselink and Russell, 2006). The velocity moment approach is generally used due to the difficulty in making measurements of sediment transport fluxes. As discussed in the Section 7.1, point measurements of sediment transport are very dependent on the instrument height, and as bed height may change during a tide (e.g. due to ripple migration and accretion/erosion) this can introduce errors that must be accounted for (Austin and Masselink, 2008).

Following the approach of previous studies (Foote et al., 1994; Russell and Huntley, 1999; Mariño-Tapia et al., 2007a), the new shape function is based on the $h/h_b$ parameter. Other cross-shore sediment transport parameterisations are based on the $L/h$ parameter (Plant et al., 2001; O’Hare et al., 2006). Plant et al. (2001) developed a parameter to describe transport as the product of a sediment stirring term and a dimensionless transport term (Section 2.2.1). The
approach was further extended by Plant et al. (2004) who used inverse modelling to tune a model coefficient to produce agreement with observations which showed onshore sediment transport at low wave steepness (low wave energy). This is in agreement with the present shape function. Parameterisations based on $H/h$ used by Plant et al. (2001) and O'Hare et al. (2006) have benefits over the $h/h_b$ approach used here in that they can be used directly to model barred profile morphology. However, the use of $H/h$ as the base parameter depends upon the accurate prediction of wave height transformation to the shoreline and ignores the presence of infragravity waves. Plant et al.'s (2004) inverse modelling approach does produce the correct flux direction, however, as modelled $H/h$ tends to decrease towards the shoreline and seawards in the shoaling zone, shoaling- and swash-zone transport is modelled by in the same manner. Furthermore, onshore sediment-transport in the surf/swash zone at low energy is modelled using the same function as onshore transport due to shoaling waves at high energy and thus, the very different physical processes that cause the onshore transport in the two different regions is ignored.

The $h/h_b$ approach is generally inapplicable on barred beaches as the effective $h_b$ changes as the waves re-shoal; this was a problem overcome by Masselink (2004) by calculating a new $h_b$ value every time a trough was encountered (see Section 2.3). The Masselink (2004) shape function was designed to predict onshore transport in the shoaling zone, and offshore transport in the surf-zone under high energy conditions, onshore transport in the surf-zone (with no shoaling zone transport) under low energy condition and no transport under very low energy conditions. This pattern is supported by the present shape function, which suggests that it may be possible to adapt the present approach for use on multi-barred beaches by using zones with different $h_b$ values (this is further discussed in Section 7.8).

Previous shape functions have been the product of a magnitude term and a shape term (e.g. Plant et al., 2001), or a shape function with an equivalent magnitude term used to normalise the sediment transport. The present shape function follows this tradition by developing four component shape functions for each of the transport components and scaling each with its own
amplitude function. It is emphasised that all these constituents can be matched with realistic physical processes and are not merely a convenient way to parameterise sediment fluxes. Under high energy conditions, the resulting shape function is in agreement with the Mariño-Tapia (2007a) shape function (the conditions for which the latter was originally designed), however, under low energy conditions, the behaviour matches the conceptual shape function of Masselink (2004).

Due to limitations of process-based models (see e.g. O'Hare et al., 2006), parametric models are best suited to modelling medium- to long-term profile evolution. The particular behaviour of the present shape function has the potential to overcome some of the limitations of previous shape function driven models, because its form is a function of the energy level. This produces a low energy shape function that can lead to the development of the typical summer/calm profile and drive onshore bar migration (this is further discussed in Section 7.8). The inclusion of the swash/surf zone transport function recreates the behaviour of the berm formation shape function of Weir et al. (2006), and would be expected to lead to berm development primarily from sediment from the inner surf zone under low energy conditions. The presence of two peaks in the onshore-directed sediment transport separated by a region of zero (or low) transport allows the berm and bar to form independently as observed by Masselink et al. (2007b). Under high energy conditions, the shape function behaves similarly to the Mariño-Tapia (2007a) shape function, although the offshore transport inside the inner surf zone is magnified at higher energy levels.

Although the proposed shape function is developed from a single beach, it includes measurements under a wide range of energy conditions \(D_{50} \approx 0.7 \text{ mm}, 0.1 \leq H_{sg} \leq 2.5 \text{ m}\). As it is an extension of the Mariño-Tapia (2007a) shape function (developed from a wide range of beaches with \(D_{50} = 0.17-0.50 \text{ mm}\) and \(0.16 < H_{sg} < 2.5 \text{ m}\)), it is reasonable to assume that the proposed shape function will also be quasi-universal for sandy beaches with alongshore uniform topography. Potentially, the most appealing attribute of the present approach is that the cross-
shore suspended sediment transport pattern can be derived from simple measurements of offshore wave height and period at a known depth (e.g. Section 3.3.8).

As the shape function exhibits a generic pattern (generally onshore transport peaks in the inner swash-zone, and shoaling zone, separated by a region of more offshore-directed transport in the surf-zone), it is possible to segregate the nearshore into generic regions. These regions are bounded by points of zero sediment transport and zero sediment gradient, and so each region is characterised by a sediment direction (onshore or offshore) and transport regime (depositional or erosional). As the shape function is defined as an algebraic expression for the absolute suspended sediment transport, the regions can be integrated to give an idea of the relative volumes of sediment transported between each region. This analysis illuminates one of the key positions on the nearshore transect, the position that coincides with the maximum offshore sediment transport (point D, separating Region 3 (offshore erosional) and Region 4 (offshore accretional) and being a point of zero sediment transport gradient). Point D is a stable point on the sediment profile, corresponding with a depth that the profile tends towards. Parts of the profile that are slightly shallower than point D are within Region 3, and are subjected to erosion, reducing the depth towards that of point D. Parts of the profile that are slightly deeper than point D, in Region 4, are subject to accretion, again tending towards point D. Thus the central part of the profile tends towards a uniform depth, associated with point D. This region is bounded by two other interesting points on the profile, unstable points B and F, which are points associated with the maximum onshore transport in the inner surf/swash zone and the shoaling zone. Point B separates Region 1 (a region of onshore-directed accretion) from Region 2 (a region of onshore erosion). This is an unstable point as sediment near point B will tend away from point B, i.e. profile slightly deeper, in Region 2, will erode deeper (and given enough time under constant conditions) towards point D. Shallow depths will accrete towards point A, which by default, becomes a pseudo-stable point (i.e. it acts like Point D (a stable point) as slightly greater depths accrete, while (according to the shape function) shorewards of the shoreline does not accrete/erode). As the sediment transport gradient at point B (and F) is zero (due to these points
being maxima), the elevation at these points does not change, only points near them. Similarly at point F, points slightly shallower are subjected to accretion towards point D, and slightly deeper points are eroded towards the depth of closure, point G, another pseudo stable point. The presence of these regions and points hints at the shape of the resulting profile that will be formed by the shape function.

7.7 The shape function model

Development of a morphological model based on the measured suspended sediment transport shape function explicitly ignores the influence of bedload transport. Other parametric sediment transport models (e.g. Plant et al., 2001; O'Hare et al., 2006), calculate bedload transport and use a sediment transport multiplier (O(10)) to include suspended sediment transport. These models therefore fix the relationship between the magnitude of the suspended and bedload transport, with suspended transport being approximately an order of magnitude greater than the bedload transport. This is supported under energetic conditions by conclusions of observational studies (e.g. Thornton et al., 1996; Gallagher et al., 1998). As the model presented here is conceptual, the suspended sediment shape function is treated as a total load sediment transport function, as increasing the magnitude of the shape function by 10% (in line with Plant et al., 2001; O'Hare et al., 2006) is within the error of the model. The magnitude of the shape function only influences the speed of the response (by increasing/decreasing the gradients). It is the shape (i.e. locations of the shape function points and regions) that drives the resulting profile. Therefore, including the bedload transport through a spatially constant multiplier is only likely to have a small effect on the resulting profile evolution.

The development of the numerical model in which to implement the shape function was a long process. Initial attempts calculated sediment fluxes using a simple centred difference scheme, which lead to problems such as significant (numerical) shoreline cutback. Initial smoothing routines lead to erroneous numerical transport and erosion/accretion dominated the calculated features on runs beyond the short term. Development and implementation of schemes to
overcome these issues were time consuming, but has allowed the model to be used for longer timescales. Model stability was established by running the model with a series of time steps and grid sizes. Initial test runs suggested that the model was producing a terrace that was unrealistically shallow (Figure 6-13). The cause of this was isolated as being the offshore swash components shape function, which enhances the mean component and shifts the peak offshore transport towards shallower water. It was decided that the as the amplitude function of this term was relatively weak, and it did not change the behavioural characteristics of the shape function (unlike the onshore swash component which is the only term leading to onshore swash-zone transport), it would be removed.

The shape function model shows sensible response to simple forcings. On forcing with a range of constant energy levels \( h_b = 0.5, 1.0, 1.5, 2.0, 2.5 \text{ m} \); Figure 6-16), the range of profiles exhibited a switch from a bermed/summer profile, to a winter/barred profile. The summer profile showed accretion at the shoreline (termed the berm) with erosion further offshore. The erosion being offshore of the accretion is in line with the low energy shape function being all onshore transport. The winter/barred profile show a large accretional feature with erosion shorewards and landwards. The bar forms in the Regions 4 and 5 of the shape function. A small berm feature may develop at the shoreline in region 1 of the shape function. The switch between the low and high energy profile in Figure 6-16 occurred between \( 0.5 > h_b \geq 1.5 \text{ m} \), although closer examination of the \( h_b = 1.0 \text{ m} \) profile suggests it is also a barred profile (the surf-zone erosional region is very small). This is in accordance with the shape function switch between all onshore transport and offshore surf-zone transport that occurs at \( h_b \approx 0.85 \text{ m} \).

When the profile is subject to near constant energy conditions, the profile tends towards equilibrium. The bar terrace tends towards horizontal, and the edge of the bar/berm becomes vertical (e.g. Figure 6-10). This reduces further evolution as the vertical sections reduced towards a single grid cell, and so although erosion and accretion can occur at this point, it is slow. As sediment transport is a function of depth, the sediment flux is constant over the horizontal section, and so with zero sediment flux gradient, there is no profile evolution.
Although this is stable, the avalanching routine tends to make the vertical sections slump down towards the angle of repose. This then makes the profile active again. The term "near-equilibrium" is used to describe the profile that is dominated by vertical and horizontal sections.

Profile response can be considered as being the result of a shape function stretched out from the shoreline to the depth of closure. Increasing and decreasing the energy level is equivalent to expanding and compressing the shape function regions. Adding a tide advects this shape function laterally across the beach with the tide. As the erosional and accretional regions are swept across the profile, the regions overlap and boundaries blur - the tide acts to smooth the morphological features. The response time of the profile is much greater than the tidal timescale, and so the profile does not respond instantaneously (e.g. the bar does not migrate with the tide). Instead the profile develops around the average shape function. As the water level is predominantly around the high and low water mark, the profile develops as the result of a pair of shape functions extending out from the high- and low-water levels. The model was run with a constant breakpoint depth \( h_b = 1.5 \text{ m} \), and a range of monochromatic tidal amplitudes \( a_{M2} = 0, 0.25, 0.5, 0.75, 1.0, 1.5 \text{ m}; \) Figure 6-17). Increasing the tidal range leads to two sets of morphology, initially overlaid for small tidal range, but increasingly separated as \( a_{M2} \) increased. The inclusion of the \( S_2 \) tidal component is equivalent to adding two further shape functions, giving a shape function extending from each of MHWS, MLWS, MHWN and MLWN (Figure 6-18).

These simple tests (response of energy to \( h_b \), tides) essentially replicate those of Fisher and O'Hare (1997) and Fisher et al. (1997). The results presented here illustrate the ability of this model to produce a more complex range of behaviour. The ability to develop a different form of profile under low and high energy conditions is not possible in the earlier models. This suggests the proposed model will be able to reproduce behaviour such as the winter/summer cycle observed on many beaches.
Having established the profile response to a range of wave and tide conditions, the response to changes in the forcing wave time series is investigated. Model runs were initialised from a linear profile, under a range of conditions ($h_b = 0.5, 1.0, 1.5, 2.0, 2.5$ m) for one month to develop an initial set of morphologies. These were then run for an additional month with a different $h_b$, and the resulting profiles were compared (Figure 6-19, Figure 6-20). The bar crest was shown to move in response to changing conditions, providing a simulation of bar migration.

As the energy level increased, the bar migrated offshore, while a reduction of energy was met by onshore bar migration. A small increase in energy ($dh_b = 0.5$ m) always lead to more profile change than an equal decrease in energy ($dh_b = -0.5$ m). This is in accordance with observations of rapid offshore bar migration in response to storm conditions, with onshore migration during calm recovery periods being much slower. For example, Sallenger et al. (1985), measured offshore migration rates during storms of $2.2$ m hr$^{-1}$, while peak onshore migration rates (e.g. greater than the average onshore migration rates) during the recovery period were $1.2$ m hr$^{-1}$.

When the initial energy level was significant (e.g. $h_b = 2.0$ m) the profile has time to form a near-equilibrium profile, and so it becomes very difficult for the low energy conditions to redistribute the sediment. When the energy level increases to a high level, it forms a similar structure irrespective of the initial profile, whereas under low energy conditions, the resultant profile is dominated by the initial morphology. This is attributed to differences in the response time of the profile under high and low energy.

Under significant reduction to the energy level (e.g. $h_{b1} = 2.5$ m, $h_{b2} = 1.0$ m), the bar is shown to decay. In terms of the shape function, this is because a terrace forming at point D (e.g. Figure 5-11) under $h_b = 2.5$ m forms at a depth of $h \approx 1.1$ m. Upon a reduction in energy to $h_b = 1.0$ m the bar is so deep that it is only subjected to weak onshore sediment transport, furthermore, as it is below the depth of the peak onshore shoaling zone sediment transport, it is in a sediment divergence, and so erodes. This process is very similar to that described by Ruessink and Terwindt (2000). In their conceptual model of bar migration, the bar lifecycle is broken down to three phases, with the final phase describing bar decay. During the third phase, the bar is at its
most seaward, deep position, the sediment transport that affects the bar is insufficient to cause bar migration. Instead, the bar is subjected to weak continuous onshore sediment transport that erodes the bar and recycles the sediment to the profile further inshore.

7.8 Long term bar modelling

This is a new approach to modelling beach profile behaviour over long time scales (10 years). Previous models (e.g. Plant et al., 1999) which have attempted to replicate morphologic response on multi-annual timescales have stripped down the processes to allow a single modelled parameter. In contrast the efficiency and stability of the proposed model allow full profile morphology to be modelled.

Although process-based models (e.g. XBEACH, Delft 3d, MIKE 3 etc.) have been shown to give very accurate results on short timescales, it has also been demonstrated that they struggle to reproduce natural bar behaviour for timescales of days to weeks (van Rijn et al., 2003; Plant et al., 2004) and have uncertain skill for longer times scales, (Roelvink et al., 1995; van Rijn et al., 2003). The nearshore has a complexity similar to other non-linear systems and so exhibits sensitivity to initial conditions; this limits the applicability of precise very-long term forecasts (Lorenz, 1963). Additionally, the imprecise knowledge of the underlying physics increases this uncertainty due to the boundary conditions.

Very few studies have attempted to model bar behaviour on multi-year time scales. However, two studies are noted here, Plant et al. (1999) and Ruessink et al. (2007). Plant et al. (1999) developed a parametric model that reduced the cross-shore profile to a single point to represent the bar crest. The location and migration of this point was then modelled over a timescale O(10 year). Ruessink et al. (2007) presented an alongshore uniform deterministic wave-averaged profile model which has subsequently been used over time scales of up to ~500 days (Ruessink and Kuriyama, 2008). The model presented here fits between these two extremes:

- It is similar to Plant et al. (1999) in that it models bar behaviour on decadal timescales,
whereas, Ruessink et al. (2007) is on the scale of O(years)

- It is similar to Ruessink et al. (2007) as it models complete profile evolution rather than just bar crest location (unlike Plant et al., 1999).

The model presented here also predicts behaviour in common with both models and so it is useful to compare and contrast these with models.

Model drift and stability are important problems when running a model for long time scales. Although the model remains stable in all the long term model runs, under some of the initial runs it was noted that when the model was run for a sufficient time with constant wave height and no tide, instabilities developed. This is because the tide (and to some extent, the varying the position of the shoreline due to run-up and set-up under varying wave heights) advected the shape function over the domain which effectively smoothes the profile. As Figure 6-17 shows, one of the areas that were associated with an anomalous feature was the shoreline, where cut back was noted. Ruessink et al.'s (2007) model also showed issues with modelling the shoreline morphology. They note that their model is unable to treat sediment in a multifractal way, and so the foreshore lag deposition noted by Stauble and Cialone (1996) was not modelled—a possible cause of their model runs ending prematurely due to unrealistic over-steepening of the foreshore. To overcome this, a fixed layer approach was taken, in that landward of the low tide line, the profile was restricted from eroding below the initial profile (sediment was allowed to accrete above this level, and then erode down to it). This approach could be taken with the proposed model if it was necessary to simulate micro-tidal regimes.

The main issue with model drift is the need to ensure sediment conservation. As described in Section 6.1.8, the model presented in this thesis strictly maintains sediment conservation. This is done by comparing the calculated volume of the profile (assuming the profile has a finite width of 1 m) at each time-step with that at the beginning of the model run. Any change in volume is rectified (i.e. added or subtracted) over the entire wet profile, in a similar manner to Mariño-Tapia et al. (2007b). This can lead to sediment erosion or accretion beyond the depth of closure.
(Section 6.1.5), which can be used as a proxy to record how much sediment is added/removed to the profile to maintain sediment conservation (i.e. Figure 6-23). Both the parametric model of Mariño-Tapia et al. (2007b) and processed based model of Ruessink et al. (2007) also strictly conserve sediment.

In the model presented in this thesis, bar development from a linear profile initialised near the breakpoint (within Region 4 and 5, about Point D). As the profile response time is greater than the tidal period, the bar forms around a tidally averaged point D. This is in agreement with the literature suggesting a breakpoint origin for sand bars (e.g. Dean, 1973; Dally, 1987). However, this result appears to be in contrast with the Plant et al. (1999) model in which bars are initialised at the shoreline. As there are no bar generation mechanisms in the Plant et al. (1999) model, bar genesis occurs at an arbitrary position. Observations from multi-barred beaches (e.g. Ruessink and Kroon (1994), Shand and Bailey (1999)) show bar generation ‘near’ the shoreline (the behaviour the Plant et al. (1999) model replicates) followed by offshore migration, whereas this model shows bar generation at the sediment convergence generally associated with the breakpoint. However, as near-shore bar formation described by e.g. Ruessink and Kroon (1994) is on a multi-barred profile, the inner bar is generated in a secondary sediment convergence zone, however, as the present model does not produce multiple bars (and their associated energy dissipation) this secondary convergence, and so nearshore bar genesis is not simulated.

The model replicates offshore migration under increasing wave conditions. This is shown in Figure 6-19, which tests the profile behaviour to changing energy conditions, and in Figure 6-30, the decadal model run. Offshore migration is due to the shape function expanding seawards, with the convergence point moving offshore. The bar becomes subjected to offshore transport, and accretion at the seaward edge. This is in agreement with observations (e.g. Sallenger et al., 1985; Sallenger and Howd, 1989). Both the Plant et al. (1999) and Ruessink et al. (2007) models showed similar behaviour. Plant et al.’s (1999) model assumed bar migration towards an equilibrium position \(X_{eq}\) that was energy dependent (e.g. (2-31)). The form of the relationship between the \(X_{eq}\) and \(H\) provided one of the main tuning parameters of the model.
Although this heuristic model was conceptually based on theory and observation, the process-based model of Ruessink et al. (2007) predicted offshore bar migration solely through inclusion of physical sediment transport processes. During energetic breaking conditions, there is net offshore directed transport over the bar (peaking at the crest) in the Ruessink et al. (2007) model, primarily caused by suspended sediment transport, although bedload transport peaked just seawards of the bar crest. There is onshore skewness induced transport in the shoaling zone, which converges with the offshore transport at the seaward flank of the bar. This leads to offshore bar migration, widening of the surf-zone and steepening of the outer edge of the bar. These suggested processes are in good qualitative agreement with the model presented here. Ruessink et al.'s (2007) shoaling zone transport is the calculated equivalent of the observed oscillatory component shape function presented here. The offshore transport in the surf-zone is equivalent to the mean component shape function. The bar evolution patterns are also in agreement with these results. The bar is shown to migrate offshore under energetic conditions in Figure 6-31 (correlation between the contour and $h_b$), surf-zone expansion can be observed in Figure 6-33 (compare December with February) and Figure 6-34 (the increasing separation between the berm (red) and the bar (blue) during the early part of the year), and steepening of the outer bar in Figure 6-32 (i.e. between Nov and peak profile in Feb).

Under low energy conditions, all three models predicted onshore bar migration. The Plant et al. (1999) model responded to $X_{eq}$ moving onshore in response to its fixed relationship with the incident wave conditions. Unlike many profile models, the Ruessink et al., (2007) did capture onshore bar migration. Traditionally profile models have failed to accurately replicate onshore migration (e.g. Gallagher et al., 1998). Marín-Tapia et al. (2007b) did model the onshore events in one of the three model experiments, however, it was still not captured as well as the offshore events. This is complicated by the energetics approach not being strictly applicable under low energy conditions. Hoefel and Elgar (2003) suggested a empirical term to allow for acceleration, which has been used to successfully model onshore bar migration. Plant et al. (2006) suggested that the alongshore bathymetric non-uniformities commonly present under
low energy conditions may be important to onshore transport, acting as a "dynamic attractor". Plant et al. (2006) hypothesise that the difficulty experienced by coupled and non-coupled models in predicting onshore transport is not due to a lack of a particular process, but rather treating the profile as alongshore uniform. This theory presents a challenge to the entire approach compressing alongshore uniform coasts to 2D profile models, however Ruessink et al. (2007) showed that this dynamic attractor was not relevant in their present study and so is not a universal mechanism. Onshore transport was modelled by the Ruessink et al. (2007) model under conditions of energetic, weakly to non-breaking conditions. Net-onshore transport associated with skewed near-bed orbital wave motions drove the onshore migration. The model presented in this thesis also replicates onshore bar migration, and like the Ruessink et al. (2007), the primary sediment mechanism is wave driven transport (the oscillatory component shape function). Ruessink et al.'s (2007) qualification of weakly- to non-breaking conditions is equivalent to what is considered to be low energetic conditions in the present study, as no definition between breaking, weakly breaking and breaking conditions is made. Ruessink et al. (2007) also note that when waves were small, net-transport rates were small and so the bar remains static. Results presented in this study show onshore bar migration under low energy conditions (e.g. Figure 6-29 - Figure 6-34). This is due to the new shape function having a different functional form under low energy conditions that allow onshore transport throughout the cross-shore profile. In-line with Ruessink et al. (2007), under very low energy conditions (e.g. \( h_b \approx 0.5 \text{ m} \)) the present model predicts transport rates that are so small that the bar is effectively static (e.g. Figure 6-19, Run 2\_1 – 5\_1).

Observations have shown that bar migration is more rapid during offshore migration, than during onshore migration (e.g. Gallagher et al., 1998). Replication of this behaviour is one of the key aspects of the Plant et al. (1999) model, as it includes a variable bar migration rate. This is included in (2-31) as \( \alpha \), which is a multiplier of the migration rate, and is a function of energy level. As the bar responds much more rapidly under high energy conditions, the annual average bar position moves offshore, as the lower onshore migration rates do not allow the bar to
completely recover from the winter conditions. This is observed in the present model in Figure 6-19 and Figure 6-20 which show that the same change in energy (e.g. $dh_b = \pm 1 \text{ m}$) leads to a larger offshore migration compared to onshore migration. The physical reason for differential migration rates is that the under high-energy conditions the sediment-transport rates are greater and occur over a larger area than under low-energy conditions, and so a larger feature develops. Once the energy level drops, the sediment-transport rates also drop, and so in addition to having a larger feature to erode, the rates of erosion are smaller.

The process-based model of Ruessink et al. (2007) includes a non-linear wave-averaged sub-model, rather than the more complex wave-resolving approach. This allows morphological predictions at the timescale of a dominant forcings (the storm-calm cycle $O(\text{days} - \text{weeks})$), with a time-step of $dt = 1 \text{ hr}$ (compared to $dt = 0.1 \text{ s}$ typical of wave resolving models). Although Boussinesq-type models have a more thorough treatment of the hydrodynamics, the intensive processing required to account for such small time-steps has limited their application to the lab (e.g. Rakha et al., 1997) and short duration (few days maximum) field data (e.g. Long et al., 2004). In contrast Ruessink et al. (2007) ran their model for a 44-day period, and subsequently Ruessink and Kuriyama (2008) ran the model of periods up to 540 days (a timescale two orders of magnitude greater than that of the forcings). Although such time scales are significantly longer than previous studies with process-based models, they are still insufficient to capture the long-term (multi-annual to decadal) behaviour that has been observed (e.g. Ruessink and Kroon, 1994; Shand et al., 1999; Shand and Bailey, 1999; Ruessink and Terwindt, 2000). In contrast, the Plant et al. (1999) point model was so abstracted that much longer time scale simulations were possible, and in such runs, the modelled bar crest does exhibit aspects of Net Offshore Migration (NOM). However, many processes were not included in the model, and so only aspects of bar behaviour can be considered. The present study falls between these models in allowing a number of aspects of profile behaviour, and long-time scales to be modelled. The model runs do replicate aspects of NOM. During the spin-up period, each winter the bar migrates further offshore than in the previous winter. This produces a signal
that is very similar to that of Plant et al. (1999). In tests of the behavioural range of the model, Plant et al. (1999) forced their model with a sinusoidal forcing time series on a shoreline initialled bar to test a range of coefficients. In the present study, the berm location (e.g. the zero contour in Figure 6-31) makes a similar pattern to bar crest of Plant et al. (1999) (Figure 2-24). Noting that the Plant et al.’s (1999) bar crest tends toward a position approximately the middle of the surf-zone, the berm behaviour (of the new model) is remarkably similar.

As the forcing $h_b$ time series in this model is based on a sinusoidal signal, each winter has the same distribution of $h_b$ as the previous, and so the bar is never hit by a significantly stronger event that would strand the entire bar. An aspect of future studies will focus on driving the model with more realistic data, including low frequency, high energy events that may lead to this behaviour. It is hypothesised that when a bar is driven offshore by a significantly higher than average energy winter event, the bar will migrate into water deeper than normal, and if the event was energetic enough, sediment transport in the recovery period will not extend far enough to affect the bar. In such a case, a series of higher than average events are required to allow the bar to migrate onshore again. In the absence of such storms, the stranded bar will be subjected to continuous, but weak, onshore directed sediment divergence that eventually decays the bar while a new bar develops further inshore.

As the model is unable to correctly model bar troughs, development of a multi barred profile is not possible. This means that the outer bar will never protect the inner bar, and so a complete cycle of NOM cannot be accurately modelled. This is because the outer bar shelters the inner bar, and its decay triggers bar generation. As the modelled bar does not protect the inner profile, its decay has limited effect. Future studies will include a mechanism to allow the incident energy to vary over the profile, depending on the morphology, and will allow the model to replicate troughs, and the outer bar to protect the inner bars.

In the present study, five model runs were undertaken to compare the profile response to a range of mean annual energy levels with the same seasonality (i.e. difference between the mean
summer and mean winter energy level). Each model was initiated with a linear profile in late summer. As the bar formed near the breakpoint, it migrated offshore with the widening surfzone. By the winter, even under the lowest energy regime tested the profile is significantly featured. As the linear profile is completely out of equilibrium with the forcing conditions, the profile development is swift. This development slows as the bar reaches a near-equilibrium. With each successive year the profile becomes closer to equilibrium with the conditions, until eventually (~1.5-5 yrs depending on energy level) each seasonal bar migration (and profile) is similar to the previous. At this point the profiles are in near-equilibrium (i.e. the model is spun-up). However, as the profile response time is greater than the seasonal cycle of the forcings, a phase lag develops, and increases with time, (reaching 60 days), and so the most extreme summer and winter profiles (termed peak profiles) occur after the solstices.

Under the lowest energy regime (run ‘a’, Figure 6-26), the profile forms a low energy berm feature similar to those developed under $h_b \leq 1$ m in Figure 6-16. The summer has negligible energy, and so there is no profile development during this period. For most of the year, the profile is subject to very low energy, and so a bermed profile forms. The winter energy level ($h_b \approx 1.3$ m) was insufficient (in terms of energy and time) to form a barred profile, and so it remains stable, slightly building outward from the shoreline with each year. With the increased energy levels in run ‘b’ (Figure 6-27), the winter energy level is sufficient to slightly erode crest of the summer berm, and so, a slight seasonal pattern emerges. However the winter profile is still effectively the summer profile with the crest slightly eroded. Increasing the energy further (run ‘c’ Figure 6-28, and run ‘d’ Figure 6-29) increases the amount of sediment eroded from the crest during the winter, but effectively the same behaviour is apparent. At the highest energy levels (run ‘e’ Figure 6-30, and to some extent run ‘d’), the profile behaviour increases in complexity. This is initially observed in run ‘d’, where the observed patterns are no longer symmetrical around the winter and summer. This can be seen in the profile as it responds to the winter conditions. Although the bar migrates off- and onshore before and after winter, the response of the berm is more complex. Initially the berm cuts shorewards as winter approaches,
and so the terrace widens, however, after winter a new berm develops by infilling the terrace in front of the old berm (which remains static). Additionally, after the bar has migrated to its maximum offshore location and depth, the dropping energy levels divide the bar in two, stranding the outer part of the bar which is seen to decay, while the inner section migrates onshore in response to the lowering energy level. As the morphology is not symmetrical about the peak summer profile, the spring and autumn profile are similar, but distinctly different (compare May and November in Figure 6-33). This is in contrast to observations of Larson and Kraus (1994) which showed very similar spring and autumn profiles.

One of the main drawbacks of the present study is the model inability to replicate bar troughs and the associated reshoaling of waves to a lower energy level. This means the model is unable to produce a true multi-barred profile. An outer bar is hypothesised to be necessary to link outer bar decay, with an inner bar moving from phase i to phase ii (Ruessink and Terwindt (2000); see Section 2.4). Near-shore bar formation is also linked to outer bar decay. These interactions have been shown to be key requirement for true NOM (Ruessink and Terwindt, 2000). While aspects of NOM have been shown to be modelled by the present model, it is not possible to model the whole process while a single $h_b$ value defines the energy level over the cross-shore profile. In an attempt to model the development of a multi-barred (ridge and runnel) coast with a $h/h_b$-based shape function model, Masselink (2004) overcame the same issue. The profile was segregated into a number of cells by the seaward troughs (defined by a gradient less than a critical value), and the $h_b$ value was reassessed for each cell. The sediment transport was assumed to be zero in surf-zone troughs (acting as sediment traps), thus the only ways sediment was transported across troughs was by shoaling transport and bar migration. In the present model, the provision has been made for the inclusion of such a mechanism. However, matching the sediment transport shape function between the different zones leads to difficulties that are beyond the scope of the present thesis, but will investigated in future studies.

The routine developed to produce forcing time series allows control over limits within which random storm/calm periods could occur. Furthermore, these limits could be controlled to
manipulate the annually integrated energy levels, seasonality and likelihood of high/low energy conditions. This allows the influence of these aspects on the forcing conditions to be tested. In the present study, a range annually integrated energy levels were compared; future studies will complement these runs by comparing a range of seasonal energy amplitudes.

As the forcing time-series still contained an inherent randomness (e.g. the wave-height of a particular storm was randomly chosen within a defined (seasonally varying) range), the model also maybe analysed in an ensemble approach, akin to climate modelling. A range of forcing time series could be created, with the same statistical properties, but with the exact timings/strengths of individual storms varying. The model should then be run with these time series and the results will be compared. This would allow the uncertainty of the model to be assessed and quantified.

No account has been taken here of the effect of the initial profile despite other studies showing that the coastal zone exhibits sensitive dependence on initial conditions (Lorenz, 1963). For example, Marín-Tapia et al. (2007b) ran their shape function model with the same forcing time series, but with three different initial profiles (an exponential Dean profile, an average of a series of modelled profiles, and a measured profile), and the resulting bar migration differed between each test. In the testing stage of model development, the effect of the initial profile was tested (see Section 6.2.4); however the influence over the longer time scales was not investigated. There is no mechanism within the model that gives it a memory beyond the previous profile (i.e. the profile is not dependent on the previous 10 profiles), and so the affect of the initial profile would be expected to influence the spin-up time of the model.
7.9 Further work

This research could be extended in two main ways, i) improving the shape function, and ii), enhancing the shape function profile model.

7.9.1 Shape function

The shape function was developed from a large amount of data, from a range of conditions and nearshore regions. However, the shape function still suffers from a paucity of data under some combinations of regions/conditions and only incorporates data from one field site. The following points are suggested foci of further studies to improve the proposed shape function:

- Measurements of sediment concentration higher in the water column may increase the proportion of actual suspended sediment measured and reduce the uncertainty associated with using the present approach to estimate suspended sediment transport rates.
- The shape function suffers from a paucity of data in the high energy shoaling zone, and so, further data from this region will strengthen the proposed shape function in this region.
- Additional flux measurements from the swash-zone and validation with swash bed level measurements will give insight into the swash zone sediment transport behaviour, and will allow further development of the swash zone function.
- As this shape function has been developed from data from a single beach, it would be constructive to compare this shape function to data from other beaches, and incorporate these data into the shape function.
7.9.2 Shape function-based profile model

Initial runs with the shape function-based profile model suggest that model is capable of simulating a range of profile phenomena, and is stable over long timescales. However there are still limitations to this approach. The following have been suggested to overcome some of these:

- The current shape function-based profile model allows only a single (outer) wave breakpoint parameterised via a single value of the breaker depth $h_b$. Consequently it is not possible for waves to reform after initial breaking and so the development of multiple areas of breaking waves and, hence, multiple bars, is not possible in the model. This has been hypothesised to prohibit the modelling of full Net Offshore Migration. Masselink (2004) suggested a mechanism to allow dissipation and multiple breakpoints in such a model and its use resulted in the development of a realistic multi-barred beach. This approach is suggested as the basis of a solution for this model although the greater complexity of the current model means that implementation of their approach is not straightforward.

- In Section 6.2.4 the response to changing energy conditions was examined by initialising the model with the near-equilibrium profile for a particular energy. This gave an insight into the dependence on the initial conditions, but this was not explored further. As the model has no intrinsic mechanism to include a memory (i.e. the future profile is only a function of the present profile and $h_b$) the different initial profile is expected to only affect the model spin-up time.

- As this was only a proof of concept, no comparisons with measured profile datasets have been made. This is an important test that should be undertaken to validate the model.
Plate 8 Sunset.
8 Conclusions

8.1 Objectives 1 and 2

The first objective of this thesis was to develop a new shape function based on measurements of depth-integrated cross-shore suspended sediment transport. Prior to this, the ability of the Maríño-Tapia et al. (2007a) shape function at replicating the new measurements was assessed. First the measured cross-shore velocity moments were compared with the Maríño-Tapia et al. (2007a) results, and showed a good qualitative agreement with little energy dependence. However, upon trying to directly translate this to a measured flux shape function, it was noted that the patterns of sediment transport showed strong energy dependence, and that the velocity moment was not applicable under low energy conditions. The cross-shore patterns in sediment transport showed different but consistent patterns under low and high energy, and so, were suitable for parameterising. Under high-energy conditions, the observed profiles of sediment transport exhibited similar patterns to those reported by Maríño-Tapia et al. (2007a), with onshore transport in the shoaling zone and offshore transport in the surf zone. Under low energy conditions, the observations show onshore-directed transport along the whole profile. This is in direct contrast to the Maríño-Tapia et al. (2007a) parameterisation.

The observed patterns of suspended sediment transport were well behaved when plotted against $h/h_s$. Upon separating the observed net transport into the mean and oscillatory component, it was apparent that the net transport shape function could be made up of component shape functions to represent the mean and oscillatory component of sediment fluxes. As these component shape functions were developed from low and high energy conditions, the shape function is applicable to a wide range of energy conditions. This satisfies part of the second thesis objective. Each component responded independently to energy level (with amplitude terms that were functions of $h_s$) and thus the net-transport shape function had a rich behaviour, giving a more accurate representation of reality.
Previous cross-shore sediment transport parameterisations have not included the swash-zone (e.g., Russell and Huntley (1999), Plant et al. (2001), Aagaard et al. (2002)), although the Mariño-Tapia et al. (2007a) shape function was developed from limited swash-zone data. Part of the second objective of this thesis was to include data from the entire nearshore region including the swash zone in the new shape function, and so the present study has focused considerable attention on developing a plausible parameterisation of swash-zone sediment transport.

The swash zone observations have shown predominantly onshore transport in the inner swash zone under all energy conditions, while the outer swash zone/inner surf-zone transport was energy dependent (offshore directed under high energy conditions and onshore under low energy). Swash transport could be represented by the sum of two opposing parameters to represent onshore and offshore transport. The observations scaled better with $h$ rather than $h/h_b$, although the function amplitude was still a function of $h_b$. Future studies will allow better representation of the individual swash zone processes.

8.2 Objective 3

The third thesis objective was to implement the shape function into a numerical model, and to explore the profile behaviour to simple forcing. This was achieved, and the profile response to simple wave, tide, and varying wave conditions was shown to be sensible. The shape function appeared to be able to predict offshore and onshore bar migration in response to increased and decreased energy conditions. The shape function also allowed bar decay when the energy conditions dropped rapidly.

The offshore swash component was shown to under predict the terrace depth, and so was removed from further model runs. Further study and more data are required to ascertain the exact behaviour of this component. The offshore swash component was the least defendable component in the net shape function, as the amplitude function is weakest.

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As the shape function represents measured fluxes rather than velocity moment, the model did not need a complex wave sub-model, and so processing times and error propagation was limited. This allowed the model to be run on long (decadal) scales. Long term runs show the model is stable and the smoothing scheme conserves sediment.

8.3 Objective 4

The final thesis objective was to run the model on long (decadal) timescales and to explore modelled profile behaviour. Long-term bar behaviour was sensible, with onshore migration under low energy condition, offshore migration under high energy conditions, bar stranding under rapidly dropping energy conditions, and decay of stranded bars subjected to conditions of onshore erosion. These are the first model runs to predict the evolution beach profiles on these timescales and thus the model potentially provide a tool for investigating long-term phenomena such as Net Offshore Migration.
Plate 9 Run-up.

18:40 10th May, 2005
9 References


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Plate 10 Martin Austin, Tim O’Hare, Jonathan Tinker, Tony Butt.

12:00 7th May, 2005