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**UNIVERSITY OF SOUTHAMPTON**

FACULTY OF ENGINEERING AND THE ENVIRONMENT

School of Civil and Environmental Engineering

# PHYSICAL DRIVERS OF SALTMARSH CHANGE IN ENCLOSED MICROTIDAL ESTUARIES

**BY**

**SARAH C. GARDINER**

Thesis submitted for the degree of Doctor of Philosophy

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ABSTRACT

FACULTY OF ENGINEERING AND THE ENVIRONMENT

SCHOOL OF CIVIL AND ENVIRONMENTAL ENGINEERING

Doctor of Philosophy

PHYSICAL DRIVERS OF SALTMARSH CHANGE IN ENCLOSED ESTUARIES

Sarah C. Gardiner

Estuaries are among the most biologically productive ecosystems on the planet, per unit area, with intertidal habitats and particularly saltmarshes providing a variety or ecosystem services and supporting large numbers of both primary and secondary producers. These habitats are globally important and are found throughout tropical to temperate climates. Micro-tidal estuaries are found throughout the world and particularly sensitive to sea-level rise, as they are limited in their ability to adjust and are considered vulnerable to future changes .Hence, at a broad scale, understanding the drivers and mechanisms of saltmarsh change in micro-tidal systems is crucial in aiding decision making in future coastal management. This thesis explores the drivers and mechanisms of saltmarsh change through the development of a conceptual model, which is then tested using Poole Harbour, UK as a case study site. The potential drivers of saltmarsh change were investigated using a multidisciplinary approach, combining a GIS historic change analysis utilising aerial photography, charts and maps, a bathymetric analysis of the harbour morphology and a 2D hydrodynamic TELEMAC model. *Spartina anglica* rapidly colonised the Harbour at the end of the 19$^{th}$ Century increasing the saltmarsh area from approximately 120ha to over 900ha during the 1920's, after which there was a decline in area that has continued to present day However, saltmarsh extent in 2005 was still approximately three times the extent prior to the colonisation of *Spartina anglica.* Poole Harbour is large and dendritic and spatially within the Harbour separate tributaries exhibit clearly distinct saltmarsh erosion and accretion trends. Accretion was seen to occur in relatively sheltered locations with short fetches, fronted by high mudflats, in areas that are flood dominant both in terms of hypsometry as well as tidal peak flow and slack duration. Erosion was seen to occur in relatively exposed areas where the marsh top and fringing mudflats are significantly lower and local sediments have a lower shear velocity than in accretionary regions. Saltmarsh erosion tends to occur in morphologically ebb dominant areas but not exclusively, suggesting multiple drivers are in operation.

Poole Harbour is used in this study as an example of a wider global problem. At a broad scale, observations emphasise that saltmarsh changes occurring elsewhere in the UK, and

potentially elsewhere in the world, may be more complex than often portrayed. Highlighting the need for detailed case by case studies, that use all the data available over a sufficient time period. Multiple drivers of change control the net evolution of saltmarsh in Poole Harbour and this is likely to be a widespread conclusion for other estuaries globally.

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# List of Abbreviations

| | |
|---|---|
| ASMITA | Aggregated Scale Morphological Interaction between Inlet and the adjacent coast |
| BP | Before present |
| CD | Chart Datum |
| DTM | Digital terrain model |
| GIS | Geographical Information System |
| HAT | Highest astronomical tide |
| HW | High water |
| LIDAR | Light detection and ranging |
| LW | Low water |
| MDhw | Mean depth at high water |
| MDlw | Mean depth at low water |
| MHW | Mean High Water |
| MHWN | Mean high water neaps |
| MHWS | Mean high water springs |
| MLW | Mean Low Water |
| MLWN | Mean low water neaps |
| MLWS | Mean low water springs |
| OD | Ordnance Datum |
| OS | Ordnance Survey |
| PHC | Poole Harbour Commissioners |
| RMS | Root mean square |
| SCOPAC | Standing Conference On Problems Associated with the Coast |
| SOC | Southampton Oceanography Centre |
| SSSI | Site of Special Scientific Interest |

# Declaration of Authorship

I, Sarah Catherine Gardiner declare that this thesis entitled 'Physical drivers of saltmarsh change in enclosed microtidal estuaries' and the work presented in the thesis are both my own and have been generated by me as the result of my own original research. I confirm that:

- This work was done wholly or mainly while in candidature from a research degree at this University;
- Where any part of this thesis has previously been submitted for a degree or any other qualification at the University or any other institution, this has been clearly stated;
- Where I have consulted the published work of others, this is always clearly attributed;
- Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own;
- I have acknowledged all main sources of help;

Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself;

Parts of this work have been presented as:

· Gardiner S., Nicholls R. and Tanton T. (2010) Management Implications of flood/ebb tidal dominance on saltmarsh and intertidal habitat stability: a case study of Poole Harbour. Littoral 2010 – Adapting to Global Change at the Coast: Leadership, Innovation, and Investment 06004 (2011) DOI: 10.1051/litt/201106004

· Gardiner S., Nicholls R. and Tanton T. (2010) Flood/ebb tidal dominance: Its influence on saltmarsh and intertidal habitat stability in Poole Harbour, UK.Physics of Estuaries and Coastal Seas 2010, Sri Lanka.

Signed:.......................................................................................................................

Date:..........................................................................................................................

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# 1 Introduction

On geological timescales tidal basins can be considered as temporary, short-lived features. Their existence is the result of a complex interaction between the inherited morphology and substrate, sea-level variations and tidal motions, sediment availability and sediment distribution processes (Van Goor *et al.*, 2003). Within estuaries physical processes form the main driver for the many complex and linked sedimentological, biological and chemical processes (Dyer, 1997). Historically, estuaries have been focal points for human activities and development. Some uses such as ports, exploit the shelter offered by the physical structure of the estuary (Buck, 1997). Other uses include exploiting the rich natural resources of fish and shellfish available within estuarine environments. Estuaries are often used by certain fish species as breeding and nursery grounds, attracting large numbers of predatory bird and wildlife species. Estuaries have also in recent years become the focus for leisure activities such as sailing and other water sports.

The use of estuaries has increased, not only for transport and port development, but also in new uses such as water extraction and discharges of waste. Population growth and development of urban industrial and agricultural areas has led to reclamation and draining of low lying areas, all of which impose pressures on river and estuary systems. Anthropogenic effects have historically been a major agent influencing the morphology of estuaries, either directly by means of engineering works or indirectly by modifying the physical, chemical and/or biological processes within the estuary.

Overexploitation, physical modification, nutrient and sediment pollution, introduction of invasive species, global climate change and sea-level rise have led to a decline in coastal habitats (Waycott et al., 2009, Valiela, 2006, Duarte et al., 2009), such as seagrass beds, saltmarshes and mangroves over the last century. As estuaries are among the most biologically productive ecosystems on the planet, per unit area, with intertidal habitats supporting large numbers of birds and fish, this is a serious issue. For example, Costanza et al., (1997) estimated that of the US$33 trillion worth of annual global ecosystem services, US$10.6 trillion was contributed by coastal systems and a further US$10.3 trillion was contributed from other marine services.

Coastal habitats occur in many different settings globally, however those situated within micro-tidal systems are particularly vulnerable, due to their inability to adapt to rising sea levels and these micro-tidal systems occur widely around the world.

As an acknowledgement of the ecological functions that estuaries perform, large areas in the UK, Europe (and more widely) have been designated as protected areas. Within Europe under the EC Habitats and Species Directive, habitats including saltmarshes and mudflats, reedbeds, sand dunes, vegetated shingle, coastal grazing marsh, saline lagoons and sea grass beds are protected. However, habitat areas in estuaries are widely found to be declining (UK National Ecosystem Assessment, 2011).

Intertidal areas in the UK have been shown to have declined with the building of extensive defence networks (notably during the 19th Century). Land reclamation, changes in sediment availability and slow subsidence due to glacial isostatic adjustment all being important influences (Carpenter and Pye, 1996). Consequently, significant losses are likely to continue into the future and these are likely to be exacerbated by sea-level rise (UK National Ecosystem Assessment, 2011, Doody, 2008). Expected responses to sea-level rise are vertical accretion and migration inland, both of which have been restricted by coastal defences (Nicholls and Wilson, 2001, de la Vega-Leinert and Nicholls, 2008, Lee, 2001).

In light of the importance of estuaries, both environmentally and commercially, understanding the processes which drive habitat change in them, the complex mechanisms by which change occurs and the consequences of change is crucial. This is needed to better manage these areas and conserve the habitats situated within them, as well as giving insight into the changes that may occur in these areas with future development. Saltmarsh loss is of particular concern (Valiela, 2006, UK National Ecosystem Assessment, 2011) and this thesis will focus on saltmarsh change (gains and losses).

## 1.1 Research Aims

Understanding the drivers and mechanisms of coastal saltmarsh change, is crucial to future coastal and resource management in estuarine environments under rising sea levels. Although much research has been done to understand the drivers of saltmarsh loss within estuaries, the balancing process of gain has received less attention, reflecting the global concern about these losses. Hence, the main aim of this research is to identify drivers and mechanisms of saltmarsh change at estuary and sub-estuary scales for gains as well as losses. The focus is on micro-tidal systems due to their high vulnerability and relatively frequent global occurrence.

This research will allow a better understanding of historic trends and the prognosis for these systems over the coming decades.

## 1.2 Research Objectives

In summary, the research has the following objectives which are expanded upon in Chapters 2, 3 and 4.

1. Develop a conceptual framework

   Through a literature review, thoroughly investigate the previously studied drivers and mechanisms of salt marsh change, creating a conceptual framework to assist in estuarine management (Section 2).

2. Select a suitable micro-tidal estuary as a test location.

   In order to study saltmarsh changes within a micro-tidal climate a suitable case study site will be selected. Criteria for the choice of case study site are determined through two main factors; local management issues involving saltmarshes and data availability (Section 3).

3. Assess historic saltmarsh trends to identify candidate mechanisms of change at the test location using an historic change analysis;

   The historic change analysis will identify any changes within the intertidal zone and will quantify historic saltmarsh trends within the selected region, using maps, charts and aerial photography available.

4. Assess the drivers and mechanisms of change;

   Firstly the setting of the changes observed from the historic change analysis will be examined by investigating the morphology of the estuary.

Using the conceptual understanding developed in Section 2 and the historic change analysis, the drivers and primarily the physical mechanisms of the changes observed will be investigated.

Mechanisms of change will also be assessed and quantified. Through this process erosional and accretional trends at an estuary and sub-estuary scale can be defined and drivers for these changes identified.

Finally chemical and biological mechanisms of change are discussed through the use of the conceptual model developed as part of objective 1.

5. Assess the implications of these results for other estuarine saltmarsh systems

## 1.3 Novelty/Originality of Research

This research requires a multidisciplinary approach in order to understand the complex biogeomorphology of saltmarsh change and by combining a thorough knowledge of the potential causes of saltmarsh change a broad overview of the drivers and mechanisms can be assessed. Several methods of analysis will be used in order to investigate the setting of the change and mechanisms of saltmarsh erosion and accretion and link these to drivers.

Saltmarshes globally as well as in Europe have been in decline throughout the 20$^{th}$ Century and in the future will be under increasing pressure due to sea-level rise, even if legislation, such the Habitats Directive in Europe, addresses the pressure of coastal development. Saltmarshes are important both in terms of designated habitats (which are protected by European law) as well as providing a variety of ecosystem services. Hence, at a broad scale, identifying and understanding the drivers and mechanisms of change in saltmarsh systems and the timescales they operate over, is crucial in assisting decision making in future coastal management.

## 1.4 Structure of Thesis

This thesis is organised into nine Chapters.  Chapter 2 will review the relevant literature, firstly discussing coastal and estuarine hydrodynamics and morphology in general and then outlining the key drivers and mechanisms of saltmarsh change, which can then be developed into a conceptual model of change. Both natural and human drivers will be considered as well as the relevant biological, chemical and physical mechanisms. This analysis focuses primarily on the importance of physical mechanisms and drivers over biological and chemical components and they form the focus in the rest of the thesis. Biological and chemical drivers are discussed as part of the conceptual model of saltmarsh change. Chapter 2 also introduces the concept of estuarine modelling as a tool for investigating the fundamental physical processes at different spatial scales. Chapter 3 outlines the selection of a suitable case study site and a background literature review to identify locally relevant potential saltmarsh change drivers and mechanisms. Chapter 4 outlines the data and methods used to investigate historic saltmarsh change  and the setting of change, at the selected case study site. This involves several methods: 1) identifying the magnitude of saltmarsh change via historical analysis, 2) understanding the mechanisms of change and their relationship to physical changes, including the (a) morphology and hypsometry of the site and (b) tidal asymmetry. The results from these methods are presented in Chapters 5, 6 and 7, respectively, with a summary presented at the end of each Chapter. A discussion, of these results and their wider implications to other sites, including recommendations for further work, are presented in Chapter 8. Chapter 9 presents the overall conclusions.

# 2 Literature Review

The following chapter reviews the relevant literature with respect to the aims and objectives discussed in Chapter 1. Saltmarshes can occur in many different forms but are generally developed in low-energy environments where wave action is limited, such as barrier coasts, embayments and estuaries (Allen, 2000). Within this study the focus is on saltmarshes situated within estuaries or semi-enclosed water bodies. However, many of the drivers and mechanisms of change are expected to be universally applicable to other saltmarshes and coastal habitats, such as mangroves.

Although each estuary has unique physical features that influence its biogeomorphology, driven by the general bathymetry, tidal range, river discharge and sediment availability, some generalisations across estuaries can be made. Firstly estuaries are discussed in general and with regards to their hydrodynamics, morphology and physical setting and ecology. For clarity these are discussed discretely, however there are crucial interactions and non-linear feedbacks that occur between the hydrodynamics, morphology and ecology. Secondly these fundamental processes are discussed in terms of saltmarsh drivers and mechanisms of change and a conceptual model of saltmarsh change is developed. Thirdly estuarine modelling as a tool to assist the classification of estuaries and saltmarsh change is described.

## 2.1 Estuaries

The term estuary, derived from the latin ‘aestus’ meaning tide, refers to a tongue of the sea reaching inland (Woodroffe, 2002). A widely used definition describes an estuary as ‘a semi-enclosed coastal body of water having a free connection with the open sea and within which sea water is measurably diluted with fresh water derived from land drainage’ (Woodroffe, 2002).

Estuarine shape and extent are constantly altered by the erosion and deposition of sediment and hence have a wide variety of forms that evolve over different time scales (Table 2.1). Most estuaries are geologically young and have developed when the last post-glacial rise in sea level inundated coastlines and drowned river valleys. Two main processes drive the evolution of an estuary. Firstly the long term sediment budget, being either from inland (predominantly from fluvial sources) or the open coast, along with the direction and magnitude of the long-term averaged sediment transport, (Dronkers, 1986). Secondly abrupt and cyclical changes in estuarine morphology cause hydrodynamic processes to vary over temporal and spatial scales, from storm events and engineering works, individual tidal cycles to the spring–neap cycle, seasonally or the 18.6 year nodal cycle, (Hanson and Nicholls, 2003, Townend, 2002). Estuaries are also home to complex habitats that develop under these conditions, evolving to cope with the extremes of constantly changing salinity and tidal levels. Through biogeomorphological feedback mechanisms, coastal habitats also contribute to the form and extent of the estuary and sediment distribution.

**Table 2.1 Geomorphological scales in an estuary. After (Hanson and Nicholls, 2003, Townend, 2002, Stive et al., 2003).**

| SCALE | TIME | SPACE |
|---|---|---|
| Very Long | Geological (1,000s-1,000,000s years) | Underlying form and geology of area and adjacent sea area. |
| Long | Historical (100s years) | Large scale features (channels/islands)<br><br>Human Influence (protection/dredging, landclaim) |
| Medium | Decadal (10-100 years)<br><br>18.6 year nodal cycle | Internal relationships- mudflats, saltmarshes, channels, creeks<br><br>Cumulative effects of long term change (e.g. sea level, sediment supply) |
| Short | Seasonal/Annual | Fluxes in and out of estuary. Internal relationships |
| Very short | Tidal period (hours) | Ebb and flood tides |
| | Wave period (minutes/seconds) | Ripples |

### 2.1.1 Estuarine Hydrodynamics

#### *2.1.1.1* **Tides**

Tides are shallow water waves, generated by the gravitational forces exerted by the sun and moon on the Earth's oceans (Brown et al., 1997). The tide is the central feature around which saltmarsh functions through platform accretion, (Allen, 2000): it sets the altitudinal range of a marsh and is crucial to the development and maintenance of the creek networks.

**Tidal Range**

The tide sets the altitudinal range of a marsh and the zonation of species within an estuary. The tidal range within an estuary, along with the slope, determines the amount of space available for the marsh to colonise.

Tidal range is typically classified into three categories, macro (> 4 m), meso (2-4 m) and micro < 2 m) tidal. The global distribution of tidal range for the M2 constituent is shown in Figure 2.1, from the OSU TOPEX/Poseidon Global Inverse Solution (TPXO), (Egbert and Erofeeva, 2002).

Examples of macro-tidal ranges can be seen in the Bristol Channel, (UK), the Fly River, (Papua New Guinea), San Sebastien Bay, (Tierra del Fuego) and the Bay of Fundy, (US/Canada). Meso-tidal ranges are found throughout the World, including large areas of the west coast of Europe, New Zealand, the Atlantic coast of Europe and Africa and large coastal areas of North and South America. Micro-tidal regions are also found extensively across the world including the Mediterranean Sea, Caribbean Sea, Red Sea, Baltic Sea, the Sea of Japan, regions in Madagascar, Brasil, Sri Lanka, South east Asia and South Australia. Micro-tidal regions are more sensitive to sea-level rise, as they are limited in their ability to adjust with sea-level rise and are considered vulnerable to future changes (cf(Nicholls et al., 1999)).

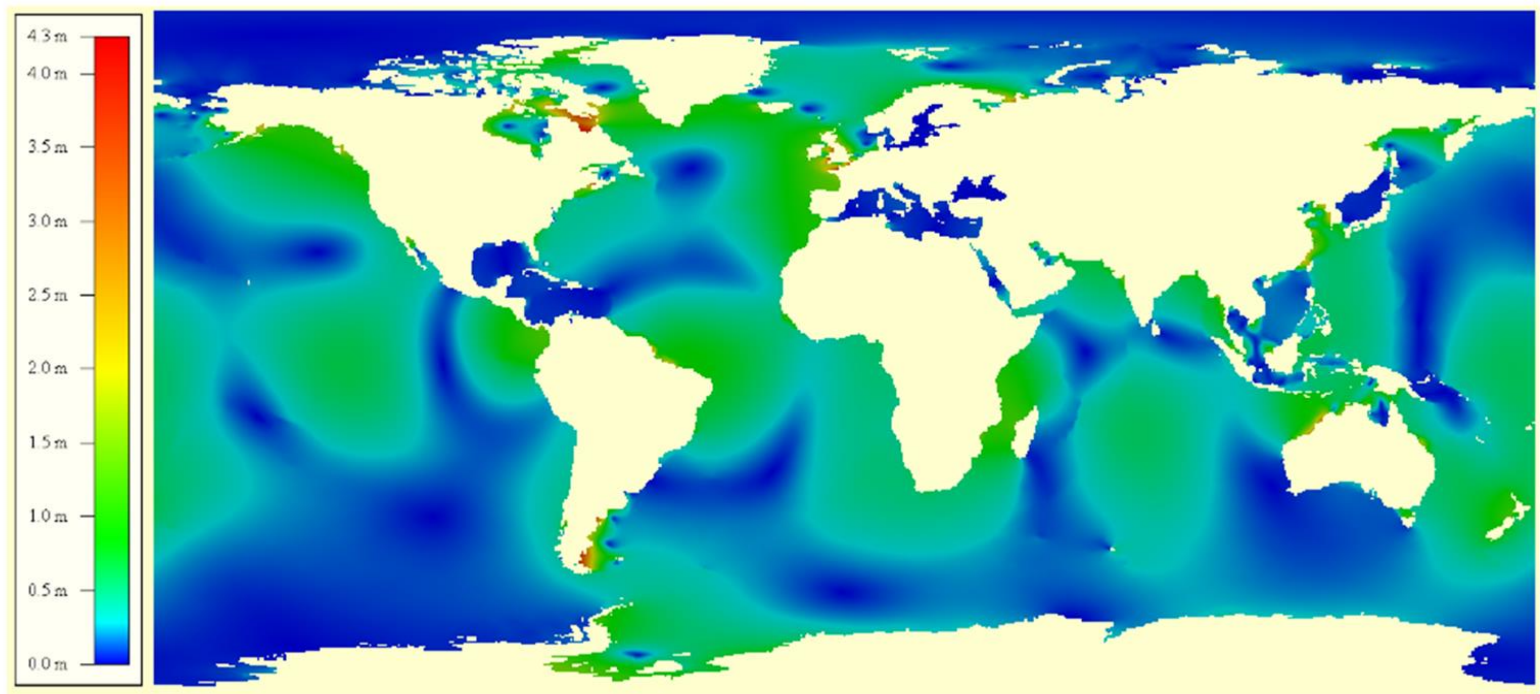



**Figure 2.1** Amplitude of the M2 tide (Data source OSU TOPEX/Poseidon Global Inverse Solution (TPXO) accessed http://volkov.oce.orst.edu/tides/global.html, Egbert and Erofeeva, 2002)

Tidal waves can become distorted when entering estuaries and embayments, either becoming compressed and increasing in tidal range as the sides of the estuary converge, or decreasing in tidal height due to the friction between the tidal waters and the estuary bed. For estuaries where the effect of convergence is greater than friction, the tidal range increases upstream and is called a hypersynchronous estuary. These types of estuaries may form a tidal bore on the incoming tide. For estuaries where the effect of convergence is less than friction, the tidal range decreases up stream and is called a hyposynchronous estuary. Where convergence equals friction the tidal range is uniform and is called a synchronous estuary (Dyer, 1997)

**Tidal Asymmetry**

The importance of asymmetric tidal cycles in the transport and accumulation of sediment in shallow estuaries is well established, (Boothroyd and Hubbard, 1975). Flood dominant estuaries, have shorter duration, higher velocity flood tides, and tend to infill channels with sediment. Whereas ebb dominant systems, have shorter, higher velocity ebb tides, and tend to flush bed-load sediment seaward, (Friedrichs and Aubrey, 1988).

Flood dominance occurs when the combined effects of bottom friction and tidal variation of the deep water is large, causing the tidal wave crest (HW) to move more quickly than the trough (LW) producing a short duration flood phase of the tide and more rapid flood currents, (Dronkers, 1986). Ebb dominance occurs within estuaries essentially by interactions between the deep channels and the shallow water areas, and the varying distribution of friction during the tide. Aldridge (1997) illustrated that tidal asymmetry throughout an estuary could be linked to sediment transport pathways and morphodynamics, it was also demonstrated that although estuaries are often generalised as either flood or ebb dominant, variations within the estuary may also occur. Large areas of tidal flats and marshes significantly alter the dynamics of an estuary, through frictional forces, sediment sinks and water storage.

The influence of tidal asymmetry on the residual fluxes of coarse and fine sediment is different owing to different transport properties of the sediments, which is later discussed in Section 2.1.2.1. The suspension load of coarse sediment (e.g. sand) is strongly limited by current speed and adapts to changes in current speed rapidly. For fine sediment (e.g. silts and clays), saturation of the suspended load rarely occurs, with most sediment deposition occurring at only very low current speeds with a settling time delay (settling lag) which can be an important control on sediment transport, (Dronkers, 1986). In general the asymmetry of peak tidal flows is considered to be the main driver of coarse sediment, whereas the difference in slack water duration before flood and ebb affects the residual transport of fine fractions (Dronkers, 1986, Friedrichs and Perry, 2001, Friedrichs, 2011). In shallow water a larger proportion of the suspended sediment will have time to settle, favouring net deposition in shallow areas for the period of the slack duration (Friedrichs, 2011). However, this is also controlled by the settling velocity which is complicated when applied to fine sediments, due to the formation of flocculates (section 2.1.2.1) which affects the settling velocity.

Dronkers (1986) distinguished two types of channel geometry in irregularly shaped estuaries (Figure 2.2). Type 1 estuaries with shallow channels that decrease with depth landward and tidal flats below mean sea level and type 2 estuaries with deep channels throughout and tidal flats above mean sea level. Where, in Type 1 estuaries the slack water period before ebb will exceed the slack water period before flood, hence a residual import of fine sediments is favoured. The opposite is true in case 2. A natural feedback between these 2 forms of sediment accretion and then erosion leads to a fluctuation of form around an equilibrium. The concept of estuarine equilibrium suggests that under a given set of hydrodynamic conditions an estuary will evolve to a stable equilibrium morphology (Moore et al., 2009). However, it is unlikely that a fully stable estuary can exist as external forces acting on the estuary are not uniform over time (Dronkers, 1986), such as human interference, tides and waves.

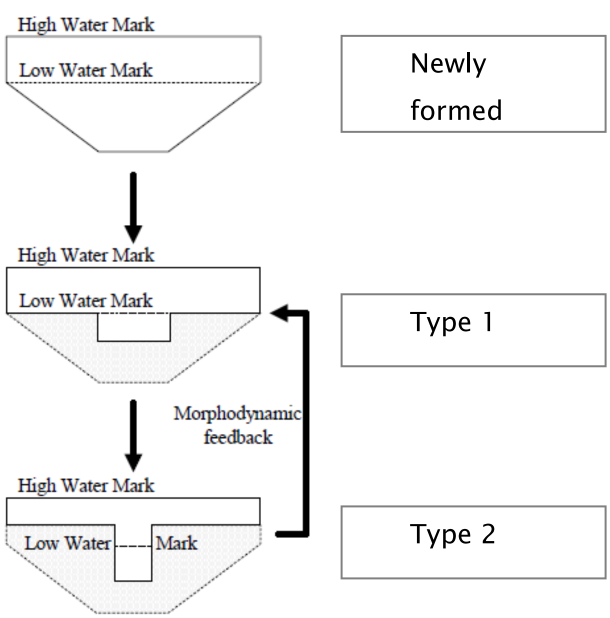



**Figure 2.2 Illustration of channel form with tidal asymmetry and feedbacks (ABPmer, 2008, Pethick, 1994)**

Dronkers (1986) developed the asymmetry ratio, shown in Equation 2.4.

$$\gamma = \left(\frac{h+a}{h-a}\right)^2 \bullet \frac{S_{lw}}{S_{hw}}$$

Equation 2.4

Where: $h$ = the average depth of the channel or the mean hydraulic depth given by, $h=a+V_{lw}/S_{lw}$, $a$ = the tidal amplitude, $S_{lw}$ = the surface area at low water, $S_{hw}$ = the surface area at high water and $V_{hw}$ and $V_{lw}$, the volumes at high and low water.

A value of $\gamma$ equal to 1 suggests a uniform tide, with values >1 indicating flood dominance and <1 indicating ebb dominance. This equation was applied by Townend (2005) to 155 estuaries across the UK, a large amount of scatter was noted in the results, potentially as a consequence of data quality, however at a cursory level a large number of UK estuaries were observed to be ebb dominant.

An alternative approach to investigate tidal asymmetry is given by Freidrichs and Aubrey (1988). It was found, in shallow estuaries of the US Atlantic coast, that the magnitude of the ratio tidal amplitude and hydraulic depth can indicate overall tidal asymmetry. For small $a/h$ values (<0.2) estuaries tend to be ebb-dominant, regardless of the extent of the tidal flats or marshes. Equally for large $a/h$ values (>0.3) estuaries tend to be flood dominant. However, $a/h$ is often most applicable to flood dominant systems and the parameter derived from the ratio between the intertidal storage in flats and marshes and volume of channels at mean sea level is mostly responsible for asymmetric tides in ebb dominant estuaries. Where $a/h$ does not signify either flood or ebb dominance If $0.2>a/h<0.3$ then $Vs/Vc$ can be used as a relative indicator between different estuaries.

Other tidal asymmetry relationships, including asymmetry that arises as a result of the distortion of the tidal wave through frictional affects, are discussed by Freidrichs and Aubrey (1988), Wang *et al*, (2002). This can be related to changes in the relative phase and amplitude of the M4 and M2 tidal constituents. A direct measurement of non-linear distortion and therefore the magnitude of the asymmetry are calculated as the M4 and M2 amplitude ratio ($M4_{Amp}/M2_{Amp}$). A ratio of 0 indicates a completely undistorted tide and a ratio > 0.01 indicates significant distortion of the tidal wave.

Secondly, the direction of the asymmetry (flood or ebb) can be defined by calculating the phase of M4 relative to M2 ($2M2_{phase}$-$M4_{phase}$). Where a relative phase between 0˚ and 180˚

indicates that the duration of the ebb tide is longer than the duration of the flood tide, as the same volume of water flows in and out of the estuary during both the ebb and the flood tidal stage the flow rate will be greatest and therefore the tide will be flood dominant. Other values of relative phase indicate that the duration of the ebb tide is shorter than the duration of the flood tide and therefore the tide can be considered ebb dominant, (Friedrichs and Aubrey, 1988).

Pethick (1980) and later Friedrichs (2010) described channel depth with relation to tidal velocities in estuaries (Figure 2.3). Illustrating how the timing of peak tidal velocity varies depending on the local morphology: an estuary dominated by channel depth (a) vs an estuary dominated by width (c).

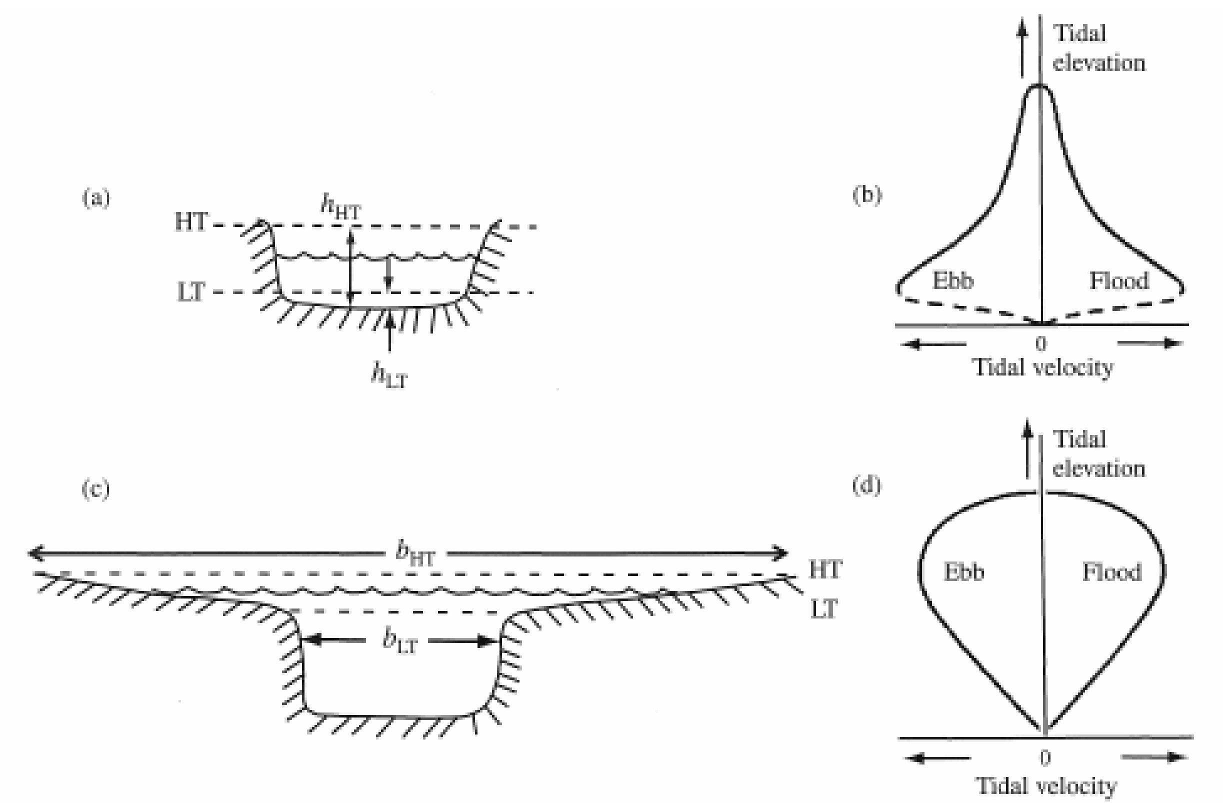



**Figure 2.3 Illustrative tidal velocity curves (b) and (d) for estuaries dominated by tidal variations in the channel depth (a) and estuaries dominated by tidal variations in estuary width (c) respectively.**

Pethick (1994) describes tidal asymmetry in terms of tidal wave progression within an estuary. When estuaries are wide and deep and the mean depth is significantly greater at high tide than at low tide, the tidal wave progression is more rapid at high water than low. Hence an asymmetric wave, giving a flood dominant velocity, resulting in the estuary behaving as a sediment sink with net sediment input. Pethick (1994) suggests that as sedimentation continues the elevation of the intertidal would increase and hence the mean depth of channel would decrease. Leading to a reduction in sedimentation rates and perhaps even a reversal to short term erosion, the estuarine form would in this way fluctuate around an equilibrium form. Hence the ratio between mean depth at high water (*MDhw*) and mean depth at low water (*MDlw*) can indicate tidal asymmetry (*MDhw* > *MDlw* flood dominant, *MDhw* < *MDlw* ebb dominant).

These asymmetry calculations and ratios are discussed further in Chapter 7 when applied in order to assess the tidal asymmetry within Poole Harbour.

#### *2.1.1.2* **Waves**

Locally generated wind waves can have a large impact on the morphological equilibrium of shallow estuaries (Fagherazzi and Wiberg, 2009), creating bed shear stresses and affecting turbidity (Anderson, 1972, Ward et al., 1984). Fagherazzi and Wiberg (2009), consider wave generated shear stresses to be the main mechanism responsible for erosion of sediment from tidal flats, influencing sediment budgets, biogeochemical processes and ultimately the evolution of the estuary. Waves mobilise sediments at the seabed through orbital velocities which attenuate with depth (Soulsby, 1997), this attenuation means that orbital velocities (and therefore bed shear stresses) are greater over intertidal areas compared to subtidal areas during windy periods. Conversely, during calm periods tidal currents are stronger in the subtidal areas compared to the intertidal areas increasing bed shear stresses in the subtidal relative to the intertidal. This gradient in bed shear stress and therefore suspended sediment, results in a seaward flux of sediment (and erosion of intertidal areas) during wave events and a landward flux of sediment (and intertidal accretion) during periods dominated by tides (Friedrichs, 2011). Field studies support this transport pattern and showing that tidally averaged fluxes of suspended sediment, in the absence of waves, are landward, but switched to a flux offshore as wave height increased (Allen and Duffy, 1998, Janssen-Stelder, 2000).

Erosion at marsh edges has been shown to be linked to wave attack in several different studies (van der Wal and Pye, 2004, Mariotti et al., 2010). Waves create bed shear stresses over intertidal mudflats eroding the sediment and depending on the local hydrodynamics exporting and depositing this sediment elsewhere, potentially leading to a drop in the mudflat level leading to cliffing at the edge of the mudflat. Marsh cliffs expose bare sediment that can be eroded by the incoming waves resulting in cliff collapse and a lateral retreat. The typical cross sectional profile for a wave dominated mudflat is discussed further in Section 2.1.2.2.

Depending on the morphology of the estuary, the potential for erosion from wind-waves tends to vary over the tidal cycle as the fetch changes due to the emergence and submergence of sand bars or mudflats (Green et al., 1997) and so the amount of wave energy acting in an estuary can be strongly related to the morphological form. It is clear that there must be a critical water depth where the bottom shear stresses produced by local wind waves are at their maximum, above this depth shoaling is not prevented by wind waves allowing the tidal flat to accrete and potentially form saltmarsh (Fagherazzi et al., 2006, McGlathery et al., 2013). Furthermore studies by Mariotti et al., (2010) using a wind-wave model have shown that if sediment were available in the system for saltmarshes to accrete further, a 15cm increase in elevation of the subtidal platform could reduce wave erosion by nearly 25%. This reduction in wave erosion potential illustrates how relatively small changes in estuary morphology and sediment supply can lead to a regime shift.

#### *2.1.1.3* **Estuarine mixing**

Net sediment transport can also occur due to gravitational circulation driven by salinity gradients in the estuary, these effects increase with increasing vertical stratification (Dyer, 1997, Winterwerp, 2011). Salinity is also important in controlling the behaviour of fine sediments, facilitating cohesion and flocculation in clay minerals (Maggi, 2005) and therefore increasing settling velocities (Portela et al., 2013). Commonly estuaries are classified based on the way in which these salinity gradients form, on this basis three main types are identified: salt wedge, partially mixed and well-mixed estuaries.

A salt wedge estuary is stratified with a sharp density and salinity gradient between the less dense river water at the surface and the more dense saline seawater beneath. This occurs where there is little tidal current to mix the two water bodies, although some mixing occurs at the stratified interface due to shear stresses as the water bodies move, creating internal waves and turbulence (Brown et al., 1997). In river flow dominated estuaries of this kind most sediment is fluvial in origin, coarse sediments settle out through the halocline whereas cohesive sediments can be carried towards the sea, where the increase in salinity leads to flocculation. The reduction in flow leads to deposition of fine sediments and if sediment discharges are large, extensive deltas can accumulate (e.g. where the Nile enters the Mediterranean Sea).

Partially mixed estuaries occur when the local tidal range and hence currents are significant causing mixing between the fresh and saline water. In addition to current shear stresses at the interface between fresh and saline water bodies, turbulence and shear stresses caused by friction at the estuary bed result in further vertical mixing (Brown et al., 1997). Isohalines in the estuary are distorted longitudinally by the seaward flow of fresh-saline mixed water at the surface and the corresponding landward flow of the saline-fresh mixed water beneath (Brown et al., 1997). The origins of sediments in partially mixed estuaries can be from either fluvial or marine sources. The flow landwards of saline water can be sufficient to move sediments up-estuary (Brown et al., 1997), fluvial sediments flocculate as they are mixed into more saline water. In some estuaries a turbidity maximum is formed where residual flows are low and sediment transport ceases, turbulence at this location, along with the high concentration of suspended sediments, enhance the flocculation of cohesive sediments (Brown et al., 1997). This turbidity maximum can migrate within the estuary depending on the spring/neap tidal cycle and enhanced/decreased river flows.

Well mixed estuaries have little vertical stratification between saline and freshwater due to the strong tidal flows with relation to river flows. However, as a result of the Coriolis force horizontal stratification can occur as more saline water flows into the estuary on the flooding tide on the right side (facing landwards, Northern Hemisphere), with any fluvial discharge flowing on the left (Brown et al., 1997), leading to a horizontal residual circulation. Thus marine sediments are deposited on the right of the estuary and fluvial sediments deposited on the left.

#### *2.1.1.4* **Extreme events**

Extreme events range in both time and spatial scale and despite being generally of low occurrence can have a disproportionately large impact on the coastal landscape (Woodroffe, 2002). Events range from extreme impact but very low occurrence phenomena, such as volcanic eruptions and tsunamis, to medium scale impact and occurrence, such as hurricanes and cyclones, to moderately frequent storms, high winds, rainfall and surges. Determining how significant high magnitude, low frequency events are, is difficult as they are non-linear (Woodroffe, 2002), with coastal systems exhibiting a range of sensitivity to changes in salinity, water quality, tide height and hence hydroperiod, sediment supply and ability to withstand strong currents and wave energy. Micro-tidal habitats are likely to be particularly sensitive to extreme events, with habitats submerged for long periods during storm surges and prolonged spring high tides.

These extreme events can be catastrophic and long reaching for coastal habitats, Woodroffe (2002) discusses several examples of hurricanes and cyclones devastating mangroves, with negligible re-establishment over 30 years later. However, in contrast small frequently occurring wave events play a significant role in the resuspension of bed sediments (Green, 2011) and therefore over a long time scale will also have a significant effect on morphology (Fagherazzi et al., 2006).

### 2.1.2 Estuarine Morphology

Estuarine morphology is a result of interactions between sediments and non-linear tidal propagation, (Dronkers, 1998). As discussed in the previous section, non-linear tidal effects can lead to a tidal distortion or asymmetry where flood and ebb duration are unequal, resulting in velocity differences during each stage of the tide. Friedrichs (2011) notes that flood/ebb dominance plays a pivotal role in estuarine sediment transport and morphodynamics. Waves are also a critical forcing factor in shaping estuarine morphology (Fagherazzi et al., 2006, Fagherazzi and Wiberg, 2009, Swales et al., 2004, Roberts et al., 2000). In this section the role of waves and tides are discussed in terms of estuarine morphology.

#### *2.1.2.1* Sediments

**Sediment Sources and Types**

Sediments in estuaries can be from a combination of many different sources, including from the catchment and rivers, localised cliff erosion or from a seaward source, but will vary greatly in both type and volume between different systems.  Both cohesive (mud, silt, clay) and non-cohesive (sand, gravel) sediments are found within estuaries. However, they behave in significantly different ways with regards to sediment transport.

**Sediment Transport**

The movement of sediment on the seabed begins when the shear stress ($\tau_0$) becomes sufficiently great to overcome the frictional and gravitational forces holding the grains on the bed, this value is the critical shear stress ($\tau_c$). Therefore for any given sediment there will be a critical shear velocity ($u_{*c}$) which determines sediment movement, (Soulsby, 1997).

The relationship between grain size and critical shear stress is not a linear one, particularly for cohesive sediments such as silts and clays that are found on mudflats and in saltmarshes. Although individual particles of cohesive sediments are by definition small, comprising clays (0.0005mm-0.002mm), silts (0.002mm-0.0625mm), and sometimes a subsidiary amount of sand (>0.0625 mm) (Brown et al., 1997), there are strong binding forces that hold the grains together once they have been deposited. They are lifted as flocculates or clumps and if they have become partially consolidated, such as on exposed mud flats, then they require high shear velocities in order to initiate transport. So although the particles only take a small velocity to transport them in water, once deposited are not easily eroded despite the fine grain size, this process is called scour lag, (Woodroffe, 2002). The cohesion of these very fine grained sediments is also influenced by water content, mineral composition, biological factors and salinity of overlying water and water trapped between the grains, (Brown et al., 1997). Mud and silts are generally transported as a suspended load. However, when the shear stress falls beneath the critical depositional shear stress is the sediment will begin to settle towards the bed. The sediment will continue to be transported for a time, this processes is called settling lag, and can be particularly important in sediment deposition within estuaries. Lags of up to 1.3 hours between maximum currents and peak suspended sediment concentrations have been recorded, (Mantovanelli *et al.*, 2004). It was also observed that current velocities less than 0.2 m/s indicated periods of slack water where sediment mixing was suppressed.  Widdows *et al.*(1998) deployed in-situ flumes in the Humber Estuary to measure critical erosion velocities, where an average critical velocity of 0.31 m/s was recorded on the upper shore immediately below the saltmarsh, and an average of 0.235 m/s on the mid shore, respectively. Other deployments found that a marked reduction in the critical erosion velocity from 0.26 m/s to 0.15 m/s between ridge and pool areas, where the pool areas are constantly submerged and the ridge areas are exposed to air for around 7 hours per tidal cycle (Widdows et al., 1998).

Sediment transport for non-cohesive sediment such as sand initiates when the value of the bed shear velocity just exceeds the critical threshold of motion, particles are carried along the estuary bottom via saltation as bed-load. As the velocity increases the sediment particles are taken into suspension as suspended load (van Rijn, 1984). As tidal velocities decrease, sand grains settle more rapidly than mud particles and thus the transport of sand adjusts to the hydrodynamic fluctuations much more quickly

In reality estuarine sediments are often a combination of cohesive and non-cohesive sediments which make studying these systems more complex, furthermore the mix of sediment can vary both spatially and temporally. The critical shear stress for erosion of mixed mud and sand sediments was studied by Panagiotopoulos et al. (1997) where an increase in the critical shear stress was found with an increase in mud content. As the mud fraction increased, (> 30%), the available space between the sand grains decreased until they were no longer in contact and the mix essentially behaving as a cohesive sediment (Waelas et al., 2007). Conversely it was found in experiments by Torfs et al. (2001) that for very small mud fractions (< 5%) within a sandy substrate, that the critical shear stress for erosion was lower than for pure sand. This was attributed to a reduction in friction between grains, with mud particles acting as a lubricant for the sand grains. Manning and Schoellhamer. (2013) investigated settling velocities with varying sediment sand/mud mixtures, for both microflocs (D<160 μm) and macroflocs (D>160 μm). Microflocs with a mix of sand and mud had higher settling velocities than microflocs consisting of 100% mud, whereas macroflocs consisting of a mix of sediments had a lower settling velocity than macroflocs consisting of 100% mud.

#### *2.1.2.2* **Cross shore profile**

As discussed in Section 2.1.1.2, sediment transport can occur due to spatially varying sediment concentrations driving sediment from areas of high concentration to areas of low concentrations (Friedrichs, 2011) e.g. seaward transport of sediments from intertidal to subtidal areas during energetic wave events (Janssen-Stelder, 2000). Simplified modelling of one dimensional cross sections (Roberts et al., 2000, Kirby, 2002, Le Hir et al., 2000) and two dimensional basins (Mariotti and Fagherazzi, 2013a) shows that a spatially consistent value of bed shear stress (i.e. no sediment concentration gradient and therefore no advection) occurs for different shaped profiles depending on whether the hydrodynamics are dominated by waves or tides. These analyses concluded that a high concave up cross shore profile occurs due to tides and/or an accretional regime and a convex up cross shore profile occurs due to waves and/or an erosional regime (Figure 2.4). These analytical approaches are supported by empirical data, for example the study conducted by Bearman et al. (2010), in San Francisco Bay. Figure 2.4 summarises the morphological difference between an accreting or eroding shoreline.

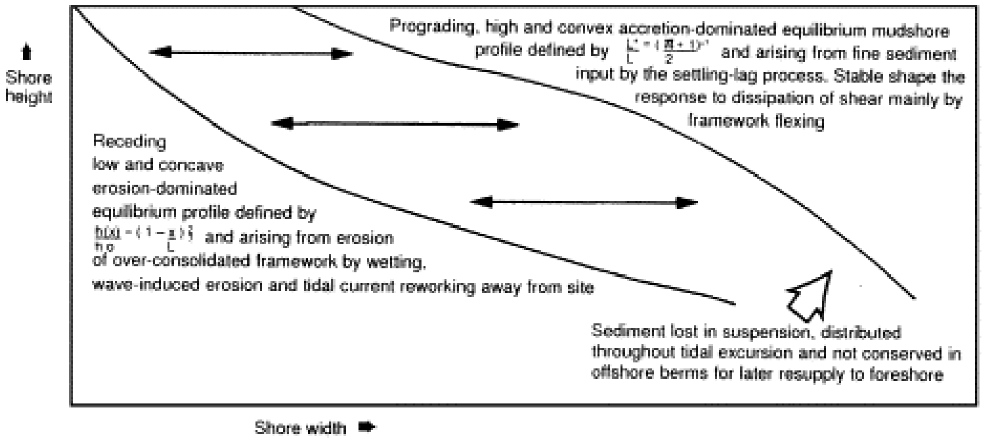



**Figure 2.4 Conceptual model of mudshore equilibrium shape (the Mehby Rule), contrasting shape of accreting / tidally dominated and eroding / wave dominanted shores. (From Kirby, 1992).**

### *2.1.2.3* Hypsometry

Hypsometry measures the cumulative area of the tidal basin with relation to elevation and allows a non-dimensional representation of tidal flat morphology to be produced. This can then be directly compared to different systems at different scales (Friedrichs and Aubrey, 1996).

Strahler (1952) describes the use of hypsometry to analyse the morphology of drainage basins, where the percentage hypsometric curve 'relates horizontal cross-sectional area of a drainage basin to relative elevation above basin mouth'. Dimensionless parameters allow curves to be described and compared regardless of original scale, with curves showing distinctive differences in sinuosity of form and proportionate area below the curve, (Strahler, 1952). Different forms could be linked to stages of estuary development with a young estuary exhibiting little sediment infill and a mature estuary typified by large volumes of sediment infill.

Several more recent studies have investigated the application of empirical formulae to hypsometrical relationships in estuaries including (Boon and Byrne, 1981, Townend, 2008, Wang et al., 2002). Other studies including (Eiser and Kjerfve, 1986, Friedrichs and Aubrey, 1996, Boon, 1975) also discuss the role of saltmarsh and intertidal storage areas, with relation to hypsometry. Boon and Byrne (1981) derived a technique to calculate the hypsometric curve for estuaries, following equations 2.1-2.3:

$a/A = G/(r+G(1-r)$ Equation 2.1

where; $G=(1-h/H)^{\gamma}$ Equation 2.2

$r=A_{min}/A$ Equation 2.3

Where $h$=height above minimum basin elevation, $H$=height between maximum and minimum basin elevation, $A$=total/maximum basin area, $A_{min}$=minimum basin area, $a$=basin area lying below contour at height $h$, and $\gamma$=factor controlling the area below the hypsometric curve (i.e. the volume of sediment in the basin, Figure 2.5).

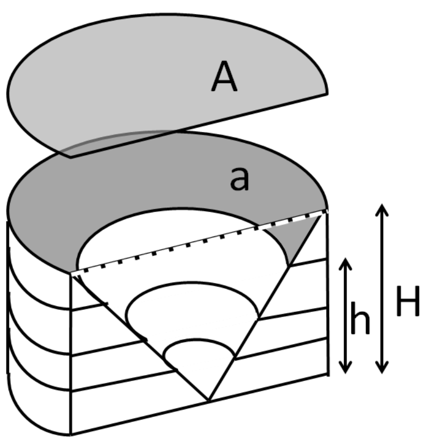



**Figure 2.5 Derivation of the dimensionless parameters used in equations 2.1-2.3.**

The parameter $\gamma$ is calculated using curve fitting, this can be used to describe the morphological state of the estuary. An estuary where $\gamma$=3.5-5.0, will be little in-filled and flood dominant, while an estuary where $\gamma$= 1.8-2.5 will be well in-filled and will be ebb dominant. Hence, this method may give some insight into the future evolution of an estuary. Hypsometry can be simply observed by plotting x= $a/A$ and y=$h/H$, where a= cross Sectional area at height $h$, $A$ is the total area of the basin and $H$ the total height of the basin. This results in a hypsometric curve allowing the comparison of the forms of basins of different sizes and elevations (Strahler, 1952). Moore et al. (2009), applied this method to the Dee estuary, usually categorised as flood dominant. However, it was found that $\gamma$= 2.2 and so it could be reaching morphological equilibrium and possibly switching to an ebb dominant phase. This could result in a decrease in accretion and possible erosion in the future.

### 2.1.3 Estuarine Habitats

Estuaries are among the most biologically productive ecosystems on the planet, per unit area, with intertidal habitats supporting large numbers of both primary and secondary producers. These habitats are globally important and are found throughout tropical to temperate climates. The broadscale global distributions of saltmarsh, mangrove and seagrass habitats are illustrated in Figures 2.6-2.8.

The upper reaches of temperate-latitude estuaries tend to be dominated by mildly salt tolerant species such as reedbeds. As salinity increases, intertidal saltmarsh communities dominate, this is replaced in tropical and subtropical latitudes by mangroves. In the shallow sub-tidal region seagrass communities and macroalgae inhabit mudflat and sandbars. Subtidal sandbar and mudflat communities may also be colonised by epipsammic algae, consisting of benthic diatoms or colonised by thick biomats of algae.

In this study saltmarshes are the primary focus, however many of the drivers and mechanisms that affect saltmarsh stability are also relevant to other intertidal habitats such as seagrass and mangroves.

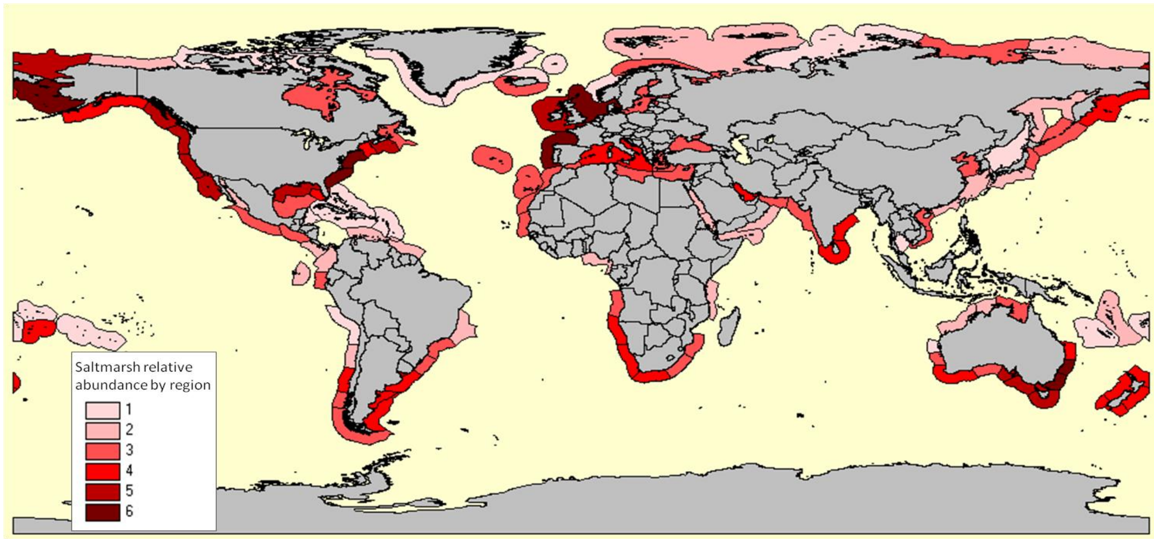



**Figure 2.6 Global saltmarsh abundance (Data derived by The Nature Conservancy and UNEP World Conservation Monitoring Centre, published in The Atlas of Global Conservation http://nature.org/atlas. (Hoekstra et al., 2010)**

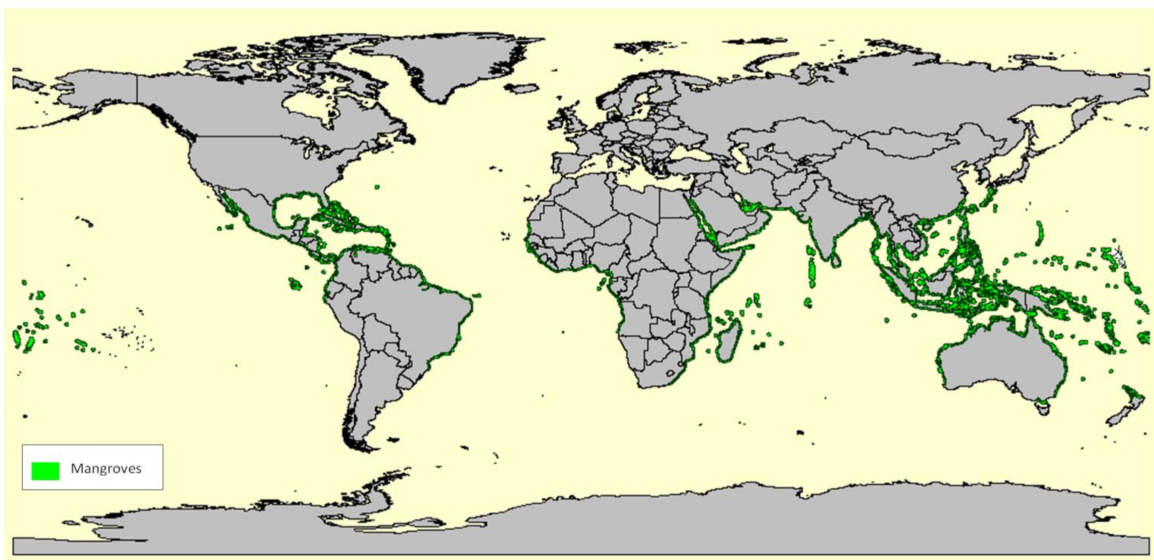



**Figure 2.7 Global distribution of mangroves (Data source: International Union for Conservation of Nature and Natural Resources** [http://www.iucnredlist.org](http://www.iucnredlist.org)

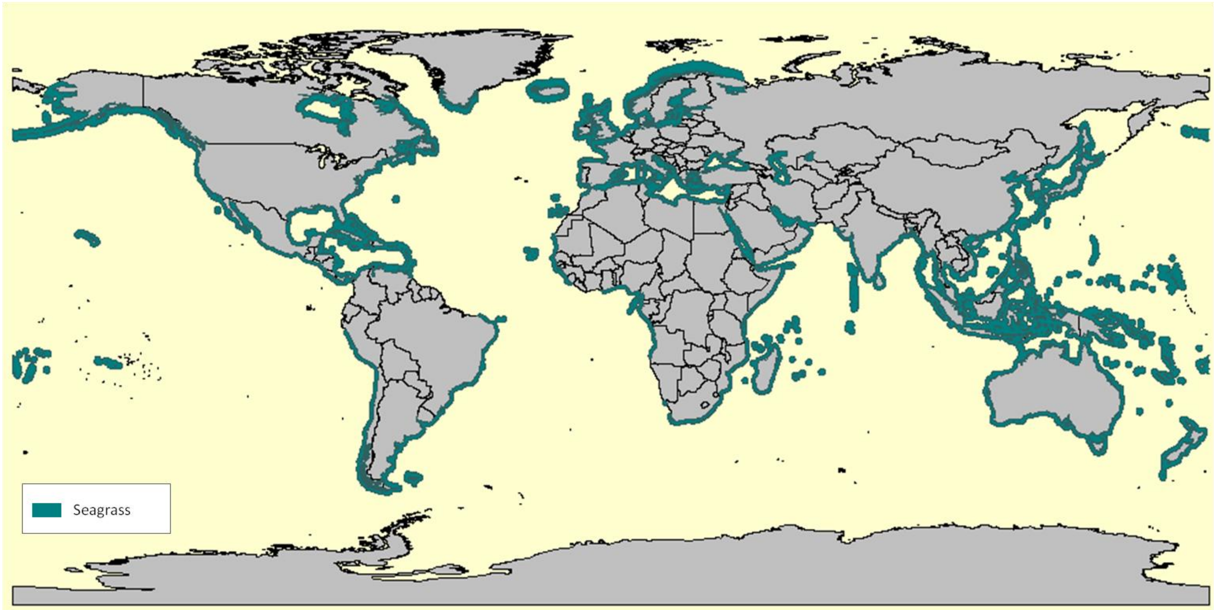



**Figure 2.8 Global distribution of seagrass (Data source: International Union for Conservation of Nature and Natural Resources http://www.iucnredlist.org/technical-documents/spatial-data#seagrasses).**

### *2.1.3.1* Saltmarshes

Saltmarshes are defined as intertidal areas of fine sediments stabilised by characteristically halophytic vegetation, and are widely developed in low-energy environments where wave action is limited (Boorman et al., 1996). The upper limit of saltmarsh colonisation appears to be determined by interspecies competition with terrestrial plants at higher elevations, as they are less well adapted to those conditions (Hughes and Paramour, 2004). However, this upper limit can often be roughly defined as the level of highest astronomical tide. The relative positioning of mudflats and saltmarsh within the tidal frame is illustrated in Figure 2.9.

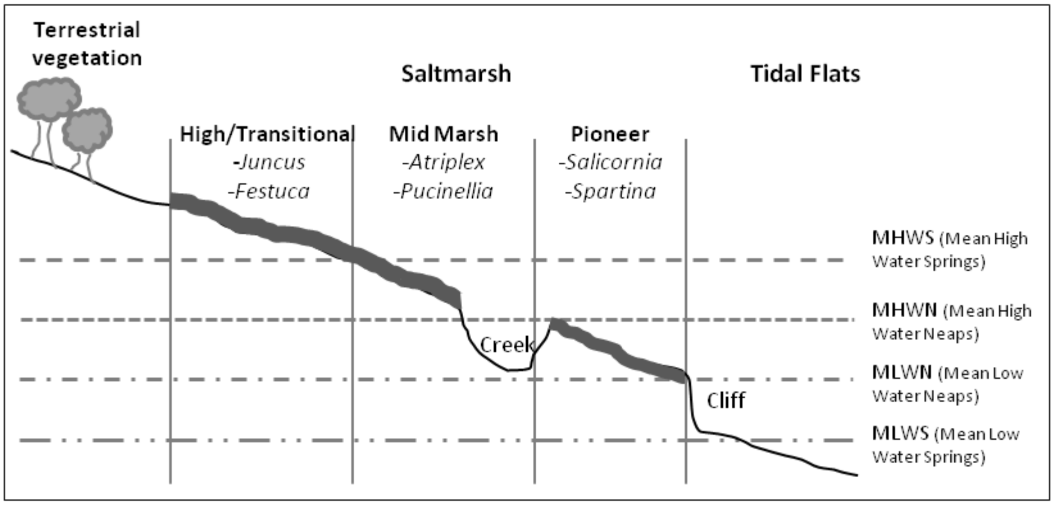



**Figure 2.9 Typical natural upland to tidal flat profile in North West Europe. The different saltmarsh zones are indicated, adapted from Williams and Lester, (1994).**

Saltmarshes can be found across coastal regions of the world (Figure 2.6), with a considerable range in terms of species composition and plant community structure (Boorman, 2003, Dijkema, 1987). More temperate marshes tend to have fewer species and a simple structure greatly influenced by the limited growing season. Sub tropical marshes tend to have a much wider range of species and are characterised by all year growth (Boorman, 2003).

Within Europe the EC Habitats and Species Directive requires member states to designate areas of importance, including saltmarshes, for particular habitats and species as Special Areas of Conservation. Together with Special Protection Areas designated under the Conservation of Birds Directive, these areas form a Europe wide network known as 'Natura 2000'. These set out measures to maintain at, or restore to a 'favourable conservation status' these designated sites and requires appropriate steps to avoid destruction or deterioration of habitats. Saltmarshes provide important ecosystem services being important habitats within the coastal zone, both as protected areas for wildfowl species, nurseries for fisheries stocks and providing an important component of coastal protection via wave dissipation (Moller et al., 2001).

Saltmarsh distribution across Great Britain has been described in several studies (Boorman, 2003, Burd, 1989, UK National Ecosystem Assessment, 2011). They are found all around the coastline of Great Britain, and vary considerably in character, Boorman (2003), describe essentially two types of saltmarsh, lowland and upland. Lowland marshes being associated with major estuaries in low lying areas such as the Wash, Essex, North Kent, the Solent, the Severn estuary Liverpool Bay and the Solway Firth. Upland areas are described as being scattered in distribution with small isolated marshes associated with minor estuaries or at the heads of sea lochs. Patterns of saltmarsh evolution are locally or regionally based, however it is clear that in areas where relative sea-level rise and constraints on saltmarsh migration are present, there will be a tendency towards low-level and often degenerating marsh forms (Boorman, 2003).

#### *2.1.3.2* **Saltmarsh change and conceptual model**

Many of the UK's saltmarshes were altered as a result of the introduction of cord grass *Spartina alterniflora* by ship from America in the early 19th century. Hybridisation occurred with the native *Spartina maritima* and the first specimen of *Spartina anglica* was collected from Lymington, Hampshire, UK in 1892 (Gray et al., 1991). Rapid expansion followed along the South coast of the UK, including Pagham, Christchurch and Poole Harbour (Oliver, 1925). Migration across the English Channel also occurred with records of *Spartina anglica* in the River Orne, on north coast of France and at the mouth of the River Seine (Oliver, 1925). By the mid 1960's it is estimated that there was 4000 to 8000ha of saltmarsh in the estuaries on the north coast of France (Ranwell, 1967). However the worldwide distribution and spread of *Spartina* has been influenced and altered by the deliberate introduction of the species, as a method of reclaiming mudflats for agriculture (Gray et al., 1991). *Spartina anglica* is now found across Europe (Nehring and Hesse, 2008) and the world, in countries including Australia (Hedge and Kriwoken, 2000, Kriwoken and Hedge, 2000), New Zealand (Lee and Partridge, 1983 , Swales et al., 2004) China (Chung, 2006) and the US (Daehler and Strong, 1996). In the UK rapid expansion of *Spartina anglica* led to it becoming a dominant saltmarsh species, but this was followed by extensive die-back, the causes of which are still not clear (Fowler, 2000).

Since the expansion of *Spartina anglica* saltmarsh has generally declined in area within the UK (UK National Ecosystem Assessment, 2011), studies in south-east England have calculated rates of loss of about 40 ha year-1 for the past 50 years (Royal Haskoning, 2004a, Pye and French, 1993). Studies in the Solent region illustrate how some saltmarshes have halved in area since 1970 (Baily and Pearson, 2007, Royal Haskoning, 2004a, Cope et al., 2008).

A conceptual model has been developed, using a driver-mechanism-outcome framework (Figures 2.10 and 2.11). Drivers are classed as either natural or human, although it is important to note that these are not isolated and have direct links to one another. Natural drivers force humans to migrate and adapt to the environment, whereas through the burning of fossil fuels and the development of agriculture, humans have increased global atmospheric concentrations of carbon dioxide, methane and nitrous oxide, leading to anthropogenic induced climate change which intrinsically affect the natural drivers.

Human drivers for saltmarsh change are ultimately controlled by societal, economic and policy decisions which drive development in coastal and catchment regions, agriculture, fisheries, pollution, invasive species. Human drivers can also be positive through the conservation and designation of habitats and species, with requirements for re-creation of habitats affected by development through conservation policies such as realignment and habitat recreation.

Natural drivers of saltmarsh change act over broad timescales, from short term drivers such as meteorology, which control physical mechanisms such as estuary and coastal morphology and hydrodynamics. Medium scale drivers include natural cycles of climate change and sea level rise and astronomical affects such as tidal variation, (e.g.  18.6 year lunar nodal cycle and Milankovitch cycles). Over long time scales evolution of saltmarsh species and geological changes also act as a natural driver. These processes can also be directly linked to human drivers, through the migration and adaptation of people and development geographically.

These drivers can either have a direct mechanistic effect on saltmarsh, eg reclamation of a marsh area for development where the habitat is directly destroyed. There are also many complex indirect mechanisms that can have linear and non-linear effects on the saltmarsh habitat. Finally within the conceptual model a saltmarsh state is observed, this will depend one spatial and temporal time scales, as different mechanisms and drivers out-weigh one another in importance, depending on the location and time.

Mechanisms of saltmarsh change broadly fall into three categories driven by, physical, biological and chemical processes. Key mechanisms for each of these three categories are discussed and an attempt at illustrating how they are interlinked with other mechanisms is shown in Figure 2.10. The non-overlapping regions in Figure 2.10 highlight mechanisms that act purely on some aspect of the estuary to bring about saltmarsh change, e.g. where agriculture allows livestock to trample and feed on the saltmarsh this is a biological mechanism. In areas where 2 or even 3 of the biogeochemical mechanisms overlap this indicates that there are feedbacks, which are potentially complex e.g. an increase in sewage has been linked to an increase in bioturbators, which in turn destabilise sediments and thus destabilise creek systems (Beardall et al., 1988) The list and model presented are by no means exhaustive, the field of saltmarsh change mechanisms crosses many disciplines, with many of the complex feedbacks still unknown or unquantified.

**Physical mechanisms**

With rising sea levels, a lack of available accommodation space for habitats to migrate into is a challenge, which can lead to saltmarshes drowning if there is a lack of sediment in the system (Ravens et al., 2009).  This process is termed 'Coastal squeeze' and it is driven by climate change and sea level rise, coastal squeeze is predicted to become more important as sea levels rise further in the future (Townend et al., 2007, Long et al., 1999, Morris et al., 2002, Pethick, 1981). Other development issues include dredging and disturbance resulting in changes to the tidal prism that has been linked to marsh front retreat (Cox et al., 2003, Pethick, 1994).

However, the presumption that historic saltmarsh loss is mainly due to coastal squeeze, where seawalls prevent the migration of saltmarsh landward in response to sea-level rise may be over simplified. The pattern of vegetation loss, primarily of pioneer species, is opposite of what it should be, where upper plants are squeezed out first (Hughes and Paramour, 2004). Also decline has occurred in areas where there is ample sediment available for the marshes to accrete and yet they do not (Hughes and Paramour, 2004). However, coastal squeeze may become an increasingly major factor in saltmarsh loss over the next century. In England, flood defences have removed most opportunities for natural landward migration, (Nicholls and Wilson, 2001, Lee, 2001). Further, while most previous research has tended to focus on single drivers, multiple drivers may be in operation. Hence, it is important that trends in coastal ecosystems, including saltmarshes, are rigorously investigated and analysed using historic data sources. Historic saltmarsh changes have been studied at a spatial scale in the Westerschelde (Netherlands) (van der Wal et al., 2008). In this study a relatively short time period, 30 years, was used. However, the study demonstrated the necessity to consider the local feedback mechanisms between plant growth, morphology and hydrodynamics of both the saltmarsh and the mudflat, when assessing the status of saltmarshes

Meteorological drivers and mechanisms include cyclic- el Nino, la Nina and ENSO events alongside extreme weather events such as cyclones and surges. These affect the seasonal fluctuations of temperature, precipitation and U.V. and can have significant affects on the salinity of the marshes and surrounding estuary. As salinity affects osmotic adjustment in saltmarsh plants (Reed, 1990, Vasquez et al., 2006) these are important factors.

Storms and extreme events also supply important sediments to the marshes (French, 2006). Increased turbidity and sediment supply may help the marshes to accrete (Anderson 1972, Ward et al 1984, Burd 1992, Swales et al 2004) however locally produced wind-wave exposure can cause erosion of the marshes (Fagherazzi and Wiberg, 2009, Mariotti and Fagherazzi, 2010, Mariotti and Fagherazzi, 2013b, Tonelli et al., 2010) and have many feedback effects on an estuary. Waves from boat wakes have also been shown to result in marsh front erosion (Ravens et al., 2009)

Increased wave action, particularly at the seaward edge, has been suggested to contribute to saltmarsh decline (Burd, 1992). Studies in Manukau Harbour, New Zealand (Swales et al., 2004) have also linked wave energy gradients with spatial differences in long-term *Spartina* growth. However, lateral erosion has been observed in both exposed and sheltered locations (Burd, 1992) and in areas where there is sediment sufficient for the mudflats to accrete in pace and so this cannot simply be due to sea-level rise leading to greater wave attenuation at the marsh front at these locations. However it may be a contributing factor in areas that are exposed and have seen a drop in mudflat profile, physically or relative to sea levels. Since the 1930s intertidal sea grass beds have also declined in abundance and distribution (Hughes *et al*., 2000). This may also contribute to increased wave attenuation at the marsh front.

Sediment distribution is also  facilitated by tidal asymmetry and the relative slack water durations between flood and ebb dominance  affecting the sediment settling lag (Aubrey and Speer, 1985, Dronkers, 1986, Voulgaris and Meyers, 2004, Wang et al., 2002).

Complex feedbacks between meteorology, geography and astronomical effects all act on the hydrodynamics of an estuary which can affect propagule supply and hence marsh distribution (Rand, 2001). This process can also facilitate the spread and distribution of predator larval species (eg snails, crabs and bivalves) that may feed on or damage the marshes and the sediments they inhabit.

Variations in tidal range including microtidal vs macrotidal spring/neap cycles and18.6 year cycles (Morris et al., 2002) along with the relative morphology of the setting dictate where saltmarshes are likely to inhabit. With large areas available in gently sloping estuaries with large tidal ranges and smaller areas suitable in steep sided estuaries with smaller tidal ranges. The geographical and latitudinal positioning can also influence the local saltmarshes with low-latitude marsh plants less palatable (Pennings and Silliman, 2005) and so less likely to be eaten by predators, but then they are susceptible to ice damage (Adam, 1990).

**Biological Mechanisms**

Biological mechanisms tend to either have a direct impact on the marshes or in some way affect the sedimentology or chemistry that control saltmarsh health.

Poaching and physical damage to saltmarsh occurs from livestock such as sheep and cattle (Kiehl et al., 1996, Ranwell, 1961). As well as from deer and other wild animals (Diaz et al., 2005). Some parasitic plants have been recorded limiting the abundance and distribution of host saltmarsh plants (Callaway and Pennings, 1998).

Direct herbivory of saltmarsh plants also occurs from geese (Kerbes et al., 1990), crabs (Bortolus and Iribane, 1999), snails (Silliman and Zieman, 2001), beetles (Rand, 2001), ungulates and livestock sheep (Turner, 1987). Where these species go unchecked due to the decline in major predators they can cause considerable damage e.g. an increase of population of herbivorous crabs feeding on saltmarshes was caused by the over fishing of top predatory fish (Altieri et al., 2012). Bioturbation and herbivory by species such as *Nereis diversicolor* (Paramour, 2002, Paramour and Hughes, 2004) , particularly in areas where this species may be in abundance due to sewage pollution (Beardall et al., 1988) is another possibility. Studies have shown that not only does *Nereis diversicolor* disrupt pioneer species, but they can also contribute to creek erosion (Paramour and Hughes, 2004).

As previously discussed, wave action can lead to the erosion of the marsh fringe, in regions that have seen a decline in sea grass beds there will be an increase in wave exposure of the marsh edge (Waycott et al., 2009). Saltmarsh sediments are sensitive to changes in chemistry, during macro algae blooms lack amounts of nitrogen are released causing eutrophication of marsh sediments(Jones and Pinn, 2006, Newton and Thornber, 2013).

Cohesive sediment flocculates consist of both organic and inorganic material affecting settling and scour of sediments including organic coatings influencing the electrostatic stability of the particles (Gibbs, 1977, Loder and Liss, 1985, Neihof and Loeb, 1972), polymer bridging(Alldredge et al., 1988, Gregory, 1978) and faecal pellet production by filter feeders (Martens and Krause, 1990). How sediments flocculate and their behaviour with regards to settling velocity and shear threshold are critically important to how saltmarshes accrete.

**Chemical Mechanisms**

Chemical mechanisms often affect the saltmarsh directly, but can also have an impact on the sediment properties and other species within the estuary which in turn affects the saltmarsh distribution indirectly.

The increased use of agricultural herbicide, has directly lead to a decline in the ability of saltmarsh plant to photosynthesise (Mason et al., 2003). The use of agricultural herbicide has also led to a decline in microphytobenthos, and epipelic diatoms which play a role in the flocculation of cohesive sediments, resulting in lower sediment stability (Mason et al., 2003). Heavy metals have also be shown to inhibit photosynthetic activity in marsh species(Weis and Weis, 2004). Heavy oiling, reported after the Deepwater Horizon spill, caused almost complete mortality of *Spartina alterniflora* and *Juncus roemerianus* species (Lin and Mendelssohn, 2012).

Nutrient enrichment leads to more vigorous saltmarsh growth. However, fewer roots and rhizomes are formed and this weakens sediment cohesion (Deegan et al., 2012). Added nutrients also boost microbial decomposition of leaves stems and biomass, destabilising creek banks (Deegan et al., 2012)

Bioturbation and herbivory by species such as *Nereis diversicolor* (Paramour, 2002) and (Paramour and Hughes, 2004), particularly in areas where this species may be in great abundance due to sewage pollution (Beardall et al., 1988) may be another alternative. Studies have shown that not only does *Nereis diversicolor* disrupt pioneer species, but they can also contribute to creek erosion (Paramour and Hughes, 2004). Salinity also affects both the growth and biomass of saltmarsh species and estuary macroinfaunal species such as decapods and polychaetes (Reed, 1990, Rutger and Wing, 2006, Vasquez et al., 2006).

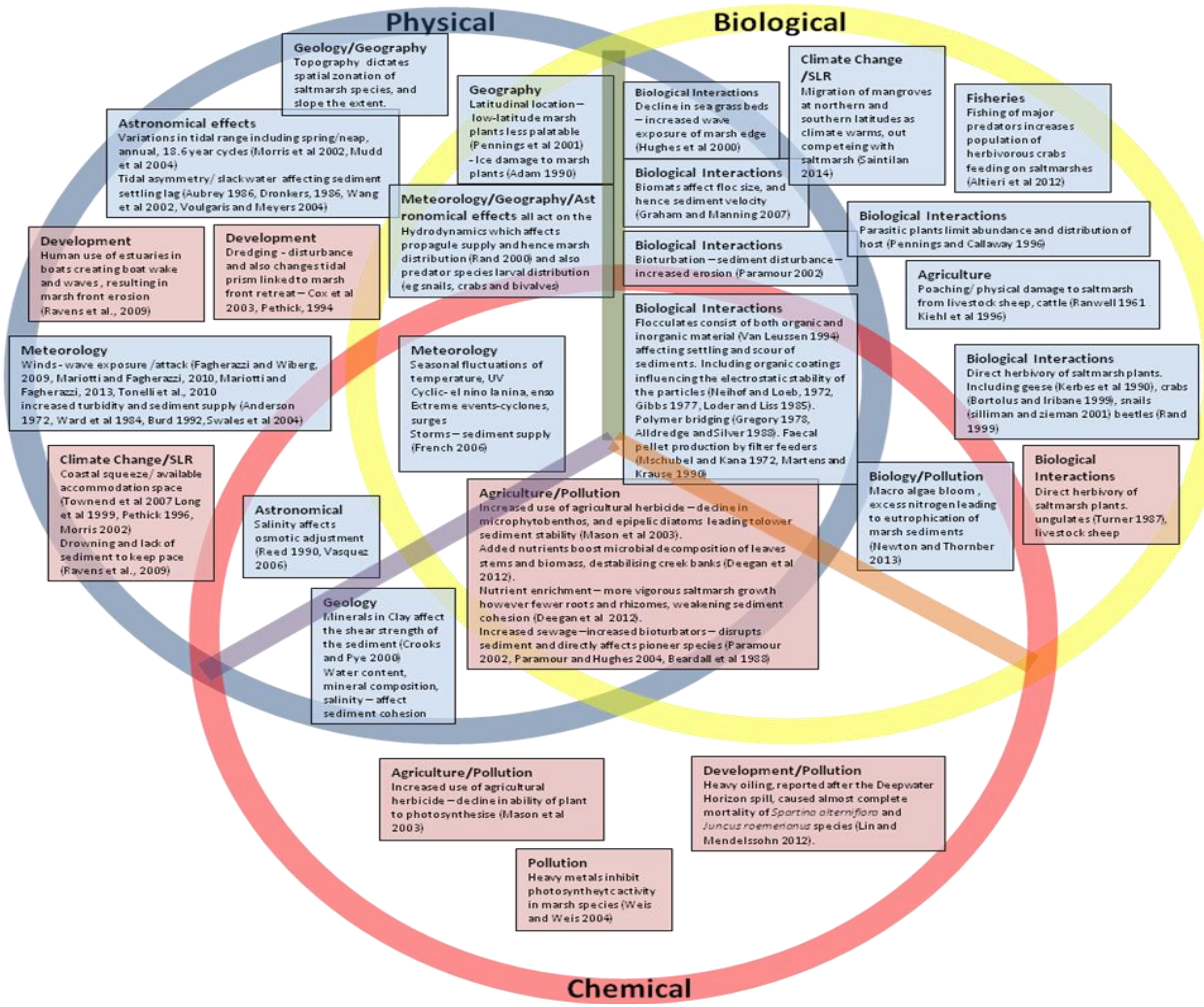



**Figure 2.10 Key biogeochemical mechanisms of saltmarsh change and their interactions (blue indicates natural drivers, pink human drivers, see figure 2.11**

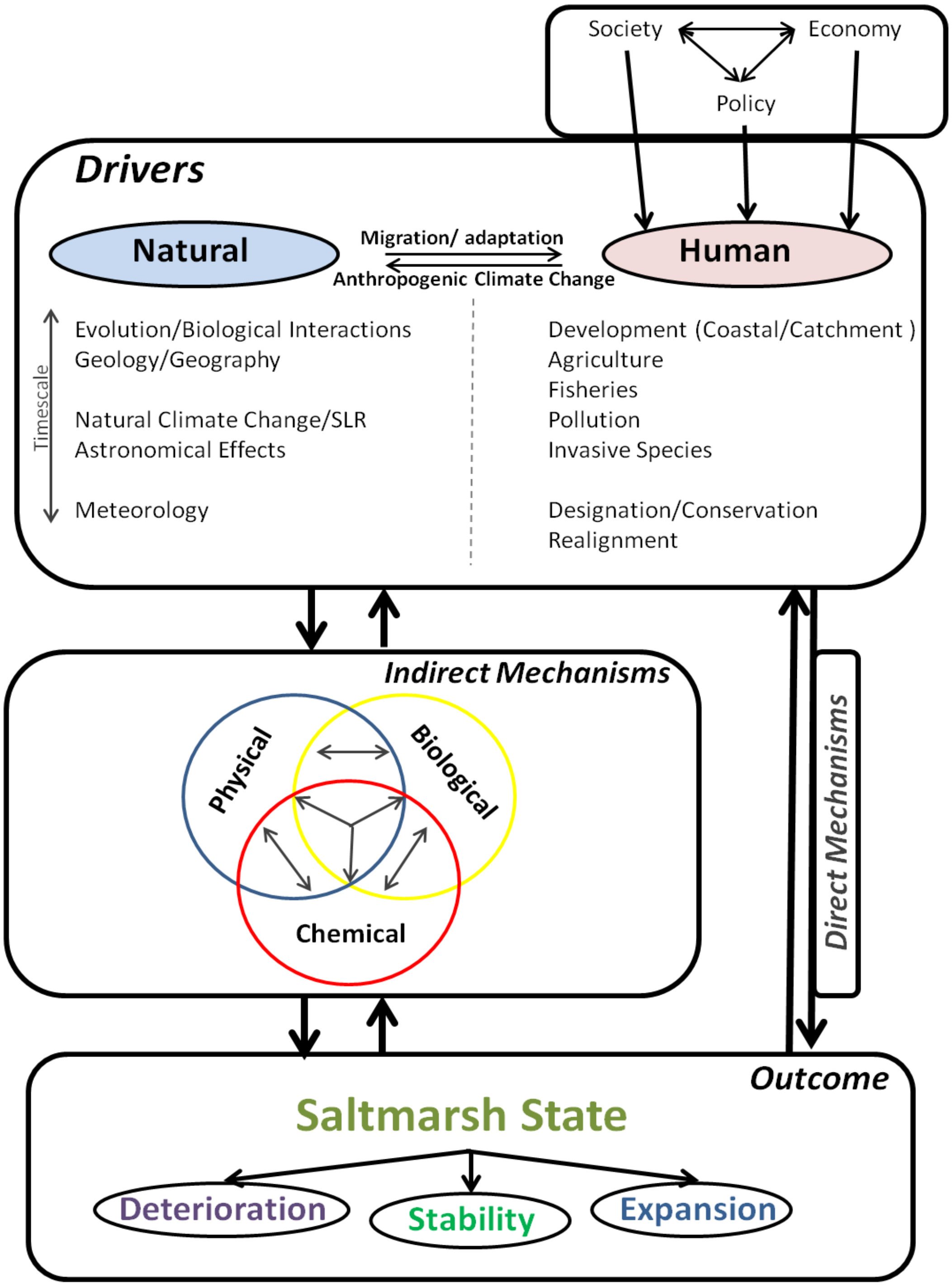



**Figure 2.11 Conceptual model of saltmarsh loss**

## 2.2 Estuarine Modelling

Mathematical models are widely used to represent estuarine processes. Numerical estuarine models can be split into three different categories process based models (bottom-up models), regime or systems approach models (top-down models) and hybrid models which combines elements of both process and regime models.

Process based (bottom-up) models aim to replicate physical processes by solving a set of equations that describe water and sediment movement. The basis of process models is usually a hydrodynamic module that represents parameters such as water levels, discharges, currents, waves, density currents and secondary circulation, this can then be coupled to a sediment transport and morphological model to predict changes to sedimentary processes (Cronin et al., 2007, Cronin et al., 2009, ABPmer, 2008) Examples of process based models include Delft 3D, MIKE and TELEMAC.

Regime or equilibrium models assume that the estuarine system is approaching a target state of equilibrium therefore based on the dimensions and hydrodynamics within the estuary it is possible to predict this future equilibrium form of the estuary (ABPmer, 2008). A number of hybrid models that combine regime (or equilibrium) theory with hydrodynamics have been developed so that the long-term predictive capability of regime models are combined with a more detailed description of the prevailing hydrodynamics (ABPmer, 2008). When using a hybrid regime model it is common to define the equilibrium or target state of the estuary and then use a hydrodynamic model in a iterative process that continually adjusts conditions towards this defined morphological state (O'Connor et al., 1990, Spearman et al., 1998).

An example of a regime model that has been used to assess the critical rate of sea-level rise that triggers the loss of intertidal volume within estuaries is ASMITA (Aggregated Scale Morphological Interaction between Inlets and Adjacent coast), (Rossington, 2008, Rossington and Nicholls, 2007). It was first presented as a behaviour-based model and consists of a schematised tidal inlet system with three main morphological elements, ebb-tidal delta volume, channel volume and flat volume (Kragtwijka et al., 2004). These elements are described by one variable representing their morphological state. A major assumption is that under constant hydrodynamic forcing each element tends towards a morphological equilibrium which can be defined as a function of hydrodynamic forcing and basin properties (van Goor et al., 2003).

As described in Section 2.1 estuarine processes are complex with linear and nonlinear biogeomorphological feedback mechanisms and therefore it is inevitable that the models are simplified and rely on inherent assumptions (Cronin et al., 2009). Process based morphological models in particular aim to replicate these complex feedback systems and the outcome of morphological modelling is highly dependent on the way these feedbacks are represented within the model. The models are also extremely sensitive to other factors such as grain size distribution, entrainment properties of cohesive sediments, compaction and flocculation processes (Coco et al., 2013, Cronin et al., 2009).

Process based models are usually more suited to short-term (days to months) predictions of morphological change as over longer time scales any prediction errors will accumulate and become amplified (ABPmer, 2008).Therefore the operation of a process based model requires a thorough understanding of the estuaries behaviour, in both morphological and hydrodynamic terms.  This enables the model to be calibrated and validated and thereby reduces the accumulation of errors when making long-term predictions.

More recently coupled geomorphological and ecological process models are being developed as predictive models of landform evolution (Fagherazzi et al., 2012). However these are still extremely simplified in terms of sediment transport dynamics, with the need to account for more complex cohesive sediment behaviour. The inclusion of the temporal variability of drivers such as storms is needed, and to account for the expansion of the channel network, wave scour and lateral erosion of the marsh edge (Fagherazzi et al., 2012).

Despite the shortcomings, numerical models are useful in understanding the behaviour of estuarine systems and the processes that drive morphological change, particularly when used in conjunction with an historical analysis of change and field observations (Cronin et al., 2009)

## 2.3 Summary

The main natural mechanisms controlling estuarine form and evolution is the non linear feedback between hydrodynamics and morphology, including tides, waves, estuarine mixing as well as the type and amount of sediment available.  Hence, these are critical in understanding saltmarsh change. A conceptual model has been developed which shows that where and how saltmarshes and coastal habitats form, are controlled through complex feedback systems, including biological, physical and chemical mechanisms (Figure 2.10), driven by both human and natural drivers (Figure 2.11). This conceptual model will be applied to the study site in Section 3.

Mathematical models are widely used to represent estuarine processes and despite the limitations the careful use in conjunction with other sources of data and analysis provides useful insight into saltmarsh change.

# 3 Site Selection

In order to study the physical drivers of saltmarsh changes in a micro-tidal estuary a suitable case study site will be selected. Criteria for the choice of case study site are determined through two factors; local management issues involving saltmarshes and data availability. Saltmarsh management issues to be considered include; regions of human impacted saltmarsh (such as seawall construction, dredging and marina/port development) as well as pristine saltmarsh in close proximity, saltmarsh with varied aspect and distribution throughout the estuary, saltmarsh of high quality and habitat designation. Considerations for data include the availability of: historic aerial photographs, maps and charts, bathymetric/topographic data such as LIDAR, some knowledge of the basic hydrodynamic processes, and potential existing models of the estuary that can be utilised and accessibility for field data.

Due to constraints regarding accessibility for field data collection, the choice of estuary was narrowed to those on the South coast of the UK, the advantages and disadvantages of these are outlined in Table 3.1. The main limiting factor was the requirement for a micro-tidal climate and after assessing the estuaries Poole Harbour was identified as a appropriate case study site.

Poole Harbour was chosen as a suitable study area for three main reasons. Firstly it has large areas of pristine saltmarsh on the southern and western sides with little human impact. Yet the northern and eastern sides hold large urban populations and an active and expanding ferry port. The saltmarshes in Poole Harbour are extensive and varied in aspect with both pristine areas as well as those impacted by dredging, reclamation and coastal squeeze along seawalls and although previous reports on saltmarsh trends exist for the Harbour (Born, 2005, Hubbard, 1965, Burd, 1989, Edwards, 2005) they are generalised and do not examine the saltmarsh changes within a spatial context. Secondly data availability was good for Poole Harbour, with readily available historic aerials for three years throughout the 20$^{th}$ Century. Thirdly the hydrodynamics in the Harbour are well characterised through previous numerical modelling conducted by Falconer (1986b) and HR Wallingford (2004).

**Table 3.1 Case study site selection criteria**

| Site | Advantages | Disadvantages |
|---|---|---|

| | | |
|---|---|---|
| Pagham Harbour | Studies underway by the Environment Agency and Royal Haskoning, with conceptual and tidal models being developed. Major management issues. | Models not yet fully developed |
| Chichester Harbour | ASMITA model applied (Rossington, 2008), intertidal area mapped. 2D TELEMAC flow model developed by HR Wallingford | Some historic aerial photography available, but further research required to assess dates and timescales. |
| Langstone Harbour | ASMITA model applied (Rossington, 2008). Quite a lot of research on habitats, *Spartina* dieback noted. | Lacks pristine saltmarsh environment to compare to the human impacted regions. Some historic aerial photography available, but further research required to assess dates. |
| Portsmouth Harbour | Management issues and *Spartina* dieback recorded, but with limited data on the health of the plants ASMITA model applied (Rossington, 2008) | Lacks pristine saltmarsh environment to compare to the human impacted regions |
| Southampton Water | Major management issues, port development, large local population. ASMITA model applied (Rossington, 2008). *Spartina* dieback recorded and highly designated. | Very large estuary, with sub-estuaries, Hamble, Itchen. Saltmarsh development previously well studied (Williams, 2006 ) |
| Beaulieu River | Some localised studies of saltmarsh habitats and CASI classification | Lacks major management issues on a regional scale. Lacks extensive historic datasets and models |
| Christchurch Harbour | Detailed sediment analysis in the Harbour. Recorded tidal asymmetry at the mouth so potentially also throughout the Harbour. | Some *Spartina* dieback, however not extensively recorded. |
| Poole Harbour | Large Harbour with varied aspects, both pristine saltmarsh and human impacted. Seawalls, dredging and reclamation. Some historic datasets including aerial photography. Bathymetry available from Poole Harbour Commissioners. Two models independently developed to observe impacts of dredging and pollution, respectively, by HR Wallingford and Falconer and Liu (1995). Microtidal and therefore vulnerable to sea-level rise. | Large and potentially complex |
| Newtown Harbour | Highly designated saltmarsh regions of both *Spartina anglica* and *Spartina maritima.* Some historic management issues with realignment | Limited historic data available, no existing models. Limited human impacts, in comparison to other local |

| | | |
|---|---|---|
| | (and more recent, unplanned seawall breaching resulting in new saltmarsh colonisation) | estuaries |
| Medina Estuary | | Small estuary |
| Western Yar Estuary | Studies on sediment rates Port management issues, some habitat mapping with Spartina dieback noted. | Small estuary |

All these features allow for a broad-scale spatial study of saltmarsh change that will be applicable to many other estuaries both in direct comparison and at a conceptual level. It is also relatively unique in the UK in that it is micro-tidal, making it particularly vulnerable to sea-level rise. However, globally there are many regions that support coastal habitats within a microtidal climate (e.g. Mediterranean, Baltic, Southern Australia and the Caribbean) all of which are sensitive to changes in sea level. Hence, an understanding about the processes and mechanisms driving saltmarsh change and development in Poole Harbour, are significant on a global scale.

The following chapter reviews the relevant literature on the history and development of Poole Harbour and the studies that have been previously conducted on saltmarshes, these are set into the conceptual model framework developed in section 2.1.3.2, in order to identify and test the suspected key drivers and mechanisms of change within the system. The models of Poole Harbour used in this study are also introduced.

## 3.1 Poole Harbour: Situation and Characteristics

Poole Harbour is a large tidal estuary situated on the south coast of Britain (Figure 3.1) with an intertidal area of 2050ha, (Buck, 1997). . It was formed during Holocene sea-level rise as the sea inundated a system of river and valley streams. The geomorphology of the Harbour results from the combined effects of marine and sub-aerial processes on both intertidal zone and shoreline, the channel hydrodynamics, anthropogenic modifications of the shoreline and channels, catchment hydrology affecting both the freshwater and sediment inputs and the spread and decline of the saltmarshes, (May, 2005).

*Spartina anglica* was first recorded in Poole Harbour in the 1890s. It initially spread rapidly, however, during the 1920s it began to decline. The average rate of saltmarsh loss, reported from 1972 to 1993, is 7.5 ha per year (accounting for 157.5 ha of saltmarsh loss over that time. This may not be a universal trend, it has been reported that in some areas of the Harbour saltmarsh has expanded. However this is not fully described in the previous literature and so this thesis will thoroughly characterise the trends and their mechanisms and drivers for south coast marshes. Previous studies concerning saltmarsh changes within Poole Harbour have been conducted at a less detailed level than within this study and have overlooked small scale changes within creek systems. Neither localised trends of erosion or accretion, or the drivers and mechanisms of the changes observed were investigated in these previous studies and the Harbour has never been studied from a comprehensive systems approach

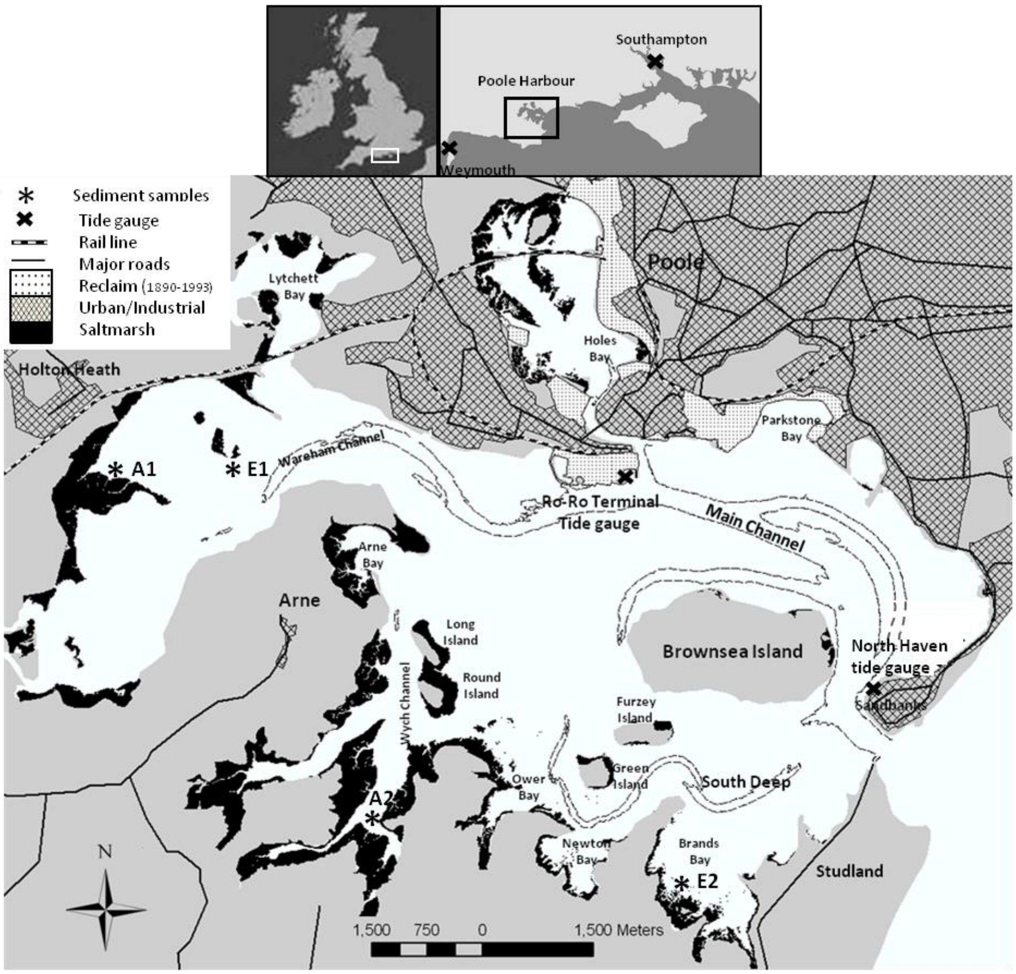



**Figure 3.1 Location of Poole Harbour including available local and regional tide gauge locations**

The Harbour has a complex dendritic form with many tributaries and some discrete bays. Holes Bay, on the northern side of the Harbour, is an almost enclosed muddy northern arm, much affected over the years by land reclamation and the spread and subsequent decline of *Spartina anglica.* Since the mid 1900's the intertidal area has been reduced from c.330 to less than 250 ha, mainly due to reclamation along the east shore for port and urban development, (Gray, 1985).

Holes Bay is lined by artificial sea walls, boulder embankments and quays, as in much of the northern shore of the Harbour. In its natural state this would have been a gradual transition from mudflat and saltmarsh through reedbeds and grazing marsh. East of Holes Bay, Lytchett Bay is considerably less modified by reclamation and has generally less muddy and nutrient-enriched sediments. The west shore which receives the outfall of the Sherbourne River in its centre is lined by a series of low earthen embankments with extensive reedbeds and woodland. Principal rivers, the Frome and the Piddle, enter the Harbour from west to east and drain the chalklands of Dorset, with a catchment area exceeding 70,000 ha along with two other minor rivers, the Sherford and the Corfe. These river outflows make the Wareham arm of the Harbour partially mixed with regards to salinity, whereas the rest of the Harbour is considered vertically homogenous (Humphreys, 2005). Large areas of floodplain have been historically reclaimed within these surrounding river valleys. In its centre are five main islands, Brownsea, Furzy, Green, Round and Long. Deep water channels within the Harbour are maintained by natural scour supplemented by dredging and are restricted, with some 80% of the Harbour area comprising of inter-tidal, fine grained mud, sandflats and marshes. The southern shore of the Harbour is made up of more pristine habitats, with extensive mudflats and saltmarsh that naturally grade to pasture, unrestricted in most areas by seawalls or infrastructure.

Poole Harbour  is regionally important in terms of Nature conservation, particularly with habitat and saltmarsh losses occurring nearby in the Western Solent (Gardiner *et al*., 2007). There is no one main current threat but the combination of shipping, habitat loss, reclamation, erosion and *Phragmites* colonisation seaward over the saltmarshes may result in a loss of habitat and biodiversity. The long term threat is that there is not enough sediment entering the system to keep pace with sea-level rise, which would result in a loss of intertidal area, and in the long term submersion of the estuary. This could be exacerbated by dredging and development particularly along the northern shore where defences prevent migration of habitats. However along the south and west there may be sufficient accommodation space as there are no artificial barriers to migration and the areas are largely managed for nature conservation purposes.

### 3.1.1 History and development

#### *3.1.1.1* **Human Development**

Poole Harbour has been used for trade and fisheries since the Iron Age, with extensive reclamation of the Frome and Piddle floodplains in the medieval period. By the thirteenth century Poole was a prosperous commercial port, it developed further from the seventeenth to nineteenth centuries, thriving on trade with Newfoundland. During the Second World War the Harbour was used intensively and was important in the preparation for the D-Day landings in 1944. From the mid-1950s, development continued with the construction of a power station on the shore at Hamworthy, reclamation and waterfront development. There are currently eight yacht clubs and ten boatyards as well as marinas attached to residential developments. Europe's largest onshore oilfield lies beneath the Harbour with wells on Furzy Island and Goathorn Peninsula and the port has recently been enlarged to accommodate larger cross channel ferries and roll-on roll-off freight.

#### *3.1.1.2* **Geological Development**

Melville and Freshney (1982), and Royal Haskoning (2004b) suggest that the majority of surface sediments around Poole Harbour today originate from alluvial deposits laid down by the rivers feeding the Harbour and that beneath and within these deposits there are seams of gravel and peat.

Edwards (2001) describes the stratigraphy at Arne saltmarshes, where 3 transects of 40 boreholes were taken. The pre-Holocene surface underlying the saltmarsh exhibits a stepped profile, in boreholes deeper than -1.1 m OD, organic-rich humefied basal peat deposits are widespread. Whereas in boreholes where the Bagshot beds (bedrock) occurs above this height the peat layers are absent. Edwards (1998), describes a similar study at Newton Bay in Poole Harbour, Here the boreholes indicate that the slope of the pre-Holocene surface is steeper than that at Arne but is similar in general form, with the Bagshot Beds sloping from +0.2m OD to -0.6m OD, where a step occurs down to -1.0m OD, again peat is observed in the boreholes where the Bagshot beds are beneath -1.0m OD.

Edwards (2001), also uses a foraminiferal transfer function for mean tidal levels in combination with radiocarbon dated material to construct a record of relative sea level change in Poole Harbour. The study concludes that since the start of the Holocene there was a composite sequence of events consisting of four phases of sedimentation and relative sea level change. Between ca. 4700 yr BP and ca. 2400yr BP, mean tidal levels appear to have risen in Poole, inundating and preserving the sequence of peat deposits. Between ca. 2400yr BP and at least ca. 1200yr BP the rate of sea-level rise appears to decrease with mean tidal levels remaining at or below -1.0m OD. During this time deeper water sediments accumulated, with the stratigraphy interrupted by sandy layers. Edwards (2001), suggest that these sandy deposits may suggest an erosional phase, with the sands derived from local cliff erosion. However, May (2005), implies that the sand layers do not necessarily imply an erosional phase and that the deposition of such material would depend upon transport patterns. Phases of greater wave energy or shifts in wind direction may also produce areas of deposition also changes in the geomorphology of the Harbour mouth could also alter depositional trends. Edwards (2001) suggests that as tidal levels fell the Harbour mouth narrowed and thus reduced the tidal prism, this would result in slower currents. Conversely, during a rise in tidal levels after ca. 1200 yr BP, the mouth may have widened under the influence of enhanced current velocities, potentially causing a switch from ebb to flood dominant tides, resulting in an influx of sandy sediments. After ca. 1200yr BP the data indicates a brief rise in mean tidal level, and by ca. 800yr BP the major phase of sand deposition has ceased with no other indications for further changes in tidal level until ca 400yr BP.

The fourth phase described in Edwards (2001), is the renewed relative sea-level rise, with an apparent rise in relative sea-level between ca 400yr BP and 200 yr BP, resulting in marsh submergence. This is indicated by the end of organic lagoonal sedimentation and the beginning of minerogenic silt-clay.

### 3.1.2 Hydraulic Characteristics

#### *3.1.2.1* **Waves**

In shallow regions, such as estuaries, wind-waves can have an effect on turbidity (Anderson, 1972, Ward et al., 1984). However, this tends to vary over the tidal cycle as the fetch changes due to the emergence and submergence of sand bars or mudflats (Green et al., 1997) and so the amount of wave energy acting in an estuary can be strongly related to the form and morphology of the estuary. Increased wave action, particularly at the seaward edge, has been suggested to contribute to saltmarsh decline (Burd, 1992). Studies in Manukau Harbour, New Zealand (Swales et al., 2004) have also linked wave energy gradients with spatial differences in long-term *Spartina* growth.

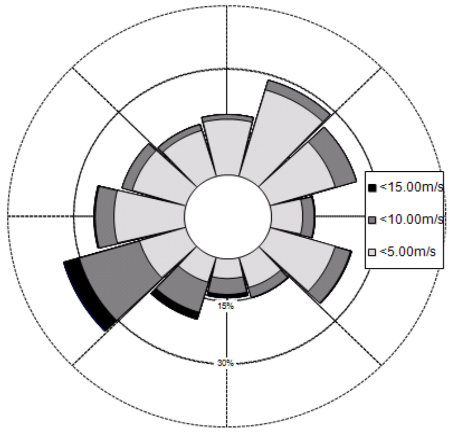



**Figure 3.2 Wind rose for speed and  direction at North Haven, 1996**

Wind data collected at North Haven (Figure 3.2) suggests that the dominant wind direction for Poole Harbour is from the South-west with a smaller peak from the north-east. For this particular year south-westerly winds dominated most of the year with strong north-easterly winds occurring during the November to January period. Wind speeds rarely exceed 15m/s, with a maximum yearly wind speed of 49m/s. The fetch across Poole Harbour, particularly from southwest to northeast, is large enough for significant locally-produced wind-waves to occur, with 1:100 year wave conditions reaching a Hs of 1m (Halcrow Maritime, 1998) and so wind direction and speed are potentially significant to erosional processes.

The capability for wave propagation within the Harbour is illustrated by the degradation of bluffs around the Harbour margins, as has historically been noted by May (1969). There is no comprehensive study into waves in Poole Harbour. However, data is available for site specific studies (Hydraulics Research Ltd, 1990, HR Wallingford, 1993a, HR Wallingford, 1993b, HR Wallingford, 1996). The wave climate is dominated by depth limited locally generated waves as storm waves do not penetrate beyond the immediate area of the Harbour entrance due to diffraction and refraction effects, (SCOPAC, 2004). Halcrow Maritime (1999) have modelled extreme wave heights based on hind casting from local and regional wind data, these varied from 0.5 to 1.2m for a 1 in 100 year reoccurrence, but this was dependant on location with respect to fetch. North-eastern parts of the Harbour are the most energetic and are exposed to longer fetches from dominant south south-westerly winds/waves.  It is has been suggested that sandy sediments from Poole Bay would have been driven by waves into the Harbour, (SCOPAC, 2004). However, Royal Haskoning (2004b) concluded that although wave breaking has a significant effect on the currents in the breaker area, the flow regime of the Harbour and approach channel is dominated by tidal action.

#### *3.1.2.2* **Tides**

The tides within Poole Harbour are highly variable in shape (Figure 3.3) due to the proximity of a local minimum in the amplitude of the micro-tidal main semi-diurnal tidal constituents in Poole Bay and the M2 degenerate amphidromic point of the English Channel. Hence, the tidal regime is characterised by a small double high water effect, with a mean tidal range of approximately 1.8m at springs and 0.6m at neaps (however these values vary with location throughout the Harbour, Table 3.2). Although relatively rare on a global scale the double high water is not unique to this region with double highs in the semi-diurnal tide observed at Den Helder, The Netherlands and Buzzards Bay, Massachusetts (Bowers et al., 2013).Tidal levels are above mean water from about 2 hours after low to approximately 2 hours before the next low (i.e. for nearly 8 hours per tidal cycle). This is of ecological significance as it limits the availability of mudflats as feeding grounds for important wader populations, while conversely increases the feeding time for many filter feeding invertebrates living in the mudflats which contribute to the diet of waders and also provide local fisheries. This also results in a relatively poor zonation of the vegetation, with a limited area between MHWN and HAT in which saltmarsh can colonise (Figure 3.3). Due to the double high water within the Harbour, with the main peak followed by a lesser high water peak, calculated mean high water spring and mean high water neaps are lower than would be expected, 0.8 and -0.8 m OD respectively (Royal Haskoning, 2004b). There is a time lag in the tide within the Harbour, which is most prominent at low tide, the North Haven and Ro-Ro tide gauges are shown on Figure 3.1.

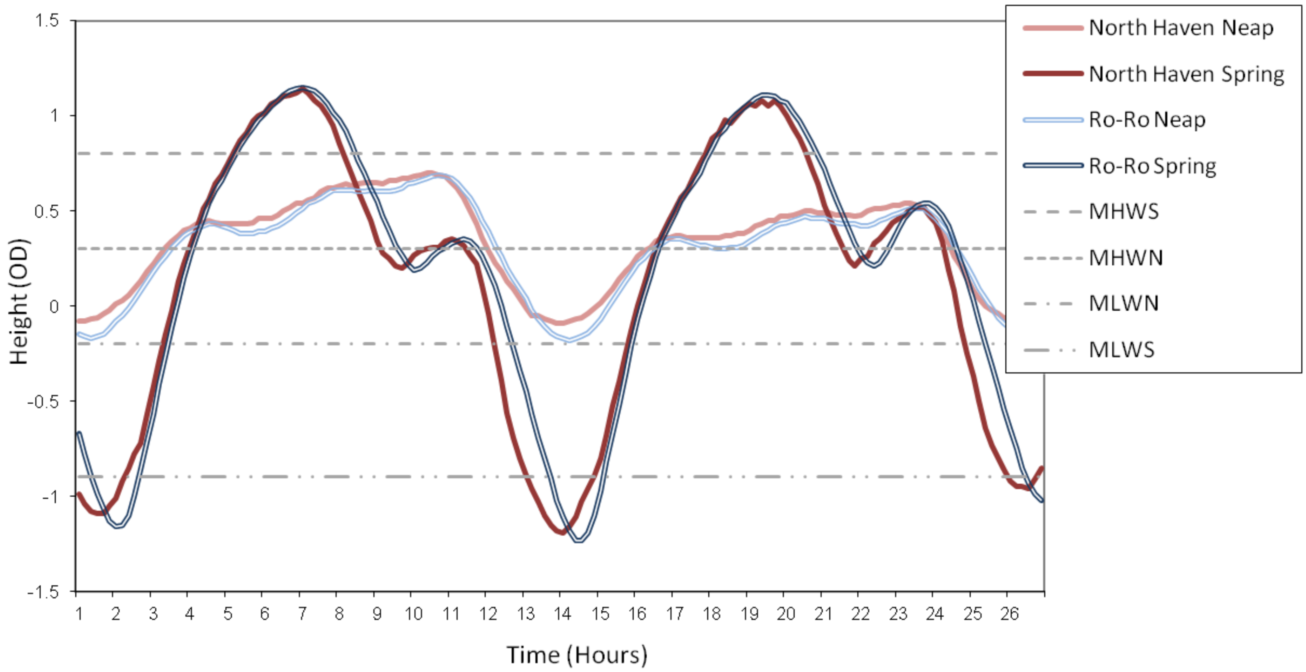



**Figure 3.3 An example of spring and neap tides for January 1997, North Haven and Ro-RO terminal (see Figure 3.1 for location of tide gauges)**

The mean tidal range at the Harbour entrance for 2007 was 1.5m and 1.12m at the Ro-Ro ferry terminal (Proudman Oceanographic Laboratory, *pers. comms.*). However, the maximum range can be much larger and also varies throughout the Harbour with up to 2.2m recorded at the Ro-Ro ferry terminal (Poole Harbour Commissioners, *pers. comms.)*, 1.2m at Arne peninsula and 1.6m at Newtown Bay, (Edwards, 2001).

**Table 3.2 Tidal levels in Poole Harbour (mOD)**

| | MHWS | MHWN | MLWN | MLWS | Range on Spring | Range on Neap |
|---|---|---|---|---|---|---|
| Harbour mouth (Royal Haskoning, 2004b) | 0.8 | 0.3 | -0.2 | -0.8 | 1.6 | 0.5 |
| Harbour mouth (Proudman Oceanographic Lab, *pers comms*) | 0.6 | 0.2 | -0.2 | -0.9 | 1.5 | 0.4 |
| Arne Peninsula (Edwards, 2001) | 0.6 | 0.3 | -0.1 | -0.6 | 1.2 | 0.4 |
| Newton Bay (Edwards, 2001) | 0.7 | 0.1 | -0.2 | -0.9 | 1.6 | 0.3 |

The ebb tidal stream at the Harbour entrance has been recorded as having higher velocities than those of flood, with max speeds of around 2m/s (SCOPAC, 2004). Characteristic velocities in the main channel are 0.5m/s (SCOPAC, 2004), indicating ebb dominant peak velocities from these Figures.

#### *3.1.2.3* Sea-level Rise and Surges

Mean sea-level trends for the English Channel over the 20th Century have been calculated as between 0.8 and 2.3 mm/yr,  with the trend at nearest stations of Southampton and Weymouth (3.1) of 1.30 ± 0.18 mm/yr and 1.81 ± 0.28 mm/yr, respectively (Haigh et al., 2009).

This region is dominated by surges generated from depressions in the western English Channel approaches. Surges recorded in Southampton water can reach levels of 1.5m, and within the English Channel positive surges tend to occur more frequently and are of greater amplitude than negative surges, (Haigh *et al.*, 2004). The maximum water levels experienced tend to correspond with moderate rather than extreme surge levels. However, this trend is not as evident at Poole due to the smaller tidal range (Haigh, *et al.*, 2004). With a low tidal range the surge can also potentially play proportionally greater role in influencing extreme water levels, (Haigh *et al.*, 2004).

Due to its microtidal regime this also suggests that the estuary, within a UK context, will be limited in its ability to adjust with sea-level rise and is vulnerable to future changes (cf(Nicholls et al., 1999)). The long term threat is that there is not enough sediment entering the system to keep pace with sea-level rise, which would result in a loss of intertidal area, and in the long term submergence of the estuary. This will be exacerbated by development particularly along the northern shore where defences prevent migration of habitats. However, along the southern shore there will be accommodation space for this migration.

### 3.1.3 Sediment Budget

The geomorphology and sedimentation of Poole Harbour is poorly described within the literature. However, localised studies have been conducted, with focus on the accumulation and release of sediments associated with the spread and dieback of *Spartina anglica* (Bird and Ranwell, 1964, Gray, 1985, Gray et al., 1990, Raybould, 1997) and the sedimentation and dredging of the main navigable channels (Halcrow Maritime, 1999, Hydraulics Research Ltd, 1990, Hydraulics Research Ltd, 1991, Green, 1940, Green et al., 1952).

May (1969) undertook a survey of Poole Harbour to assess the way in which shoreline changes have taken place, focusing particularly on Holes Bay. In this study it was attempted to recreate the shoreline at the end of the last marine transgression (6,000 years BP), Figure 3.4., this was also illustrated in Halcrow Maritime (1998). Since that date, it was concluded that change has mainly taken the form of;

- Deposition of sediment
- Cliff erosion
- Build-up of marshland as a result of vegetation growth on mudflats (e.g. *Spartina*)
- Human interference, including the construction of seawalls and embankments, dumping of town waste and reclamation of marshland

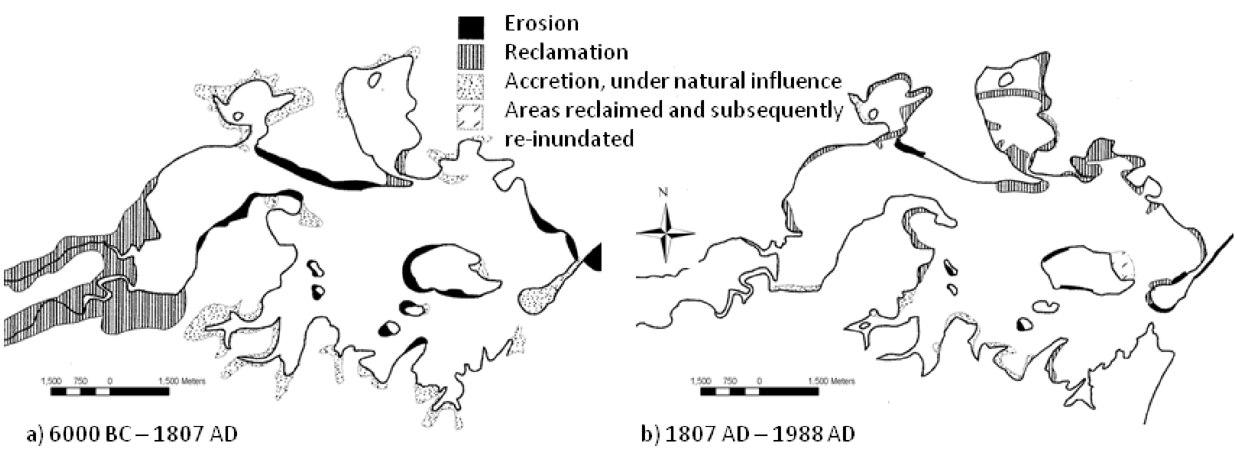



**Figure 3.4 a and b. Inferred evolution of Poole Harbour (Halcrow Maritime, 1998, May, 1969)**

The possible sources of sediment to the Harbour were assessed  as from offshore, cliff erosion, saltmarsh erosion, beach erosion, channel erosion, and river flows, (Halcrow Maritime, 2003) . Of these the offshore source has been identified as the most significant source of sandy material, although this has not been quantified. Neither cliff erosion, beach erosion, channel erosion nor river flows have been considered to provide significant amounts of sediment to the system and hence the system is considered a closed or near-closed system with regards to fine sediments. From bathymetric studies (Royal Haskoning, 2004b) calculated the net loss of fine sediment from Poole Harbour being between 56,000 and 76,000 $m^3$/year, the sediment was not specified as being sand or silt/clay. This was derived using the best available data in each area and chart analysis for the years 1984 and 2003. This study concluded that broadly speaking the intertidal mudflat area is staying approximately constant, with the source of the sediment is predominantly from the eroding saltmarshes.

#### *3.1.3.1* **Poole Bay**

Studies of sand mobility at the Harbour entrance indicate an un-quantified potential for sediment transport into the Harbour during combinations of storm wave and flood tide conditions (SCOPAC, 2004, Hydraulics Research Ltd, 1986, Hydraulics Research Ltd, 1988, Hydraulics Research Ltd, 1991, HR Wallingford, 1993b). Sand and gravel flood tidal deltas at the entrance of Poole Harbour, alongside sandy sediments on the bed support the occurrence of this process, (SCOPAC, 2004). Generally the Harbour bed comprises sandy material around the swash channel at the entrance and in the eastern part of the middle ship channel, further in towards the port the bed sediments contain an increasing proportion of fine sediment, (Royal Haskoning, 2004b).

#### *3.1.3.2* **Fluvial Sources**

Two major rivers flow into Poole Harbour, the Frome and Piddle, along with two smaller ones (Sherford and Corfe), there are also a number of small streams from tributary catchments which may supply sands and clays.

Both the Piddle and the Frome rivers have been recently studied through the Natural Environment Research Council's Lowland Catchment Research (LOCAR) thematic programme, which was created to improve the knowledge about lowland catchments, investigating hydrological, chemical, biological and physical processes. Some of the results of which are presented in (Collins and Walling, 2007).

The upper Frome and Piddle basins are formed in chalk, the upper Corfe in mainly Wealdon clays and sands, with the lower basins on tertiary deposits, which are composed of a series of sands and clays that are easily erodible by gullying and sheet erosion. These deposits form the major source of sediments carried into the Harbour by rivers, (May, 1969). The amount of sediment carried in the rivers depends on a number of variable factors linked to surface run-off. The run-off depends on local sub-soils with more surface movement during periods of heavy rainfall. Due to this it is considered difficult to assess the past volumes of sediment moved by the rivers, the rate of run-off depends largely on not only immediate rainfall amounts but also on the degree of previous saturation of the soil, (May, 1969). Changes in landuse of the area will also affect run-off, (May, 1969) identified 3 major changes in land use that are likely to have had major effects on sediment transport. The planting of conifers on the tertiary deposits will have decreased surface run-off (approximately 200 yr BP), thus slowing the amount of sediment to the rivers. However the creation of Ministry of Defence ranges and the expansion of them in 1943, with the subsequent destruction of surface vegetation and soil by vehicles on the tank ranges near Wool will have increased the run-off. Another change in landuse that will have affected the dynamics and sediment movement in the rivers is the creation of water meadows, particularly in the Piddle valley, where they interfere with water movement and trap large quantities of sediment. The extensive reclamation of the Frome and Piddle floodplains began in the medieval period.

The Frome and Piddle catchment areas are ~437 $km^2$ and ~183$km^2$ respectively. Average annual precipitation decreases eastwards from 1040 to 860 mm in the Frome and from 1020 to 840 mm in the Piddle. Collins and Walling (2007) measured the mean daily flow for the Frome (at Holne Bridge) as exceeding 6.4 $m^3$ $s^{-1}$ and the Piddle (at Baggs mill) as 2.4 $m^3$ $s^{-1}$ , it was noted that both rivers are considered to be impacted by channel sedimentation. Total values of fine sediment storage over the study period between Feb 2003-July 2004, were calculated as 795t (7 t $km^{-1}$) in the Frome with a mean of 918 g $m^{-2}$ and a range of 410-2630 g $m^{-2}$ over 16 sites, and 730t (9 t $km^{-1}$) in the Piddle with a mean of 1580 g $m^{-2}$ and a range of 260-4340 g $m^{-2}$ over 13 sites. It was noted that no consistent pattern was seen to occur with respect to sediment storage. Temporal variation also occurred over the sampling period of fine bed storage.

Continuous monitoring of discharge and suspended sediment concentration at East Stoke in the Frome and Baggs Mill in the Piddle were also conducted throughout the LOCAR programme, Feb 2003-July 2004 (Collins and Walling, 2007). The mean annual suspended sediment load in the Frome was calculated as 4370t, and 1281t in the Piddle.

#### *3.1.3.3* **Localised Erosion**

Much of the natural shoreline is marked by a low bluff (commonly less than 5m in height) and eroding cliffs (May, 2005). Cliff erosion provides the source of the many small beaches with gravel and sand, with gravels often forming layers on the upper part of the intertidal flats, (May, 2005). For much of the twentieth century *Spartina* protected existing cliffs and retreat rates fell with many former cliffs degraded to form well vegetated slopes. However, as saltmarsh in the Harbour has retreated, cliff erosion rates increased to an average of 0.85m $year^{-1}$, (May, 2005).

Elsewhere in the Harbour erosion has been reported, although rates have not always been calculated, these areas include Rockley Cliff, (Gray, 1985), (May, 1969), Brands Bay and Goathorn Peninsula (Gray, 1985) and Shipstal Point, (May, 1969). During several field trips as part of this research in May, 2008, erosion was also noted at several locations within Poole Harbour, including Furzey Island and along the south coast of Brownsea Island.

Royal Haskoning (2004b) reported observations under stormy conditions showing peak suspended concentrations of up to 600mg/l, these concentrations were considered the result of erosion due to locally generated wind-waves. Data collected by the EA indicated that suspended sediment concentrations were of the order of 10mg/l or less, with background levels in creeks with intertidal areas being in the order of 50mg/l, (Royal Haskoning, 2004b).

### 3.1.4 Dredging

Regular maintenance dredging of navigation channels occurs, with detailed records held by Poole Harbour Commissioners, historic volumes are shown in Table 2. The majority of dredging is carried out on a bi-annual basis by trailing a suction dredger. Sandy material arising from maintenance is now used for beach nourishment within Poole Bay and Swanage Bay.

Dredge volumes in Poole Harbour are low in comparison to dredging activities that occur in other south coast estuaries, for example the volume of sediment extracted within Southampton water from 1994-1997 was over 6,000,000 $m^3$ for capital dredging, maintenance dredging in the estuary has been calculated between 1994-2002 with a total volume over that period of over 4,000,000 $m^3$, (Horter, 2003).

**Table 3.3 Historic Dredge Volumes**

| Date | 1969-1975 | 1975-1984 | 1985-1990 | 1990-1997 | 1969-1997 |
|---|---|---|---|---|---|
| Volume ($m^3$) | 138,618 | 349,800 | 2,017,000 | 1,531,336 | 4,036,754 |
| Source | (McMullen, 1982, McMullen, 1985) | (McMullen, 1982, McMullen, 1985) | (Hydraulics Research Ltd, 1990) | (Hydraulics Research Ltd, 1990) | |

The middle ship channel has been progressively deepened since 1986. Prior to 1986 the natural depth was around 3m below CD, deepening to 10m below CD at Brownsea Island. In 1986 the channel was dredged to a declared depth of 5m below CD and in 1991-92 the channel was deepened to a declared depth of 6m below CD. Prior to 1986 the North Channel was primarily used as the navigation channel with a minimum depth of 3.6 m below CD, (Royal Haskoning, 2004b).

Since the channel deepening in 1991-92 it has been noted that changes to the local seabed morphology has occurred, (Royal Haskoning, 2004b). This includes the deepening of Wych channel, with the intertidal areas to the south of Brownsea and the north of the channel reducing in their extent. However, between the middle and north channels the shoals of Parkstone shoal and Middle ground have become larger, (Royal Haskoning, 2004b).

More recently a channel deepening project was conducted to widen and increase the depth of the middle ship channel from 6m to 7.5m in order to accommodate larger ferries at all states of the tide, the turning basin, little channel and swash channel were all dredged during this scheme. Almost 2,000,000 $m^3$ of sand, gravel and silt were removed from the channels both inside the Harbour and from the approaches. Of this 1,100,000 $m^3$ were made available for beach replenishment at Bournemouth and Swanage. Unsuitable material was disposed of at a licensed disposal ground off the coast at Swanage. Additionally trials for the disposal of silt and muddy material, dredged through maintenance dredging, to be redistributed within the Harbour started in May, 2008.

### 3.1.5 Habitats, Species and Historic Change

Poole Harbour is an estuarine environment and therefore exhibits high biological productivity, the enclosed and sheltered nature of the estuary has contributed to a notable diversity of habitats and species. Over 65% of the Harbour is intertidal area, this includes extensive mud and sand flats mostly fringed by reedbeds or saltmarshes, Figure 3.1. Much of the saltmarsh is dominated by Cord grass (*Spartina anglica*) with Eelgrass beds (*Zostera* sp.) occurring in areas of the sub-littoral. However, various types of saltmarsh are found within Poole Harbour, these include Atlantic salt meadows, *Salicornia* species colonising mudflats and Mediterranean and thermo-Atlantic halophilous scrubs and salt meadows. Surveys held by Dorset environmental records centre indicate that of the 480 ha of saltmarsh within Poole Harbour in 2001, around 200 ha were made up of the saltmarsh types mentioned above, none of which include the species *Spartina*. This leaves 280 ha of unspecified saltmarsh which presumably is made up of *Spartina sp*.

Since 1999, Poole Harbour has been classified as a Special Protection Area (SPA) under the European Birds Directive due to its internationally important population of birds. The islands within the Harbour give ecological value, small colonies of Blackheaded and Mediterranean Gulls as well as sandwich and common terns shelter on the Islands. The Harbour and its adjacent landscape hold a number of other European and national statutory designations including that of a European Marine Site, others include:

- Poole Harbour Site of Special Scientific Interest (SSSI)
- Poole Harbour Ramsar Site

Despite its high conservation value the Harbour has a history of problems of contamination and hyper-nutrification, which appears to have affected species abundance and distribution (Langston et al., 1987, Langston et al., 2003). The rivers are suggested to be the main sources of nutrient input to the Harbour, together with effluent discharge from the three main sewage treatment plants at Poole (Holes Bay), Lytchett Minster and Keysworth, as well as storm water discharge (Falconer and Liu, 1995). Diffuse pollution, particularly from agricultural land runoff, is seen as an important issue within the Harbour, farm animal waste and fuel oil storage are also potential sources of pollution to rivers feeding Poole Harbour.

#### *3.1.5.1* Saltmarsh Loss

Both the rapid spread of *Spartina anglica* and the subsequent decline have been previously described (Gray and Pearson, 1984, Born, 2005, Raybould, 2005, Hubbard, 1965). The first record of *Spartina anglica* in Poole Harbour is generally reported as a single clump in Ower Bay in 1899 (Hubbard, 1965). After this date, it was reported to spread rapidly and by 1913 was found throughout the Harbour. The colonisation did not occur uniformly and was confined initially to the margins of the Harbour, with a gradual invasion of central regions, (Oliver, 1925). Channels deepened (Gray et al., 1990) as *Spartina* spread within the Harbour, presumably removing from circulation large volumes of sediment.

The expansion was dramatic or short-lived: and by the 1920s, some of the saltmarshes were reported to have begun to erode, (Raybould, 2000). This was initially attributed to creek and channel migration, undercutting saltmarsh stands, but it was also reported that tidal scour had occurred around projecting spits of saltmarsh (Oliver, 1925). It is noted that the continuous high winds of 1924 caused wave driven erosion in exposed areas, 'resulting in hundreds of acres of saltmarsh loss' (Oliver, 1925). From the early 1930s onwards shoaling occurred in the major navigation channels, consistent with the release of sediments from the eroding marshes (Gray et al., 1990). The broad pattern within the Harbour by the 1940's was a general decline in saltmarsh area. However, even in the 1960's *Spartina* continued to thrive in some locations, with vertical annual accretion rates recorded as 80 mm in 1963 and up to 150mm in 1966 (Hubbard and Stebbings, 1968) in localised studies at Keysworth marshes in the west of the Harbour.

Previous Harbour wide studies have focused primarily on the loss of saltmarsh post 1924. Studies prior to this time tend to be localised and have focused on accretion rates rather than the location and mapping of *Spartina*. Hubbard (1965) describes the pattern of colonisation of *Spartina* in the Harbour and includes the earliest Harbour wide estimation of saltmarsh area in 1924. This is compared to the extent in 1952 with a decrease of 172ha or 19.8% loss of the 1924 area. Significant losses have also been described between 1947 and 1993, with the area of saltmarsh in the whole Harbour decreasing by 245 ha (38% of 1947 extent) (Born, 2005). The corresponding rate of saltmarsh loss between 1972-1993 averaged 7.5 ha per year, accounting for 157.5 ha of saltmarsh loss over that time, (Halcrow Maritime, 2003). A survey of saltmarsh extent was also undertaken in 2001-2002 using a hand held GPS, (Edwards, 2005). According to this study approximately 423 ha of saltmarsh remained with the vast majority of this being lower saltmarsh dominated by *Spartina anglica.* Middle and upper vegetation was found to be limited in extent and frequently found as linear stands just below mean high water. It also indicated a present loss of around 5 ha per year, (Edwards, 2005).

However, all the previous studies only consider erosion and do not discuss the possibility of accretion or migration of saltmarsh occurring within the Harbour. Further east within the

Solent region, saltmarsh losses have been widely reported. However where estuaries are not fully constrained by seawalls, some migration and accretion has occurred, *eg*. Newtown and Pagham Harbours (Baily and Pearson, 2007, Gardiner et al., 2007): hence this is also possible in Poole Harbour.

Raybould (2005) discusses several reasons for the decline of saltmarsh in Poole Harbour, the first is erosion at the marsh edge, particularly the break up of marsh islands on intertidal flats rather than marshes fringing land. The second reason is saltmarsh die-back, where the *Spartina* has been observed to degenerate in patches within the body of the sward rather than at the edge. This process seems to be associated with badly drained, highly anaerobic soils in which the *Spartina* rhizomes may be poisoned by sulphide ions and lack of oxygen (Gray *et al*., 1991). Another potential driver is that *Spartina* may be lost through the invasion of other species from the landward edge, in areas with low salinity *Phragmites communis* has replaced marsh.

The maximum submergence tolerance for *Spartina is* 6 hours (Oliver, 1924, Oliver, 1925) and (Goodman et al., 1959). However Ranwell et al. (1964) recorded tidal submergence of as much as 9 hours at equinoctial spring tides within Arne Bay. This however would be a rare occurrence and was recorded outside of the active growing season for the plants (April to October). It was also theorised that the rapid development of marshlands around Poole Harbour since the 1890s has reduced the extent of tidal exchange in the upper Harbour, with result of prolonged tidal submergence in the lower Harbour, this may also be a contributing factor to the dieback of *Spartina* in this area.

There appears to be little discussion in the literature regarding the future trends of saltmarsh in Poole Harbour. Born (2005) extrapolated historic losses linearly to 2053, suggesting expected losses to be between 183ha and 244 ha (47%-63% of 1993 extent).

#### *3.1.5.2* **Saltmarsh Gain**

Long term sediment accretion within Poole Harbour has been observed using *Pinus* pollen frequencies as a biostratigraphic marker (Long et al., 1999). Sediment accretion rates between ca.1750 AD and ca.1890 AD rose from 0.29 to 1.14 mm/yr: it has been suggested that this may reflect an acceleration in the rate of sea-level rise as observed at the Brest tide gauge (Woodworth, 1990). However, following the establishment of *Spartina anglica* in ca.1890 AD, sediment rates accelerated to 7.17 mm/yr, and so the marshes rose relatively within the tidal frame.

Accretion rates on the intertidal area were first recorded between 1961-62, (Ranwell, 1964). It was found that quarterly changes of sediment levels were too small to be considered significant, although a uniform slight accretion of between 5-10mm per year was suggested. It was noted that the landward end of the transect used, passed through a belt of *Phragmites communis*, which has been observed invading the *Spartina* marsh. Again in the *Phragmites* zone annual accretion rates were recorded as 5-10mm. It was concluded that most of the Poole Harbour marshes were nearing their upper limit of growth and were accreting very slowly and since many of the marshes are cliffed at their seaward edges and eroding, the mud supply must be limited and is being recycled.

Ranwell (1964) notes that *Spartina anglica* rosettes were found at least 1m below the surface at Keysworth marsh and so indicate that prior to this at least 1 m of silt has accumulated since *Spartina* first invaded approximately 50 years previously. This would therefore give an average accretion rate for the first 50 years of colonisation as 20mm/year, the saltmarshes may have simply risen within the tidal frame as observed elsewhere, (Allen and Duffy, 1998, Allen, 2000, French and Reed, 2001). Studies by Marshall et al. (2007) investigated accretion rates on Arne marshes using radionucleotides, this indicted that the accretion rate remained at 1.9mm/yr during the early twentieth century and rose to 8.3mm/yr around 1972, this sudden acceleration was explained by an episode of localised die back in a nearby part of Poole Harbour, releasing sediments to be re-deposited on the Arne saltmarshes. These Figures do appear to be fairly low, although, it was noted in Hubbard and Stebbings (1968) that an accretion gradient occurs within the Harbour. In the study it was found that 180 cm had accreted at the Keysworth marshes since *Spartina* colonisation whereas only 70cm had accreted on the Arne marshes.

In Hubbard and Stebbings (1968), the stratigraphy of Keysworth Marsh was investigated for *Spartina* rhizomes, which was generally down to a level of -0.06 m OD with an extreme value of -0.96m OD. The surface level of Keysworth marsh at the time of this study (1968) was between +0.11m and +0.85 m OD with approximately 95% of the area above +0.65m OD.

Elsewhere in the Harbour bathymetric surveys of south deep, south of Brownsea Island (Royal Haskoning, 2004b), show significant accretion in the subtidal areas, erosion in the intertidal areas of the lower foreshore and some deposition on the upper intertidal profile between 1984 and 2003. According to Gray *et. al.*(1995), there was little change in patterns and channels, mudflats and fringing marshes until the end of the nineteenth century.

#### *3.1.5.3* **Reedbed Change**

The area of reedbeds in Poole Harbour was reported to have increased by 47 ha (63% of 1947 extent) between 1947 and 1993, (Born, 2005), replacing *S. anglica* (i.e. it is a *Spartina* loss mechanism). Born (2005), extrapolated historic gains linearly to 2053, gains are expected to be between 0 and 61ha (0-50% of 1993 extent). All areas of major reed beds were surveyed again in 2000, (Cook, 2001), 175 ha were recorded during this survey representing 60% of the county's reedbeds and 30% of the reedbed total for the southwest of England. However, erosion around the Harbours edge is posing a future threat to this habitat in areas and changes in future salinity levels due to sea level rise and changing weather patterns will also have a significant effect on this habitat.

### 3.1.6 Poole Harbour Models

As this study aims to relate the distribution of saltmarsh to hydrodynamics, a process based model capable to replicating tidal velocities and water levels at an appropriate resolution is required.

Several models have been developed for Poole Harbour, including a TELEMAC 2D model by HR Wallingford and a hydrodynamic water quality model, developed to predict water elevations, depth averaged velocity and pollutant concentrations (Falconer, 1986a, Falconer, 1984a, Falconer, 1986b, Falconer, 1984b, Falconer and Chen, 1991, Falconer and Liu, 1995) both are process based models. The HR Wallingford TELEMAC model was used in this study as it was considered to be the most up to date and model outputs were more easily integrated with the results of the saltmarsh change analysis.

**Poole Harbour TELEMAC Hydrodynamic model**

With permission from HR Wallingford and Poole Harbour Commissioners, the TELEMAC model for Poole Harbour was used for this study. The TELEMAC model satisfies the requirements of this research and can provide average tidal flow vectors under present conditions indicating areas within the harbour that are flood and ebb dominant and potential correlations with saltmarsh and mudflat erosion from the historic analysis.

The underlying tin mesh varies with accuracy throughout the Harbour, as the model was developed to investigate possible effects of dredging in the main channels, reported in (HR Wallingford, 1993a), therefore it is these areas that have the highest resolution. However the model resolution will be sufficient to give insight into hydrodynamic processes in other areas of the Harbour also, particularly the southern intertidal shore and Wareham Channel.

The model was calibrated by HR Wallingford using flow data collected from current meters at 7 locations within Poole Harbour and 6 tidal diamonds, during the 11$^{th}$ and 12$^{th}$ March, 1990, tidal data was also collected at this time. However, these validation points were all positioned in the north-east of the Harbour adjacent to the main channel, which was originally the focus of the model. Further details on the calibration of the model are outlined in the methods section 4.3.2.

## 3.2 Summary

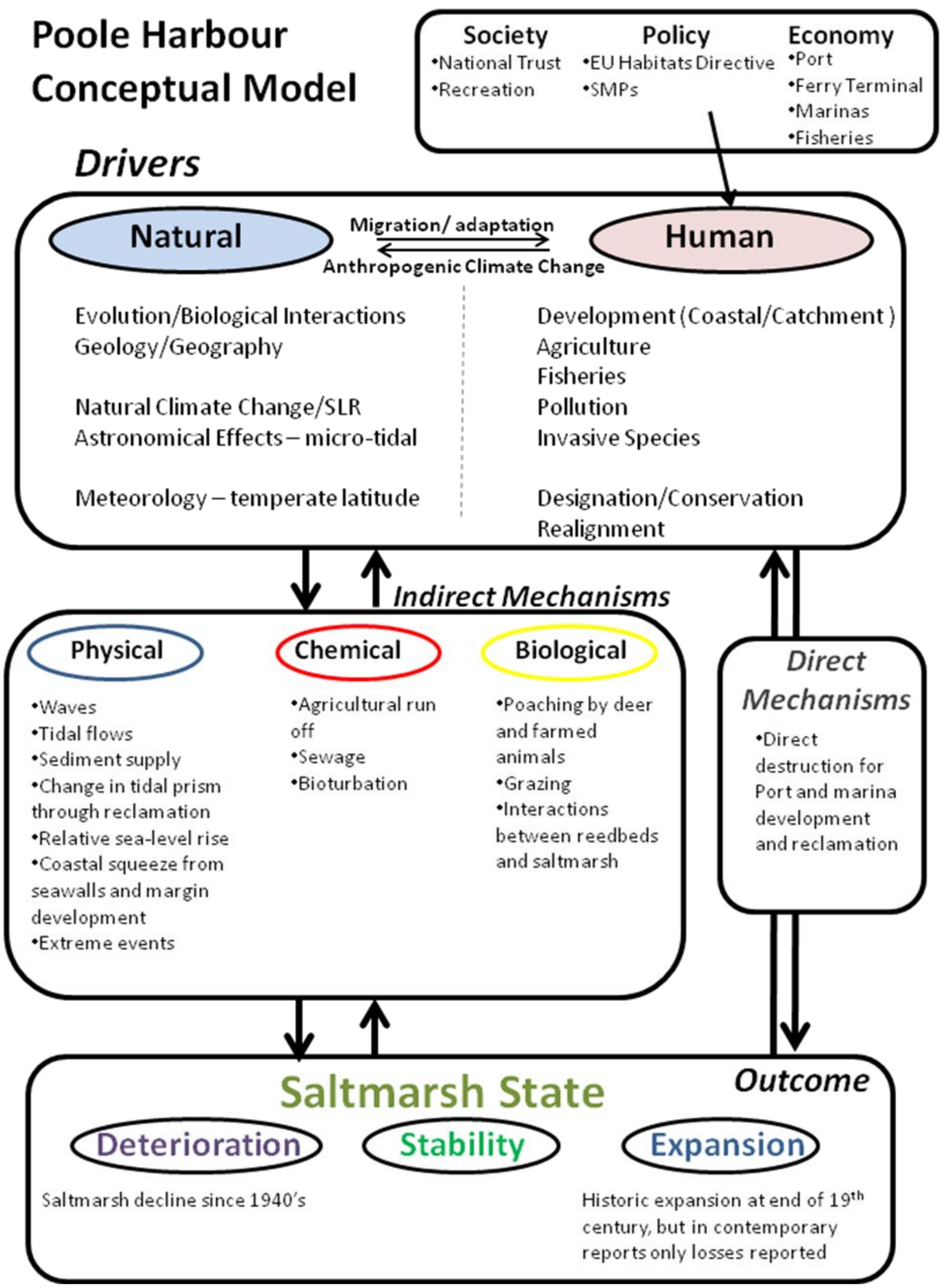



**Figure 3.5 A conceptual model of saltmarsh change in Poole Harbour noting significant drivers and mechanisms from the literature.**

Based on the conceptual model framework created in Chapter 2, a site specific framework has been developed for Poole Harbour that brings together the potential drivers of change and the relative pressures from human developments, and policy.

Saltmarshes are important coastal habitats providing multiple ecosystem and coastal protection services. Hence, understanding the processes which affect saltmarsh areas and the services they provide is vital. Within the last century saltmarsh changes in Poole Harbour have been dramatic with several studies identifying saltmarsh losses. However, these studies tend to be localised rather than Harbour-wide, and those which have studied the entire Harbour have done so at a low resolution. Future trends have been predicted by simply interpolating historic losses without identifying drivers of loss. Chapter 4 describes the methods undertaken for the three stages of analysis, firstly the historic change analysis, secondly investigating the morphology of the Harbour through hypsometry and cross shore profiles and thirdly investigating tidal asymmetry in order to identify the drivers of saltmarsh changes.

# 4 Methodology

The main aim of this research is to explore saltmarsh change, identifying both accretional and erosional drivers and mechanisms and identifying trends of saltmarsh change at estuary and sub-estuary scales exploring the physical processes of these changes in detail.

This study has been undertaken in four main stages. Stage 1 is a re-examination of historic saltmarsh trends within Poole Harbour and uses multiple sources, encompassing a historic analysis using Ordnance Survey (OS) maps, charts and aerial photography and gives improved insight into historic trends and processes within the Harbour. Intertidal features, such as saltmarshes and creek systems have been re-examined, mapped and changes quantified. An uncertainty analysis also examines the potential errors. In previous research crucial spatial trends have not been investigated which may provide insight into long term saltmarsh change trends.

In Stage 2 the morphology of the Harbour is analysed using bathymetric data, both from LIDAR and admiralty charts. Hypsometry at estuary and sub-estuary scale is calculated and the examination of intertidal profiles gives insight in to contemporary saltmarsh processes. Velocity shear thresholds from sediment samples taken from the Harbour are also analysed using flume tests. In Stage 3 tidal hydrodynamics and in particular tidal asymmetry is explored in the Harbour, firstly using generalised geometric and hydrodynamic relationships. Secondly tidal flow vectors are investigated, particularly flood and ebb dominance, using modelled data, in order to illustrate the spatial distribution of flow within the Harbour and the drivers that instigate the changes seen from the historic saltmarsh change analysis

Stage 4 involves using an annular flume to assess the critical shear velocitiy of sediment samples taken from the Harbour, these critical velocities will be used to alongside the hydrodynamic model outputs in Chapter 7 to define slack durations within the Harbour.

The methodology of each of these three stages is described in the following Sections.

## 4.1 Stage 1: Historic Analysis of Change

Several techniques to look at historic changes within the Harbour were applied across a range of scales. The analysis of maps, charts and aerial photography have been assessed and are discussed in turn and then the results are integrated together

Whilst examining historic changes within an estuary it is important to understand the geomorphological scales involved and appropriate drivers (Table 2.1). Several important drivers must be taken into consideration, the first being the 18.6 year nodal cycle. This is caused by the amplitude of the lunar declination increasing and decreasing over an 18.61 year period. The effect of this is a decrease of the equilibrium tide by 3.7% when the declination amplitudes are greatest and a corresponding 3.7% increase 9.3 years later (Pugh, 2004). Sufficient data was not available at Poole Harbour to chart the possible effects of the lunar cycle, Figure 4.1 shows the lunar nodal cycle at Newlyn. Both calculated and measured data are shown indicating a small variation around the calculated values, key dates of data used within this study are shown. As the tides in Poole are generally considered to be micro-tidal 1.8m (although variations throughout the Harbour occur, Section 3.1.2.2), the variation of 3.7% increase and corresponding decrease in tides due to the lunar nodal cycle will be small, 6.6cm on springs and 2.2cm on neaps. However, this is still an important driver to be aware of and its potential impact on any results, especially in areas where the foreshore has a low gradient.

Seasonal variations are also important, particularly when observing ecosystems and saltmarshes. Several studies have been conducted on the accretion and heights of saltmarshes. Surface heights of saltmarsh creeks have been found to have seasonal variations of up to 2cm (Carr and Blackley, 1986), with the changes attributable to the swelling of clay particles during the winter months.

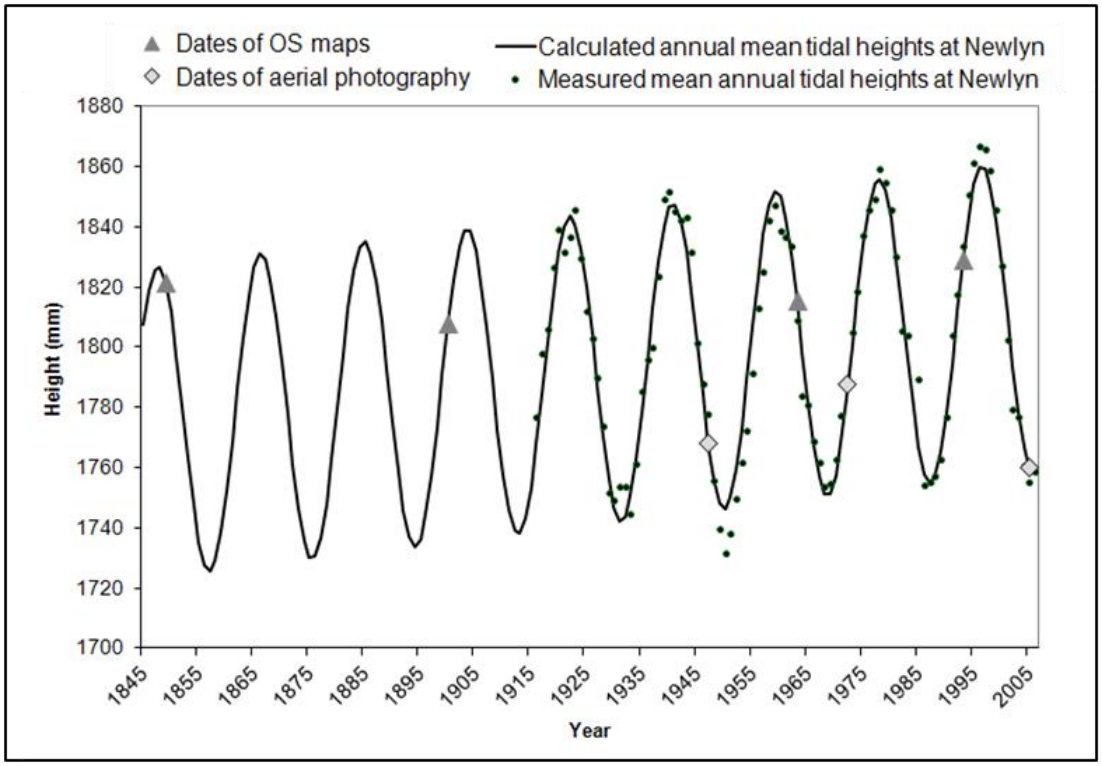



**Figure 4.1The 18.6 year lunar nodal cycle calculated and measured at Newlyn and dates of data used within the study. (Data supplied by Ivan Haigh, pers. comms.)**

Other studies within the UK (Ranwell, 1964) have suggested that 75% of accretion occurs during the period between August and October and may be connected to the high tides rising through August and September to the maximum levels of the autumn equinox. Unfortunately the time of year at which the data sources were collected is not always available. However, this must be acknowledged as a source of uncertainty, but is unlikely to be important over the medium- to long-scale of relevance to this study.

### 4.1.1 Historic Maps

Historic map sources can be digitised in order to study coastal change (Carr, 1986, Crowell et al., 1991, Moore, 2000). In the UK, maps are produced by the Ordnance Survey (OS). When using OS maps, it is important to be aware of the limitations of the data, inaccuracies within OS data can be from a number of sources and occur either during the mapping or surveying of the data. Historically mapping was achieved using a line and sight. However, during the 1990s this was superseded by GPS measurements. The estimated accuracy from

OS maps ranges from 3.5m (Lee and Clark, 2002) to 10m (Nicholls et al., 2000) based on cliff interpretation: errors for saltmarsh are harder to assess but may be larger.

MHW and MLW locations would originally have been surveyed by hand in the nineteenth century, this practice continued until the 1940's when aerial surveys took over (Baily and Collier, 2010). Depending on the shore slope this can lead to errors in the mapping of MHW. In a large estuary the flight can be long enough that the tide height varies from start to finish. This can lead to a gradient effect within the estuary and so the data can have errors related to the tide level at which the data was collected. When using historic datasets, shoreline indicators can be used to observe change MHW, MLW and cliff tops, out of these MLW is the least reliable in historic maps due to the methods used before aerial photography was widely available, (Nicholls *et al.*, 2000, Hanson and Nicholls, 2003). OS maps are also prone to displacement errors where datasets do not exactly match up, however this can be avoided by taking prominent points that have not changed, such as prominent buildings (e.g. churches), in order to reposition the data sets directly above one another.

Historic OS maps of Poole Harbour were acquired through Digimap (http://edina.ac.uk/digimap/description/overview.shtml) and studied within a GIS environment. Freely available maps only extend back to 1890, a summary of the data used can be seen in Table 4.1. These were compared to one another in order to identify changes, including reclamation and realignment. MLW and MHW lines were digitised and areas of apparent saltmarsh noted, maps used include; Country series 1:2500 1st Ed. 1890, Country series 1:10560, 2nd revision 1925, National grid 1:10560 1963, and National grid 1:10000 latest edition (1993). Subsequent years could then be compared to one another in order to observe and quantify area changes and reclamation.

**Table 4.1 Summary of digital data used including details of Aerial Photography and OS maps of Poole Harbour**

| Date | Scale/cell size | Source | Description | Data issues |
|---|---|---|---|---|
| Pub.1890 (1849-1890) | 1:2500 | Digimap | Rectified OS map | Surveys collected between 1849-1890, published in 1890 |
| Pub. 1925 (1900-1925) | 1:10560 | Digimap | Rectified OS map | Surveys collected between 1900-1925, published in 1925 |
| 1947 | 0.5-0.6m | Dorset County Council | B/W photographs (59 images unrectified) | Missing data: Arne, Lytchett Bay, Sandbanks, Brownsea Island |
| 1963 | 1:10560 | Digimap | Rectified OS map | |
| 1972 | 0.5-0.6m | Dorset County Council | B/W photographs (34 images, unrectified) | |
| 1993 | 1:10000 | Digimap | Rectified OS map | |
| 2005 | 0.1m | Channel Coastal Observatory | Colour photograph (1 image rectified) | Missing data: Lytchett Bay |

### 4.1.2 Historic Charts

A number of issues must be considered when interpreting historic charts; the primary factor of which is accuracy. Where possible the original sounding data on fair charts should be used rather than the interpretive charts created from them. For earlier charts, bathymetry was measured with a hand lead line and for more recent charts by an echo sounder. The use of an echo sounder improved both the accuracy and coverage of soundings (Lee and Clark, 2002, van der Wal and Pye, 2003). Even more recently, greater improvements in accuracy have been made through the use of high-resolution swathe multibeam bathymetric systems. The methods used for the positioning of the measurements have also improved; whereas in the past fixes where made using triangulation, GPS has been used more recently contributing to the overall accuracy and precision of the charts (van der Wal and Pye, 2003).

Bathymetry charts are attended for navigation and therefore do not necessarily provide an accurate representation of the seabed and land but instead draw attention to features of navigational interest, such as dangerous waters (Lee and Clark, 2002). Because of this charts are unlikely to provide a complete and accurate representation of the bathymetry or intertidal areas outside those areas of navigational interest.

Bathymetry charts were scanned and digitised within a GIS environment and georectified using the OS map National grid 1:10000 latest edition (1993), and 2005 aerial photography. Spot heights from each individual map were then digitised and the resulting data interpolated within ArcGIS and initially added to the LIDAR (2007) data to create a continuous digital terrain model (DTM). However, a more contemporary bathymetric data (2005) of a better quality was supplied by Poole Harbour Commissioners (PHC), which replaced data set.

### 4.1.3 Aerial Photography

Aerial photography used in the production of maps and charts is of a high resolution and as such, is suitable for the analysis of shoreline movement, cliff erosion and saltmarsh change. As previously mentioned (Section 3.1.2.2), low tide within Poole Harbour only occurs for a short duration which may affect interpretation of the photography, including the location of channels. Errors can also arise through interpretation of the images, for example, when interpreting cliff lines or distinguishing saltmarshes from surrounding mudflats.

Aerial photography was acquired for three years; 1947, 1972 and 2005 (Table 4.1). The 2005 data was supplied processed into one single georectified image in full colour. However, the 1947 and 1972 aerial photography data was supplied as 59 and 34 individual black and white, non-rectified images, respectively. These images were georectified within a GIS environment using the 2005 aerial photography and OS maps as a guide. Throughout this process the RMS (root mean square) errors of the georectification points were monitored to ensure that accuracy was maintained and that the error was minimised. Typical RMS errors for the georectification varied between 0 and 5m. Saltmarsh extent and channel location were then digitised into polygons for all datasets, this was supplemented with data supplied by Dorset Environmental Records Centre, showing generalised saltmarsh, reedbed and intertidal habitat extent within the Harbour in 2003. Incomplete coverage of aerial photography was noted (Figure 4.2) the 1947 dataset has a 73% coverage of the Harbour and the 2005 dataset a 96.6% coverage. The digitised saltmarsh areas and channel locations for 1947, 1972 and 2005 was then compared, to observe accretional and erosional trends within the Harbour.

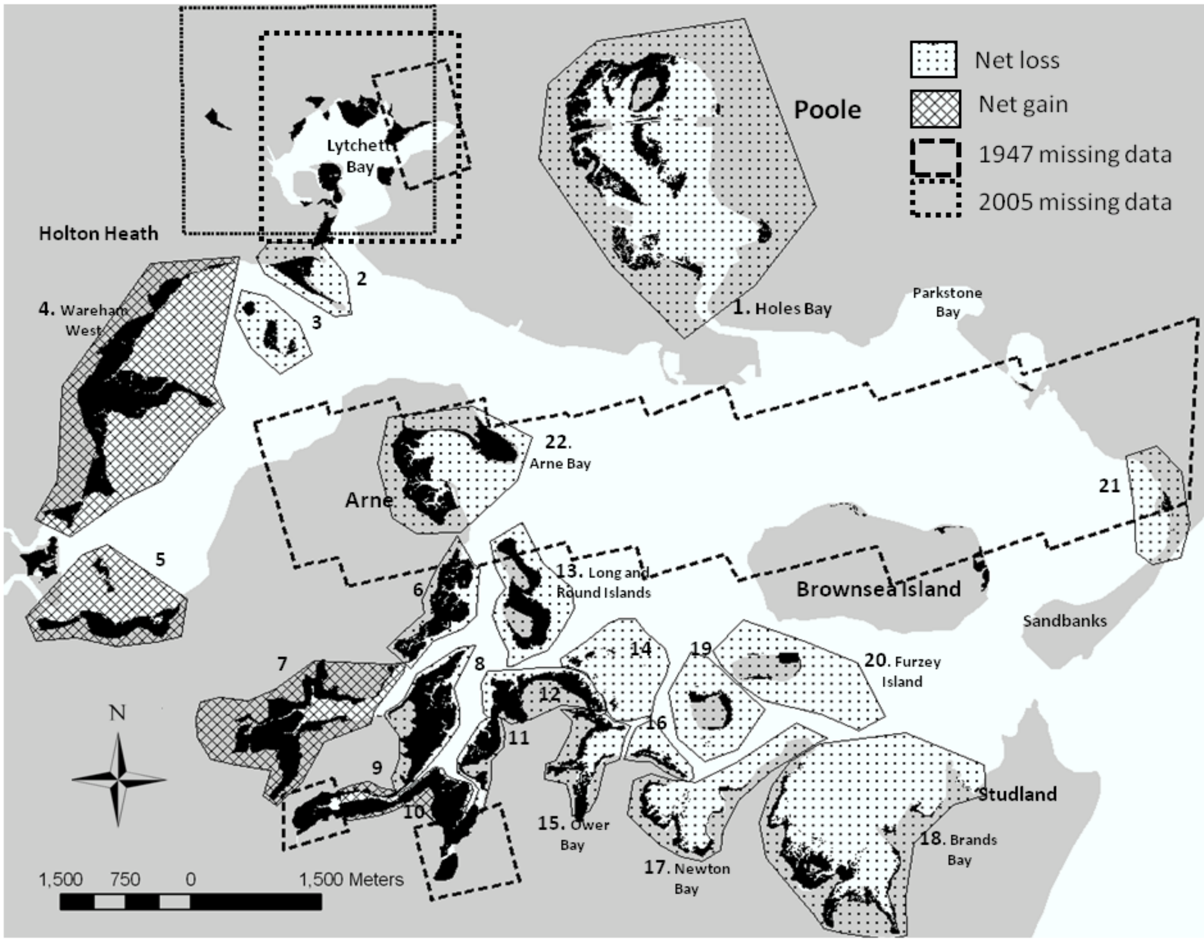



**Figure 4.2 Poole Harbour regions used for saltmarsh analysis (Boxes show areas of missing aerial photography)**

1) Holes Bay, 2) Wareham North, 3) Wareham Islands, 4) Wareham West, 5) Wareham South, 6) Grip Heath, 7) Middlebere Lake, 8) Wych Lake North, 9) Wych Lake South, 10) Wych Farm, 11) Wych Lake East, 12) Fitzworth North, 13) Long and Round Islands, 14) Fitzworth Islands, 15) Ower Bay, 16) Cleavel Point North, 17) Newtown Bay, 18) Brands Bay, 19) Green Island, 20) Furzey Island, 21) Sandbanks, 22) Arne

Several interpretive difficulties were encountered whilst digitising saltmarsh extent. The landward extent of the saltmarsh, particularly on black and white aerials, was not easily identifiable and so the well-defined landward extent from the 2005 aerials was used to interpret all the photographs. This prevented the identification of saltmarsh migration inland but still allowed the measurement of the important process of frontal retreat/expansion. Given that sea level rose by a maximum level of 14 cm since 1947 (following Haigh et al., 2009) any landward migration is expected to be negligible. Distinguishing reedbed from saltmarsh in the black and white aerials was also problematic; these were generally small isolated locations accounting for less than 10ha. Where possible, these areas were compared to previous work and maps of current known reedbed extent in order to verify habitat type. Misidentification of reedbed areas in the historic aerials may lead to either an over or under-estimation of reedbed take-over, but is unlikely to greatly affect the large scale trends affecting the saltmarsh change over the entire Harbour.

Channels were not obvious in many locations, both geographically and for different years, this may be due to the time relative to the tidal stage at which the photographs were obtained, with the lower flats already covered in water, obscuring channel networks.

## 4.2 Stage 2: Analysis of Estuary Morphology

As discussed in Section 2.1.2, the morphology of an estuary or Harbour is closely linked to the hydrodynamic regime. Using detailed bathymetry data some of these relationships can be investigated. LIDAR (Light Detection And Ranging) is an airborne laser mapping technique for obtaining topography data (x, y and z coordinates) of terrain surfaces and features such as buildings, roads and trees.  It has been used successfully to investigate coastal habitats (Gardiner et al., 2007, Blott and Pye, 2004). A complete LIDAR dataset of Poole Harbour is available from the UK Environment Agency, dated 2007. This dataset, combined with bathymetry data (2005)  provided by PHC, can be used to investigate areas of saltmarsh and creeks, the position of intertidal habitats within the tidal frame, areas that are prone to flooding now and in the future and the morphology of the estuary.

### 4.2.1 Estuary Hypsometry

Estuary hypsometry, as discussed in Section 2.2.2, is the way in which the plan area of a drainage basin varies with elevation: variations in this form can alter the way the tide propagates and can change the flood and ebb tidal properties, (Townend, 2008).   The LIDAR data was used to investigate the hypsometry of the estuary. However, the LIDAR coverage is patchy and inaccurate over deep water areas, this can be remedied by combining the data with navigation charts or bathymetric data. Bathymetry data (dated 2005), in the form of digitised contours, was acquired from Poole Harbour Commissioners (PHC). This was then interpolated within ArGIS to form a continuous digital terrain model (DTM) for the channels within the Harbour. This dataset was then added to the 2007 LIDAR, which had data missing within deep water areas and a complete DTM was created. From this, the hypsometry of Poole Harbour was calculated as described in Section 2.2.2 by calculating how the area of the Harbour changes with height above the seabed.

### 4.2.2 Intertidal Profiles

The tidal flat shape was investigated to identify erosional/depositional trends. Figure 4.3 shows the 151 intertidal profiles that were extracted from the 2007 LIDAR dataset within a GIS environment. The focus of this area of study was informed by the results of the historic saltmarsh change analysis.

As discussed in Section 2.1.2 and illustrated in Figure 2.2, eroding and accreting mud/intertidal shores can exhibit distinct profile shapes with high and convex cross-sectional shapes attributed to an accreting or tidally dominated shore and low concave cross-sectional shapes attributed to an eroding or wave dominated shore. Therefore correlations between areas of erosion and accretion and hydrodynamic forces may be evident.

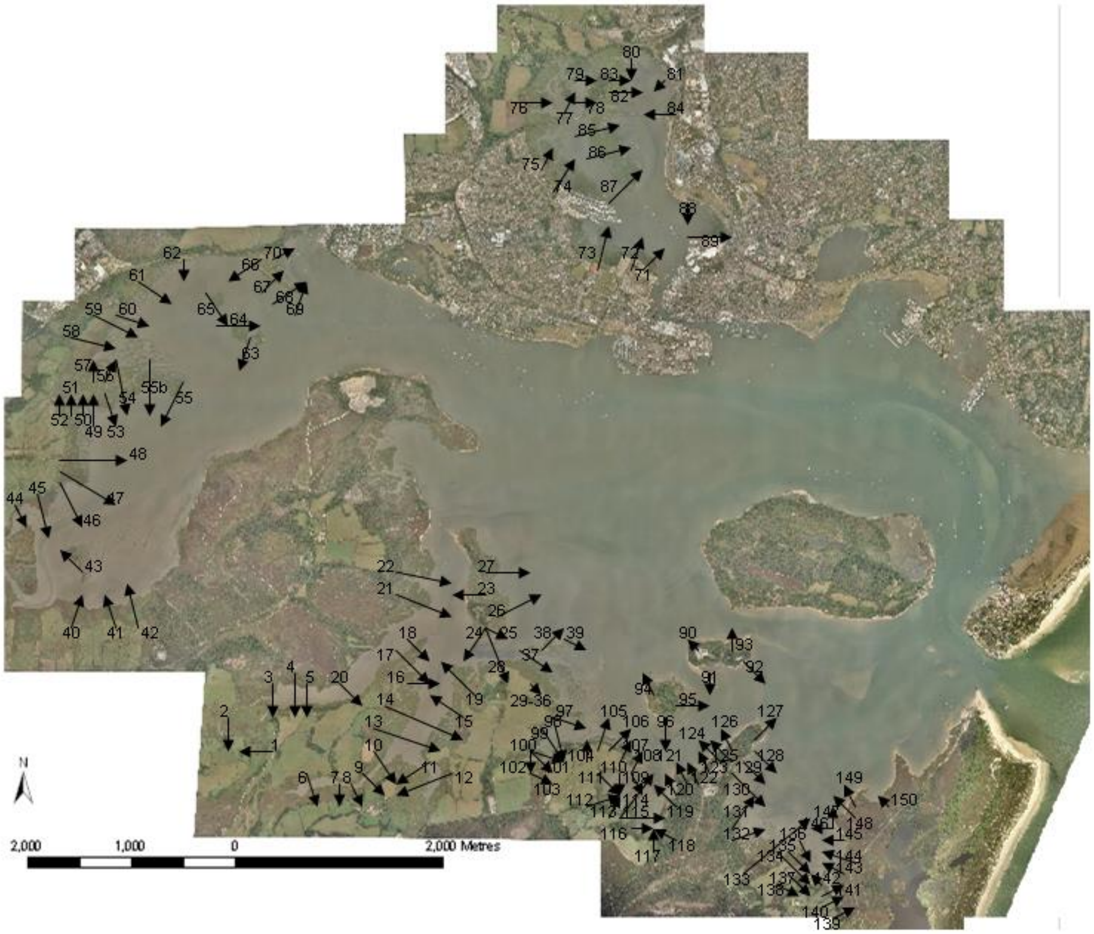



**Figure 4.3 Profiles extracted from the 2007 LIDAR dataset to examine intertidal morphology**

## 4.3 Stage 3: Analysis of Tidal Asymmetry

The type and direction of tidal asymmetry due to both peak velocity and slack duration has been assessed using two approaches. Firstly, using calculations that infer net tidal asymmetry (over the whole basin) based on the estuaries dimensions and tidal constituents, and secondly by directly extracting flow speeds and water levels from a hydrodynamic model.

### 4.3.1 General Asymmetry Calculations

As discussed in Section 2.1.1.1 general asymmetry parameters can be used to describe the tidal asymmetry patterns in estuaries and therefore infer the net direction of sediment transport based on the estuaries dimensions and tidal constituents. These are broad scale methods and give a indication of estuary-wide tidal asymmetry. A DTM of Poole Harbour was created using LIDAR (2007) data supplied by the Channel Coastal Observatory, combined with sub-tidal bathymetry data collected and supplied by Poole Harbour Commissioners (2005), as described in Section 4.2.1. Tidal parameters were analysed in MATLAB using tide gauge data (one year duration collected in 1997) located near the mouth at North Haven (Figure 3.1) using T-tide, (Pawlowicz et al., 2002).

Six indicators of tidal asymmetry have been calculated (Section 2.1.1.1 for complete description);

- *a/h* (Friedrichs and Aubrey, 1988) Indicating the magnitude and direction of asymmetry
- *Vs/Vc* (Friedrichs and Aubrey, 1988) Used in combination with the first indicator and only applicable if *a/h* does not indicate significant asymmetry
- *MDhw vs MDlw* (Pethick, 1994) Indicates magnitude and direction of asymmetry
- Gamma $\gamma$ (Dronkers, 1986) Indicates magnitude and direction of asymmetry
- M4/M2 (amp) (Friedrichs and Aubrey, 1988) Indicates magnitude of asymmetry
- 2M2 - M4 (phase) (Friedrichs and Aubrey, 1988) Indicates direction of asymmetry

### 4.3.2 TELEMAC 2D Model

To compare processes with the spatial variation in saltmarsh change a sufficiently detailed description of hydrodynamic processes was required. As discussed in Section 2.2 this is possible through the use of a numerical process based model representing Poole Harbour.

Several models have been developed for Poole Harbour (Section 2.2), including TELEMAC (HR Wallingford, 2004) and a hydrodynamic model described in (Falconer, 1986b). Both models were made available within this study however, the TELEMAC model was used as it is created in a more contemporary modelling software program, is based on more recent calibration data and the results were more easily integrated with the results from the historic saltmarsh analysis.

The TELEMAC process modelling system was developed initially at the Laborotoire National d'Hydraulique, a department of the research branch of Electricite de France (Hervouet, 2000). TELEMAC-2D provides the hydrodynamics: horizontal depth-averaged velocities and water depth. Many physical phenomena are taken into account, such as friction, turbulence, wind velocity, variations of atmospheric pressure and astronomic tide-generating processes. TELEMAC has been used for many different studies, including modelling of cohesive sediment transport (Le Normant et al., 1998, Le Normant, 2000) modelling the hydrodynamics of river flow (Corti and Pennati, 2000) modelling the flows within a dam break (Le Normant et al., 1998) and modelling tidal flows (Kuang and Stansby, 2006).

The 2D TELEMAC model for Poole Harbour provides depth-average tidal flow vectors under present conditions, (http://www.opentelemac.org/). TELEMAC-2D uses an unstructured triangular grid that allows variable model resolution and the direct incorporation of observational data regardless of how it is distributed (Figure 4.4). The 2D hydrodynamic model was built and calibrated using a variety of existing and newly surveyed bathymetric and flow data as part of the Poole Approach Channel deepening studies. The model was validated against newly surveyed tidal flow data observed using a vessel mounted acoustic Doppler current profiler (ADCP) across three transects at the harbour entrance as well as current meters at 7 locations within Poole Harbour and 6 tidal diamonds, during the 11th and 12th March, 1990, tidal data was also collected at this time (HR Wallingford, 2004). The spatial resolution of the unstructured triangular mesh used by the model in Poole Harbour is variable and ranges between 20 and 100 m.

Using this data, potential correlations with saltmarsh and mudflat loss and gain from the historic analysis and the flow asymmetry can be analysed. For the present analysis, a grid of points was created in ArcGIS, with a spatial scale of 250m. At each point, data was extracted from the TELEMAC model and processed, the data included x and y coordinates, time, velocity U m/s, velocity V m/s, water depth and velocity magnitude m/s. These were supplied for every 20 minutes over the 12.5 hour tidal cycle for neap and spring tides. Figure 4.5 shows the gridded point locations at which data was extracted.

The limitations and advantages of a process based hydrodynamic model to calculate tidal dynamics is discussed in Section 2.2.

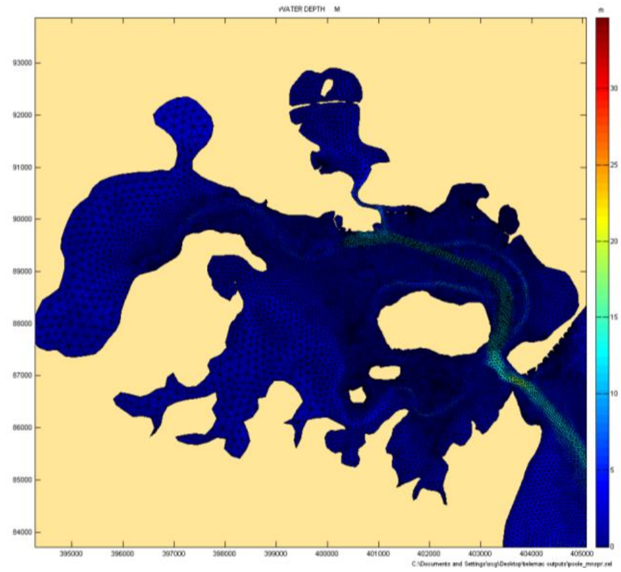



**Figure 4.4 Tin mesh within the TELEMAC model of Poole Harbour**

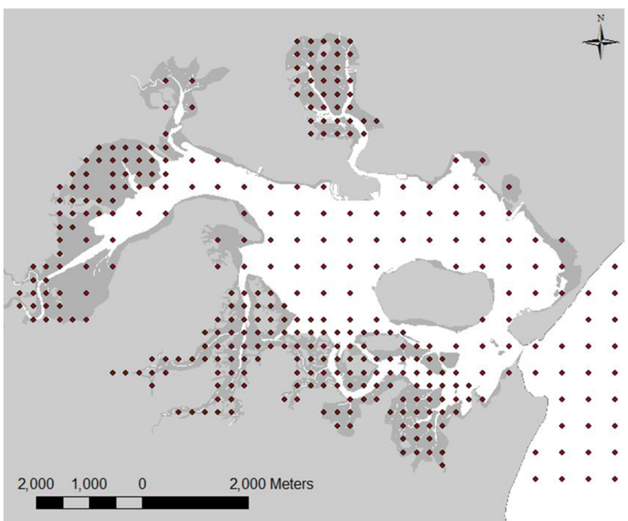



**Figure 4.5 Gridded points used to extract data from the TELEMAC hydrodynamic model.**

## 4.4 Stage 4: Assessing the critical shear velocity of sediment samples

Based on the results of the historic saltmarsh change analysis, sediment samples from both regions that have experienced historic erosion and expansion were taken from Poole

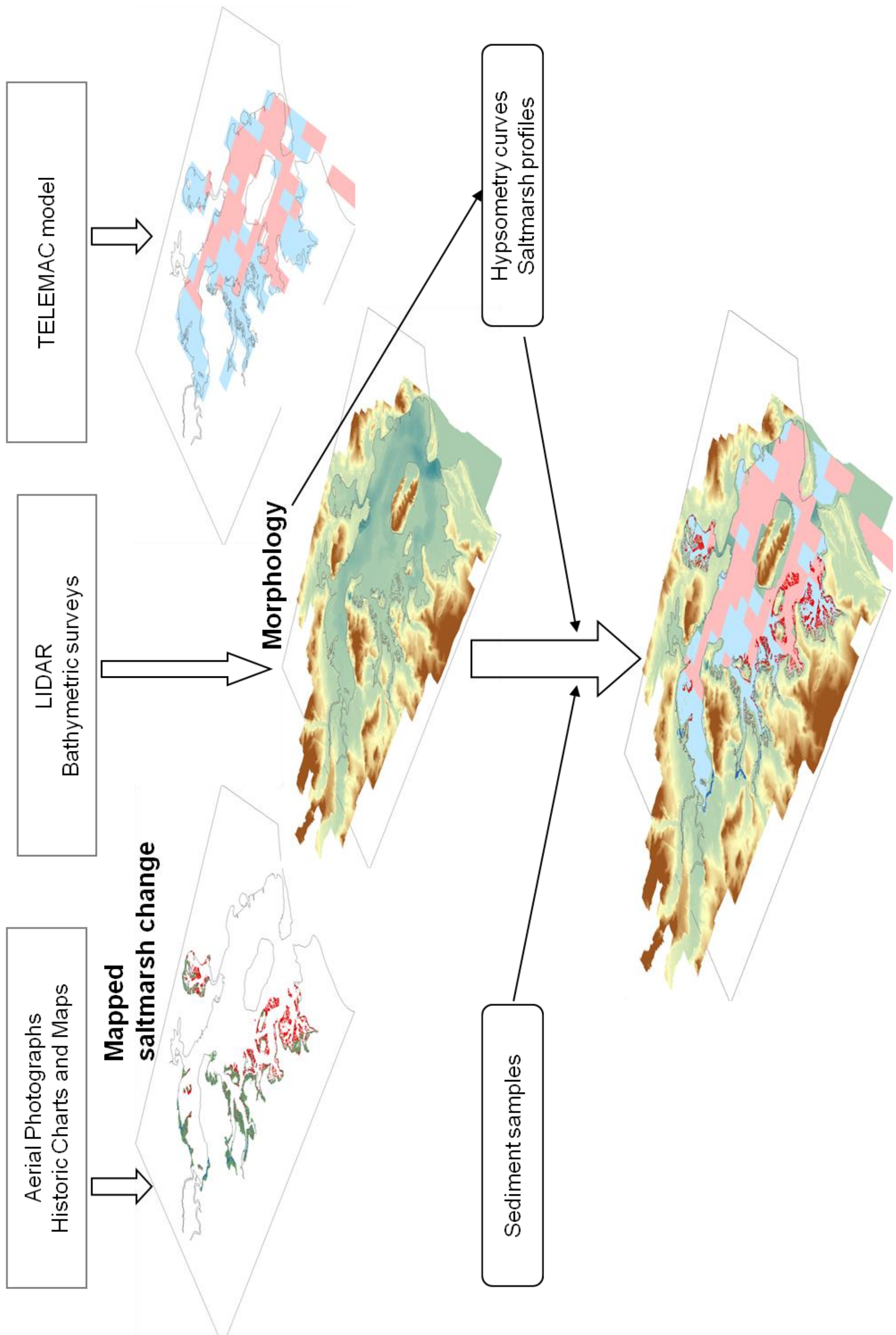
Harbour. These samples were analysed using the annular flume at the Southampton Oceanographic Centre (SOC) (Figure 4.6) to assess the shear velocity threshold for sediments in Poole Harbour and determine if there are differences in sediment composition and characteristics between regions of historic erosion and expansion, results are presented in Section 6.3 and Figures A1 –A8 in Appendix A.  The velocity thresholds calculated by the annular flume were also used when determining the critical velocity thresholds for the tidal asymmetry analysis (Sections 4.3 and 7).

**Figure 4.6  Annular mini flume at Southampton Oceanography Centre used to assess critical shear velocities of sediments.**

The flume is equipped with 3 optical backscatter sensors and an electromagnetic (EM) flow meter. The flume sits within a tray containing the sediment sample to be tested, this is prepared several days in advance and left to settle, the tray is covered to prevent a biofilm from forming. The sediment sample is subjected to steady flows of increasing magnitude in a series of steps and data analysed to assess the critical shear threshold over which suspended sediment concentrations rose and thus the bed erosion threshold.

## 4.5 Summary

A wide variety of methods have been used to assess historic saltmarsh changes in Poole Harbour and to link these changes to sediment types and composition and also the main physical drivers and mechanisms of change. This is summarised in Figure 4.7. The following Chapters 5, 6 and 7 outline the results of these methods, and briefly summarise these results before being discussed together in Chapter 8 and final conclusions presented in Chapter 9.




**An understanding of the settings of saltmarsh change and the key drivers and physical mechanisms of change within a spatial and temporal context.**

Figure 4.7 Summary of methods

# 5 Historic Analysis Results

As discussed in the literature review Poole Harbour has historically experienced a significant change in the area of saltmarsh, with previous studies focusing on more recent large scale changes post *Spartina anglica* colonisation (Born, 2005). Smaller-scale processes that may contribute to change, such as creek accretion, have been over-looked, potentially leading to an overestimation of historic erosion and the assumption that erosion is the only process and will be the long term trend in the future, with accretion being negligible or zero. Previous studies have also not investigated or linked drivers to these changes.

This chapter describes the results from a study to investigate historic changes within Poole Harbour, quantifying rates of saltmarsh gain and loss and reinterpreting previous results from the literature. In this study this is achieved by investigating three main data types, historic OS maps presented in section 5.1, hydrographic charts presented in section 5.2 and aerial photographs presented in section 5.3. Uncertainties encountered through the analysis of these datasets are assessed in Section 5.4 and the suitability of using these datasets to observe historic change is discussed in Section 5.5. The main findings are summarised in Section 5.6.

## 5.1 Historic Maps

Historic OS maps were acquired from Digimap (Table 5.1) and potential changes within Poole Harbour were measured by digitising Mean High Water (MHW) (Figure 5.1), Mean Low Water (MLW) levels and the indicated saltmarsh are using a Geographical Information System (GIS) system.

**Table 5.1Historic OS maps used in analysis.**

| Year | 1890 | 1925 | 1963 | 1993 |
|---|---|---|---|---|
| Map type | Country series 1:2500 1st Ed. | Country series 1:10560, 2nd revision | National grid 1:10560 | National grid 1:10000 latest edition |

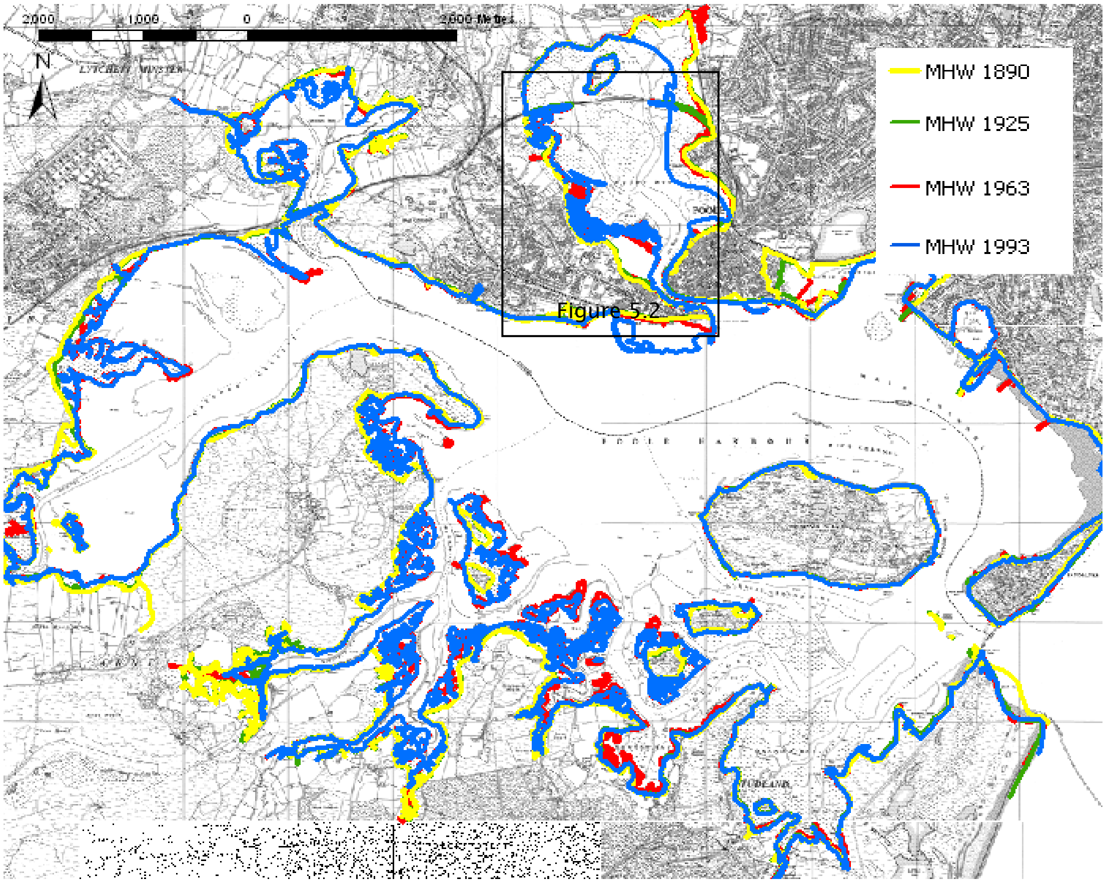



**Figure 5.1Mean High Water contours from historic maps. (Box indicates location of following figure 5.2)**

From examining the mapped changing historic shorelines, one prominent historic trend of saltmarsh change identified in these sources is the land claim that has taken place along the north shore and the adjacent bays. Figure 5.2 shows the land claim within Holes Bay and the northern shoreline, land claim is often to the detriment of saltmarsh and mudflat. According to these datasets approximately 150 ha of former intertidal area has been lost to land claim between the 1890's and 1993.

Figure 5.3, shows the area below mean low water within Poole Harbour, as digitised from 1890 and 1993 maps. Changes between the data sets are quite clear, where areas that were classed as above MLW in 1890, with detailed creek systems, were below MLW in 1993. Figure 5.4 illustrates the change in area below MHW and MLW from 1890 to 1993. The change in MHW also includes the 150 ha lost through land claim, the rest are areas where mudflats have become colonised by saltmarsh, lifting it above MHW. The area below MLW has increased greatly, suggesting that the MLW contour has moved landward with a reduction of nearly half the intertidal area. However, this could be due to errors within the datasets and how MLW was plotted, as discussed in Section 4.1.1.

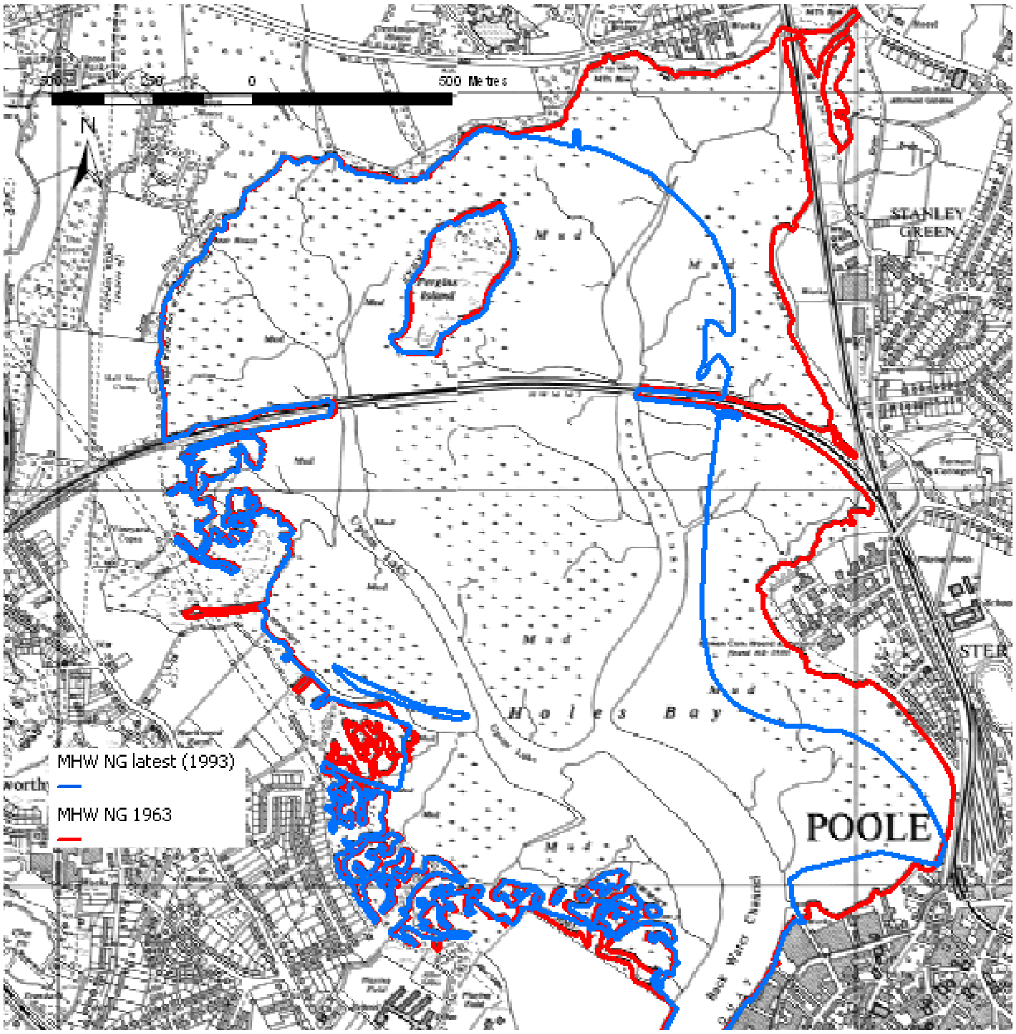



**Figure 5.2 Historic OS data illustrates land-claim between 1963 and 1993 along the north shore of Poole Harbour in Holes Bay.**

Channel movement can be identified from these datasets (Figure 5.5) the Wareham Channel appears to have straightened and widened. No records could be found for direct man-made intervention, and hence it is assumed to be a natural process. In the 1890 dataset channels and a lake-like area below MLW exist where now saltmarsh is present.

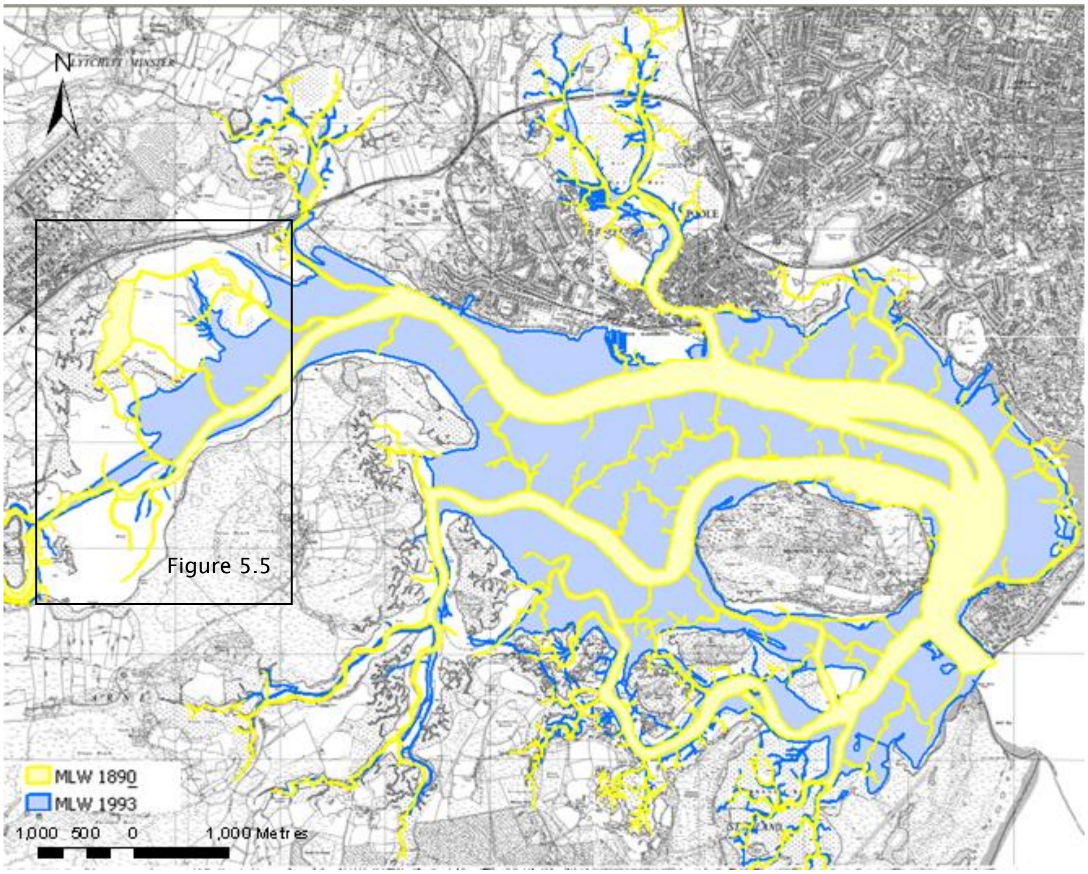



**Figure 5.3 Area below Mean Low Water (MLW) for Poole Harbour from; Country series 1:2500 1st Ed. 1890 and National grid 1:10000 latest edition (1993). (Boxed area shows location of figure 5.5)**

The Historic OS maps clearly suggest that change has occurred in Poole Harbour, but it is difficult to accurately quantify without verification alongside other datasets.  These results are incorporated into the results presented in Section 5.3.

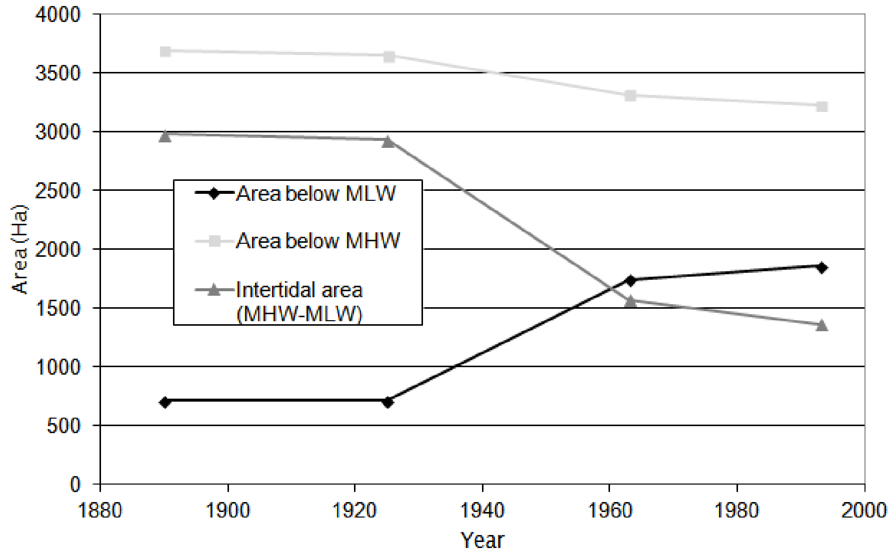



**Figure 5.4 Area below Mean Low Water (MLW), Mean High Water (MHW) and the 'intertidal' area between MHW and MLW, between 1890 and 1993 for Poole Harbour. From digitised OS map data.**

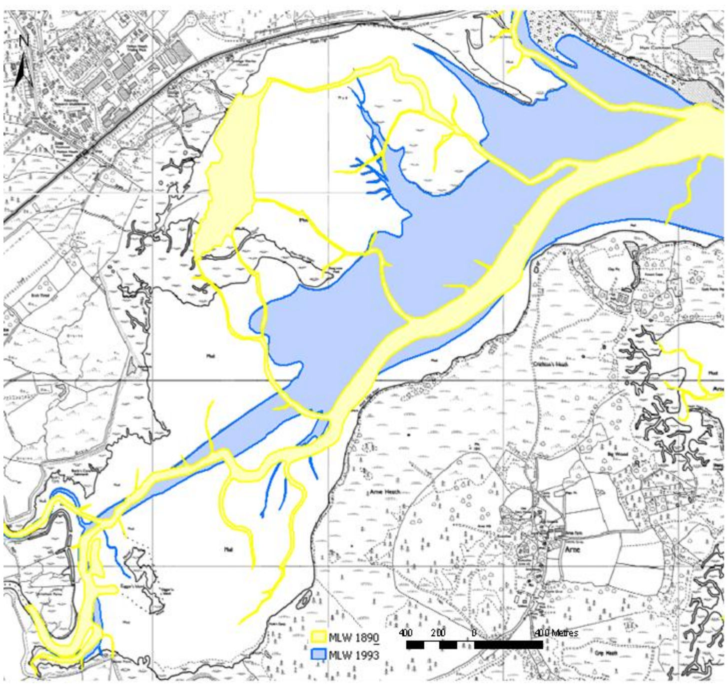



**Figure 5.5 Changes in area below MLW in the Wareham Channel, between 1890 and 1993. (See boxed area on figure 5.3)**

## 5.2 Historic Hydrographic Charts

Charts were acquired and digitised for 1785, 1849, 1878, 1910 and 1934. These were often only partial charts of the Harbour and contained limited information regarding saltmarsh and tidal flats. The small tidal range prevents major surveys of the intertidal and the charts are referenced back to OS maps. These charts were unsuitable for the study of saltmarsh change. Most of the detail on the Charts was focused on the main channels at the mouth and leading up to the ferry terminals and docks and hence the analysis of this data source was not pursued further in this study.

## 5.3 Aerial Photography

Results are firstly presented at the Harbour scale, integrating previous studies, results from Section 5.1 and the newly digitised aerial photographs and OS data into a consistent and comprehensive perspective of change. Localised saltmarsh changes at a sub-estuary scale are then analysed in greater detail to examine both losses and gains of saltmarsh area and finally the setting of change is discussed.

### 5.3.1 Saltmarsh Change in Poole Harbour

Trends of saltmarsh change, between 1947 and 2005 digitised from aerial photographic analysis are illustrated in Figure 5.6., showing large losses of saltmarsh across the intertidal region and accretion in the upper creek systems.

In order to measure saltmarsh changes over a longer time period, digitised saltmarsh areas from OS maps (Section 5.1) were combined with aerial photographic results and other published literature. A historic timeline of saltmarsh area within Poole Harbour has been created and is shown in Figure 5.7. This extends the historic saltmarsh change analysis, back to 1849 and gives a longer assessment of changes. Published data from various sources (later discussed) are also incorporated into the timeline.

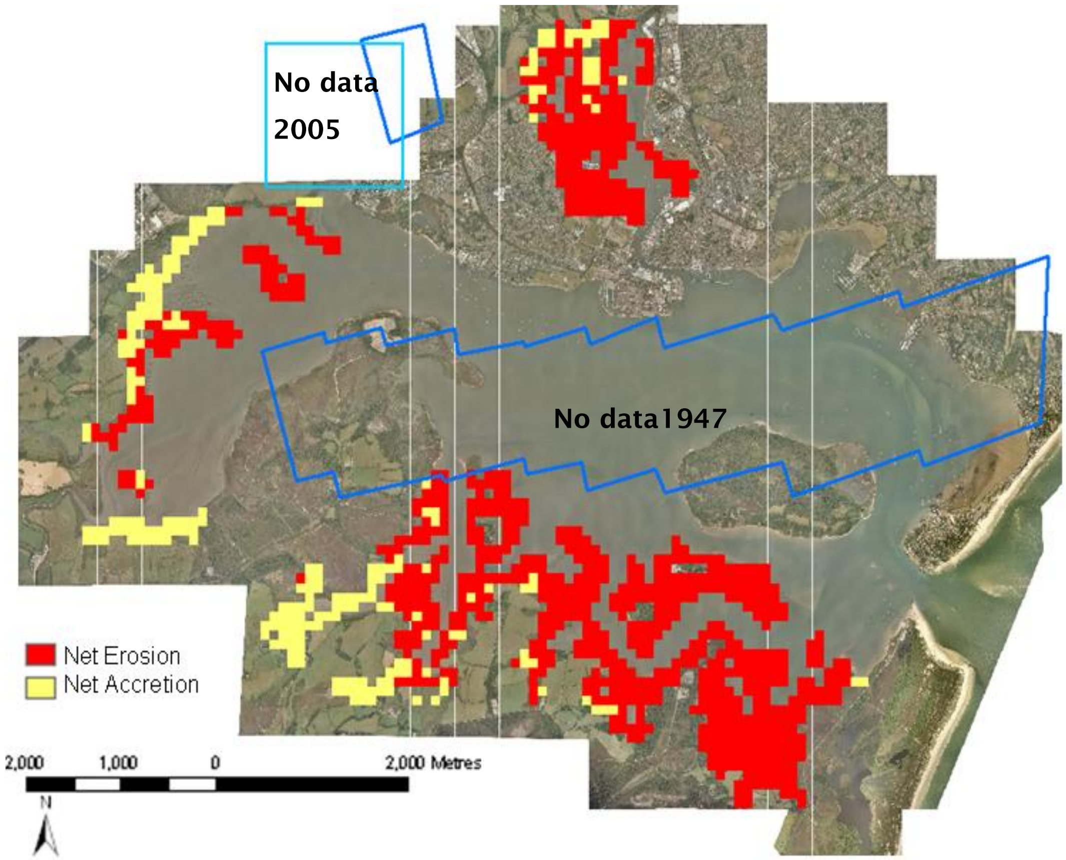



**Figure 5.6 General trends of saltmarsh change in Poole Harbour (100m cell size). (Boxes indicate where aerial photographic data is missing).**

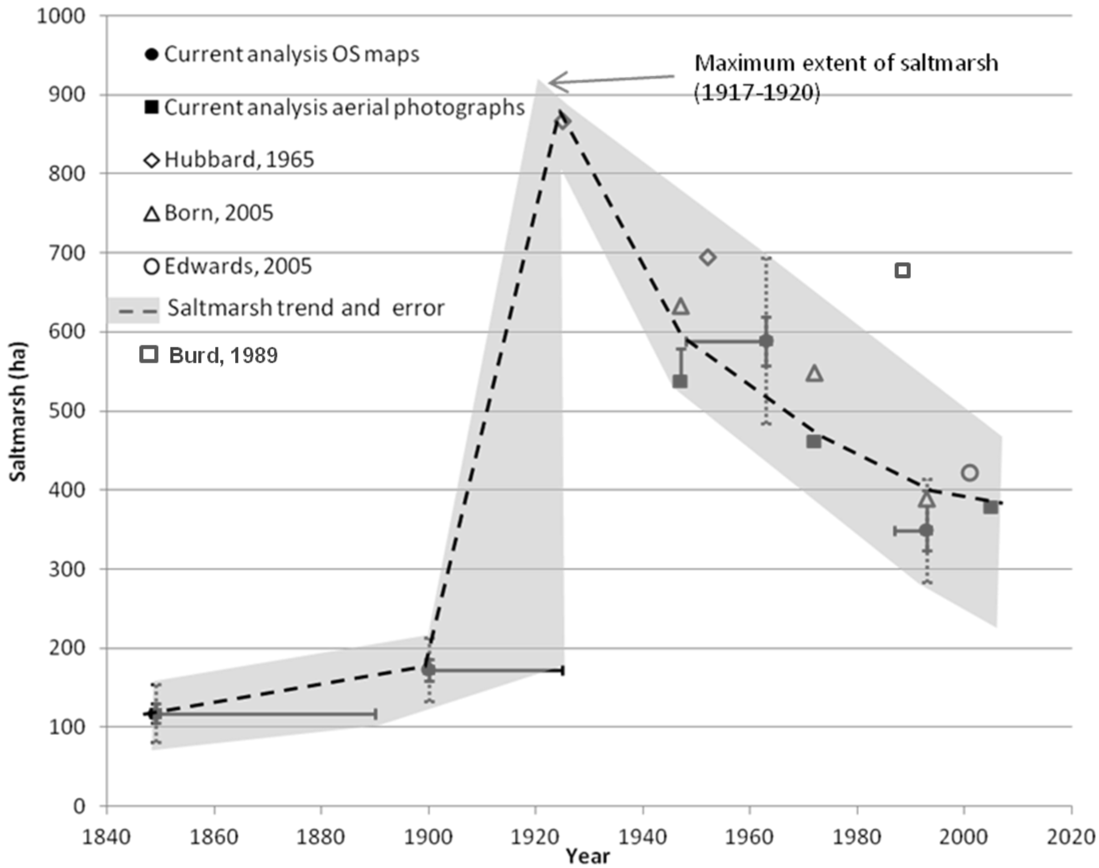



**Figure 5.7 Trends in saltmarsh area in Poole Harbour from OS maps and Aerial Photography analysis. Other data plotted from previous studies and surveys. Horizontal errors include published date ranges for OS data. Uncertainties include assessment of accuracy for aerial photographic and OS data interpretation of saltmarsh area. Errors not published and available for previous studies in the literature.**

An expansion of saltmarsh area is clearly seen during the early 1900's, interpreted as the colonisation of *Spartina anglica,* leading to a rapid fourfold expansion. Followed by a slower decline in saltmarsh area post 1925 (Raybould, 2000, Hubbard, 1965). A loss of 140 ha of saltmarsh was calculated between 1947 and 1972. However, 29 ha were gained through accretion during this period, giving a net loss of 111ha. It should be noted that the datasets for this calculation were clipped to a common area as they do not have uniform coverage, hence the error range. The 1947 aerials lack data for Arne and Sandbanks, and so for the whole Harbour losses and gains could be larger. Between 1972 and 2005 101ha were lost and 25 ha gained, giving a net loss of 76 ha. Figure 5.7 puts into perspective the relatively recent changes alongside the longer term trends, with saltmarsh area in 2005 exceeding that prior to *Spartina anglica* colonisation at the end of the 19th Century, in round terms, by a factor of three. Other data plotted on figure 5.7 was derived from previous studies and surveys of saltmarsh extent within Poole Harbour, these studies do not discuss in any detail errors, accuracy or how data was processed. The values were calculated using various techniques, including fixed point photography, (Hubbard, 1965) analysis of aerial photography, (Born, 2005) and GPS surveys, (Edwards, 2005). According to Hubbard (1965) the maximum extent of saltmarsh occurred between 1917 and 1924, which unfortunately has not been captured in the OS maps or aerial photography available, and so uncertainties are difficult to assess.  In general, the other studies report slightly higher values of saltmarsh extent; the largest variation is the survey by Burd (1989), which is over 300 ha more than the amount recorded in 1993, both in this thesis and Born (2005).

Figure 5.8 shows the average rate of loss and gain of saltmarsh for the entire study period, 1849-2005 and between each year of data analysed. Again the colonisation of saltmarsh and the subsequent loss is clear, but when observed over the long-term there has been a net gain over the past 156 years, which was not recognised in the previous studies. The rate of loss has also decreased over time since 1947, suggesting there may be a slowdown of erosion within the Harbour.

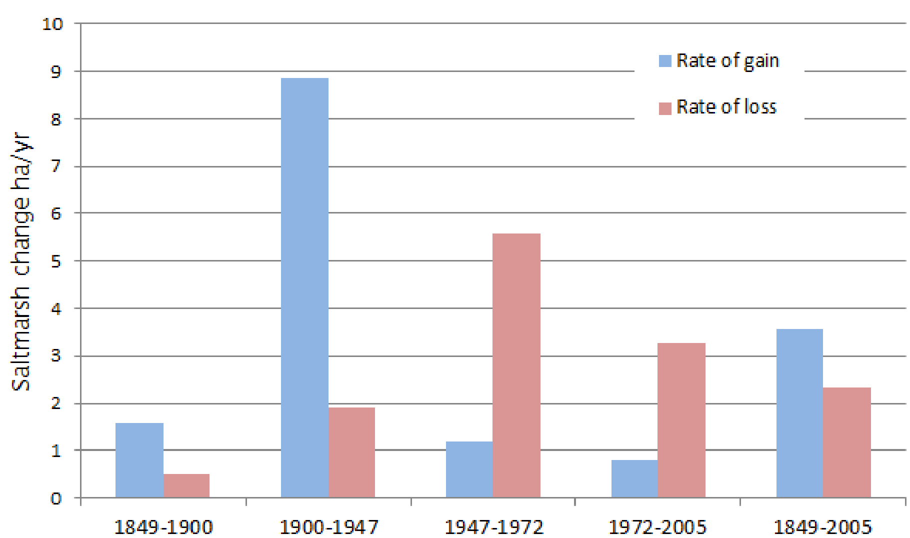



**Figure 5.8 Annual rates of change, loss and gain of saltmarsh, between available datasets.**

These losses and gains can be analysed over the entire Harbour allowing potential patterns of zonation to be identified, in order to understand the factors that may have driven them. In figures 5.9-5.12 the location of saltmarsh change has been identified and the proportion of erosion/loss and accretion/gain calculated for $50m^2$ cells. This allows the change to be linked to the geomorphic settings and the possible physical processes causing the change. For example where only accretion has occurred in an area this is indicted by 'all gain' (white) hence in this cell no loss (erosion) was recorded. Where only erosion has occurred this is indicated by 'all loss' (black), hence in this cell no gain (accretion) was recorded. Where a combination of erosion and accretion processes has occurred locally together, this is represented by a varying tint of grey depending on the proportion. Figures 5.9-5.12 show which of these processes have been the dominant driver of change between each dataset investigated for the whole Harbour. Figures 5.9 and 5.10 use OS map derived data and so are generally only useful for observing large scale trends, such as the widespread saltmarsh colonisation in the centre of the Harbour and reclamation in the eastern part of Holes Bay. Figures 5.11 and 5.12 illustrate the dominance of saltmarsh loss, between 1947 and 2005, within the centre of the Harbour and the dominance of accretion up tidal creeks and to the west of the Harbour. A mixture of both accretion and erosion appears to occur within the creek systems of the fringing marshes where channel and creek migration occurs.

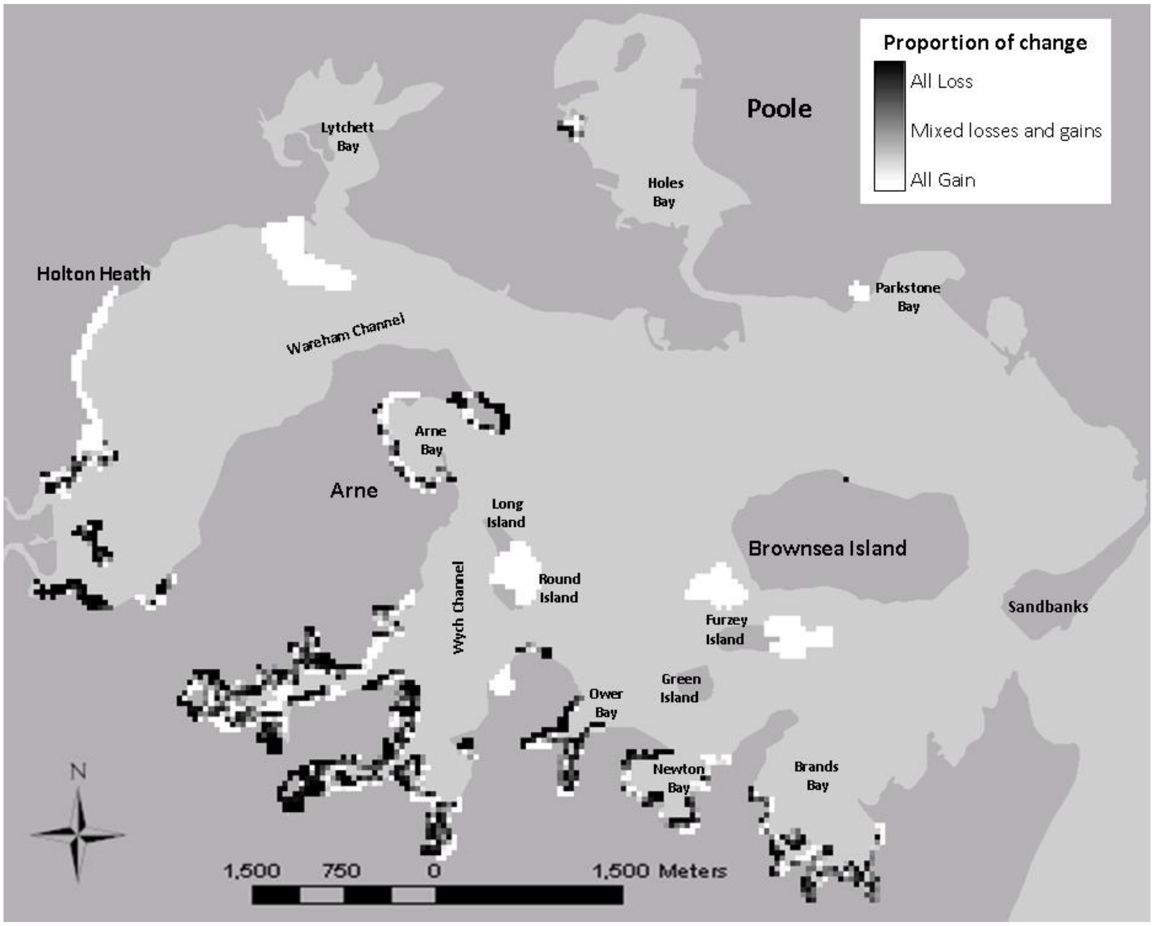



**Figure 5.9 Trend of saltmarsh change processes between 1849 (+41 years) and 1900 (+25 years), by area (cell size 50x50m).**

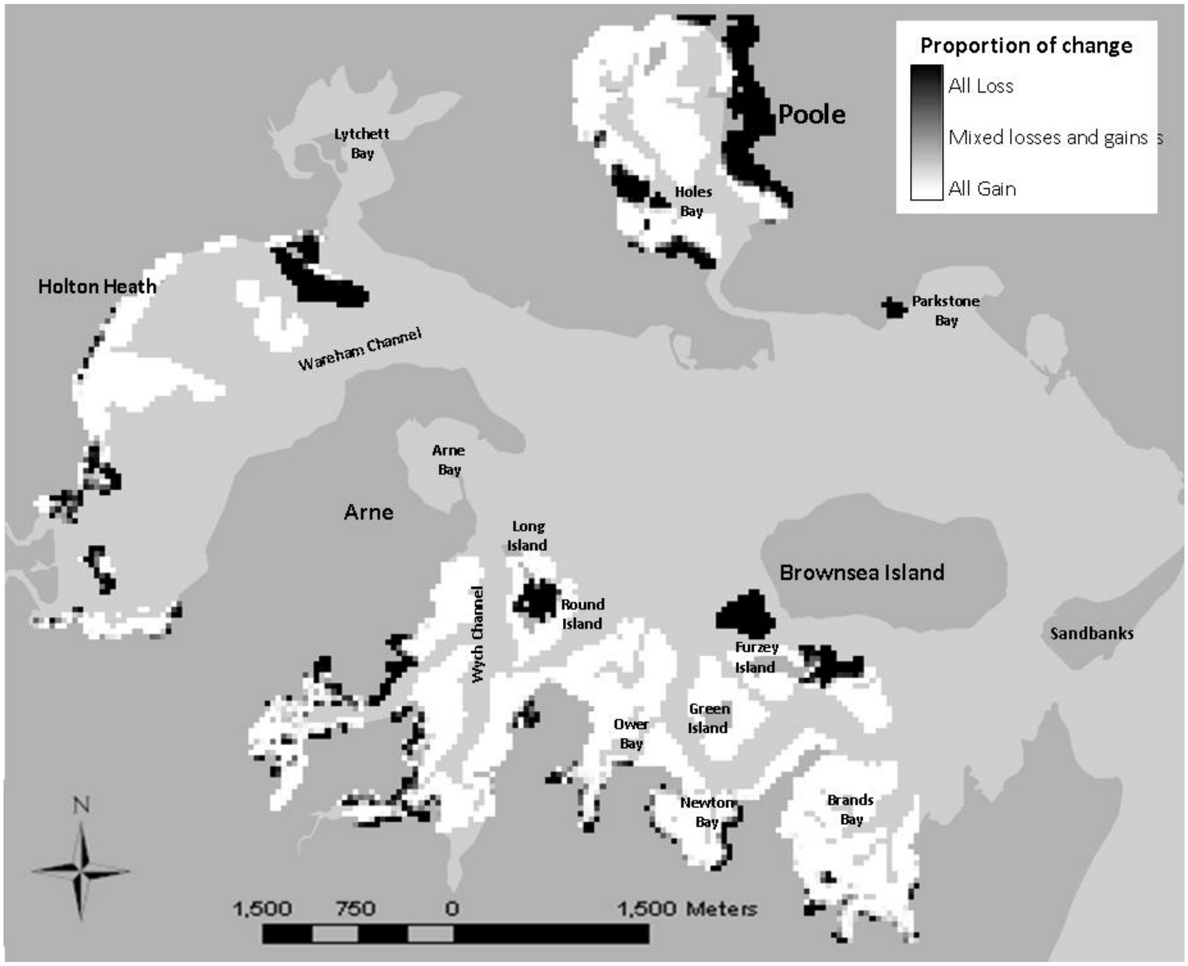



**Figure 5.10 Trends of saltmarsh change processes between 1900 (+25 years) and 1947, by area (cell size 50x50m).**

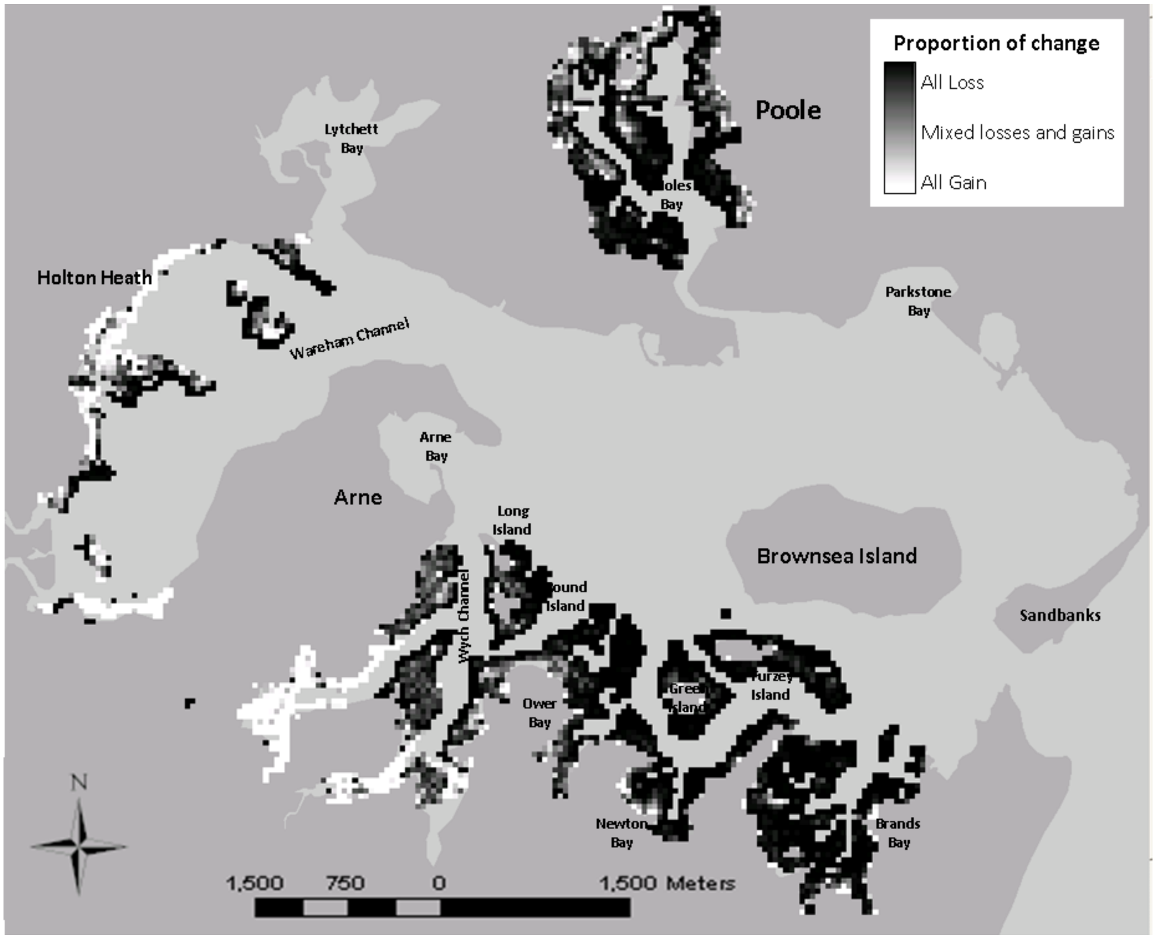



**Figure 5.11 Trends of saltmarsh change processes between 1947 and 1972, by area (cell size 50x50m).**

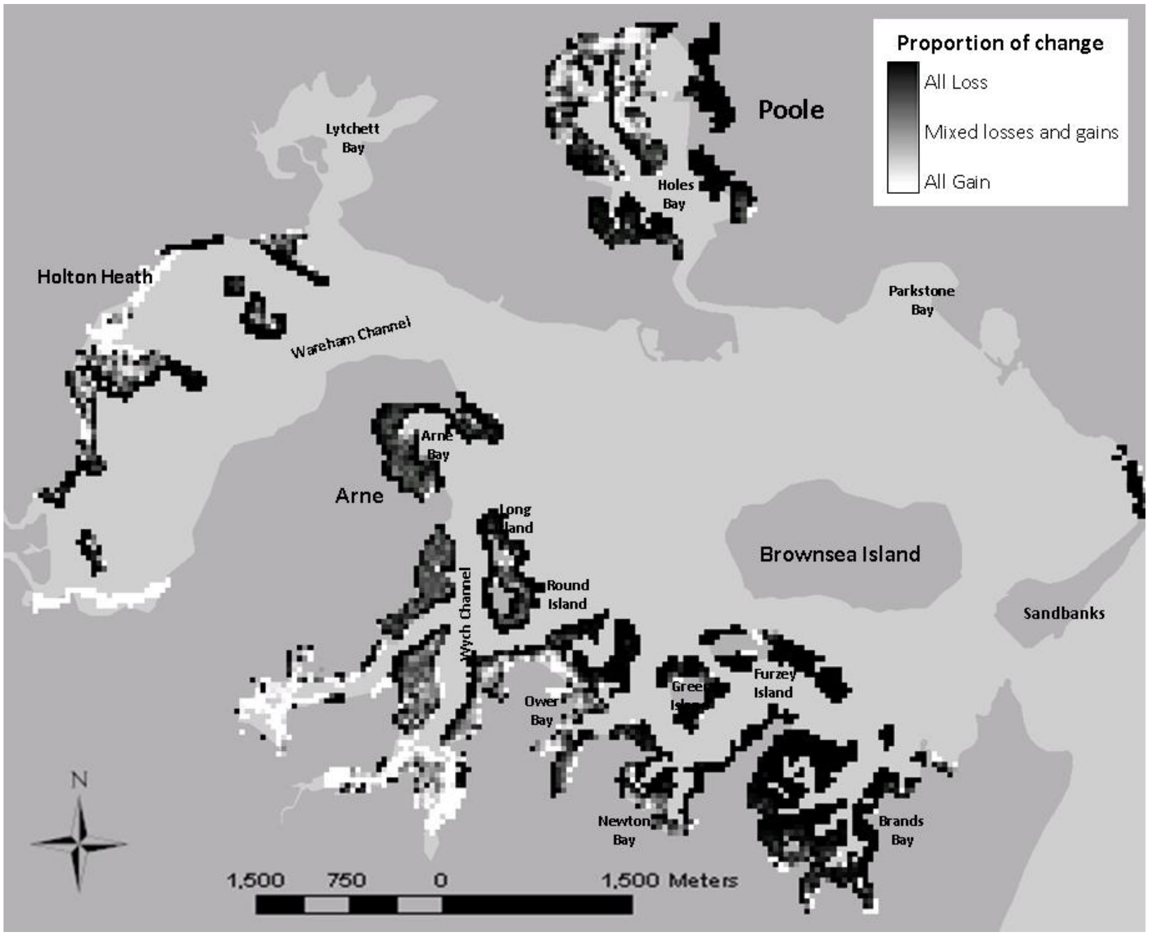



**Figure 5.12 Trends of saltmarsh change processes between 1972 and 2005, by area (cell size 50x50m).**

## 5.3.2 Localised Saltmarsh Change

Figures 5.9-5.12 show that there are patterns of erosion and accretion trends within the Harbour, these trends are analysed further in this section. The net saltmarsh trends have been divided by region: Figure 5.13 shows the resulting regions within Poole Harbour, with saltmarsh loss and gain calculated (Table 5.2). Relative spatial trends (by percentage) are shown in figure 5.14, relative to 1947.

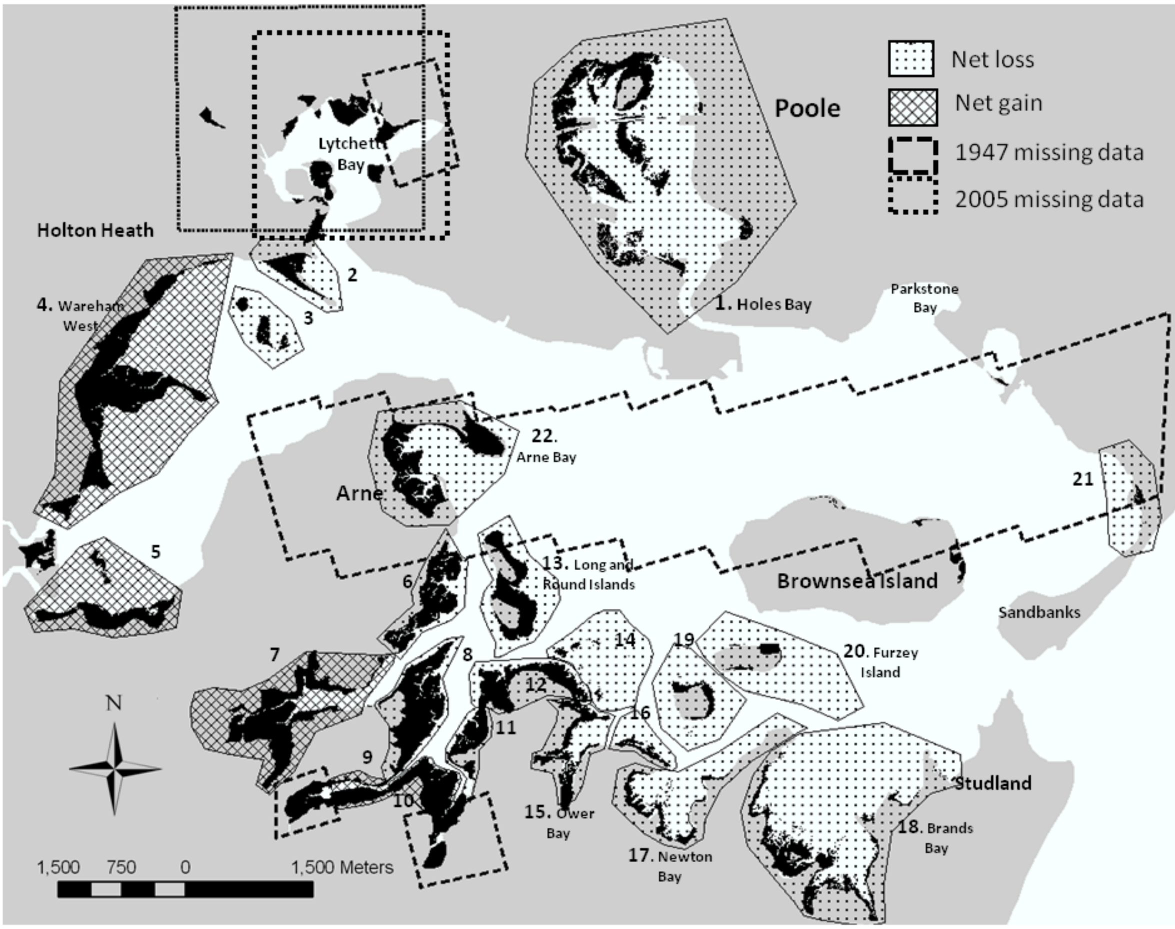



**Figure 5.13 Poole Harbour regions used for saltmarsh analysis (Boxes show areas of missing aerial photography)**

1) Holes Bay, 2) Wareham North, 3) Wareham Islands, 4) Wareham West, 5) Wareham South, 6) Grip Heath, 7) Middlebere Lake, 8) Wych Lake North, 9) Wych Lake South, 10) Wych Farm, 11) Wych Lake East, 12) Fitzworth North, 13) Long and Round Islands, 14) Fitzworth Islands, 15) Ower Bay, 16) Cleavel Point North, 17) Newtown Bay, 18) Brands Bay, 19) Green Island, 20) Furzey Island, 21) Sandbanks, 22) Arne

**Table 5.2 Saltmarsh area (ha) by region, overall change in area between 1947 and 2005 and percentage change**

| Location | Saltmarsh (ha) | | Net Change | % Change |
|---|---|---|---|---|
| | 1947 | 2005 | | |
| 1) Holes Bay | 87.5 | 52.7 | -34.8 | -39.8 |
| 2) Wareham North | 9.1 | 7.0 | -2.1 | -23.1 |
| 3) Wareham Islands | 11.0 | 4.5 | -6.5 | -59.1 |
| **4) Wareham West** | **62.9** | **66.0** | **3.1** | **4.9** |
| **5) Wareham South** | **9.9** | **18.2** | **8.3** | **83.8** |
| 6) Grip Heath | 21.7 | 19.9 | -1.8 | -8.3 |
| **7) Middlebere Lake** | **25.9** | **35.3** | **9.4** | **36.3** |
| 8) Wychlake North | 31.3 | 30.2 | -1.1 | -3.5 |
| 9) Wychlake South | 5.3 | 7.4 | 2.1 | 39.6 |
| **10) Wytch Farm** | **12.9** | **14.1** | **1.2** | **9.3** |
| 11) Wychlake East | 10.3 | 9.6 | -0.7 | -6.8 |
| 12) Fitzworth North | 19.9 | 17.6 | -2.3 | -11.6 |
| 13) Long and Round Island | 24.2 | 15.2 | -9 | -37.2 |
| 14) Fitzworth Island | 22.2 | 1.5 | -20.7 | -93.2 |
| 15) Ower Bay | 13.2 | 11.1 | -2.1 | -15.9 |
| 16) Clevel Point North | 6.3 | 2.5 | -3.8 | -60.3 |
| 17) Newtown Bay | 18.1 | 7.6 | -10.5 | -58.0 |
| 18) Brands Bay | 67.7 | 22.8 | -44.9 | -66.3 |
| 19) Green Island | 15.7 | 3.4 | -12.3 | -78.3 |
| 20) Furzey Island | 20.5 | 2.4 | -18.1 | -88.3 |
| Total | 495.450 | 348.946 | -146.6 | -29.6 |

Five regions in Figure 5.13 have experienced an overall net gain in saltmarsh area: Middlebere, Wych Farm, Wych Lake south, Wareham south and Wareham west. These accreting regions are all at the western end of the Harbour up tidal creeks and are mostly protected from waves produced by the locally dominant south-westerly winds. An important and widespread trend is the decline in accretion and erosion rates from 1947-1972 to 1972-2005 (Figure 5.14). The most pronounced exception is the Wareham Islands area, where the percentage of loss has accelerated. This is due to the area being composed entirely of islands not attached to the mainland; they have no room for migration and as the islands are eroding from all sides there is proportionally greater loss and potentially a absolute loss.

Wareham Islands also experienced the highest lateral erosion rate, calculated as nearly 3m/yr between 1972 and 2005. Elsewhere within the Harbour average lateral erosion rates between 1947 and 1972 were 1.7m/yr and between 1972 and 2005 were 1.3m/yr reflecting the decreasing trend of saltmarsh loss. Lateral accretion rates have also been recorded, with up to 2m/yr noted at Wareham south and Wareham west sites for both the 1947-1972 period and the 1972-2005 period.

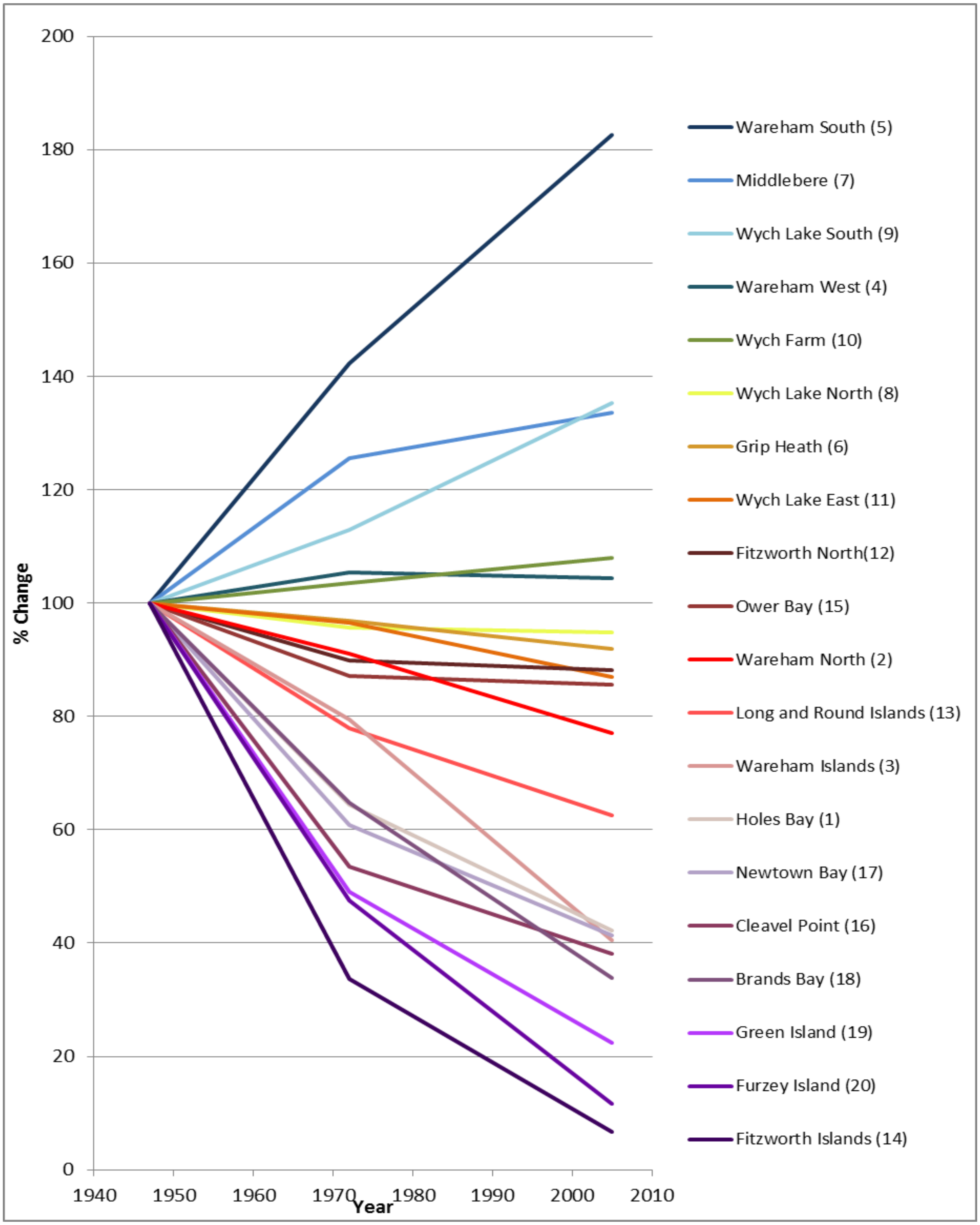



**Figure 5.14 Percentage change in saltmarsh area for regions within Poole Harbour (numbers according to Figure 13)**

### 5.3.3 Classification of Saltmarsh Change Mechanisms

Although the OS map data was useful for measuring Harbour wide trends, it is not accurate enough to observe small local scale trends. This section focuses mainly on the results from the aerial photographic analysis from 1947-2005. Examples of the types of loss in Poole Harbour are illustrated in figure 5.15 and include: 1) island erosion, 2) frontal erosion and 3) creek erosion.

Island erosion was classified where islands of marsh, unconnected to the mainland with no elevation over HAT have partially or wholly eroded, frontal erosion was classified as where areas on open or semi-open saltmarsh had retreat landwards from the front edge, this is essentially the same as island erosion but the marsh is backed by land and potentially able to migrate. Creek erosion was classified as any erosion that had taken place within sheltered creek systems.

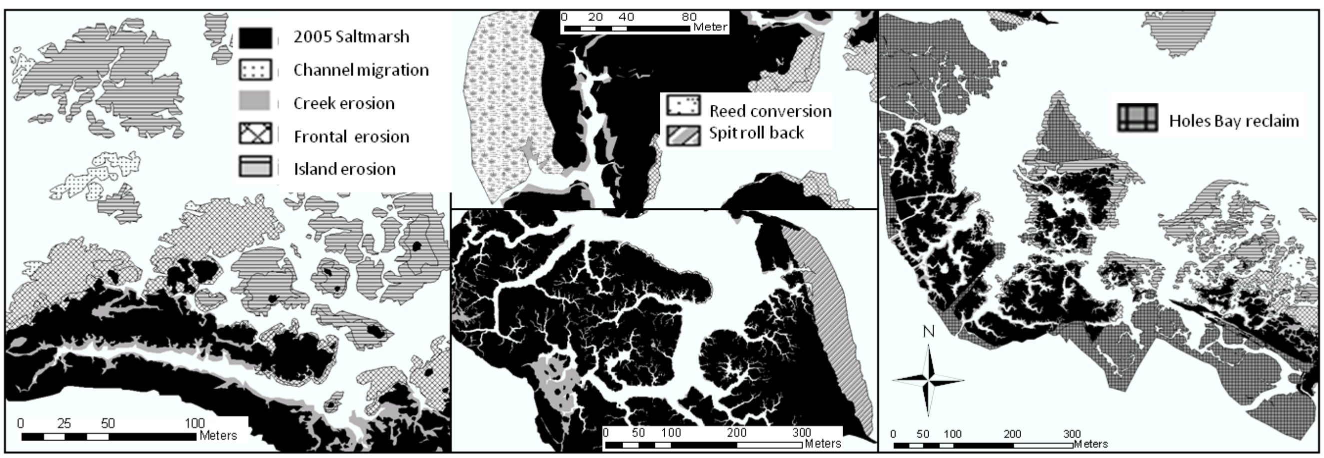



**Figure 5.15 Examples of saltmarsh loss mechanisms (1974 to 2005)**

Erosional mechanisms are presented in Figure 5.16a by area and Figure 5.16b by rate, to make the datasets and rates of loss comparable they have been cut to the same area for 1947, 1972 and 2005. The main mechanisms of loss for both the 1947-1972 and 1972-2005 periods are island erosion followed by frontal erosion. Together these make up 83% and 69% of all erosion experienced during those time periods, respectively. Understanding why and where island erosion occurs is important to fully understand these historic losses and to better understand the future changes that may happen at this site.

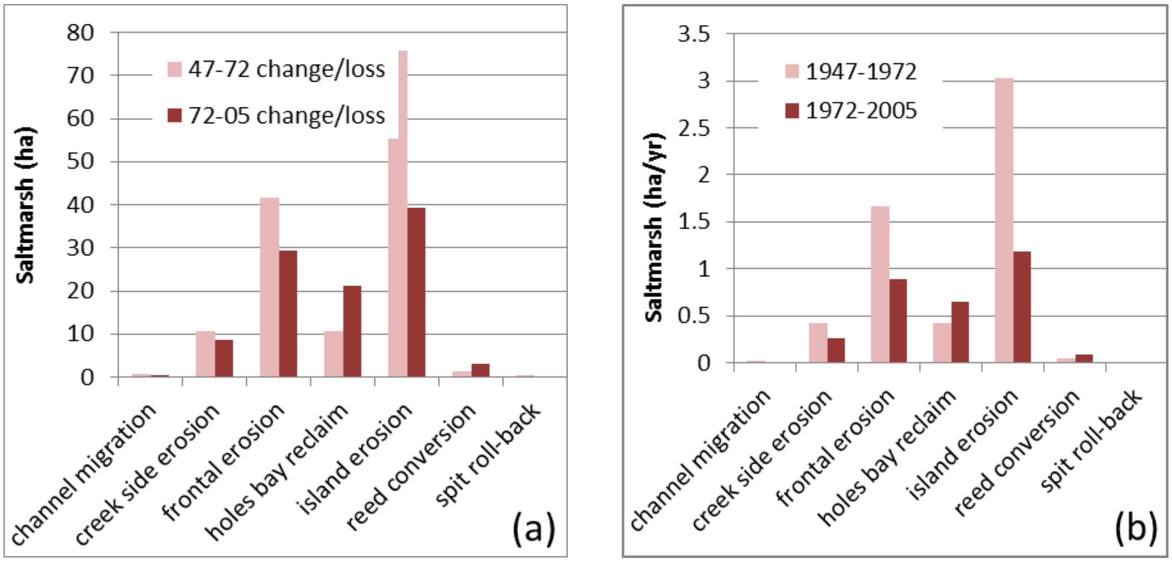



**Figure 5.16 Saltmarsh loss by different mechanisms (a) area loss and (b) rate of area loss**

Mechanisms such as reed bed conversion, spit roll-back and channel migration are limited to small, specific locations and although these are important locally, they have much less of an impact at the scale of Poole Harbour. The reclamation within Holes Bay is clearly relevant to the entire Harbour representing 13% of all saltmarsh loss since 1947. However, this is a direct anthropogenic impact so the cause of loss is quite apparent. Saltmarsh and intertidal area has been deliberately built over, rather than a natural process or an indirect anthropogenic mechanism e.g. dredging, pollution or ship-wash. The mechanisms of saltmarsh gain in the Harbour can be similarly classified to the saltmarsh losses (Table 5.4 and Figure 5.17).

The realignments that have occurred in Poole Harbour are mainly small localised former agricultural areas, situated in Ower Bay and Wych Lake East (figure 5.13 for location). These account for less than 1ha of saltmarsh gain. However, in the future realignment around Poole Harbour could be significant, particularly in the valleys of the Frome and Piddle rivers. Saltmarsh gain mechanisms are seen in Figures 5.18a by area and 5.18b by rate, to make the datasets and rates of gain comparable they have been cut to the same area for 1947, 1972 and 2005. The main mechanisms for both the 1947-1972 and 1972-2005 periods is creek side accretion; accounting for 14ha, 48% of accretion between 1947 and 1972 and 12ha, 49% of overall saltmarsh gain between 1947 and 2005. Frontal accretion accounts for 12ha, 43% of saltmarsh accretion between 1947-1972 period and 11 ha, 43% of saltmarsh accretion between 1972 and 2005. Understanding these dominant processes of accretion may give insights into how the net saltmarsh area in Poole Harbour may change in the future. Channel infill, island accretion and realignment together account for 9% and 8% of accretion for 1947-1972 and 1972-2005 periods, respectively.

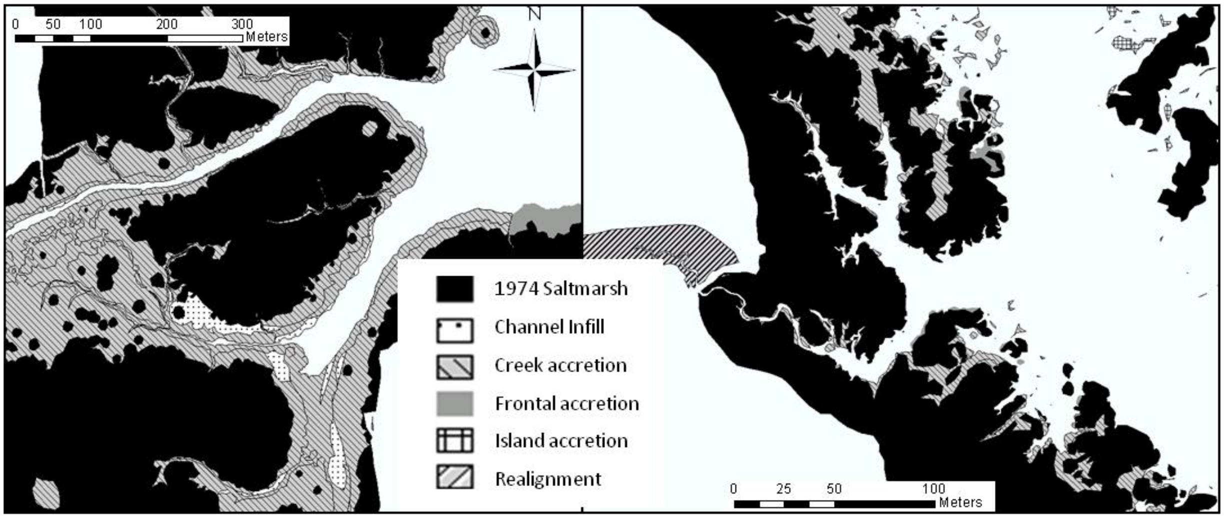



**Figure 5.17 Examples of saltmarsh gain mechanisms (1974-2005 extent)**

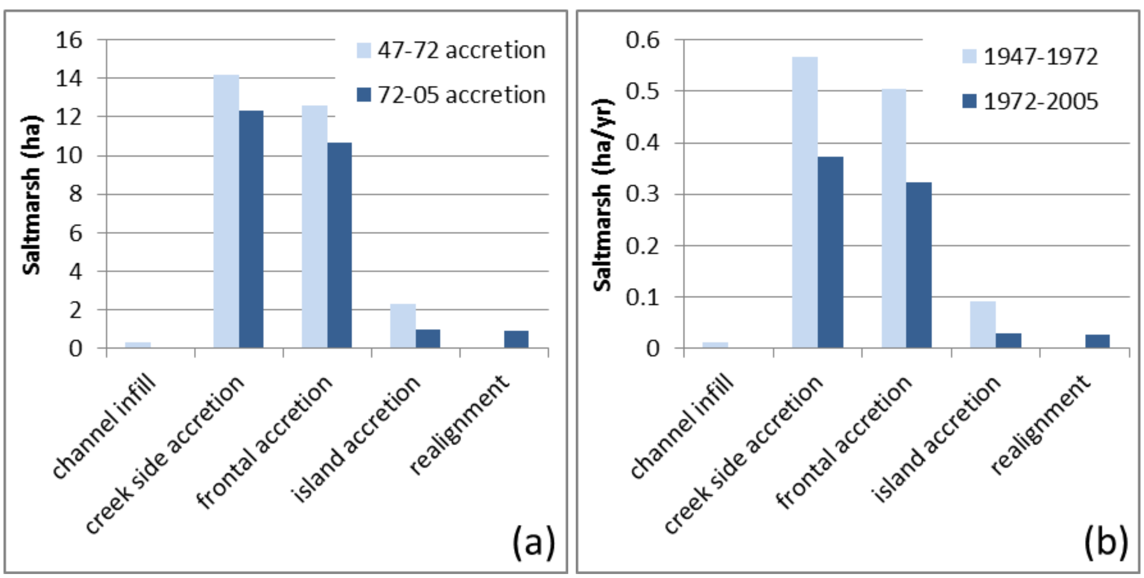



**Figure 5.18 Saltmarsh gain by different mechanisms (a) area gain and (b) rate of area gain**

## 5.4 Uncertainty analysis

No previous analyses of saltmarsh changes in Poole Harbour considered uncertainty in their estimates of saltmarsh area. Here these uncertainties are considered in order to define our confidence in the results and particularly the trends observed in Figure 5.7.

### 5.4.1 Date Uncertainties

Uncertainties were found in the dates of the OS maps. The dates specified are when they were published. However, surveys may have been up to 41 years prior to this date, as in the survey from 1890. When compared to previous data collected on saltmarsh within Poole Harbour, particularly the 1925 OS map and the 1924 analysis by Hubbard (1965), the OS map appear to be from an earlier date than published when *Spartina* was not as well established. Hence the range of dates of survey has been considered.

### 5.4.2 Uncertainty Analysis From OS Maps

Errors for the area of saltmarsh calculation were also assessed. From the OS data, MHW was digitised. However, saltmarshes are often found between HAT and MHWN, and so this indicates a minimum extent, particularly for pioneer species such as *Spartina anglica*. All the OS datasets lack detail in these areas. However, some earlier OS maps did indicate saltmarsh areas not bound by MHW, and this was also digitised. The data from the 1993 OS map lacked this indicative data and neglected to show any saltmarsh within Brands Bay, Newtown Bay or from the north of Holes Bay (see figures 5.13 for locations). When compared to the aerial photography for 2005 it is clear that saltmarsh still exists in these areas, although it may be below MHW and so an approximate area of saltmarsh was calculated from the aerial photography to compensate for this error. Due to the inaccuracies previously discussed (section 4.1.1) error buffers either side of the digitised saltmarsh, of 3.5 metres and 10 metres was applied and the area calculated. Hence, an error range can be defined, Table 5.5.

**Table 5.5 Estimated digitising errors from OS map analysis.**

| Published Date | Saltmarsh Area | 3m Buffer | % Difference (3m) | 10m Buffer | % Difference (10m) |
|---|---|---|---|---|---|
| 1849 | 117.1 | 12.2 | 10.4 | 36.6 | 31.2 |
| 1900 | 172.5 | 13.8 | 8.0 | 40.5 | 23.5 |
| 1963 | 588.5 | 30.9 | 5.3 | 104.8 | 17.8 |
| 1993 | 348.6 | 25.2 | 7.2 | 65.9 | 18.9 |

### 5.4.3 Area Uncertainties For Aerial Photography

Error calculations for saltmarsh digitised from aerial photography was performed by repeating the digitisation of one area and calculating the standard deviation. Hence a percentage error can be calculated (Table 5.6).

The errors made when digitising the 2005 aerial photography are much lower than for the other datasets. This is because the photographs are colour rather than black and white and so the interface between the mudflats and saltmarsh is much easier to distinguish. Also the resolution of the 2005 data is 0.1m (Table 2) as opposed to 0.5-0.6m resolution as in the earlier photographs. Hence the total area of saltmarsh in Poole Harbour amounts to 377.4 ± 0.6 ha in 2005, 461.1 ± 3 ha in 1973 and 537.3 ± 3.2 ha in 1947. This still demonstrates significant net losses between these observations even taking into account the errors calculated here.

The 1947 aerial photography did not have full coverage for the Harbour, the most significant areas missing being the Arne peninsula, the top of some creek systems in the Wych Channel and a small area at Sandbanks (see figure 4.2 for locations). Rates of loss at these locations between 1972 and 2005 were calculated and extrapolated linearly backwards to give a figure for saltmarsh in this area in 1947, this is also included in the error on the graph.

Other errors such as displacement may occur during the georectification of the datasets. The implications of this are not likely to affect the total area of the saltmarsh, but could be significant when looking into the details of saltmarsh location and thus where erosion or accretion has occurred over time

**Table 5.3 Estimated digitising errors from aerial photography analysis.**

| Year | 2005 | 1972 | 1947 |
|---|---|---|---|
| Original (m2) | 25339 | 19730 | 24950 |
| Rep 1 (m2) | 25368 | 19552 | 25259 |
| Rep 2 (m2) | 25332 | 19736 | 25050 |
| Rep 3 (m2) | 25296 | 19559 | 25230 |
| Rep 4 (m2) | 25348 | 19607 | 25149 |
| Rep 5 (m2) | 25411 | 19801 | 24895 |
| Rep 6 (m2) | 25286 | 19896 | 25260 |
| Mean (m2) | 25340 | 19697 | 25113 |
| Stad Dev. | 42.4 | 129.9 | 150.5 |
| % Diff | 0.2 | 0.7 | 0.6 |

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## 5.5 Assessment of Historic Datasets

To summarise, different data was found to be suitable for different purposes and scales of assessment. Historic OS maps were useful to observe large scale changes over time, such as reclamation and building development. However, it was found that saltmarsh indicators on the maps could be inaccurate and that MHW was sometimes mapped landward of saltmarsh areas and at other times seaward of it. Similarly MLW lines on the graphs are not up to date and do not reflect the positioning of channels at the published date. However, for a general, large scale view of changes within a system they are useful to inform the smaller scale studies. Historic charts were found to be most detailed in main channel areas. Whereas intertidal areas were often not surveyed, with data taken from OS maps. Poole Harbour has extensive areas of shallow intertidal areas, and this combined with the micro-tidal climate make these areas difficult to survey. Within other estuaries charts may be much more accurate and so their usefulness in studying intertidal changes must be assessed on a site by site basis.

Aerial photography is particularly useful for studying intertidal habitat changes, as well as reclamation and development within the coastal zone. However, historic aerial photography is fairly scarce and is often incomplete. Major errors can be incurred through the processing of the historic photography, which must be correctly georectified. Errors are frequently also made during the interpretation of coastal habitats. Historic data is often black and white, which makes observing the landward extent of saltmarsh difficult, particularly when backed by reedbeds and other marshland habitats. The time at which the aerial photographs are taken also dictates their usefulness, the data for Poole Harbour was not taken at low tide and so channel networks are difficult to interpret.

It must also be noted that due to the limited data available, short term changes and fluctuations will not have been observed. The formation of pans within saltmarshes has been observed in many other estuaries (Boston, 1983, Pethick, 1974), although this process was not observed within Poole Harbour. However, if these pans form over a short time period this process may have been missed or obscured by other long term processes such as frontal erosion or subsequent reedbed takeover.

## 5.6 Summary

The main findings from the preceding chapter are summarised below, a detailed discussion of the findings of this chapter set in the context of the aims and objectives, laid out in Chapter 1, is presented in Chapter 8.

The main objective of this Chapter has been to quantify historic saltmarsh trends within Poole Harbour. This has been achieved through the analysis of maps, charts and aerial photography.

When set into a post-1849 context, saltmarsh area expanded significantly due to the colonisation of *Spartina* from 1900 to 1920, followed by a decline which continues today. While saltmarsh in Poole Harbour area has declined rapidly during the latter half of the 20th century, the changes are more complex than previously reported, with a net loss as erosion exceeded accretion. However, the rate of saltmarsh loss is decreasing and the total area of saltmarsh in 2005 exceeds the area estimated in 1849 and 1900, this is an important contemporary process in Poole Harbour. The processes that are controlling these changes can be inferred from the geomorphic setting of the change. The dominant erosional processes are island and frontal erosion occurring in exposed areas of the Harbour. The dominant accretional processes are frontal and creekside accretion occurring in sheltered creek systems and the potential for erosion and accretion to continue in these locations needs to be considered when evaluating future possible trends. Hence while the future of saltmarsh in Poole Harbour needs to be carefully evaluated, recent changes are not as adverse as earlier work suggests (as discussed in Chapters 1 and 3).

The main findings of this stage are:

- A more complex set of saltmarsh changes, than those reported by earlier research, is occurring in Poole Harbour and both accretion and erosion have been observed.
- Saltmarsh extent in 2005 was approximately three times the extent in 1900 prior to *Spartina* colonisation.
- Peak saltmarsh extent occurred around the 1920 's and can be attributed to *Spartina* colonisation
- Since 1947 the saltmarshes, have experienced a net loss of 187ha, including 241 ha of loss and 54 ha of accretion.
- Observed erosion and accretionary trends are spatially variable
- The dominant erosional processes are frontal and island erosion
- The dominant accretional processes occurs up creek systems and are creek-side and frontal accretion
- Rates of loss have declined since 1947, in all but one region of the Harbour surrounding the Islands in the Wareham Channel

# 6 Estuary Morphology Results

Chapter 5 described the detailed historic trends of saltmarsh change within Poole Harbour, in Chapter 6 these historic results are examined with respect to the second stage of research, as proposed in Section 1.2. The main objective was to examine the morphology of the Harbour and how it varies between eroding and expanding regions of saltmarsh. This includes an analysis of the hypsometry of the Harbour (Section 6.1) which can indicate whether the estuary is importing or exporting sediment. This will have an impact on the intertidal habitats ability to keep pace with local relative sea-level rise and erosional or accretional trends. Sub-estuary variations in hypsometry are also assessed and compared to the historic change analysis, discussed in Chapter 5, to observe any correlations with saltmarsh change.  Saltmarsh morphology is examined in Section 6.2, through mapping of cross sections of the intertidal. The cross shore profile shape can indicate erosional and accretional trends; this will give insight into contemporary processes within the saltmarshes and drivers of change. These results are then combined with a sediment analysis for selected areas within the Harbour, where velocity shear thresholds were analysed through flume testing (Section 6.3). Then further combined with knowledge of dominant wind and wave directions and fetch (Section 6.4), which may be responsible for the changes observed in Chapter 5. The main findings are summarised in Section 6.5

## 6.1 Hypsometry

As previously discussed in Section 2.1.2.3, hypsometry describes how the horizontal surface area of an estuary varies with respect to the elevation (or depth). The resulting hypsometry curves can help to describe an estuarine system in terms of tidal asymmetry and its morphological state, e.g. is it an eroding or accreting system, (Boon and Byrne, 1981, Strahler, 1952).  The Hypsometry relationship between area and height used in this study was defined in equations 2.1-2.3 (Boon and Byrne, 1981) and figure 2.5 (Section 2.1.2.3).

In some previous studies (Boon, 1975, Dieckmann et al., 1987, Kirby, 1992),  hypsometry has been used to describe the changes that occur over the intertidal region only. Hence, A is the total basin area (area at highest astronomical tide) and $A_{min}$ would be the basin area below lowest astronomical tide, which can be used to find the value of parameter r. The smaller the value of r the larger the proportion of area above LAT in the estuary and hence the larger the intertidal area. However, in studies investigating the total estuary profile $A_{min}$ is no longer applicable in the calculations and hence r cannot be resolved and so is empirically determined, Boon and Byrne (1981) use a value of 0.01. The parameter γ is often found through curve fitting (Boon and Byrne, 1981, Strahler, 1952), in order to illustrate the affects that these values have on the morphology of an estuary an idealised case has been calculated using equations 2.1-2.3.

Figures 6.1 and 6.2 illustrate how γ alters the hypsometric curve and intertidal profile. In this example the curve and intertidal profile are similar as the estuarine model used to illustrate the profile changes was a simple circular basin in shape, with other estuary shapes the profiles may vary. The value γ, adjusts the area below the hypsometric curve and describes the maturity of the estuary, or how infilled it is. An estuary where γ=3.5-5.0 will be little in-filled and will be flood dominant, while an estuary where γ= 1.8-2.5 will be ebb dominant (Boon and Byrne, 1981). The parameter r, when applied to whole estuary calculations, controls the amount of basin curvature in terms of slope at the point of inflection (Boon and Byrne, 1981). Hence, r determines the steepness of the channel sides and the extent of the intertidal areas. This is illustrated in figures 6.3 and 6.3, as r increases the shape of the hypsometric curve flattens with a lowering of the intertidal region.

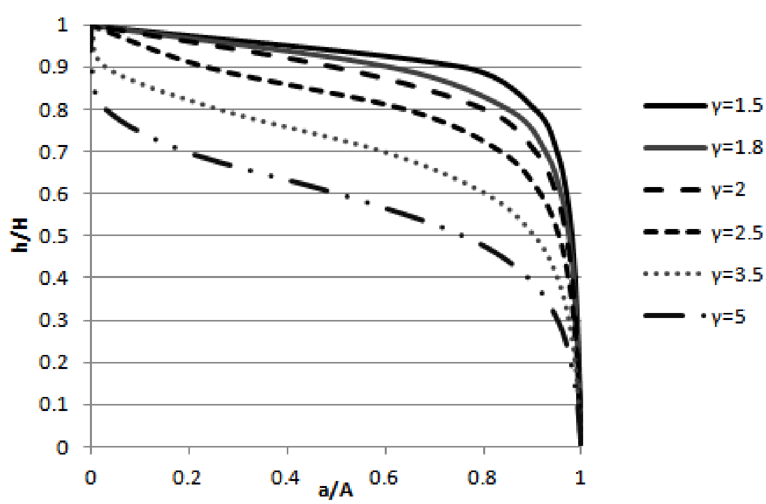


**Figure 6.1 Illustration of how value γ alters the hypsometric curve (r=0.01)**

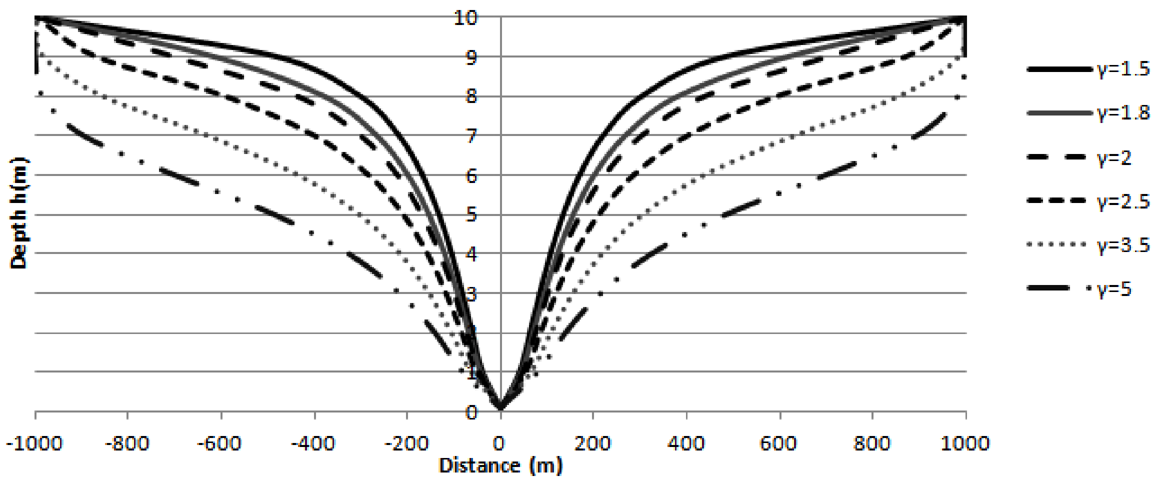


**Figure 6.2 Illustration of how value γ alters the intertidal profile (r=0.01)**

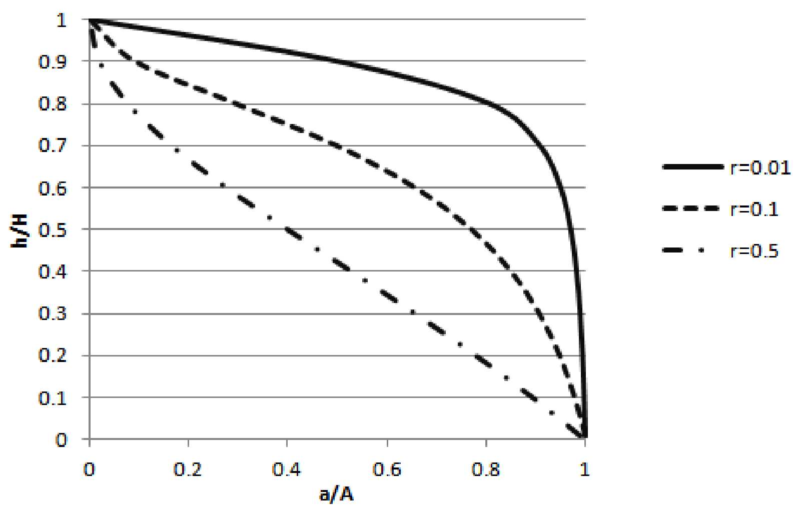


**Figure 6.3 Illustration of how value r alters the hypsometric curve (γ=2)**

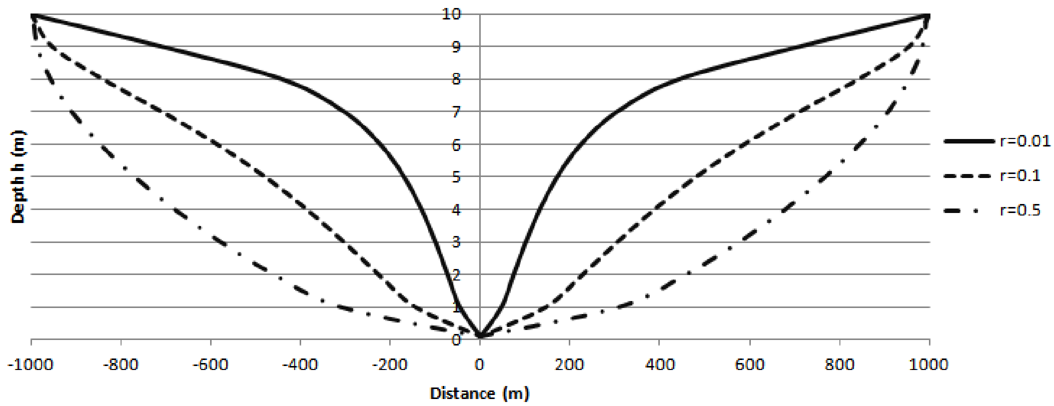


**Figure 6.4 Illustration of how value r alters the intertidal profile (γ=2)**

Using a simple model to plot intertidal profiles from a hypsometric curve, it can also be illustrated that although several profiles may have the same γ and r values and hence the same hypsometric curve, that they may have different cross-shore profiles (Figure 6.5). Depending on the tidal amplitude within these estuaries, they may have very different intertidal distributions. However, if the tidal ratio to depth is the same for each estuary then they would have the same distribution of intertidal area (assuming no other changes in external forcing).

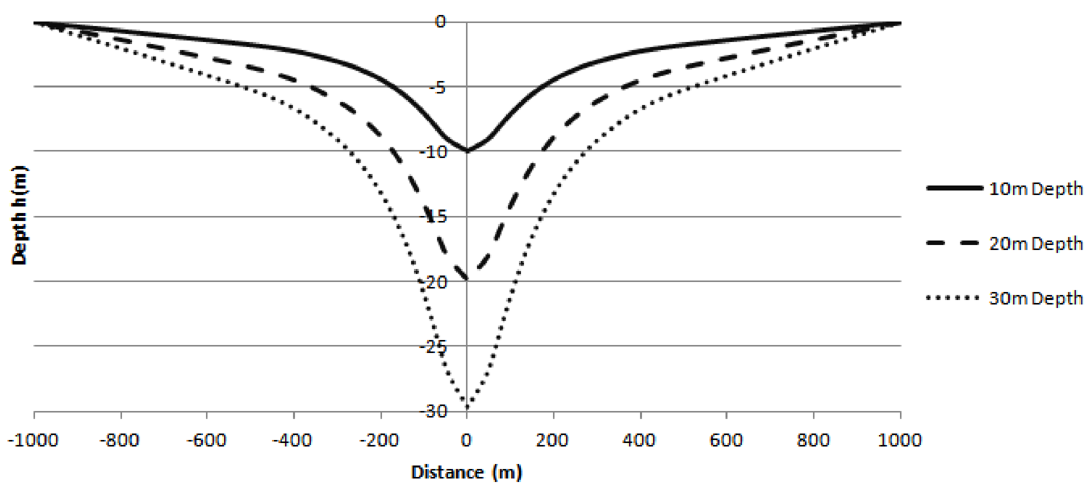


**Figure 6.5 Illustration of how changing depth affects the intertidal profile (γ=2, r=0.01)**

By combining LIDAR data collected in 2007 (source Channel Coastal Observatory), with hydrographic bathymetry of the sub-tidal areas (2005), supplied by Poole Harbour Commissioners, a digital terrain model (DTM) of the Harbour has been created. From this DTM, hypsometric curves for the entire Harbour (Figure 6.6) and for sub-sections of the Harbour (figure 6.7) could be extracted (Figures 6.8 and 6.9). Hypsometry in this example is applied to the full depth (approximately 14 m) of the Harbour. These profiles can then be compared to empirical hypsometry curves derived in (Boon and Byrne, 1981, Strahler, 1952). Parameters from these curves can then be calculated to indicate whether these areas are likely to behave as flood or ebb dominant and hence importing or exporting sediments.

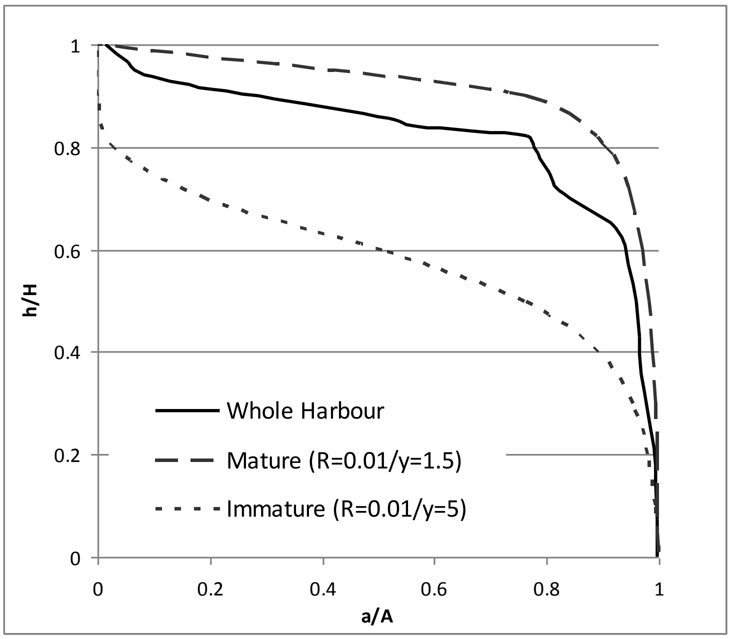


**Figure 6.6 Hypsometric plot for the whole of Poole Harbour**

Figure 6.6 shows hypsometry plots for the whole Harbour, mathematically derived lines using equations 2.1-2.3 in Section 2.1.3 for γ=1.5 and γ=5, represent a theoretical mature and immature estuary respectively. The immature estuary would describe Poole Harbour in its early stages of evolution with low intertidal areas of limited extent, prior to initial infilling at the start of the Holocene. This morphology would have a tendency towards flood dominance and hence import sediment into the system (Pethick, 1994), which would accrete in the intertidal areas, in extent and height. Conversely the mature estuary could potentially be represented by Poole Harbour at the peak of *Spartina* colonisation with high expansive mudflats and intertidal areas stabilised by saltmarshes. This form tends to be ebb dominant (Dronkers, 1986, Fortunato et al., 1999) and hence following the rapid build up of intertidal areas the ebb dominance could have increased tidal currents to a magnitude whereby export of sediment and hence erosion, occurred.

These two models illustrated in Figure 6.6 represent two extreme examples or end points on continuum in estuary evolution and as such these forms are inherently unstable, therefore following *Spartina* dieback the intertidal areas have eroded with a tendency to conform to a dynamic equilibrium state between the two extremes.

The hypsometry of the whole Harbour is now compared to individual creek systems within the Harbour. Figure 6.7 defines these sub-regions, while Figures 6.8 and 6.9 shows the results for the areas that have had historic accretion and erosion, respectively. The hypsometric curves of these sub-regions deviate substantially from the Harbour as a whole. The accreting and eroding areas are grouped in terms of the form of the hypsometry, plotting closer to the mature and immature theoretical endpoints, respectively (Figures 6.8 and 6.9). In fact the eroding regions often extend below the expected lower theoretical boundary of Boon and Byrne (1981). This can be attributed to these regions not being closed systems and instead need to be considered within the estuary system as a whole, as sediment can move between these sub-regions.  Or in other words, when averaged over the entire system (Poole Harbour) these extreme results (for the sub-regions) are averaged out resulting in a hypsometric curve that falls between the expected hypsometry envelope (Figure 6.6).  Although the sub-section curves do not conform to the general hypsometric thresholds, the hypsometric method still represents a useful tool. Morphologically the areas that are delineated through hypsometry as flood dominant (accreting) and ebb dominant (eroding) correlate with historic saltmarsh changes mapped in Chapter 5.

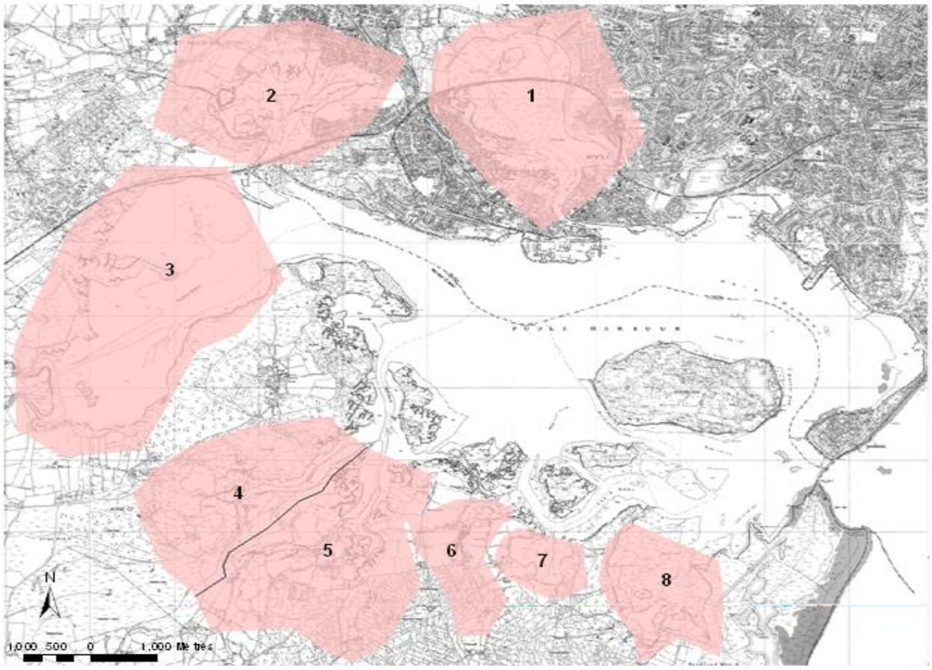


**Figure 6.7 Areas at a sub-estuary scale for which hypsometry curves have been derived. (1. Holes Bay; 2. Lytchett Bay; 3 Wareham Channel; 4. Wych Lake left; 5, Wych Lake right; 6. Ower Bay; 7. Newtown Bay; 8. Brands Bay)**

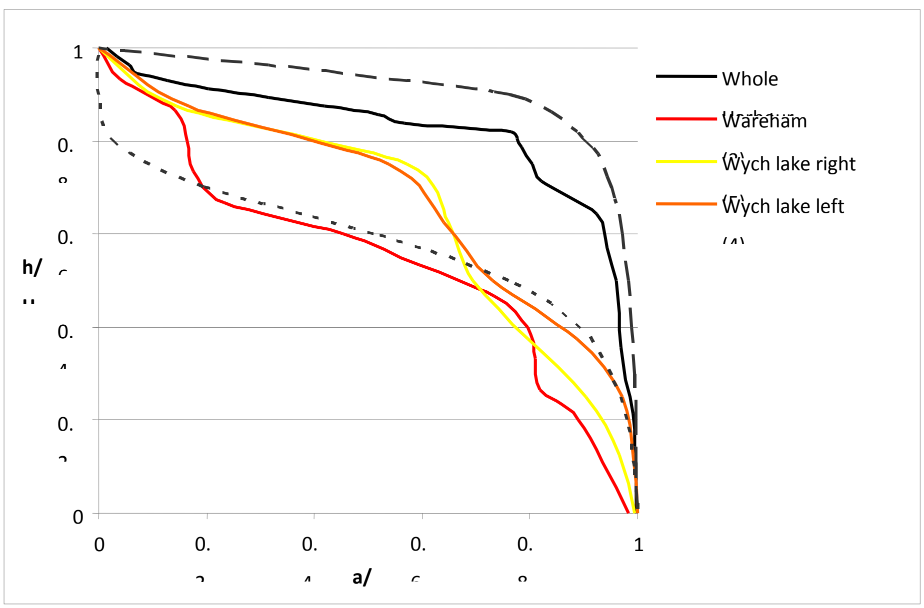


**Figure 6.8 Hypsometric plot of accreting regions of Poole Harbour (reference numbers on figure 6.7)**

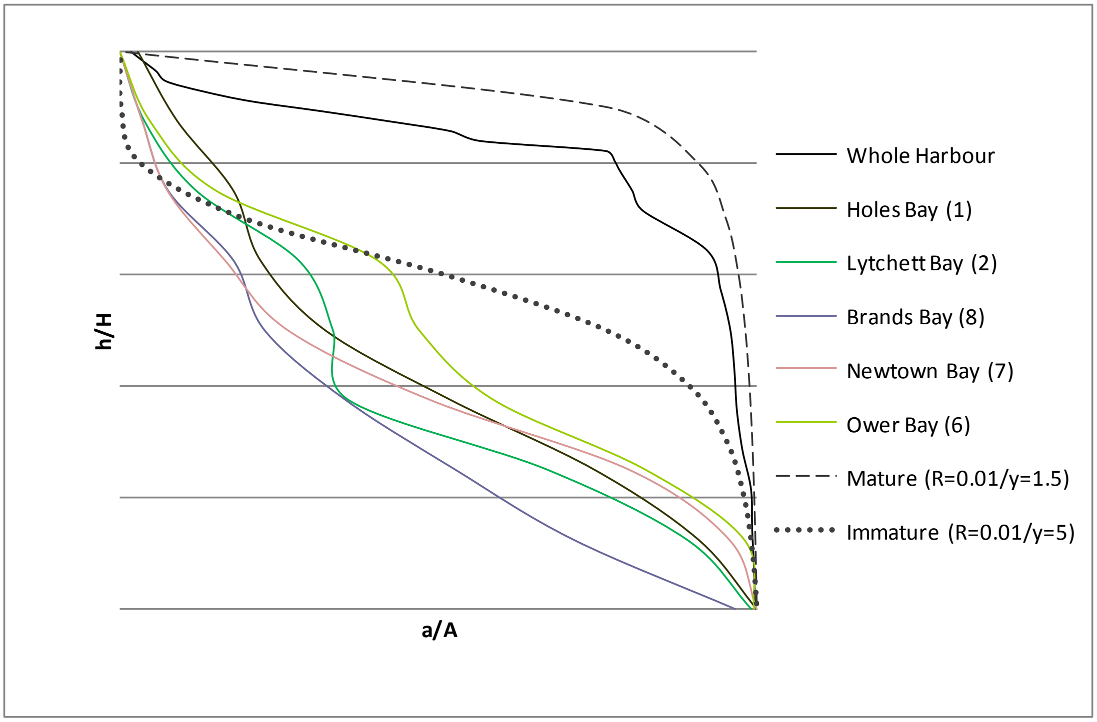


**Figure 6.9 Hypsometric plots of selected eroding regions within Poole Harbour (reference numbers on figure 6.7)**

## 6.2 Saltmarsh Morphology

The morphology and shape of the intertidal profile has been linked to erosion and accretion (Kirby, 2002, Roberts et al., 2000) as discussed in section 2.1.2. This section analyses the shape and morphology of the intertidal and further links to the results in Chapter 5 of the spatial variation in historic erosion and accretion. Profiles were taken across the saltmarsh and mudflats using LIDAR data (section 4.2.2), Figure 6.10. In total 151 representative profiles around the Harbour were examined and plotted to show their shape and morphology, these were positioned at relatively uniform intervals around the Harbour as a representative sample. However, it must be noted some errors, +7cm (Montane and Torres, 2006), may occur in the LIDAR data and for areas of thick vegetation it may show the top of the saltmarsh canopy rather than the intertidal flats they are situated on. On each profile graph, mean high water spring (MHWS), mean high water neap (MHWN), mean low water neap (MLWN) and mean low water spring (MLWS) have been plotted.

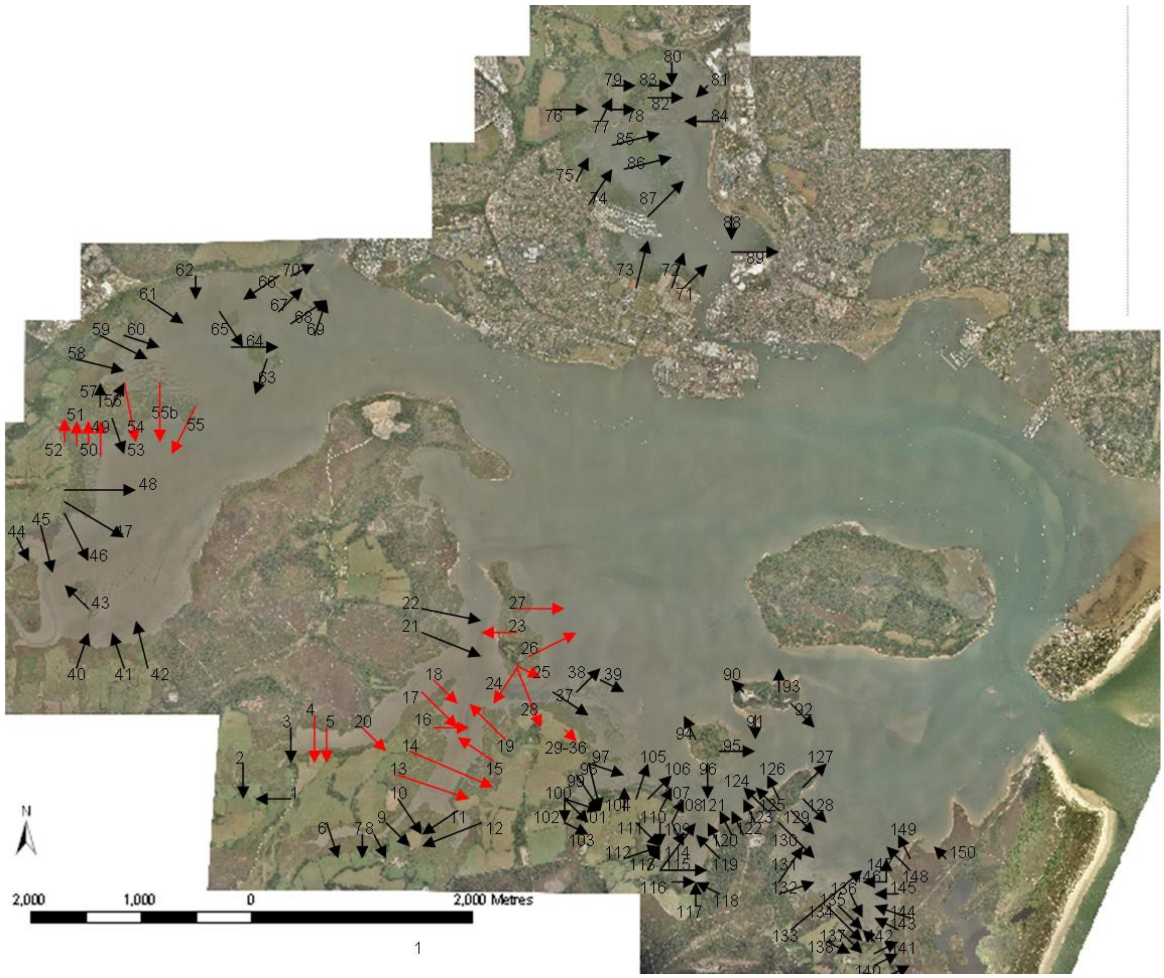


**Figure 6.10 Location of saltmarsh profiles (Profiles in red used as example in figures 6.11-6.17.)**

Figures 6.11 and 6.12 both show saltmarsh to mudflat profiles from areas where frontal erosion has been observed. The saltmarsh platform occurs around 0.8m OD (MHWS) in these areas, in most cases this then drops fairly steeply to below 0m OD between MLWS and MLWN, with a more gentle slope evident in profiles 28 and 16.

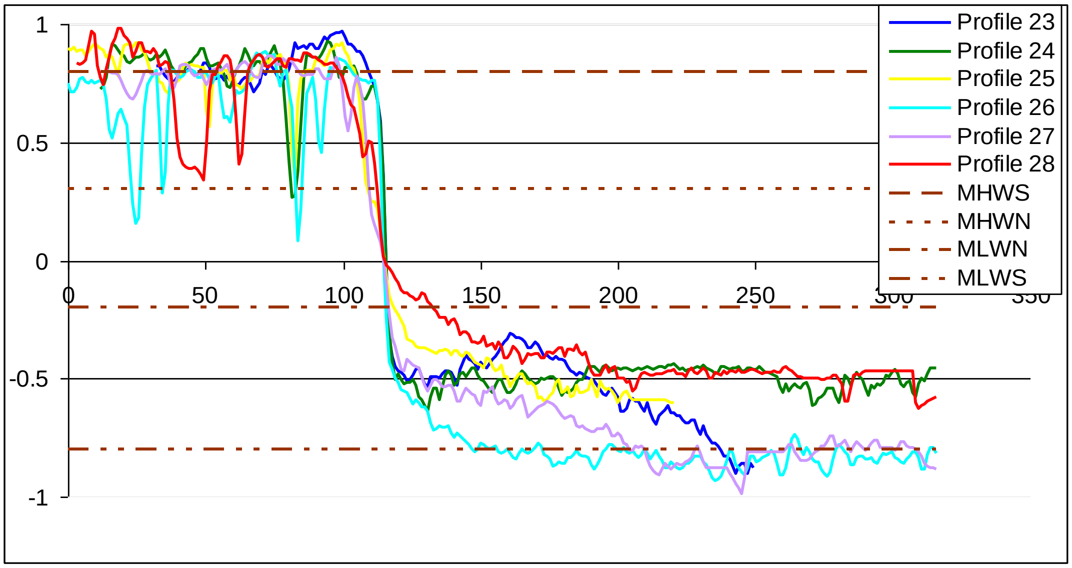


**Figure 6.11 Long and Round Island (areas of frontal erosion).**

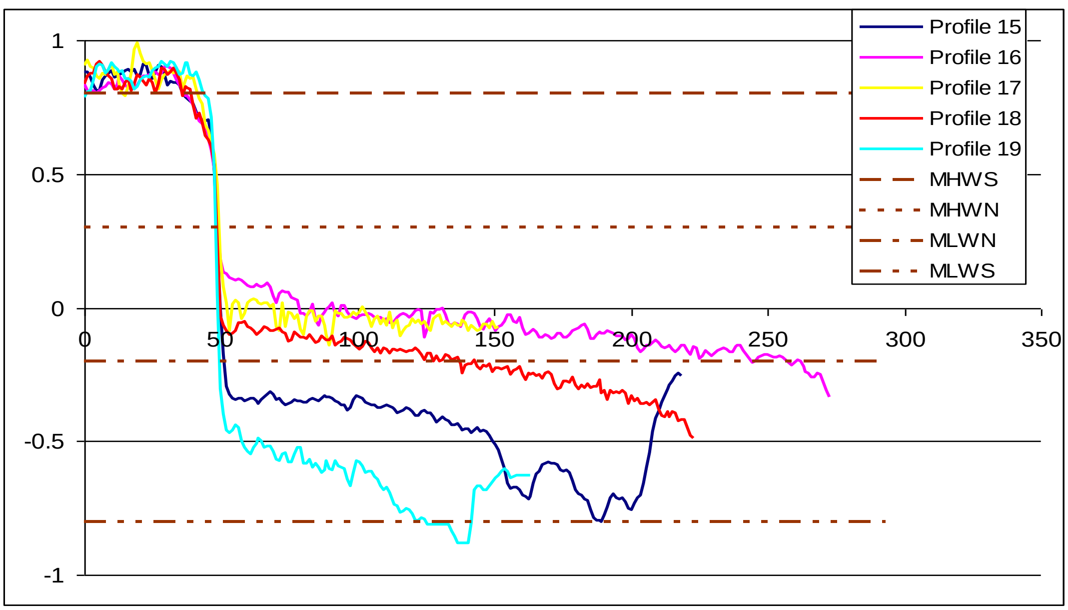


**Figure 6.12 Wych Lake (area of erosion)**

Figure 6.13, shows a cross creek profile where saltmarsh on both sides of the creek has been observed as eroding. The amount of historic erosion on the western side has been fairly small in comparison to the eastern side. On the eastern side the profile drops straight from the saltmarsh platform at around 0.8m OD to below 0m OD and into a tidal creek. The western side drops from the saltmarsh platform at 0.8 m OD to just above 0, where it gently slopes downwards across the mudflat to the channel.

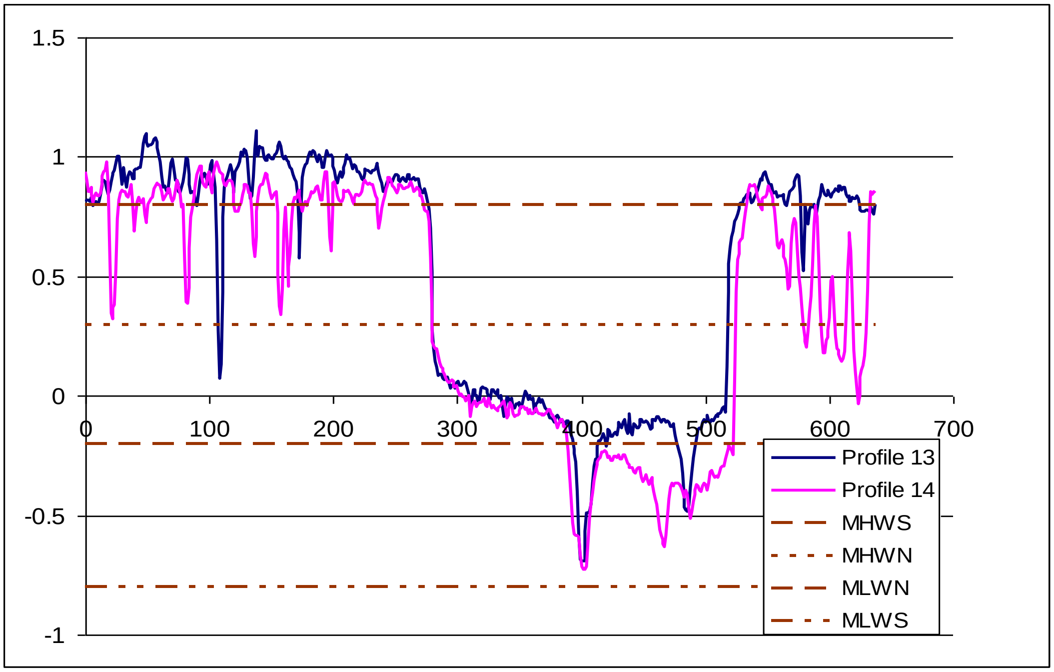


**Figure 6.13 Wych Lake (across channel W-E both eroding)**

Figure 6.14 shows profiles across a saltmarsh promontory, from north to south, in West Wareham. On the southern side of the marsh, erosion is the dominant process and the marsh platform (between 1 and 0.8m OD) sharply drops to around -0.5m OD. However, at profile 54 on the northern side there has been accretion and the mudflat in front of the saltmarsh is much higher gently decreasing from 0.25m to 0m OD. Erosion has been observed on the northern side for profiles 5 and 55b, where the mudflat is lower and sits between -0.5 and 0m OD.

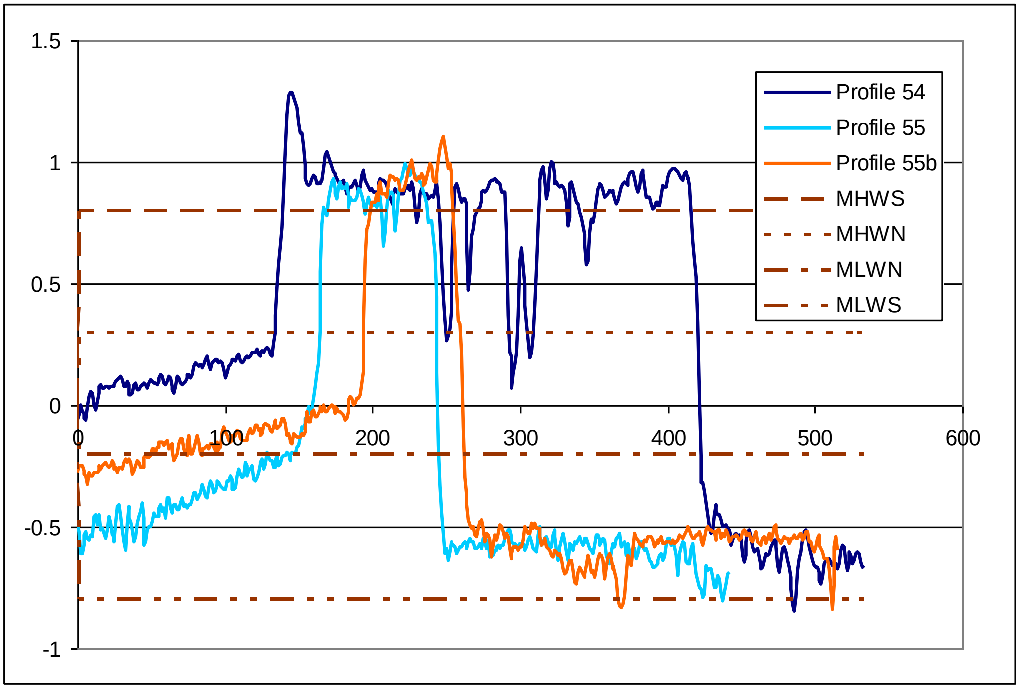


**Figure 6.14 West Wareham (across saltmarsh promontory, N-S)**

Figure 6.15 and Figure 6.16 show profiles across an accreting creek system from the mouth to the head of the creek. As shown in Figure 6.15, the creek entrance is wide and gradually narrows inwards towards the head. The channel is shallow and high in the tidal frame at 0.18m OD, with broad mudflats either side at the mouth, which slope up to the marsh platform at around 0.8m OD. As the profiles progress towards the head of the creek, the mudflat area either side of the creek narrows and the creek becomes relatively deeper, until the mudflats disappear and the marsh drops straight into the creek. In Figure 6.16, profile 20 is furthest towards the mouth of the creek and profile 4 furthest away. Again the creek has broad mudflats either side before sloping up to the saltmarsh platform. However, in this case the saltmarsh is at different heights on either side of the creek, on the south side it is around 0.8m OD but is over 1m OD on the north side, and the channel is much deeper at -0.5 m OD.

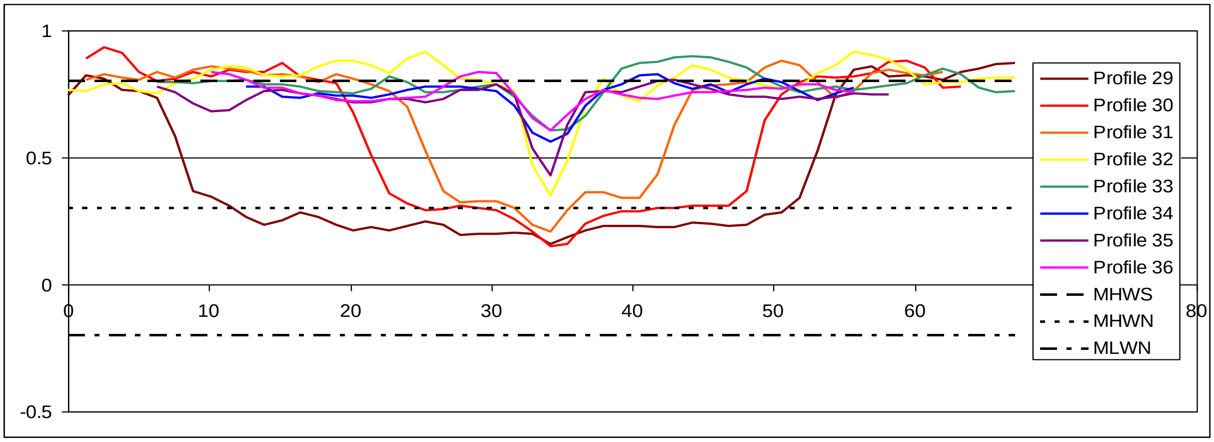


**Figure 6.15 Fitzworth north (across accreting creek, N-S)**

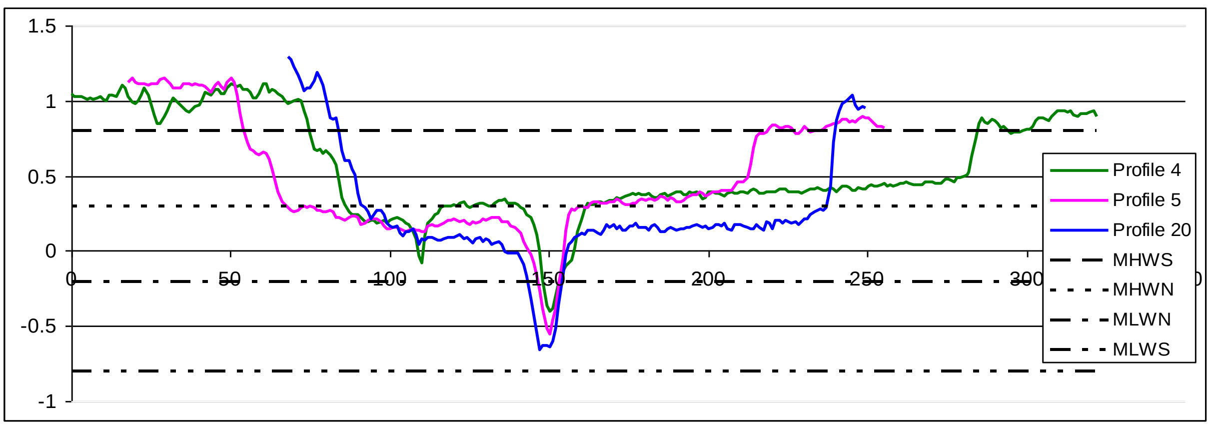


**Figure 6.16 Middlebere (accreting creek, N-S)**

Figure 6.17 shows profiles along an eroding creek system, profile 49 is at the mouth of the creek, the sides are steep from the saltmarsh platform, at 0.8m OD, dropping straight into the channel with no fringing mudflat. The channel depth gradually decreases from the head of the creek to profile 52, however, the profile stays the same.

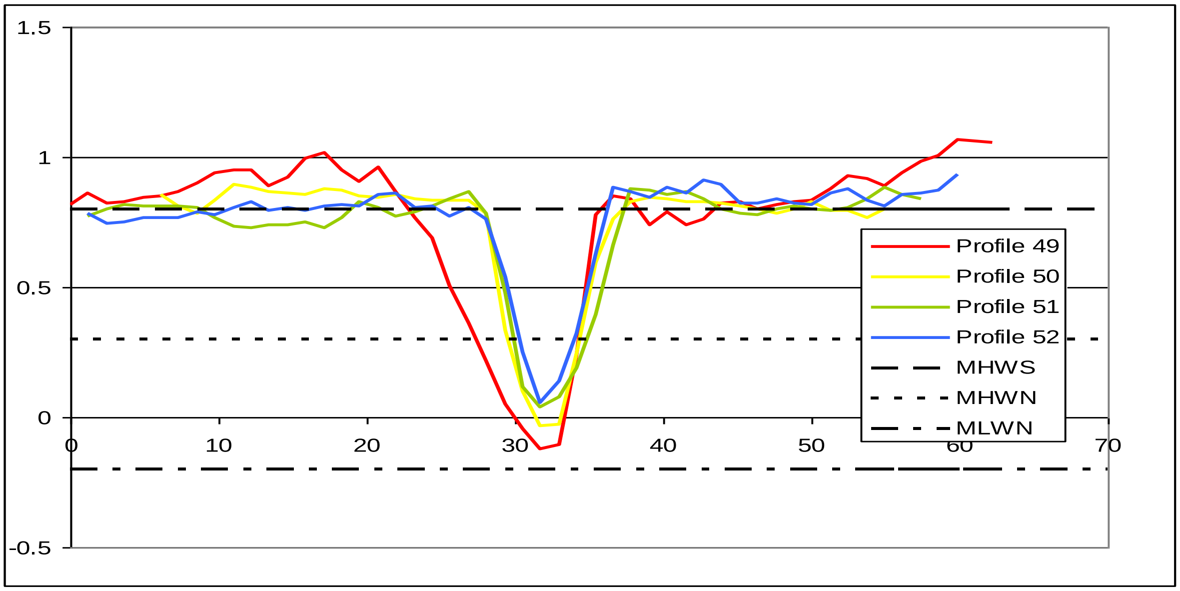


**Figure 6.17 Wareham west (eroding creek S-N)**

These profiles help classify accreting and eroding areas within the Harbour and illustrate processes that may be driving the saltmarsh change. For example in exposed areas, where cliffs occur extending below MLWS, wave attack is likely and could be the dominant driver of saltmarsh erosion. However, if cliffing occurs in sheltered locations, such as creeks, this may be due to instability of sediments due to bioturbation.

The height of the saltmarsh at the marsh edge and the height of the mudflat immediately in front of the marsh were measured for areas of erosion and accretion. These trends were then linked to rates of historic changes (Figure 6.18), there appears to be no significant relationship between the rate of accretion and either the height of the marsh or the fronting mudflats. In areas of historic saltmarsh erosion, the rate of saltmarsh loss increases with the lower elevations of both marsh and fronting mudflat height.

Statistical analysis of the data sets, involving homoscedastic, unpaired T-tests, were performed, in order to determine whether the levels of mudflat and saltmarsh in accreting and eroding areas were significantly different in height. It was concluded that there is a significant difference between the levels of eroding and accreting saltmarsh and mudflats.

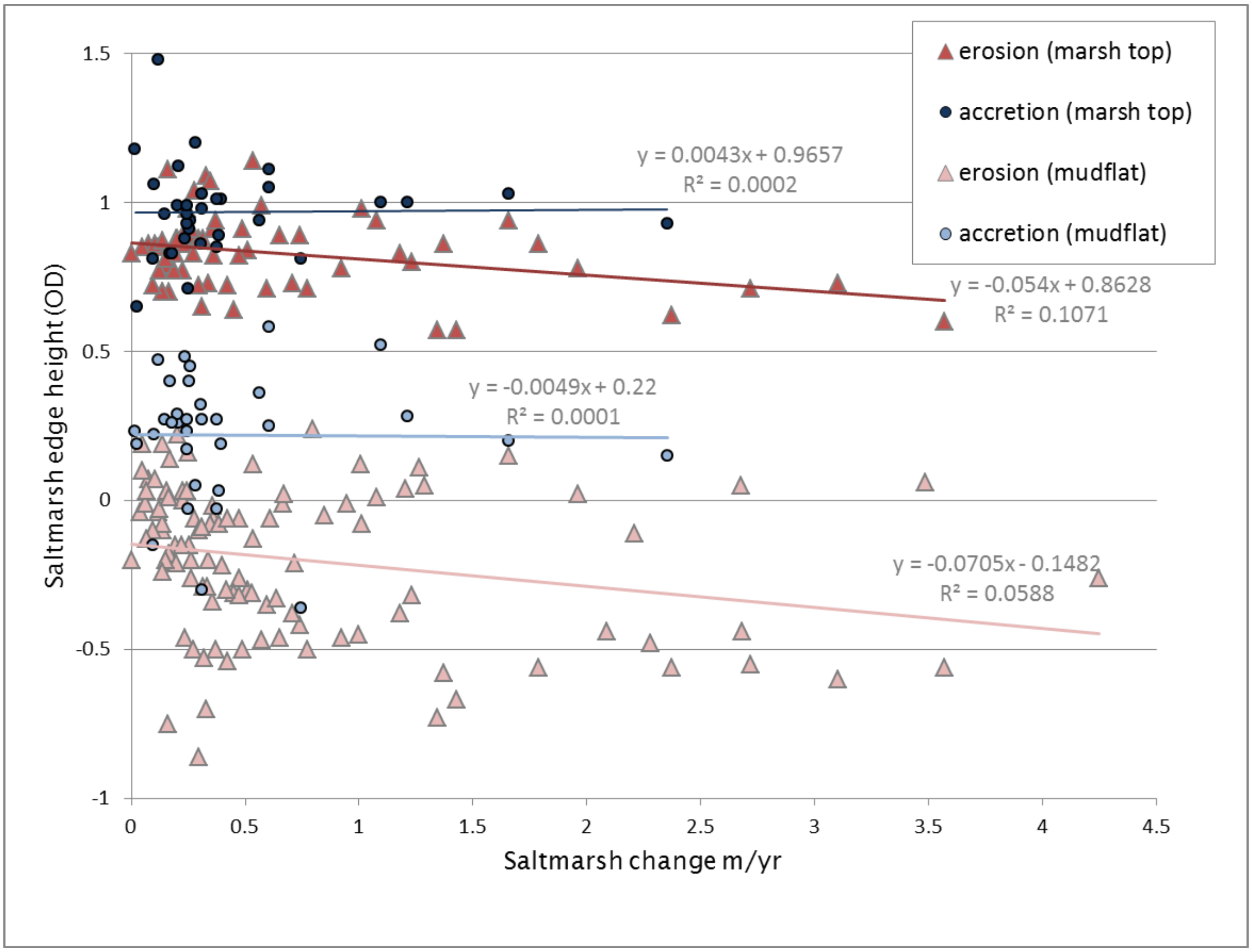


**Figure 6.18 Relationship between rate (m/yr) of saltmarsh change and the height (OD) of saltmarsh at marsh edge and mudflat directly in front of the marsh.**

The histogram in Figure 6.19 shows the present bed height (from LIDAR and bathymetry ) where saltmarsh accretion and erosion trends have historically occurred since 1947 Although the height at which previously eroded saltmarshes were positioned cannot be calculated, it can be shown to what level these areas have been reduced to or changed. The majority of area now sits between 0.2 and -0.8 m (OD) which corresponds to between MLWN and MLWS and has been converted from saltmarsh to intertidal mudflat. Some regions lower than this, down to roughly -3.0 m (OD), can be seen and are where channel migration has occurred.

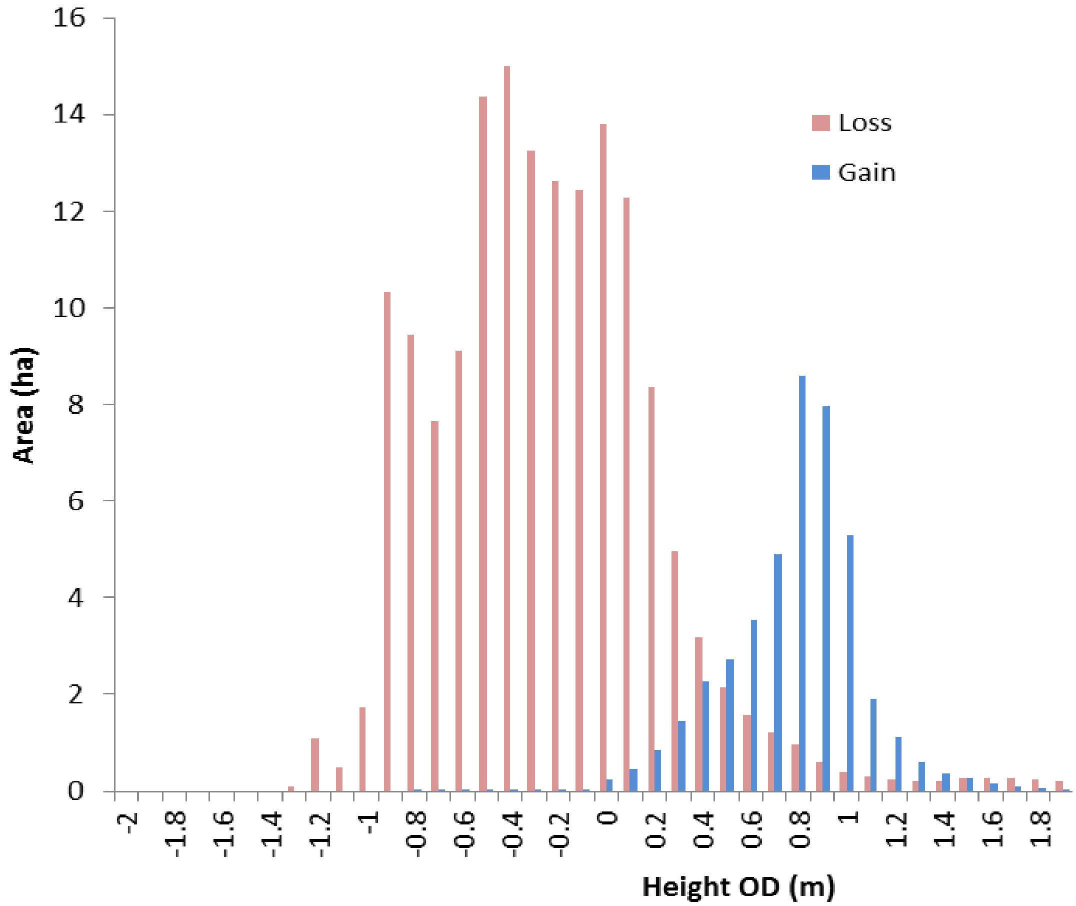


**Figure 6.19 Histogram of height at which saltmarsh change has occurred**

As discussed in Section 5.3.3, channel migration has been one driver of saltmarsh loss in Poole Harbour as well as some reclamation for marinas in Holes Bay which are responsible for this drop in elevation. Some areas of previous erosion, can be observed high in the tidal frame and extend up to 2m (OD), reclamation and reed bed take over are responsible for the losses in these regions. The height of saltmarsh that has previously accreted is situated between 0 and 1.5m (OD) peaking at 0.8-0.9m (OD) around MHWS. This correlates with the profiles taken across the intertidal regions presented in figures 6.11-6.17.

## 6.3 Sediment Properties

As previously discussed in Section 2.1.2 estuarine morphology is a result of interactions between sediments and hydrodynamics. The critical shear velocity of different sediments determines sediment transport and movement. Hence, in order to help understand the spatial variation in saltmarsh erosion and accretion within the Harbour, sediment samples were taken within Poole Harbour and the critical shear threshold assessed using annular flume experiments.  The critical shear threshold was used in Chapter 7, alongside modelled tidal velocity outputs to infer erosion and deposition spatially and throughout the tidal cycle in Poole Harbour. Samples were collected from both eroding (E) and accreting (A) areas (Figure 3.1).

Figures A1 –A8 in Appendix A, show time series plots of annular flume experiments for each site and sample, including erosion rate, total suspended solids (TSS) and shear stress (Tau). The calibration of the OBS sensor to suspended sediment concentration, measured from samples taken from the flume, are shown in Figures A9 – A16. Estimates of shear thresholds using the relationship between bed shear stress and suspended sediment concentration are calculated in Figures A17-A25.

The average critical shear velocity threshold for eroding sites was 0.16 m/s and 0.24m/s for accreting sites, giving an overall average shear velocity threshold of 0.2m/s (Table 6.1).

**Table 6.1 Samples taken at eroding (E) and accreting (A) sites.**

| **Sample** | **Critical Shear Velocity** | |
|---|---|---|
| | **Pa** | **m/s** |
| E1-1 | 0.33 | 0.2 |
| E 1-2 | 0.13 | 0.13 |
| E 2-1 | 0.18 | 0.15 |
| E 2-2 | 0.15 | 0.14 |
| A1-1 | 0.36 | 0.21 |
| A 1-2 | 0.3 | 0.19 |
| A 2-1 | 0.86 | 0.33 |
| A 2-2 | 0.43 | 0.23 |
| Average | 0.34 | 0.2 |

Examination of organic content showed that the sample taken from the erosionary sites had an average organic content of 13.5% whereas the samples from the accretion sites had an organic content of 9.5%. Visually the sediment from the erosion sites had large pieces of organic matter, including dead saltmarsh stems, within the mud. No large organic matter was observed in the accretion samples.

Grain size analysis using a coulter counter (Figures A25-A33) revealed an average grain diameter of 17μm and 16μm for sediments from erosionary and acretionary areas respectively, indicating a medium silt (Figure 6.20). It was also shown that there are 2 distinct types of sediment within the Harbour with a bimodal spike on the sediment distribution graph at approximately 17μm and 100μm, indicating that there is both fine silt fractions and very fine sand fractions within the Harbour, (Wentworth, 1922). Although some fine sediment may be input to the Harbour from cliff erosion (Section 3.1.2) fine sand may have been transported through the mouth of the Harbour.

| Millimeters (mm) | | Micrometers (μm) | Phi (ϕ) | Wentworth size class | | Rock type |
|---|---|---|---|---|---|---|
| | 4096 | | -12.0 | Boulder | Gravel | Conglomerate/ breccia |
| | 256 | | -8.0 | Cobble | | |
| | 64 | | -6.0 | Pebble | | |
| | 4 | | -2.0 | Granule | | |
| | 2.00 | | -1.0 | Very coarse sand | Sand | Sandstone |
| | 1.00 | | 0.0 | Coarse sand | | |
| 1/2 | 0.50 | 500 | 1.0 | Medium sand | | |
| 1/4 | 0.25 | 250 | 2.0 | Fine sand | | |
| 1/8 | 0.125 | 125 | 3.0 | Very fine sand | | |
| 1/16 | 0.0625 | 63 | 4.0 | Coarse silt | Silt | Siltstone |
| 1/32 | 0.031 | 31 | 5.0 | Medium silt | | |
| 1/64 | 0.0156 | 15.6 | 6.0 | Fine silt | | |
| 1/128 | 0.0078 | 7.8 | 7.0 | Very fine silt | | |
| 1/256 | 0.0039 | 3.9 | 8.0 | Clay | Mud | Claystone |
| | 0.00006 | 0.06 | 14.0 | | | |

**Figure 6.20 Sediment size classification (Table from Wentworth (1922)).**

## 6.4 Wind/wave effects

In shallow regions wind-waves can affect turbidity and is considered a major factor in saltmarsh decline in other esturies, as discussed in Section 2.1.1, with wave energy linked to spatial differences in long-term *Spartina* growth (Swales et al., 2004). Rates of saltmarsh change (Figure 4.3) and fetch length were compared for sites in Poole Harbour.

The highest rates of saltmarsh gain within the Harbour occur where the marshes are orientated towards the North-west and the South-east (Figure 6.21), which is opposite to the predominant wind directions and hence most sheltered from locally derived wind-waves.

However, rates of saltmarsh loss do not appear to be directly related to orientation within the Harbour (Figure 6.22).

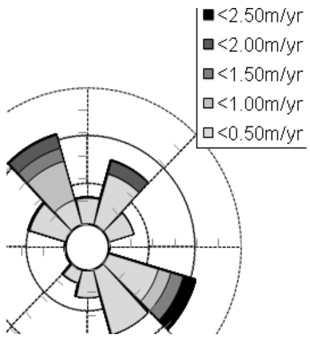


**Figure 6.21 Rose showing the orientation and rate of saltmarsh gain within Poole Harbour**

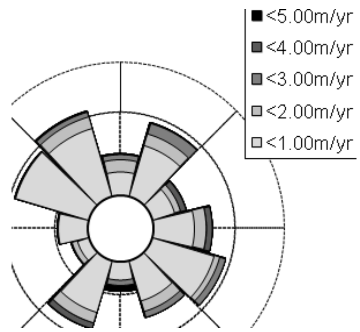


**Figure 6.22 Rose showing the orientation and rate of saltmarsh loss within Poole Harbour**

Figure 6.23 illustrates that the majority of accreting sites have a fetch less than 250m. However, accretion does occur in a few regions within the Harbour where the fetch exceeds 1000m, the majority of these are aligned to the South-east (91-180 degrees). Areas where saltmarsh erosion has occurred are often exposed to longer fetches, particularly from 0-89 degrees and 180-269 degrees. However, there is no clear correlation between rate of erosion to either distance of fetch or direction of fetch.

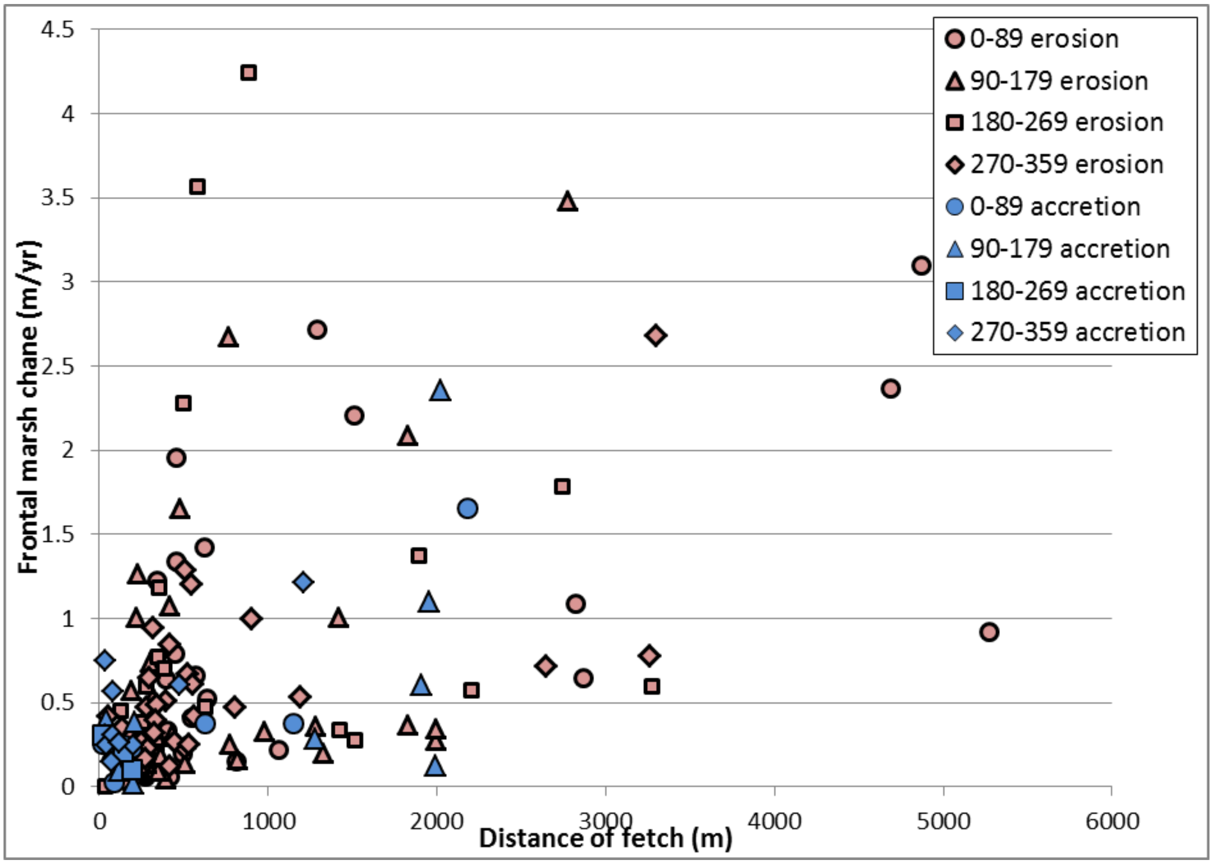


**Figure 6.23 Relationship between the rate of saltmarsh change between 1947 and 2005 (m/yr), the distance of fetch perpendicular to the saltmarsh front and the direction of fetch**

## 6.5 Summary

The main findings from Chapter 6 are summarised below. A detailed discussion of the findings of this chapter set in the context of the aims and objectives (Chapter 1) is presented in Chapter 8.

The main objective of this Chapter has been to investigate the morphology of the Harbour and how this relates to the saltmarsh changes observed in Chapter 5. This was achieved by examining the hypsometry and cross sectional profiles of the saltmarshes. In summary, saltmarsh accretion and loss have been observed within close geographical proximity in Poole Harbour and appear to be linked to various physical drivers.

Accretion has generally been observed where:

- The height of the fringing mudflat is significantly higher than in eroding areas
- The height of the marsh front is significantly higher (than in eroding areas)
- Hypsometry profiles are convex in form
- Sediment shear thresholds are higher than in eroding areas
- It is sheltered from the prevailing wind direction and hence locally produced wind-waves
- Fetch lengths are generally less than 1000m (but not entirely limited to)

Accretion occurs in relatively sheltered locations with short fetches, but is not limited to these areas, as seen in the Wareham Channel where some of the highest accretion rates occur fronting a fetch length of over 2000m. The saltmarshes tend to be fronted by high mudflats, in areas indicated through the hypsometry as being flood dominant. This is likely to be due to the hydrodynamics transporting sediments eroded from other regions and depositing them in sheltered (flood dominant) locations, facilitating saltmarsh accretion in this area. Fronting mudflats may also be accreting through this process, which acts as a postive feed back dissipating any wave energy that may otherwise contribute to frontal erosion.

Erosion has generally been observed where;

- The height of the fringing mudflat is significantly lower than in accreting areas
- The height of the marsh front is significantly lower than in accreting areas
- Hypsometry profiles are concave in form

- Sediment shear thresholds are lower than in accreting areas and contain more biological content

Erosion occurs in relatively exposed locations and often occurs where the fetch is large. However, no clear Harbour-wide correlation between fetch direction and erosion and hence wave height has been observed. The marsh top and fringing mudflats are significantly lower and the mudflats have a lower sediment shear velocity than in accretionary regions, which may lead to greater erosion of the fronting mudflats than elsewhere. This may allow larger waves to propagate across the fringing mudflats leading to edge erosion. Hypsometric analysis suggests that saltmarsh erosion tends to occur in ebb dominant areas but not exclusively, suggesting a complex combination of drivers.

# 7 Tidal Asymmetry Analysis

This chapter describes the results from the third stage of research as proposed in Section 1.2. The main objective was to investigate tidal asymmetry and hydrodynamics within Poole Harbour. As discussed in Section 2.1.2, tidal asymmetry can lead to dominant flow directions, which controls net sediment transport and distribution.  This in turn has a major impact on intertidal habitat location and stability. Saltmarshes rely on sufficient sediment supplies in order to accrete vertically within the tidal frame and maintain relative position in response to sediment compaction and local sea-level rise. Where the opportunity to migrate and/or sufficient sediment are not available, these habitats will slowly drown and revert to mudflat. Hence, understanding the hydrodynamics is fundamental to determine future trends and then develop suitable management strategies for these habitats.

The objectives were completed using three general approaches. Firstly, asymmetry was calculated using generalised geometric and hydrodynamic relationships, which is described in Section 7.1. Secondly, tidal flow vectors and tidal asymmetry were investigated spatially, particularly flood and ebb dominance, using data from a numerical model of tides for Poole Harbour (Section 7.2). Thirdly tidal stage diagrams for locations around the Harbour were examined to see at what stage of the tide the peak tidal flows and slacks occur with relation to the saltmarsh zonation and the general morphology of the Harbour. The limitations of the methods used are discussed in section 7.3, and the main findings of this chapter are summarised in section 7.4.

## 7.1 General tidal asymmetry parameters

For the first stage of this analysis, direct measurements of both Poole Harbour's geometry and tidal characteristics were analysed.

Geometric parameters were extracted from a DTM of Poole Harbour, created using LIDAR (2007) data supplied by the Channel Coastal Observatory, combined with sub-tidal bathymetry data collected and supplied by Poole Harbour Commissioners (2005). Tidal parameters were extracted using tide gauge data (one years duration collected in 1997) located at North Haven (Figure 3.5) using T-tide (Pawlowicz et al., 2002).

Six indicators of tidal asymmetry, as discussed in Section 2.1.2 were calculated, using the data in Table 7.1. These are broad scale methods which give an initial indication of estuary-wide tidal asymmetry. The results are shown in table 7.2 and unanimously suggest that Poole Harbour is flood dominant in character.

**Table 7.1 Morphological parameters for Poole Harbour**

| Parameter | Value |
|---|---|
| Mean depth (MD) at HW (m) | 2.04 |
| Mean depth (MD) at LW (m) | 0.66 |
| Volume at LW | 20078384 |
| Volume at HW | 79509880 |
| Surface area at HW | 38838716 |
| Surface area at LW | 13269610 |
| Inter-tidal storage (m3) | 38200120 |
| Volume in Channels LW | 30694072 |
| M2 (phase/amp) | 306.82/0.4224 |
| M4 (phase/amp) | 99.11/0.1599 |
| Tidal amplitude | 0.8m |

**Table 7.2 Tidal asymmetry indicators for Poole Harbour**

| Asymmetry relationship | Definition | Theoretical values | Poole Harbour | Result |
|---|---|---|---|---|
| a/h (Friedrichs and Aubrey, 1988) | Magnitude and direction of asymmetry | <0.2 ebb<br>>0.3 flood | 0.39 | Flood |
| Vs/Vc (Friedrichs and Aubrey, 1988) | Only applicable if a/h does not indicate significant asymmetry (ie 0.2<a/h<0.3) | n/a (can be used as a relative indicator between different estuaries) | 0.8 | n/a |
| MDhw vs MDlw (Pethick, 1994) | Magnitude and direction of asymmetry | MDhw > MDlw flood dominant<br>MDhw < MDlw ebb dominant | MDhw>MDlw | Flood |
| Gamma (Dronkers, 1986) | Magnitude and direction of asymmetry | γ=1 uniform<br>γ>1 flood<br>γ< 1 ebb | 1.446 | Flood |

| | | | | |
|---|---|---|---|---|
| M4/M2 (amp) (Friedrichs and Aubrey, 1988) | Magnitude of asymmetry | Negligible distortion< 0.01 | 0.379 | Strongly distorted and hence asymmetric |
| 2M2 - M4 (phase) (Friedrichs and Aubrey, 1988) | Direction of asymmetry | 0-180 flood dominant<br>180-360 ebb dominant | 153 | Flood |

## 7.2 Modelled asymmetry parameters

The HR Wallingford's 2D TELEMAC model for Poole Harbour was used to investigate the spatial variability of tidal curves, peak flows and slack duration of tides. A description of this model is given in Section 4.3.2. This is then compared to the historic saltmarsh change analysis from Chapter 5. Firstly velocity shear thresholds are investigated, when the tidal velocities within the Harbour exceed this threshold there is potential for bed erosion and sediment transport. Both of which are crucial to the mudflats that saltmarshes inhabit as discussed in Section 2.1.2. Secondly the timing and position of peak tidal flows and slack duration are investigated. Flood dominant estuaries, discussed in Section 2.1.4, have a shorter duration, higher velocity flood tide, which erodes sediment and carries it into the estuary, tending to infill with sediment. If the longest slack duration occurs after the flood then sediments have a longer period to drop out of suspension and accrete on the bed. . Ebb dominant estuaries, discussed in Section 2.1.4, have a shorter duration, higher velocity ebb tide, which erodes sediment and carries it out of the estuary. If the longest slack duration occurs after the ebb then sediments are deposited outside of the estuary.

### 7.2.1 Velocity shear thresholds

The shape of the tide curve in Poole Harbour is unusually variable due to higher order tidal harmonics and the complex morphology of the site. Spring tides generated within the Poole Harbour TELEMAC model have several different forms (Figures 7.1-7.5), these occur in different areas of the Harbour. A velocity shear threshold of 0.2m/s was used to assess the duration of slack water, derived from sediment samples taken from within the Harbour, as discussed in Section 6.3.

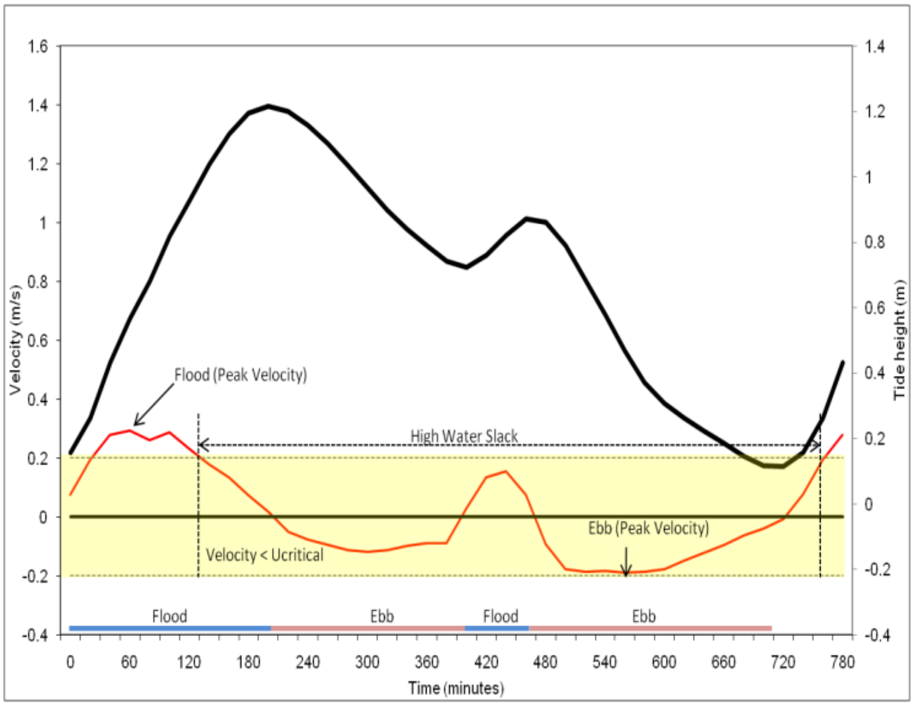


**Figure 7.1 Example from TELEMAC Model where a single flood peak exceeds the shear velocity for a tidal cycle (Black line- tidal height, red line –modelled tidal velocity)**

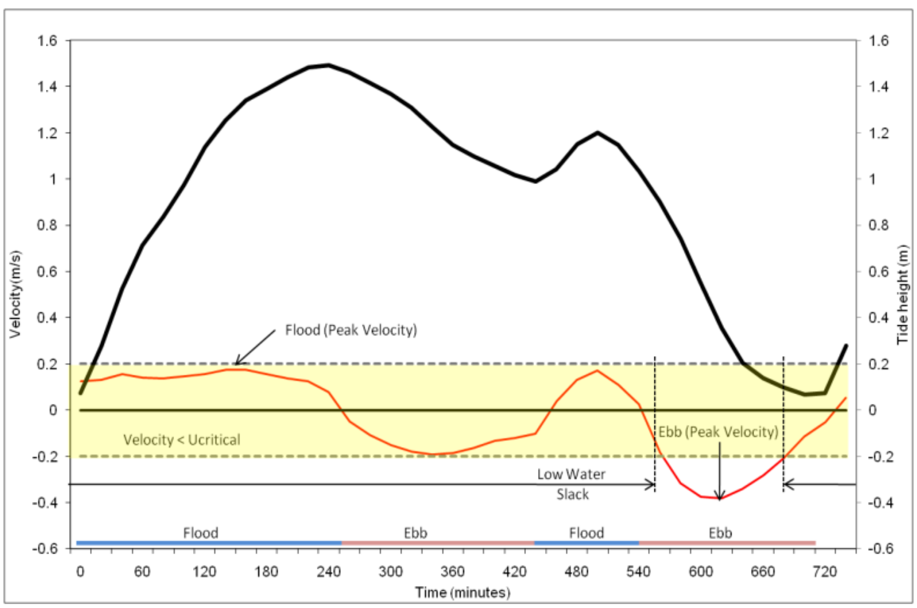


**Figure 7.2 Example from TELEMAC Model where a single ebb peak exceeds the shear velocity for a tidal cycle (Black line- tidal height, red line –modelled tidal velocity)**

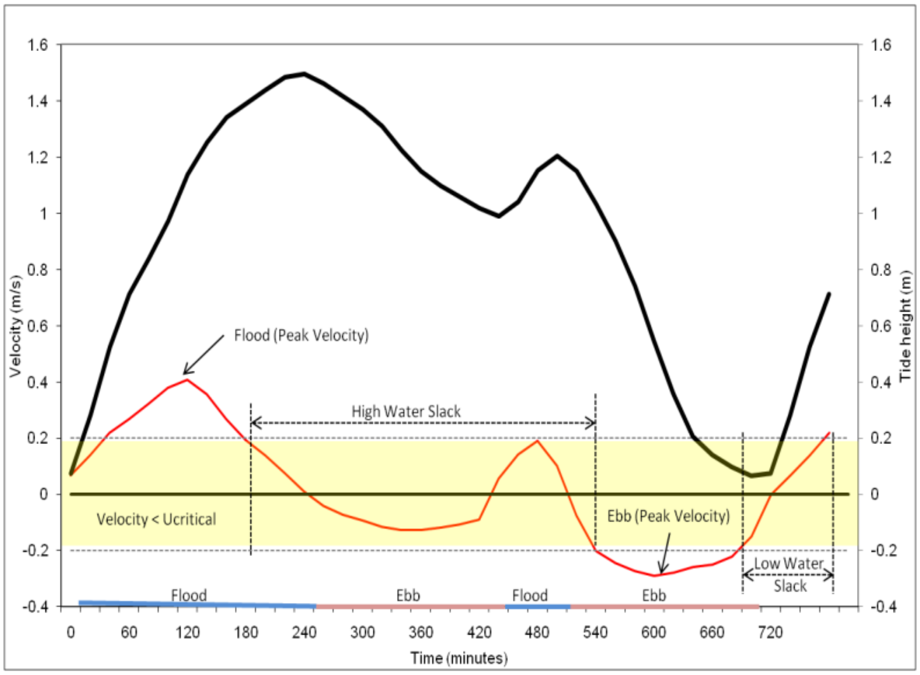


**Figure 7.3 Example from TELEMAC Model where a single flood and single ebb peak exceed the shear velocity for a tidal cycle (Black line- tidal height, red line –modelled tidal velocity)**

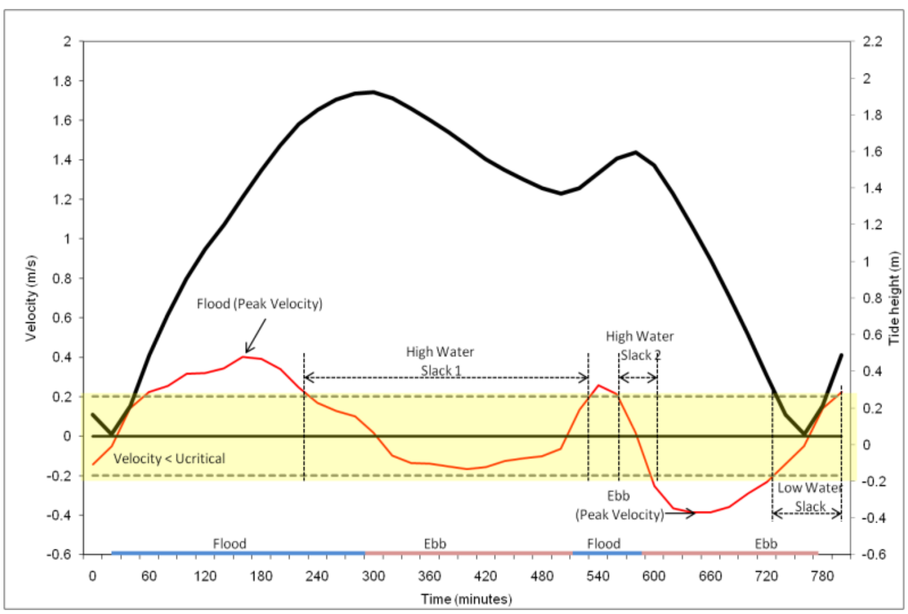


**Figure 7.4 Example from TELEMAC Model where a double flood and single ebb peak exceeding the shear velocity for a tidal cycle (Black line- tidal height, red line – modelled tidal velocity)**

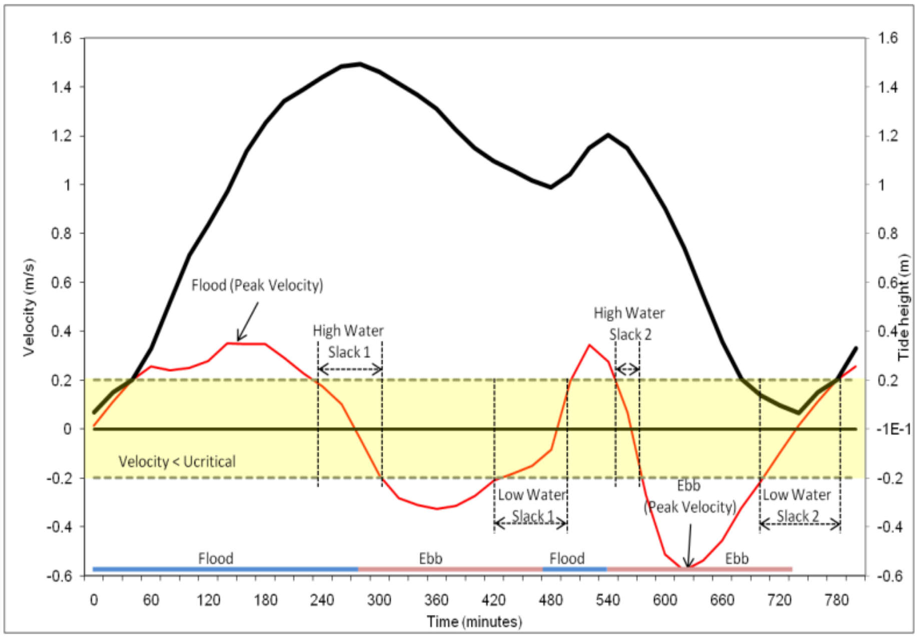


**Figure 7.5 Example from TELEMAC Model where a double flood and double ebb peak exceeding the shear velocity for a tidal cycle (Black line- tidal height, red line – modelled tidal velocity)**

The different forms of tidal curve affect currents and hence how sediment is transported and deposited within the Harbour. Peak flows for flood and ebb have been calculated and are important for non-cohesive sediment transport, (Dronkers, 1986). However, slack duration is particularly important for the deposition of fine silts and cohesive sediments, as discussed in Section 2.3.1. In areas where there is just one peak above the velocity shear threshold any sediment eroded during the peak flows will have the rest of tide to settle out of suspension before the next tidal cycle. However, where the flows exceed the velocity shear threshold many times over the tidal cycle, this results in transport of the sediments backwards and forwards within the Harbour.

Neap tides for the Harbour were also analysed. They produced similar patterns to Spring tides but rarely exceed the threshold of 0.2m/s, so negligible sediment transport is thought to occur on neap tides, and they are not considered further here.

### 7.2.2 Peak flows

Peak flows are defined as the maximum velocity reached for flood and ebb stands during a tidal cycle. Therefore if the maximum velocity occurs during the flood or ebb stage of the tide the system is often described as flood or ebb dominant respectively.

Figure 7.6 shows peak flow velocities on the flood and ebb, also indicating were the flows exceed the sediment shear threshold of 0.2m/s. The key has six categories, category one shows where peak flows occur on the flood and both flood and ebb flows are below 0.2m/s, category two shows where peak flows occur on the ebb but both flood and ebb flows are below 0.2m/s. In these situations we would not expect to see any sediment transport occurring. Category three shows where only the peak flood flow is higher than 0.2m/s and the peak ebb below 0.2m/s, and category four shows where only the peak ebb flow is higher than 0.2m/s and the peak flood below 0.2m/s. In these situations sediment transport would be limited to the flows where they are higher than 0.2m/s, therefore showing strong tidal asymmetry. Category five shows where peak flow is on flood, but peak flows on flood and ebb are both above 0.2m/s and category six where peak flow is on ebb, but peak flows on flood and ebb are both above 0.2m/s. In this situation we would see sediment transport occurring on both flood and ebb but to differing extents. Data from figure 7.6, of peak flows during ebb and flood dominance, and data from Figure 7.7, of dominant saltmarsh accretion or erosion over 100x100 m cells, were combined. A chi-squared test was performed, Table 7.3, to identify if there was any statistical significance between areas where flood dominance and saltmarsh gain were present and saltmarsh loss and ebb dominance were present.


**Figure 7.6 Peak flows on flood and ebb according to flow speed (2004 mean spring)**

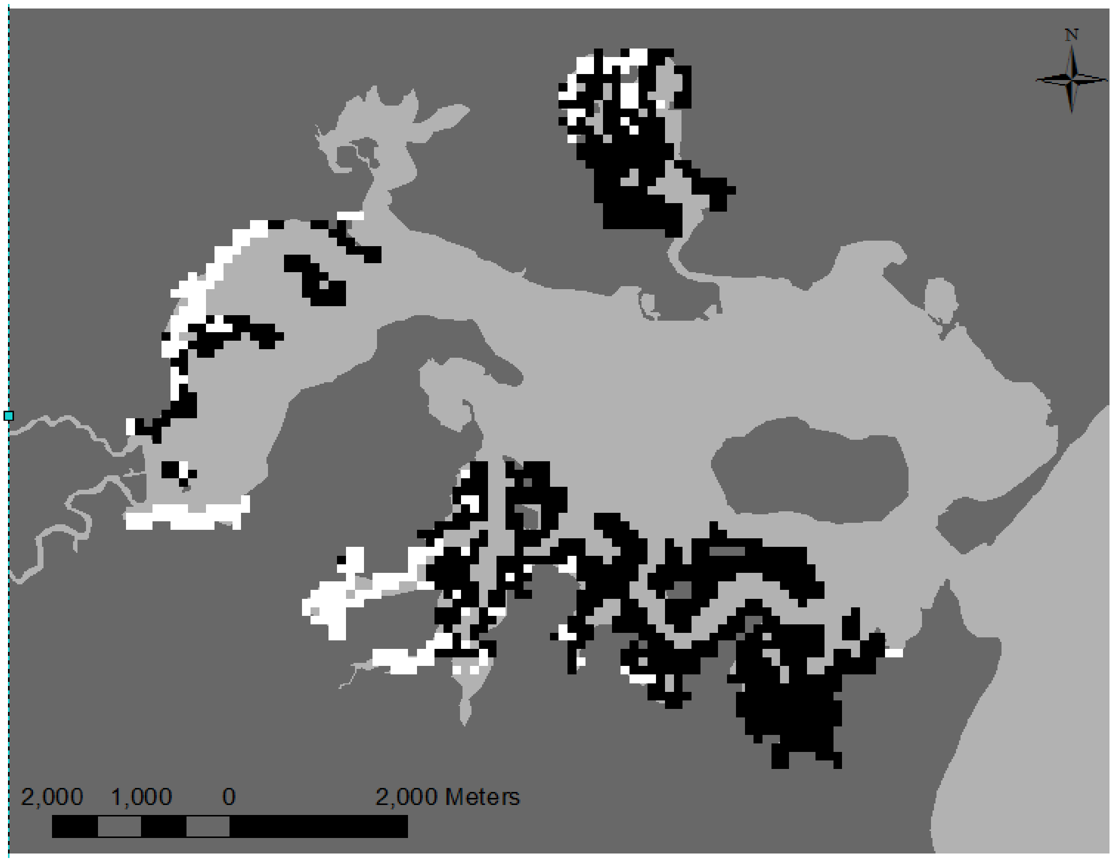


**Figure 7.7 Dominant saltmarsh process between 1947 and 2005 at a 100x100 m resolution. Black = Loss, White = Gain**

**Table 7.3 Chi-square test for saltmarsh changes and peak flow velocity**

| **Saltmarsh Gain** | **Peak Flow** | |
|---|---|---|
| | **flood** | **ebb** |
| observed (o) | 10 | 1 |
| expected (e) | 11 | 0 |
| deviation (o-e) | -1 | 1 |
| Deviation$^2$ (d2) | 1 | 1 |
| d2/e | 0.009 | 0 |

| **Saltmarsh Loss** | **Peak Flow** | |
|---|---|---|
| | **flood** | **ebb** |
| observed (o) | 27 | 10 |
| expected (e) | 0 | 37 |
| deviation (o-e) | 27 | -27 |
| Deviation$^2$ (d2) | 729 | 729 |
| d2/e | 0 | 19.7 |

For saltmarsh gain, the test shows a significant relationship ($p>0.05$). Hence the null hypothesis that there is no statistical significance between flood dominance and saltmarsh gain in Poole Harbour was rejected. Thus, indicating that accretion is significantly associated with flood dominance. For saltmarsh loss the test shows an insignificant relationship ($p<0.05$). Hence, the null hypothesis that there is no statistical significance is accepted. This indicates that saltmarsh erosion is not strongly related to ebb dominance, and while it may be a factor in some cases other drivers of loss are playing an important role.

### 7.2.3 Slack duration

Slack duration was defined as, the period of time when the tidal flow velocity was less than the critical shear velocity of 0.2m/s.

Figure 7.8 shows whether the longest slack period over a tidal cycle was on the flooding or ebbing tide. Figure 7.9 shows what proportion of the total slack period over a tidal cycle, is taken up by flood or ebb slacks. Maps for slack duration were compared to historic gain in saltmarsh area, Figure 7.7. For areas of gain 61% were in regions where the flow velocities did not exceed the critical shear velocity of 0.2m/s, over the tidal cycle and hence slack duration was not possible to calculate. Locally it is unlikely that erosion will occur, however if sediment is eroded in nearby areas and carried into this region then it will likely be deposited. For regions that have a clearly defined slack duration a chi-squared test was performed to investigate if there was any statistical correlation to the historic saltmarsh gain. This is presented in Table 7.4 and shows that areas of saltmarsh accretion are statistically correlated with regions where the after flood slack is longer in duration than the after ebb slack.

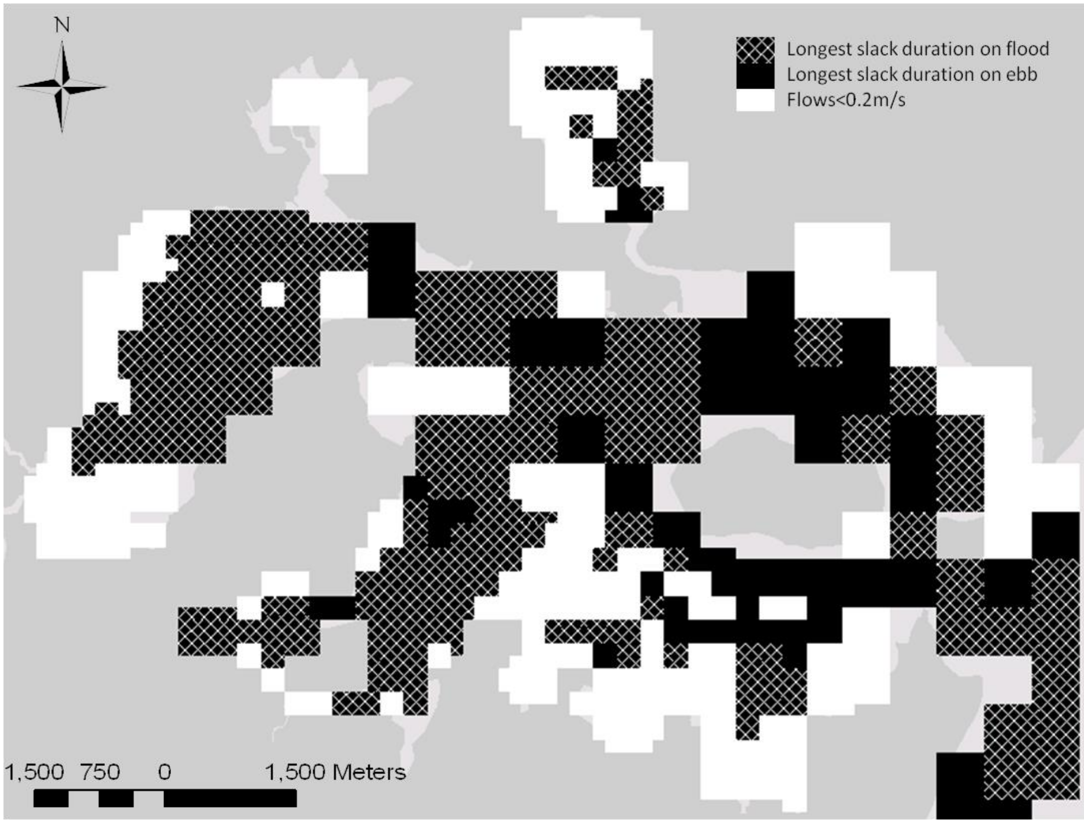


**Figure 7.8 Maximum slack duration on flood or ebb. (2004 mean spring)**

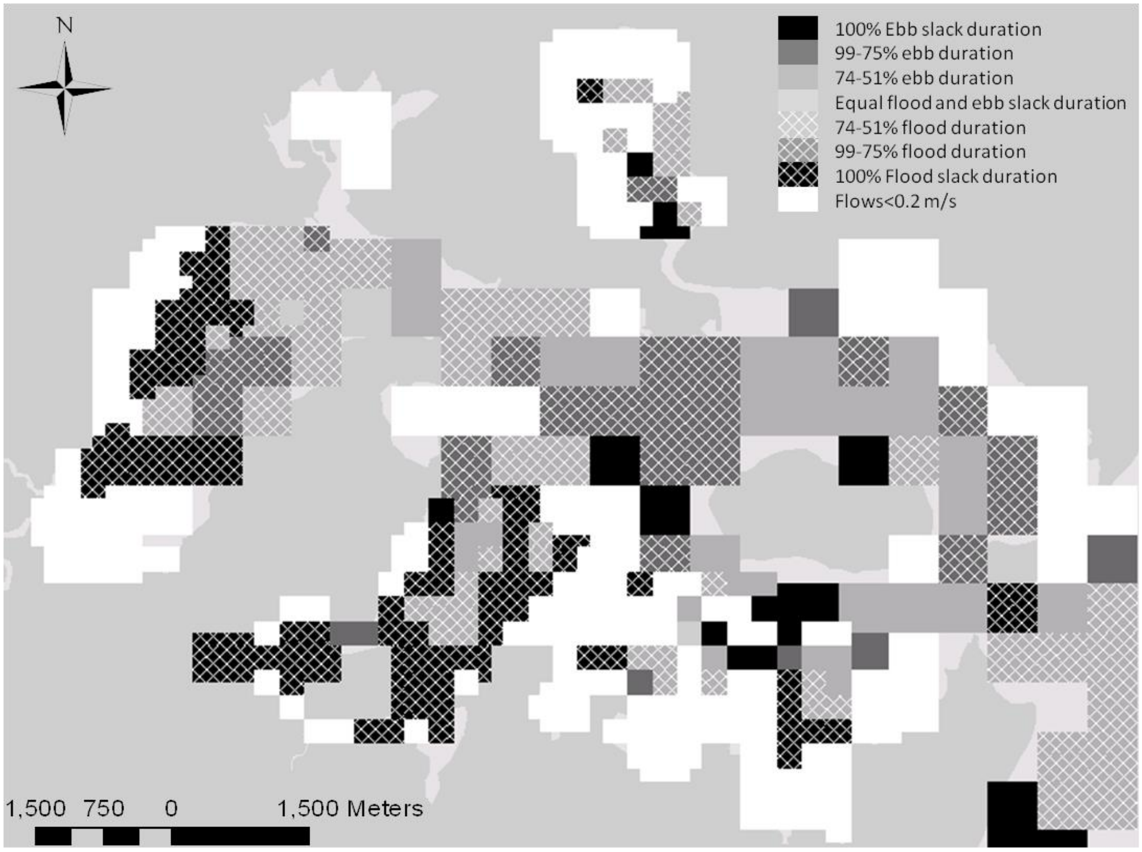


**Figure 7.9 Percentage of total slack duration over tidal cycle taken up by flood or ebb slack (2004 mean spring)**

**Table 7.4 Chi-square test for saltmarsh gain and slack duration**

| Saltmarsh Gain | Slack duration | |
|---|---|---|
| | After flood | After ebb |
| observed (o) | 12 | 2 |
| expected (e) | 14 | 0 |
| deviation (o-e) | -2 | 2 |
| Deviation$^2$ (d2) | 4 | 4 |
| d2/e | 0.285714 | 0 |

## 7.3 Tidal stage diagrams

Tidal stage diagrams, plotted from the results of the HR Wallingford's Telemac Poole Harbour model, for locations throughout the Harbour (Figure 7.10) on a spring tide are shown in Figures 7.11-7.20. Peak tidal flows and slacks with relation to vertical saltmarsh zonation and the velocity shear threshold (0.2m/s) for sediments in the Harbour are also shown.

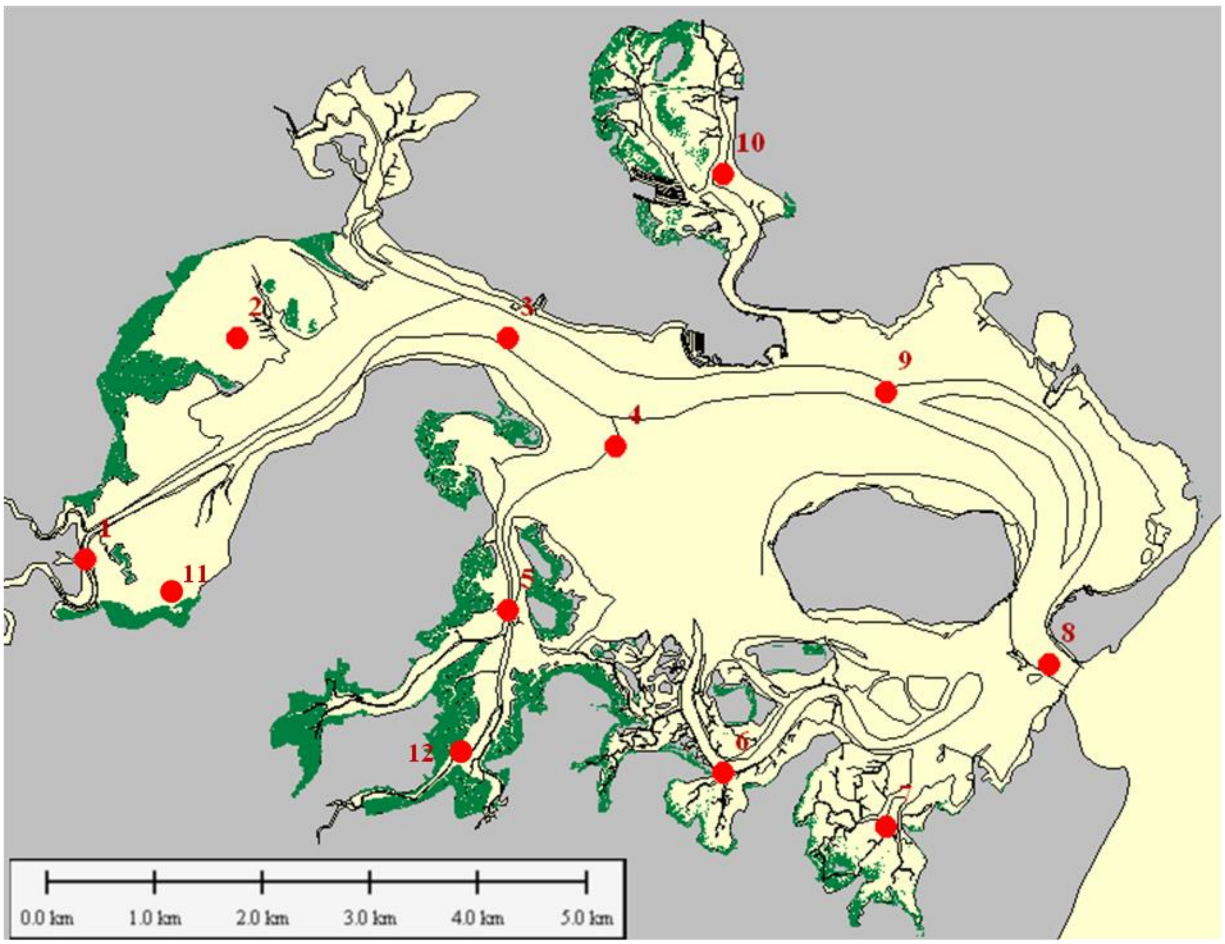


**Figure 7.10 Locations of tidal stage diagrams**

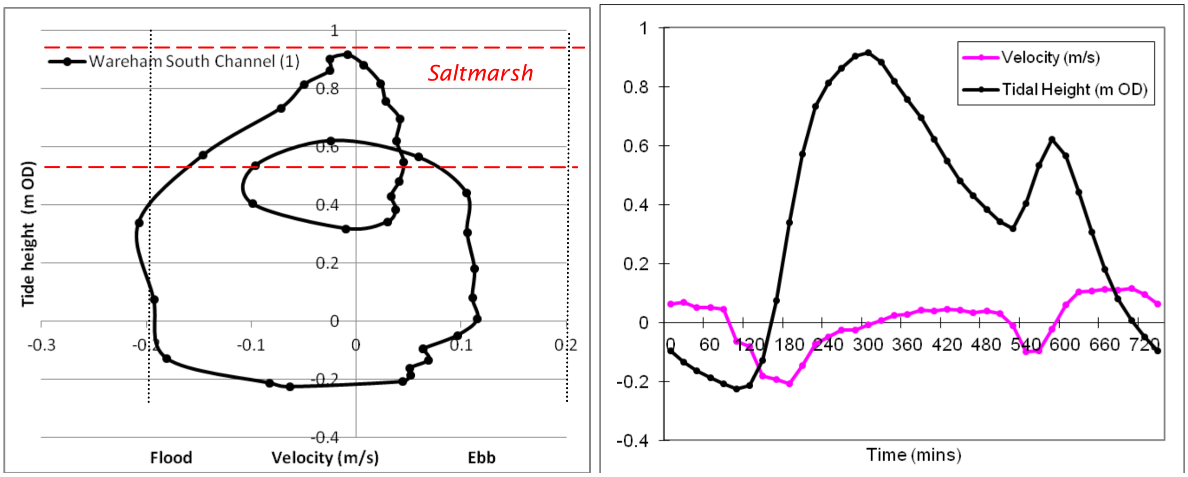


**Figure 7.11 Tidal velocity curve at site 1 , Wareham South channel**

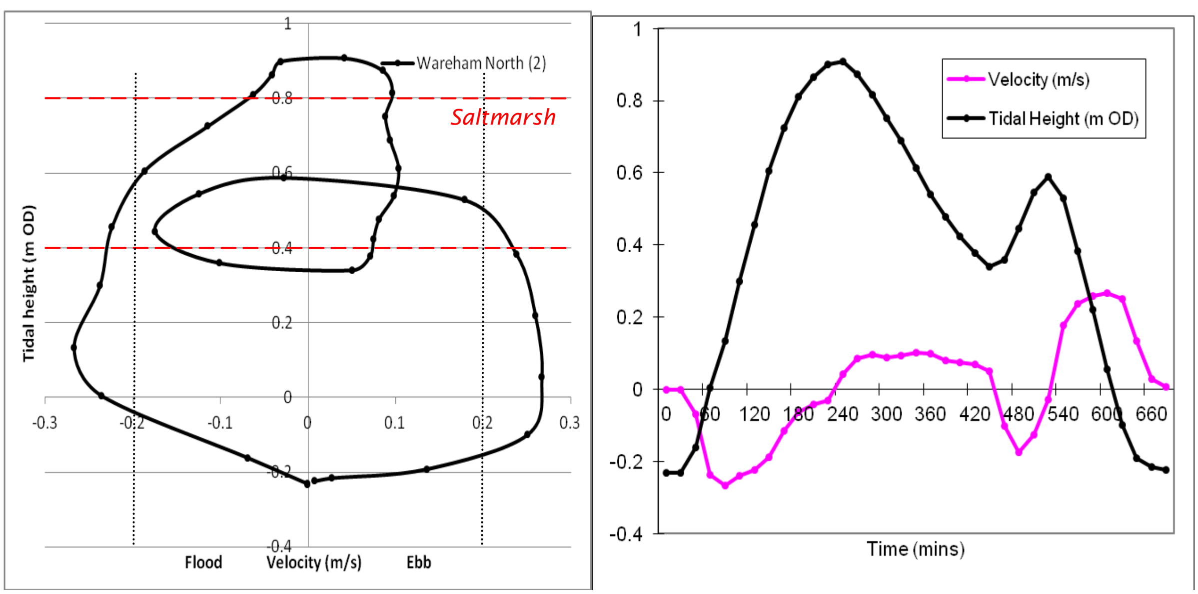


**Figure 7.12 Tidal velocity curve at site 2, Wareham North.**

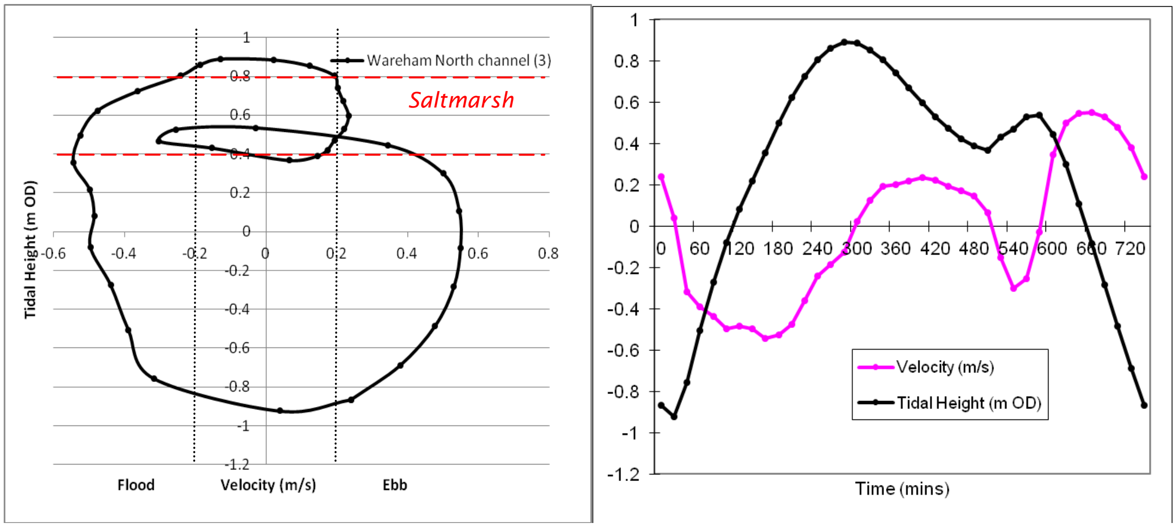


**Figure 7.13 Tidal velocity curve at site 3, Wareham North Channel**

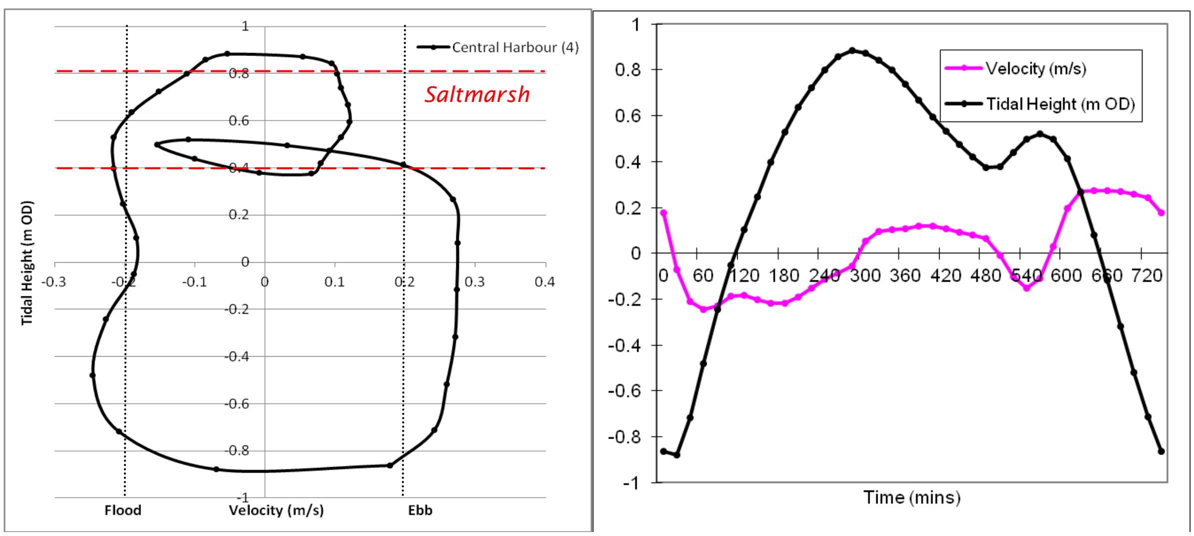


**Figure 7.14 Tidal velocity curve at site 4, Central Harbour**

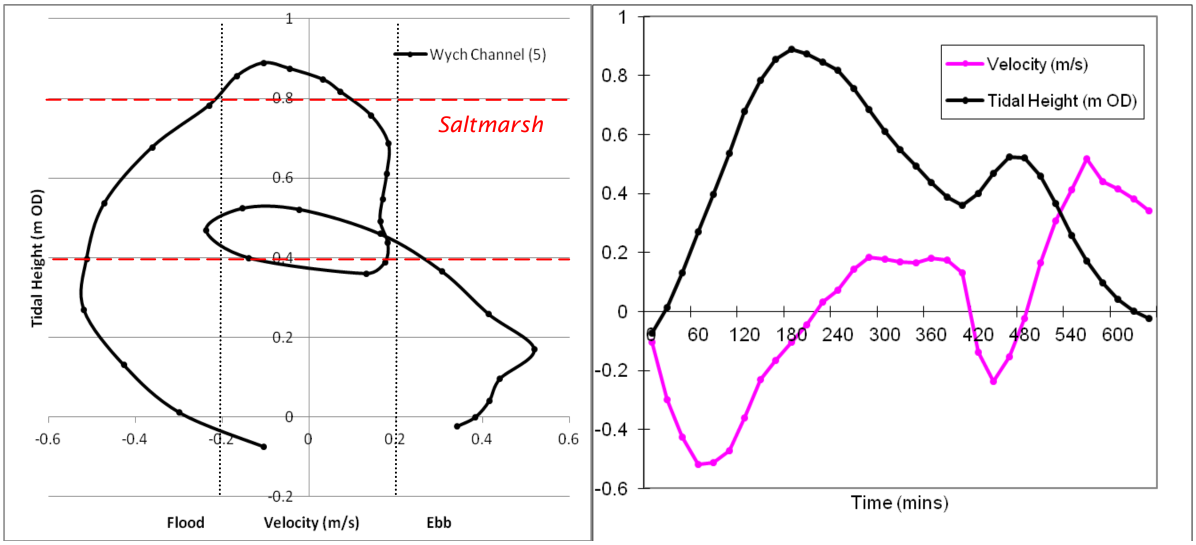


**Figure 7.15 Tidal velocity curve at site 5, Wych Channel**

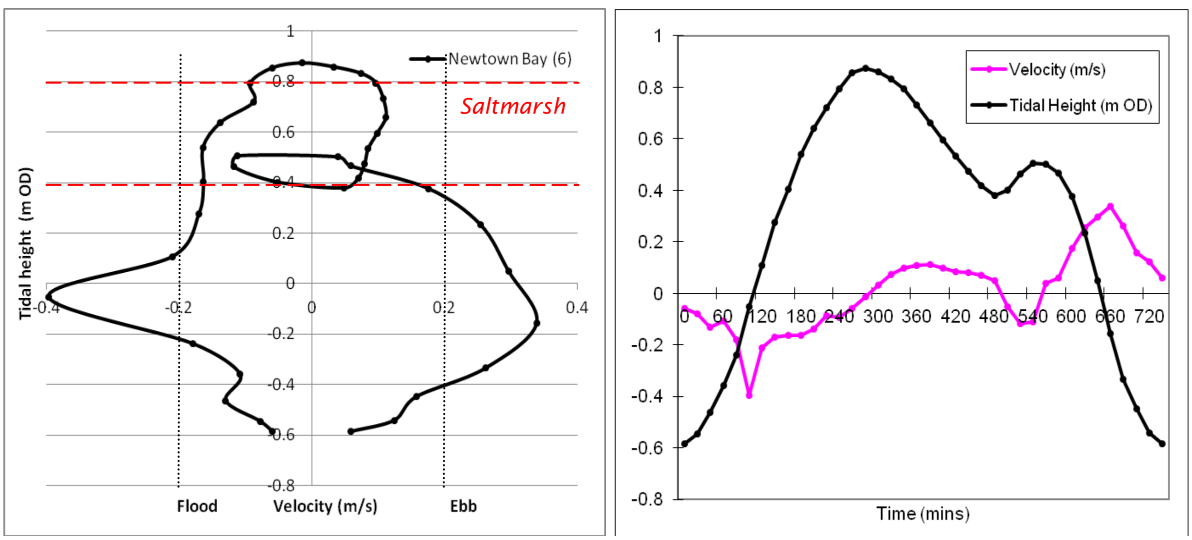


**Figure 7.16 Tidal velocity curve at site 6, Newtown Bay**

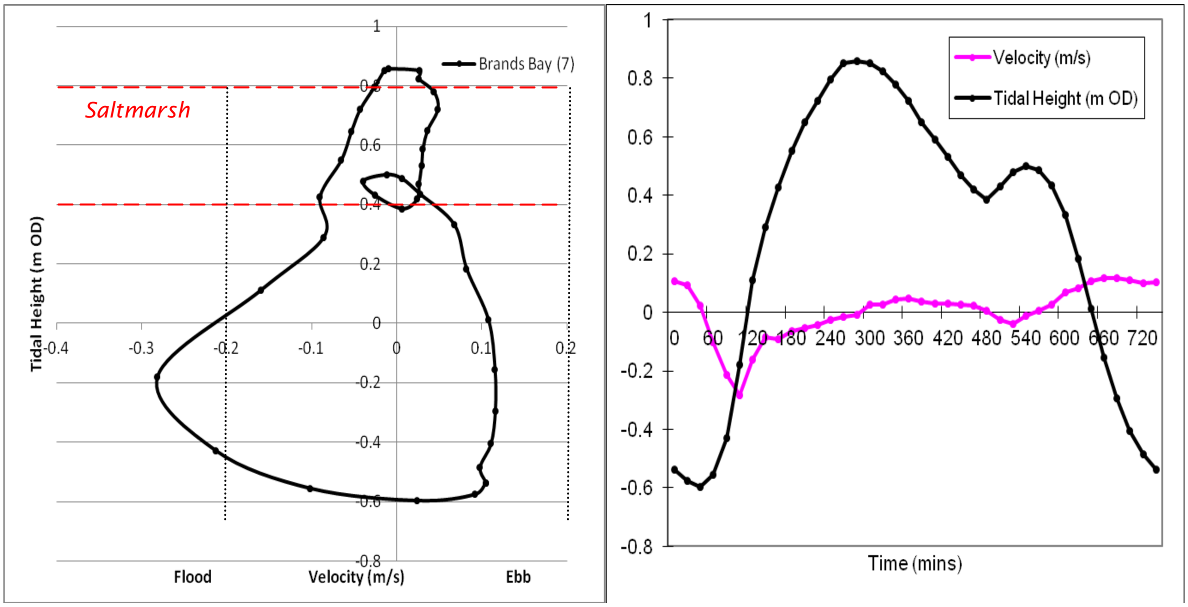


**Figure 7.17 Tidal velocity curve at site 7, Brands Bay**

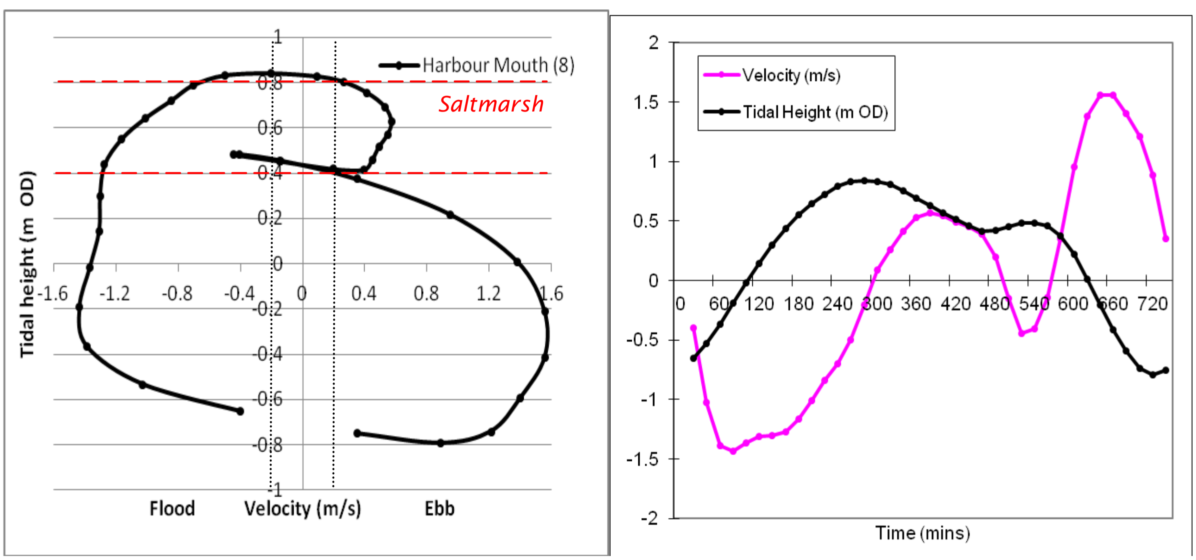


**Figure 7.18 Tidal velocity curve at site 8, the Harbour mouth**

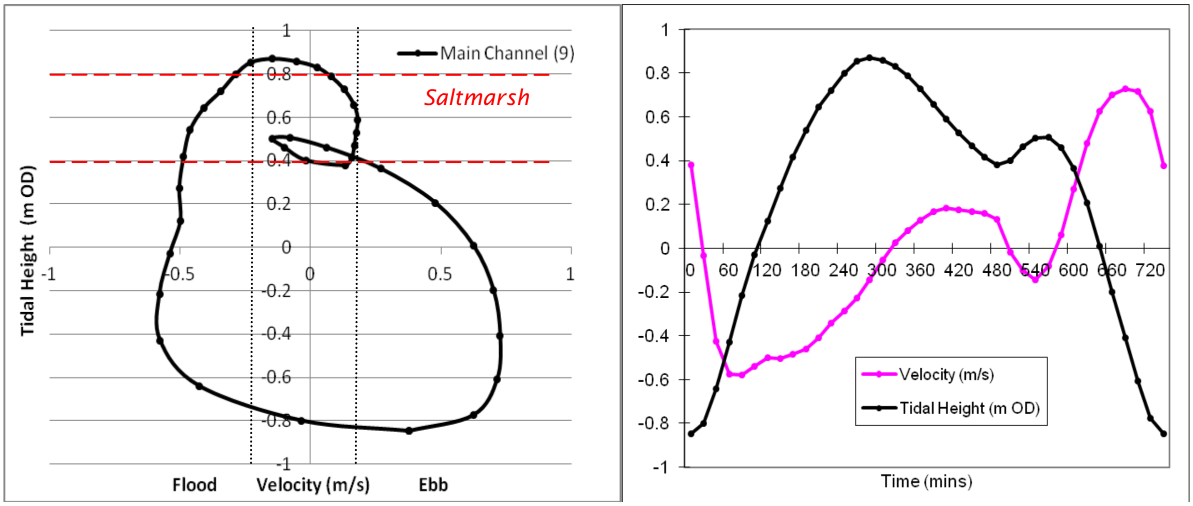


**Figure 7.19 Tidal velocity curve at site 9, Main Channel**

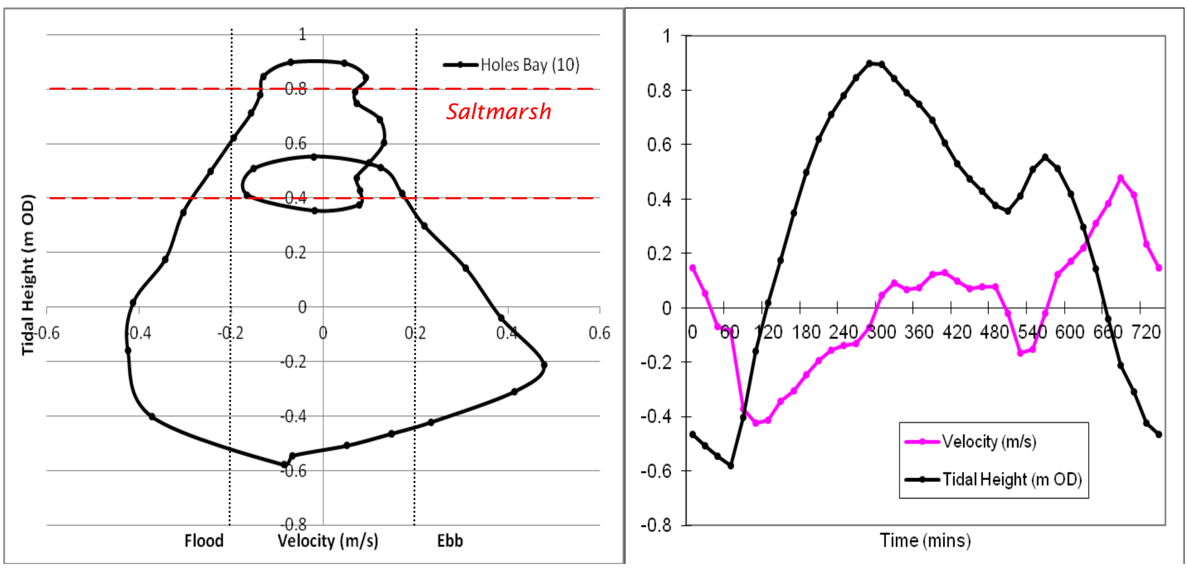


**Figure 7.20 Tidal velocity curve at site 10, Holes Bay.**

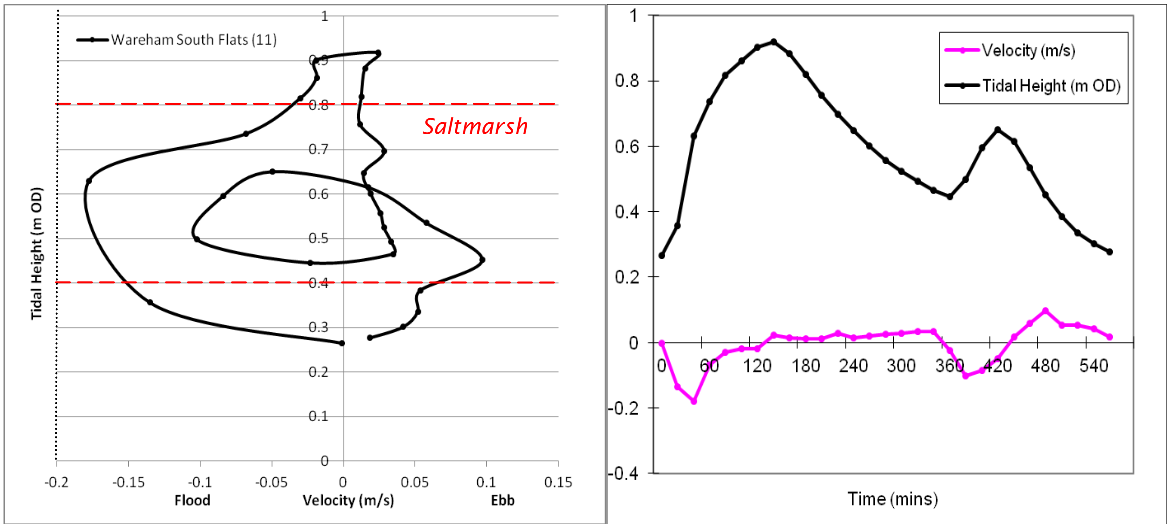


**Figure 7.21 Tidal velocity curve at site 11, Wareham South Flats.**

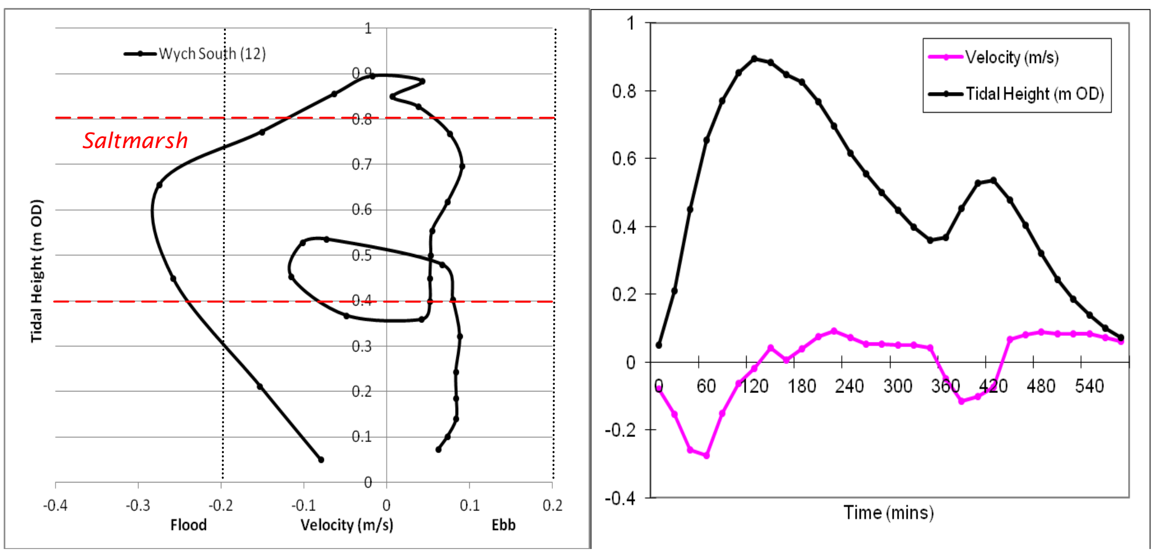


**Figure 7.22 Tidal velocity curve at site 12, Wych South.**

In Section 7.2 the asymmetry of the tide, in terms of peak flows and slack duration, was assessed spatially throughout the Harbour. The tidal velocity curves in figures 7.11-7.22

illustrate at what stage of the tide these velocity peaks and slacks occur in relation to the vertical position of the saltmarsh within the Harbour. The most prominent feature of these tidal stage curves is the effect the double high water has, illustrating how a tidal distortion of this kind leads to long duration slack periods after the flood in Poole Harbour. Slack duration extends both over the upper marsh region and the marsh-tidal flat interface, allowing sediments to settle over the entire marsh region. As seen in section 7.2.2, tidal asymmetry of peak flows changes throughout the Harbour. However, it can be seen that the peak flows for flood and ebb sections of the tide mainly occur at a tidal stage corresponding to the low intertidal flat region rarely exceeding the critical shear velocity during tidal stages corresponding to salt marsh zonation.

The largest velocities can be seen in Figure 7.18 at site 8, the Harbour mouth, where flows exceed 0.2m/s for the majority of the tide both for flood and ebb, the slack duration after both the high water stands are clear. Conversely at both sites in the Wareham South area, furthest from the Harbour mouth (Figure 7.11 site 1 Wareham South channel and Figure 7.21, site 11 Wareham South flats), velocities do not generally exceed the critical shear velocity threshold, although both sites still show a flood dominant tidal asymmetry with regards to peak flows.

## 7.4 Limitations of Approach

Chapter 7 describes three different approaches to describing hydrodynamics and tidal asymmetry within an estuary. The first utilised broad geometric descriptions, which are often used for a preliminary assessment of estuaries throughout the world. The second and third used a more sophisticated numerical modelling approach which requires substantial time, effort, skill and data, but provides more information on spatial variability.

The general asymmetry parameters have two major limitations, in that flood and ebb asymmetry vary throughout an estuary and this cannot be characterised by a single descriptor. Also these parameters have a number of inherent limitations, these have been discussed in Section 2.1.2, and are summarised below.

- Dronkers (1986) equations were derived on the basis that the tide is roughly sinusoidal with periods of equal flood and ebb tide, and hence due to the complex tidal curve in Poole Harbour this may not be wholly applicable.
- Friedrichs and Aubrey (1988), derived their equations from the application of a 1D model for estuaries along the east coast of the United States. As Townend (2005) discusses, this may not be appropriate for UK estuaries. In addition the Friedrichs and

Aubrey (1988) study focused on tidal distortion within the estuary, and did not consider distortion occurring on the adjacent shelf. Other tidal constituents are likely to contribute to distortion of the tidal curve within Poole Harbour, the impacts of these constituents on tidal asymmetry are not well understood, (Wang et al., 2002).

- Due to the complex nature of the Poole Harbour tidal curve, pertaining to the double high water and large variability in shape between neap and spring tides, the characterisation of mean high and low water, and hence mean sea level, is problematic. As the basis of these equations relate to the relationship between intertidal height and mean sea level, depending on how this value is calculated could greatly influence the inferred tidal asymmetry.

Although, numerical modelling also has limitations, particularly when dealing with an estuary that has complex morphology and tides such as Poole Harbour, it is a preferential method of analysis when compared to the broad scale descriptive methods, enabling the mapping of tidal asymmetric spatial variability, rather than one single value for a large and complex system. Descriptions of the Poole Harbour model and how it was calibrated is discussed in Section 4.3.2 and is summarised in HR Wallingford (2004).

## 7.5 Summary

The main findings from the preceding chapter are summarised below, a detailed discussion of the findings of this chapter set in the context of the aims and objectives, laid out in Chapter 1, is presented in Chapter 8.

The main objective of this Chapter has been to investigate the key hydrodynamic drivers of tidal asymmetry in Poole Harbour. This has been achieved through the analysis of generalised geometric and hydrodynamic relationships and using modelled data to map tidal flow vectors and tidal asymmetry.

The main findings of this stage are:

- Simplified geometric and constituent asymmetry parameters indicate that Poole Harbour is flood dominant in character.
- Numerical modelling shows that the Harbour experiences variations in tidal velocity exceeding the critical shear threshold, both spatially and throughout the tidal cycle. This is particularly relevant where it exceeds shear thresholds only once per tidal cycle either on the flood or ebb, allowing the sediments to resettle for the rest of the tidal cycle.

- Peak flows on the flood tend to occur up tidal creeks and to the west of the Harbour. With regions in the centre of the Harbour and around the mouth experiencing, peak flows on the ebb, which is important for non-cohesive sediment transport.
- Peak flood velocity is correlated with areas of historic saltmarsh accretion. However, peak ebb velocity is not correlated with historic saltmarsh erosion
- Slack duration is important for the settling and consolidation of cohesive sediments and the modelled results suggests that the longest overall slack durations occur after the flood for the majority of the Harbour.
- Regions where the longest slack is after the flood are correlated with areas of historic saltmarsh accretion.
- A few areas in the centre of the Harbour experience the longest slack after the flood, even though these regions may have the peak flow on the ebb, suggesting complex sediment transport patterns in these regions.
- Tidal velocity stage curves illustrate the affect that the double high water has on slack duration and the elevation, with relation to saltmarsh zonation, at which it occurs.
- Peak flows for both flood and ebb stages rarely exceed the critical shear threshold of 0.2m/s

A broad scale single descriptor of tidal asymmetry is often used to summarise the morphology of an estuary system and its patterns of sediment transport. These generalisations can often be misleading and result in assumptions being made concerning how an estuary may evolve in the future and hence the future viability of the coastal habitats within it. This is illustrated within Poole Harbour, where flow asymmetry trends at an estuary scale are not uniform at a sub-estuary scale, with more complex spatial variations occurring for peak flows and slack durations. It appears that historic saltmarsh accretion, described in Chapter 5, is correlated with peak flows on the flood and areas that have the longest slack duration after the flood. This facilitates the transport and deposition of sediments, which enable the saltmarsh to accrete and migrate and also the saltmarsh rhizomes that allow colonisation of new areas. However, there does not appear to be any correlation between historic saltmarsh erosion and peak tidal velocities on the ebb, suggesting that erosion is controlled by other drivers.

# 8 Discussion and Synthesis

Within this chapter the main findings of the thesis are discussed and placed within the context of the research objectives detailed in Chapter 1. Firstly the conceptual model of drivers and mechanisms of saltmarsh change, developed in Section 2.1.3.2. is described. Secondly the study site at which the conceptual model has been tested is reviewed. Thirdly historic saltmarsh changes and the setting of changes observed are discussed, including the spatial variations in morphology, and hydrodynamics. Mechanisms for these changes are evaluated and the drivers of these changes are discussed in order to revaluate and refine the initial conceptual model. The management implications resulting from the findings are considered not only for the study site, but also for micro-tidal estuaries and other estuarine systems in general. Finally, further work arising from this thesis is discussed.

## 8.1 A preliminary conceptual framework of drivers and mechanisms of saltmarsh change.

A conceptual model of saltmarsh change has been developed, using a driver-mechanism-outcome framework. Where and how saltmarshes and coastal habitats form are controlled through complex feedback systems: including biological, physical and chemical mechanisms (Figures 2.10 and 2.11), driven by both human and natural drivers. This conceptual model illustrates the multidisciplinary nature of coastal habitats and is useful in identifying the multiple drivers and mechanisms that can result in changes in habitat extent. Although this conceptual model was developed in order to test saltmarsh changes in Poole Harbour, a micro-tidal environment within a temperate region, it has applicability to other coastal habitats such as seagrass and mangroves, other climatic zones and meso or macro-tidal ranges. The Poole specific model (figure 3.5) was limited by the published literature on local saltmarsh change drivers, however using a conceptual model to explore all the potential drivers and mechanisms, provides a broad overview of a system and identifies key aspects to investigate further or knowledge gaps that should be addressed.

## 8.2 Site selection

Micro-tidal estuaries are found throughout the world including the Mediterranean Sea, Caribbean Sea, Red Sea, Baltic Sea, the Sea of Japan, regions in Madagascar, Brazil, Sri Lanka, South East Asia and South Australia. Saltmarshes and other coastal habitats in these regions  are particularly sensitive to sea-level rise, as they are limited in their ability to adjust and are considered vulnerable to future changes (cf(Nicholls *et al.*, 1999)). Hence, understanding the drivers and mechanisms of saltmarsh change in micro-tidal systems is crucial for informed decision making in future coastal management.

Poole Harbour was chosen as a suitable study area for three main reasons. Firstly the saltmarshes in Poole Harbour are extensive and varied in aspect with both pristine areas as well as those impacted by dredging, reclamation and coastal squeeze along seawalls and although previous reports on saltmarsh trends exist for the Harbour (Born, 2005, Hubbard, 1965, Burd, 1989, Edwards, 2005), they are generalised and do not examine the saltmarsh changes within a spatial context. Although the micro-tidal regime within Poole Harbour makes the saltmarsh setting relatively unique within a UK context, the development and colonisation of *Spartina anglica* is not unique to micro-tidal systems and has been observed in estuaries across the globe (as discussed in Chapter 2). The subsequent decline of *Spartina anglica* is common to many other estuaries locally, such a Portsmouth, Langstone and Chichester harbours (Burd, 1989, UK National Ecosystem Assessment, 2011). Hence the outcomes of this research based on the Poole Harbour case study are relevant and applicable elsewhere.

Secondly the hydrodynamics in the Harbour are well characterised through previous numerical modelling conducted by Falconer (1986b) and HR Wallingford (2004). The tidal curve in Poole Harbour is complex, with a double high water; in a UK context this is unique. However, other areas with saltmarsh exhibit a similar double high water tidal curve such as at Den Helder, The Netherlands and Buzzards Bay, Massachusetts (Bowers et al., 2013).

Thirdly data availability was good for Poole Harbour, with readily available historic aerials for three dates throughout the 20th Century as well as historic charts. In order to study the spatial changes in saltmarsh extent over a suitable time period this data was crucial and is lacking in many other estuaries. This requirement for historical data highlights the importance of consistent, long term monitoring and data collection. Although aerial photography was available, bathymetric and topographic surveys of the harbour and its intertidal regions were lacking, and this data gap subsequently caused problems in fully identifying the key drivers and mechanisms of saltmarsh changes observed within the Harbour (illustrated in Chapter 6). The issue of data availability is encountered across many estuaries throughout the world and where management of the coastal environment is required, effort should be made to establish baselines and effective monitoring implemented to address this data gap.

## 8.3 Historic saltmarsh trend analysis

When set into a post-1849 context, saltmarsh area expanded significantly in Poole Harbour due to the colonisation of *Spartina anglica* between 1900 and 1920 (Chapter 5, Figure 5.7), followed by a decline which continues to the most recent dataset. While saltmarsh area in Poole Harbour has declined rapidly during the latter half of the 20th century, the changes are more complex than previously reported (Born, 2005, Hubbard, 1965, Burd, 1989, Edwards, 2005), with a net loss, as erosion exceeded accretion. However, the rate of saltmarsh loss is decreasing and the total area of saltmarsh in 2005 exceeds the area estimated in 1849 and 1900, this colonisation and subsequent dieback of *Spartina anglica* is an important contemporary process in Poole Harbour.

When investigating saltmarsh change it is important to look at the settings of the change in order to identify mechanisms and ultimately drivers. Many different biogeochemical mechanisms and drivers can lead to saltmarsh change with complex non-linear feedbacks between them. When Poole Harbour is broken down into separate regions comprising of tributary arms, some areas experience a net gain of saltmarsh (Figure 5.14). This complex behaviour of both loss and gain in close spatial proximity has not been identified in preceding studies: for example, Born (2005) only describes saltmarsh loss, estimating 245 ha between 1947 and 1993, whereas in this study losses were only 187 ha. This suggests that although some saltmarsh loss has occurred, concerns regarding saltmarsh loss in this region may be overstated, and put into an historical context the saltmarsh area is currently roughly four times larger than that recorded in 1849, or even 1900. Due to erosion and accretion occurring in close proximity within the Harbour large scale biological and chemical mechanisms were considered to be the unlikely key mechanisms of change. Hence within this study physical mechanisms were the main focus.

The saltmarsh losses and gains identified within this study can be linked to discrete mechanisms following their geomorphic setting (Tables 8.1 and 8.2). This allows the dominant loss mechanisms to be identified (e.g., (Downs et al., 1994)).

**Table 8.1 Classification of saltmarsh loss mechanisms for Poole Harbour. The observed loss mechanisms are linked to the typology of loss mechanisms of Crooks and Pye (2000) where appropriate and the physical mechanism of loss. (Arrows indicate where processes may be linked through feedback mechanisms)**

| **Inferred setting of loss in Poole Harbour (see figure 5.15)** | **Generic saltmarsh loss mechanism (Crooks and Pye, 2000)** | **Physical mechanism of loss** |
|---|---|---|
| Island Erosion– erosion on the front of island stands of saltmarsh separate from the main land | Stripping of root bound turf immediately landward of clifflet top | Changing hydrodynamics and/or morphology<br>Direct Wave Attack<br>Sediment supply |
| | Retreat of ramped marsh front | |
| Frontal Erosion– erosion occurs along the fronting edge of a saltmarsh backed by land | Retreat of near-vertical clifflets at the marsh edge | |
| Channel migration- a channel moves across an area of saltmarsh directly eroding it | Not described | Changing hydrodynamics and/or morphology |
| Creek side erosion- erosion occurs up creek systems away from significant wave affects | Incision of the natural marsh creek with associated bank collapse and headward erosion | Direct wave attack/channel edge processes including draw down driven by changing sediment budget |
| Conversion to reedbed– reed beds overtake saltmarsh | Not described | Changing hydrology (reduced salinity) |
| Spit roll-back– a spit migrates landward across saltmarsh area. | Not described | Indirect wave effects/reduced sediment supply |
| Direct Human destruction– saltmarsh directly destroyed | Not described | Direct human destruction |

Crooks and Pye (2000), identified six main mechanisms of erosion within saltmarshes: 1) retreat of near-vertical clifflets at the marsh edge, 2) stripping of a root bound turf immediately landward of the clifflet top, 3) retreat of a ramped marsh front, which may be incised by erosional furrows, 4) incision of the natural marsh creek with associated bank collapse and headward erosion, 5) vegetation die-back and erosion of the surface mud over large areas of the interior of the marsh, and 6) incision coalescence of drainage ditches or agricultural ridge and furrow systems. It has been  found within this research that in addition to those mechanisms described by Crooks and Pye (2000) a further four processes of saltmarsh loss exist, which cannot be classified according to the generic saltmarsh loss mechanisms that they describe (Table 8.1). These are; 1) Channel migration- where a channel moves across an area of saltmarsh directly eroding it, 2) Conversion to reedbed– reed beds overtake saltmarsh, 3) Spit roll Back– a spit migrates landward across saltmarsh area, 4) Direct Human destruction– saltmarsh is directly destroyed.

Channel migration and creek side erosion was observed at a local scale, these processes are likely driven by a change in hydrodynamics, potentially through a change in morphology which could also lead to increased wave attack. The conversion of upper saltmarsh to reed beds was also observed, where the marsh had accreted out of the tidal frame. Alternatively this was often observed in areas of development. It is hypothesised that in such areas where large regions are paved or made impermeable this could lead to the flow of fresh water during periods of heavy rainfall which may lower the salinity in the upper marshes and thus create a habitat more favourable for reed beds. Similar observations of development and reed bed take over has been noted within the Hamble Estuary (BRANCH partnership, 2007). However, no field work was conducted to verify this theory; further work could be completed in this area. Spit roll-back occurred at a few discrete locations within the Harbour, the mechanisms of which are indirect wave effects and sediment supply. The second largest mode of saltmarsh loss observed within Poole Harbour was the development of marinas and land reclamation, with the driver being direct human destruction of saltmarshes due to coastal development.

The primary modes of saltmarsh loss appears to be island erosion and frontal erosion (Figure 5.16), which is similar to the other Harbours in the Solent region (Baily and Pearson, 2007). Island erosion tends to occur as fragmentation, with channels forming and incising the saltmarsh, whereas frontal erosion is a steady lateral movement landward across the saltmarshes. Once island loss is complete the landward saltmarsh frontage is more exposed, potentially leading to increased wave exposure and hence greater rates of frontal erosion in the future. However, the increase in frontal loss has not been observed as yet, with rates of loss having declined in all but one area in Poole Harbour over the past 58 years, although this must remain a concern for the future. The mechanisms responsible for these losses are likely driven by a change in hydrodynamics; potentially through a change in morphology which could also lead to increased wave attack.

Accretion occurred generally within sheltered creek systems along creek-sides (Figure 5.18), some channels were entirely in-filled with sediment and saltmarsh. However this process was not entirely limited to sheltered areas, some frontal accretion did occur within the open estuary in small local areas and even some new island stands colonising mudflat area was observed. Through field observations, it was also noted that these areas of accretion were of mixed marsh species, including *Spartina anglica*. The main mechanisms of accretion are hydrodynamics, potentially through a change in local morphology and sediment supply.

A very small (0.028ha) region of realignment had also occurred within the Harbour, recreating some saltmarsh, this is a result of a direct human driver and depending on local management decisions, room exists for substantial realignment options within the Frome and Piddle river valleys.

**Table 8.2 Classification of saltmarsh gain mechanisms for Poole Harbour. (Arrows indicate where processes may be linked through feedback mechanisms)**

| Inferred setting of gain in Poole Harbour (see figure 5.17) | Physical Mechanism |
|---|---|
| Channel Infill– an area formerly occupied by a channel infill's with sediment to the level where saltmarsh can colonise it | Change in hydrodynamics- channel migration Localised reduction in hydrodynamic forcing/localised increase in sediment supply |
| Creek side accretion- accretion has occurred up creek systems | Localised reduction in hydrodynamic forcing/localised increase in sediment supply |
| Frontal accretion– accretion occurs along the fronting edge of a saltmarsh backed by land | |
| Island accretion– new stands of saltmarsh accrete to form islands separate to the mainland or around a n already existing island | |
| Realignment– an area previously reclaimed from the intertidal is allowed to re-flood (this can be either planned or unplanned breaching | Human intervention |

A more complex set of changes than those reported by earlier research has occurred in Poole Harbour. Poole Harbour experienced a net gain of over 400 ha of saltmarsh between 1849 and 1947, with a peak of up to 800ha gain reported in the 1920's (Hubbard, 1965). This extent would have represented 25% of the area of the Harbour as opposed to the just under 10% that saltmarsh occupied in 2005. Between 1947 and 2005 the Harbour experienced a net loss of 187ha, representing 241 ha of loss, and an accretion of 54 ha (where data coverage permits). This saltmarsh loss reflects the recent general trends elsewhere on the UK south coast, such as within the Solent to the east, where significant saltmarsh loss has been recorded (Burd, 1989, UK National Ecosystem Assessment, 2011). However, these trends are spatially variable and Poole Harbour does appear to be behaving in a similar manner to other large estuaries such as Pagham Harbour and the Newtown River, where saltmarsh accretion has also been observed, (Baily and Pearson, 2007, Gardiner et al., 2007).

Saltmarsh and wider coastal habitat loss is a global problem, overexploitation, physical modification, nutrient and sediment pollution, introduction of invasive species, global climate change and sea-level rise have led to a decline in coastal habitats (Waycott et al., 2009, Valiela, 2006, Duarte et al., 2009). As coastal habitats are amongst the most biologically productive ecosystems, supporting large numbers of birds and fish, it is crucial that these systems are managed carefully based on a thorough understanding of the drivers and mechanisms of change, these are discussed in the following section.

## 8.4 Physical mechanisms and drivers of saltmarsh change

Chapters 6 and 7 within the thesis examined the results from the historic change analysis and investigated the relevant morphological and hydrodynamic mechanisms and drivers responsible for the changes observed, the main mechanisms of change identified through this study are discussed below.

**Mechanisms of saltmarsh change**

Previous authors (Bearman et al., 2010, Kirby, 2002, Roberts et al., 2000, Friedrichs and Aubrey, 1996), describe a correlation between cross shore tidal shape and the dominant hydrodynamic mechanisms. With wave dominated and/or erosional regions typified by a concave shape and tidal flow and/or accretional dominated regions typified by convex shape. Within this study this distinction is not apparent and appears to be due to the existence of a marked cliff between the saltmarsh and the intertidal. However, a difference in cross shore saltmarsh profile shape is observed between the areas of erosion and accretion, areas of erosion showing a lower frontal marsh height and a lower height of mudflat immediately seaward of the marsh (Figure 6.18). It is not clear whether the elevations are lower due to another mechanism which accelerates erosion rates, or whether the higher erosion rates cause slumping and a lowering of these areas. Whatever the cause of the lower elevations of the mudflat region, this will allow larger waves to reach the marsh face facilitating erosion.

Sediment samples taken from areas of erosion and accretion, when tested in flume experiments, had different critical shear thresholds. The average threshold for eroding sites was 0.16 m/s and 0.24m/s for accreting sites, giving an overall average shear threshold of 0.2m/s These thresholds are similar to other studies on critical shear values of estuarine sediments (Widdows et al., 1998). Eroding sites have a lower average critical shear threshold than accreting sites, which will also potentially contribute to erosion and the removal of sediments from these regions. The organic content of the eroding samples was higher than that of the accreting samples, containing large pieces of dead saltmarsh stems. It was observed during the flume tests that these stems created extra friction on the bed and when the critical shear threshold was met, surrounding sediment was also taken into suspension attached to the stems, thus enhancing erosion. Sediment samples contained both sand and silt fractions (Section 6.3), this mix may contribute to larger critical shear velocities for erosion, but can also lead to mixed flocculates which can potentially lead to higher settling velocities, enhancing sediment deposition (Manning and Schoellhamer, 2013)

The distance of fetch within the Harbour varies with tidal height, as mudflats emerge and submerge. Due to the unusual tidal curve in Poole Harbour and the extended period of high tide (Section 3.1.2.2), wind/wave effects due to the extended fetch may be more significant than in other estuaries. But this is not readily identified from the results, particularly for areas where erosion has occurred. However, accretion does appear to have occurred in sheltered areas orientated away from the predominant wind directions of South-west and North-east (Section 6.4). Elsewhere locally generated short period waves are considered to be a major contributing factor to saltmarsh erosion (Fagherazzi and Wiberg, 2009, Mariotti and Fagherazzi, 2010, Mariotti and Fagherazzi, 2013b, Tonelli et al., 2010). As discussed in Green *et al* (1997) waves contribute to and can control the vertical re-suspension of sediment from the intertidal flat. However, it is the tidal current that controls the movement and horizontal flux of the suspended sediment (Green et al. 1997) and so in estuaries the two processes are intrinsically linked in understanding the sediment regime.

A number of simplified geometric and constituent asymmetry parameters were applied (Friedrichs and Aubrey, 1988, Pethick, 1994, Dronkers, 1986), as described in detail in Section 2.1.1.1. When applied to measured parameters for Poole Harbour these unanimously showed that the Harbour is flood dominant in character and is inconsistent with the hypsometry, which suggests the Harbour is mature and potentially ebb dominant. A main limitation of these approaches is that they assess the asymmetry of the Harbour as an entire system and therefore do not account for spatial variability. An illustration of this is where tidal current measurements were taken at the mouth of the Harbour (SCOPAC, 2004) showing that the ebb current reached higher speeds than the flood current and hence the Harbour was incorrectly classed as ebb dominant.

A single descriptor of tidal asymmetry is often used to summarise the morphology of an estuary system and infer patterns of sediment transport.  These generalisations can often be misleading, as found by Brown and Davies (2010) and Wang et al., (2002) who note a large variability of tidal asymmetry throughout an estuarine system. This study has taken this approach a step further by comparing the spatial variability in tidal asymmetry with patterns of habitat change (Section 7.2). Using only these single descriptors can result in false assumptions being made concerning how an estuary may evolve in the future and hence the future viability and management of the coastal habitats within it.

A hydrodynamic model was used to investigate both peak flows and slack durations. Peak flows are considered to be more important in the transport of coarse bedload material whereas slack duration is more important for the transport of the cohesive sediment fraction (Dronkers, 1986). Although both of these measures of tidal asymmetry are important in understanding sediment transport, slack duration is likely to be more applicable to the study of erosion and deposition of sediments within saltmarshes due to the inherent nature of the fine sediments.

Results from the numerical modelling, Section 7.2, show that the Harbour experiences variations in tidal velocity exceeding the critical shear threshold, both spatially and throughout the tidal cycle. This is particularly relevant where it exceeds shear thresholds only once per tidal cycle either on the flood or ebb, allowing the sediments to resettle for the rest of the tidal cycle. This would lead to large spatial variations of erosion and deposition throughout the estuary. If the geometric and constituent asymmetry parameters, derived in Section 7.1, were used exclusively then this spatial variability would not be apparent, and therefore could be misleading for coastal habitat management.

Peak flows on the flood were observed to occur up tidal creeks and to the west of the Harbour (Section 7.2.2). With regions in the centre of the Harbour and around the mouth experiencing, peak flows on the ebb, which is important for non-cohesive sediment transport. Peak flood velocity is correlated with areas of historic saltmarsh accretion. However, peak ebb velocity is not correlated with historic saltmarsh erosion.

The modelled results suggest that the longest overall slack durations occur after the flood for the majority of the Harbour, this pattern is reinforced by the distinctive double high water tidal curve, which prolongs slack water over the intertidal region (Section 7.3). Regions where the longest slack occurs after the flood are also correlated with areas of historic saltmarsh accretion. A few areas in the centre of the Harbour experience the longest slack after the flood, even though these regions may have the peak flow on the ebb, suggesting complex sediment transport patterns in these regions. With the potential for the net import and deposition of fines and the net export of coarse sediments

Despite the shortcomings (discussed in Section 2.2), numerical models are useful in understanding the behaviour of estuarine systems and the processes that drive morphological change, particularly when used in conjunction with an historical estuarine habitat change analysis this process can also be used for habitats such as mangroves and seagrass beds (McGlathery et al., 2013).

**Other potential mechanisms**

Agriculture, fisheries and pollution were all noted as being potential contributors to saltmarsh change within the literature review. Agricultural runoff such as herbicides, nutrient enrichment due to fertilisers or sewage act by destabilising sediments, enhancing bioturbation and directly affect the saltmarshes through biogeochemical processes. Although these mechanisms may affect small discrete regions of the case study site in close proximity to their input into the system, their relative impact is more likely to be as a more secondary contribution rather than the dominant estuary wide driver. This conclusion is primarily due to the spatial patterns of change, where gains and losses of saltmarsh have been observed together over short geographical scales.

Medium scale factors such as the 18.6 year nodal tidal cycle are important to take into account as the historic analysis results are simply snapshots of several states of the saltmarsh over many years. The years for when aerial photography was analysed, 1947, 1972 and 2005, all lie close to or on, the lowest points of this nodal cycle, thus the tides at these points will have been of a similar magnitude and so we can assume that the results are comparable. In a Harbour such as Poole with low gradients the effect of the nodal cycle on tidal height could lead to large areas covered or uncovered by the tides and may facilitate cycles of saltmarsh colonization and erosion over 18/19 years.

Sea-level rise could be a contributing factor to saltmarsh changes by modifying the tidal prism, increasing fetch lengths where intertidal areas are submerged, and thus increasing wave attack at the saltmarsh front. Haigh *et al.*, (2009) estimated average sea-level rise from tide gauges along the English Channel. It was found that local mean sea level at Southampton and Weymouth had risen by 1.30 ± 0.18 mm/yr and 1.81 ± 0.28 mm/yr, respectively over the past century. Which while typical globally, is more rapid than that recorded in the $19^{th}$ Century (Woodworth et al., 2011, Woodworth et al., 2009) and while these are small rises, micro-tidal estuaries are expected to be sensitive to even small changes in tidal height due to their small tidal range.

Coastal squeeze has been identified as an important mechanism of future saltmarsh loss (Townend et al., 2007, Long et al., 1999, Morris et al., 2002, Pethick, 1981). Within this research coastal squeeze as a driver may be contributing to some losses but there is no obvious evidence of this processes having been a major contributor to losses observed over the past century. In the north and east of the Harbour surrounding Holes Bay, saltmarshes in this region cannot migrate due to seawalls backing the fringing saltmarshes. However, this is only an issue where sediment starvation prevents the marshes from accreting vertically (Paramour and Hughes, 2004) and in this region although net losses were observed, the erosion was not spatially uniform as might be expected as a result of coastal squeeze with marked areas of accretion also apparent. Elsewhere in the south and west of the Harbour there are no restrictions on saltmarsh migration other than natural topography. Locally, natural elevation constraints will limit saltmarsh migration to along stream and creek systems. Overall the lack of coastal squeeze identified within this study shows that sediment supply and favourable hydrodynamics allow the continued accretion of saltmarsh and the presence of seawalls does not necessarily result in habitat loss. However, with future sea-level rise coastal squeeze may become an increasingly major factor in saltmarsh loss over the next century. In many coastal regions, flood defences have removed most opportunities for natural landward migration, (Nicholls and Wilson, 2001, Lee, 2001). Poole Harbour is thought to be a closed or near-closed system in terms of sediment budget, implying an exchange between erosion in one area and accretion elsewhere. Just as erosion rates have slowed between 1972 and 2005, so have the accretion rates, supporting this interpretation. If erosion does slow in the future, accretion rates will presumably follow this pattern, potentially leading to coastal squeeze in some areas constricted by seawalls, especially if sea-level rise accelerates.

**Drivers of saltmarsh change**

Two prominent drivers of saltmarsh change were clearly identified from this study both as a result of human development, including the direct destruction of saltmarsh and the invasive colonisation of *Spartina anglica.* From the historic aerial photographic analysis it was seen that13% of all saltmarsh loss since 1947 was due to direct destruction from reclamation and marina development, mostly concentrated around Holes Bay (Figure 5.16), this is also clearly observed from the historic OS chart analysis (Figure 5.2).

One of the most prominent drivers of the change in the recent history of Poole Harbour is the human assisted, invasive colonisation of *Spartina anglica*. However, in lacking long term and accurate baseline data it is difficult to determine whether the recent changes in saltmarsh extent are also part of long term cyclical trends (meteorology and regime shifts).

## 8.5 A refined conceptual framework of drivers and mechanisms of salt marsh change in micro-tidal estuaries

The use of conceptual models is useful in allowing dynamics and linkages to be seen in context and relative importance weighted, giving a broad overview of a system across disciplines. The conceptual model developed within this study is applicable elsewhere and to other estuarine habitat systems such as mangroves and seagrass beds that occupy similar ecological niches (McGlathery et al., 2013). Figure 8.1 shows the primary, secondary and tertiary drivers in terms of importance, as identified within this study. Other drivers and mechanisms that were identified as part of the literature review (Chapter 3) may also be important within the case study site but were not identified within this analysis.

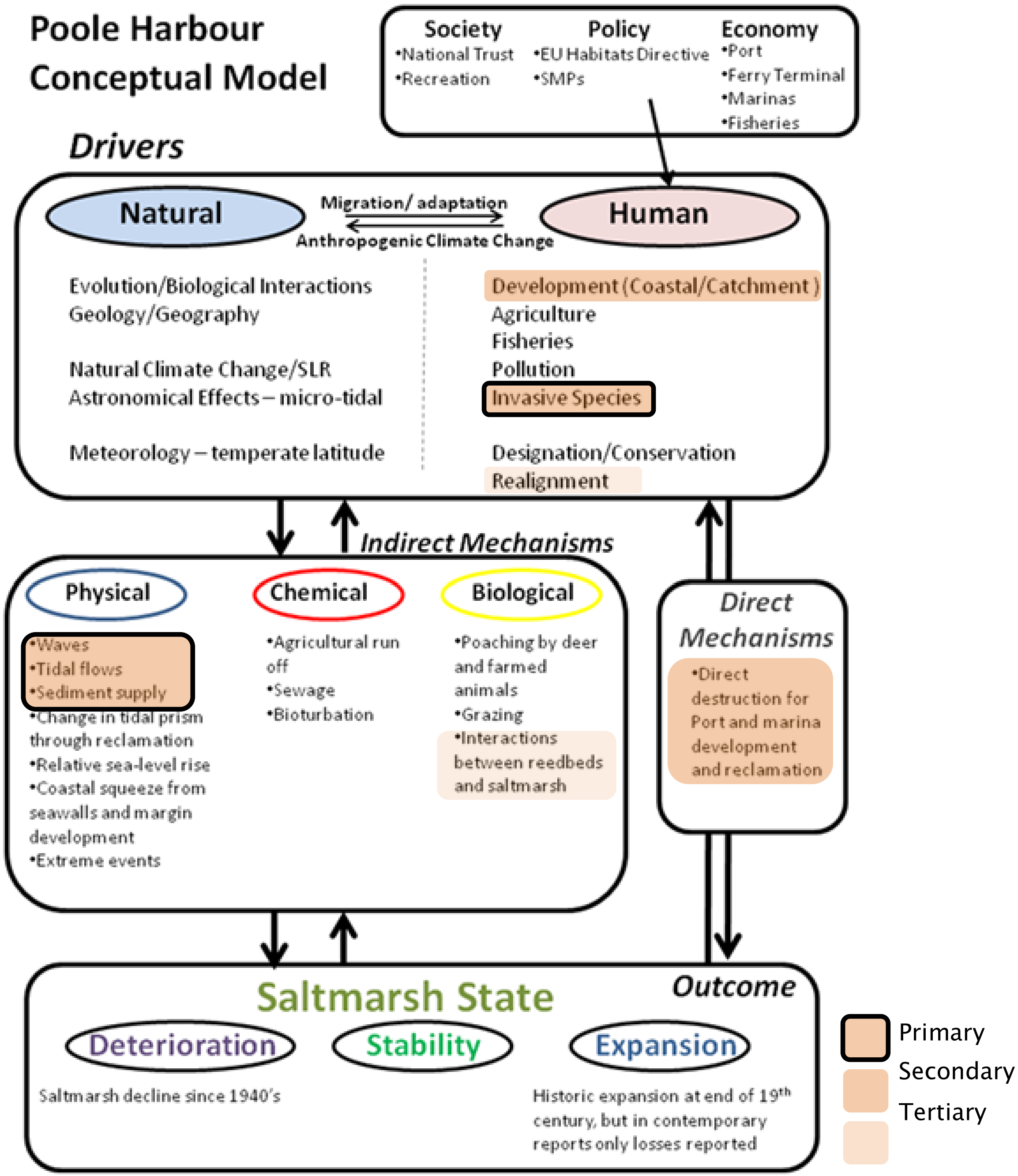


**Figure 8.1 Refined conceptual model for Poole Harbour showing the primary, secondary and tertiary drivers and mechanisms as recognised from the study.**

While saltmarsh area within Poole Harbour has experienced a net loss since 1947, the changes are complex at a sub-estuary scale, with both erosion and accretion being important processes in Poole Harbour. The processes that are controlling these changes can be inferred from the setting of the change and are summarised in Figure 8.2. The dominant erosional process is frontal loss including the islands: once these islands are gone, erosion will continue in the fronting flats, which will become increasingly exposed, but the future rate of loss is uncertain. The dominant accretional processes are creekside and frontal accretion.

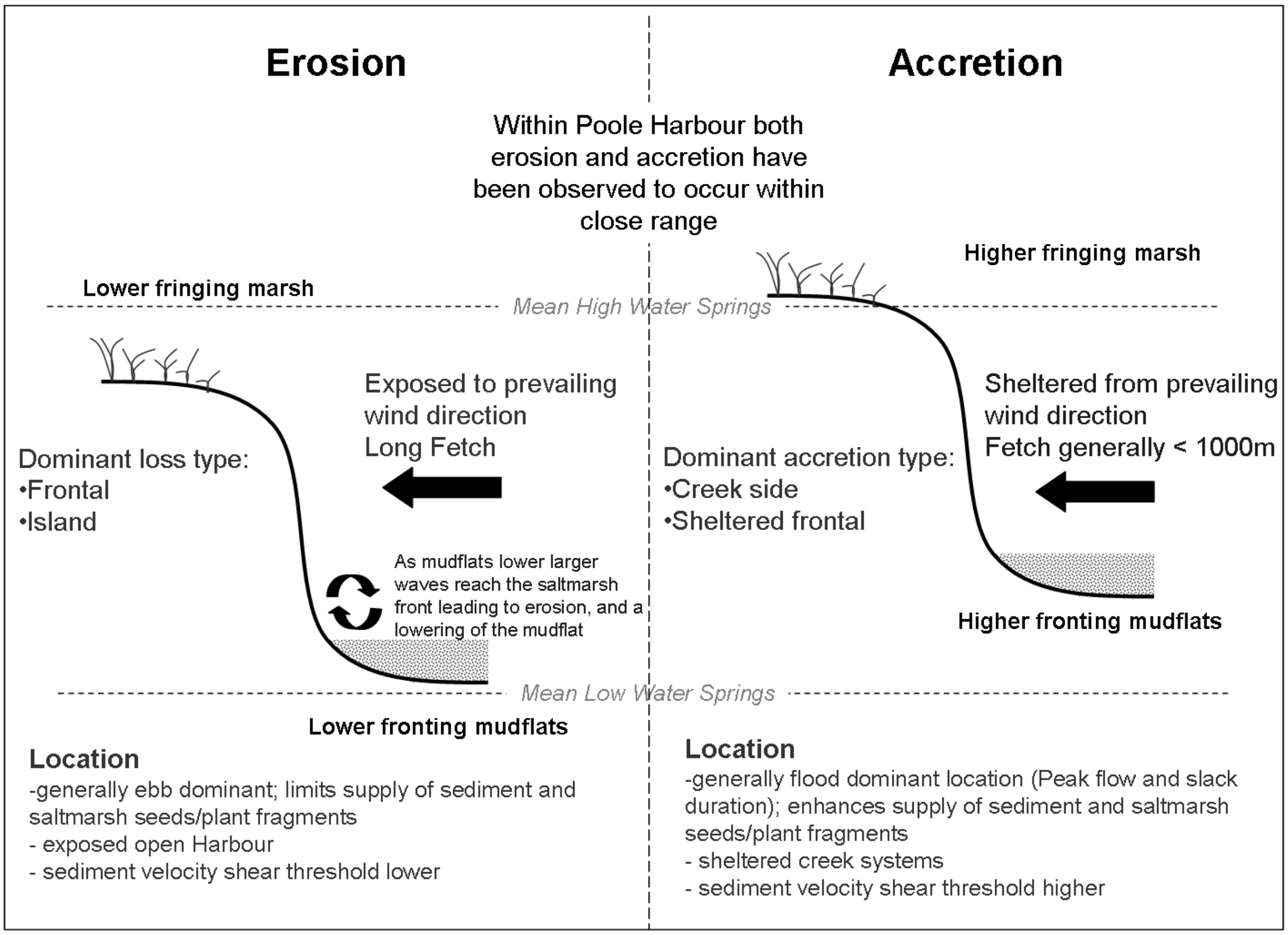


**Figure 8.2 Synthesis of erosion and accretion mechanisms in Poole Harbour and the settings for these mechanisms .**

Flow asymmetry trends at an estuary scale are not uniform at a sub-estuary scale, with more complex spatial variations occurring for peak flows and slack durations, this has been observed elsewhere (Brown and Davies, 2010). It appears that historic saltmarsh accretion, described in Chapter 5, is correlated with peak flows on the flood and areas that have the longest slack duration after the flood. This facilitates the transport and deposition of sediments, which enable the saltmarsh to accrete and migrate. Accretion also occurs in sheltered areas orientated away from the predominant wind directions of South-west and North-east and hence away from locally produced wind-waves.

Historic saltmarsh erosion has not only occurred in regions of peak ebb tidal velocities, suggesting that erosion is not entirely controlled by this mechanism. Elsewhere locally generated short period waves are considered to be a major contributing factor to saltmarsh erosion (Fagherazzi and Wiberg, 2009, Mariotti and Fagherazzi, 2010, Mariotti and Fagherazzi, 2013b, Tonelli et al., 2010) and it is likely that a combination of peak ebb tidal velocities driven by the local morphology and exposure to large fetch length and hence locally generated waves, are the likely cause of the majority of erosion in Poole Harbour.

The contemporary hypsometric form of Poole Harbour exhibits characteristics typical of a relatively mature estuary (Section 6.1). However, without a time series of bathymetry to assess the previous hypsometric form, it is difficult to predict whether the future trend will be to infill further or erode, as this analysis only gives us one snapshot in time. The observations in Chapter 5 suggest that, although trends are spatially variable, the estuary is currently in an erosive stage. However the fate of this sediment is unknown and therefore may not be removed from the system and instead is redistributed elsewhere in the Harbour and is the source of sediment for the accreting regions of saltmarsh. Large sediment infill, the source of which is unknown, occurred in some locations of the Harbour during *Spartina anglica* colonisation and this sedimentation would have raised the elevation of the intertidal areas.  Although, we know from anecdotal evidence that the channels in Poole Harbour were shoaling prior to *Spartina* colonisation and hence there was sediment available to facilitate a shift in regime.

An increase in elevation of the intertidal areas can enhance ebb dominance (Boon and Byrne, 1981, Friedrichs, 2011)  and therefore would result in the subsequent saltmarsh losses observed. However, some regions are still accreting and the hypsometry of these areas reflects this. To test this theory further it would be necessary to assess the Harbours hypsometric form in ten or twenty years. If the Harbours morphology is adjusting to the *Spartina anglica* colonisation, through intertidal erosion, then the overall hypsometric form will change to a less in-filled form in the future. This would demonstrate that Poole Harbour could be approaching a quasi-equilibrium form, following the large sediment volumes accumulated in the intertidal during *Spartina anglica* colonisation. Thus, historic losses may not reflect future changes and these should not simply be linearly extrapolated to predict a future state, as is often done (Born, 2005).

*Spartina anglica* colonisation occurred throughout the south of the UK and so changes observed in these other estuaries may also be a result of the change in estuarine morphology that occurred because of this, with estuaries now returning slowly back to a new equilibrium form. Hence, saltmarsh trends require a more detailed analysis concerning erosion and accretion than appears to have been the customary in many earlier assessments. This includes assessing the likely levels of uncertainty to provide better data for scientific and management analysis.

A wide variety of saltmarsh change mechanisms have occurred across the case study site (e.g. spit roll- back, small scale realignment, reed bed conversion) and only through a spatial assessment, categorising the change mechanisms can this be measured. Models where only singular drivers or mechanisms are used eg. (Fagherazzi et al., 2006) are useful in their approach, allowing the isolation of single hydrodynamic parameters, but are over simplistic. Coastal habitat change is driven by complex process with feedbacks between multiple biological, physical and chemical mechanisms and within this study it has been difficult to identify a singular driver of habitat change at the case study site and it is likely to be a combination of drivers contributing to the overall net changes observed. Therefore the simple single parameter models will need to become more complex in the future with the inclusion of more variables in order to adequately replicate the observations of saltmarsh change within this research.

## 8.6 Management implications

The conceptual diagram developed in Section 2.1.3.2 and the associated mechanisms analysis from Section 2.1.3.1 are applicable to other saltmarsh habitats as well as being easily adaptable for other intertidal habitats such as mangroves. Clearly there are many different mechanisms and drivers of change, the key ones and the relevant inputs of secondary drivers will change on a case by case basis. Estuaries are naturally driven with varying levels of human influence and together with the associated complex mechanisms of change, contribute to the wide form and function of estuaries.

In identifying these mechanisms and drivers accurately, effort can be made to assess how best to mitigate for these. For example if habitat loss in an estuary was due to eutrophication  as a result of sewage outflow, leading to the destabilisation of sediments from bioturbators and saltmarsh loss, this would be unacceptable and efforts would be made to ensure waste water was treated appropriately. Conversely if saltmarsh was lost due to shingle spit roll back due to a natural change in hydrodynamics and sediment supply, this may be more acceptable. Although saltmarsh may be lost due to natural causes, other important habitats may be gained and maintaining a natural system that is allowed to evolve as a whole, may be more important than maintaining stocks of habitat. However, without examining the setting of the change and identifying the mechanisms and drivers, management of the system may not be appropriate. This reinforces the need to make more detailed spatial analyses concerning saltmarsh change in order to fully understand the system as a whole.

**How is the baseline defined?**

'Shifting baseline syndrome' is a phenomenon first identified by Pauly (1995), in this instance it arose because each generation of fisheries scientists accepted the baseline stock size and species composition as that at the beginning of their careers. As generations of fisheries scientists progressed this resulted in a shift of baseline, a gradual accommodation of the decline in resources and an inappropriate reference point for evaluation or for identifying targets for rehabilitation.

Shifting baseline syndrome extends beyond population level or relative size of species to the perception and functioning of habitats and entire ecosystems, in order to counter this we need firmly formed baselines, based on as much evidence as possible. Pauly (1995) advocated this through the collection of historic anecdotal evidence, any evidence or trend noted was of relevance in order to question the preconceived notions surrounding the 'current' knowledge and to overcome shifting baseline syndrome.

During this study the use of historic map data, despite the inaccuracies involved, has had similar results, in that historic trends of saltmarsh colonisation and subsequent decline have been substantial when put into perspective alongside the recent trends in Poole Harbour, Figure 8.3. The colonisation of *Spartina anglica* in Poole has been described in previous literature; however the magnitude of the changes experienced were not explicit. This study, along with Kirwan et al., (2011), have illustrated that this is not an isolated case and that other estuaries may have experienced dramatic changes, we simply have not been looking for them, using an arbitrary state as the baseline. Mariotti et al., (2010) have shown that a regime shift can occur rapidly with relatively little sediment input or change, fundamentally altering the system over only a short period of time.

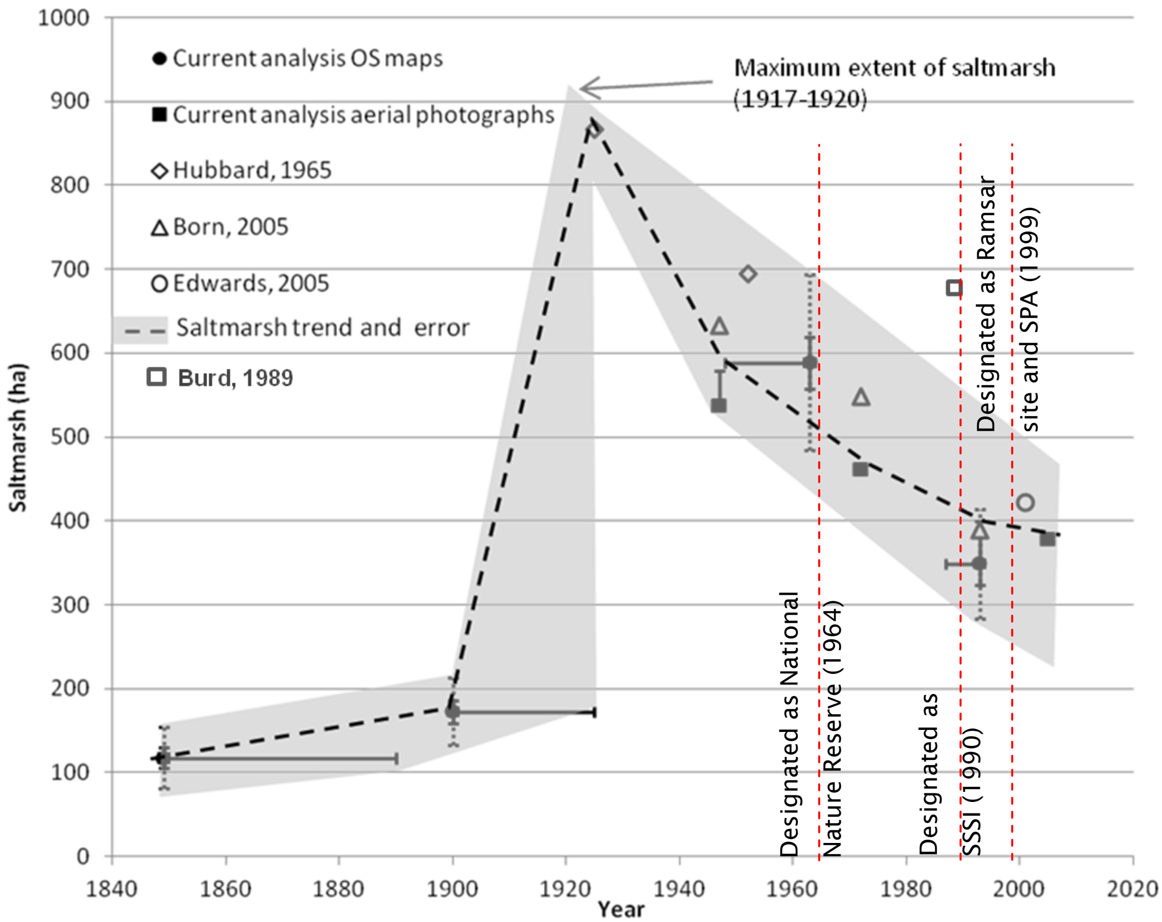


**Figure 8.3 Trends in saltmarsh area in Poole Harbour from OS maps and Aerial Photography analysis. Other data plotted from previous studies and surveys. Horizontal errors include published date ranges for OS data. Uncertainties include assessment of accuracy for aerial photographic and OS data interpretation of saltmarsh area. Errors not published and available for previous studies in the literature.**

One of the most interesting results of the study is shown in Figure 8.3, the change in saltmarsh area over time, clearly showing *Spartina anglica* colonisation and the subsequent decline. Poole Harbour was designated in 1964 as a National Nature Reserve (UK), a Site of Special Scientific Interest (UK) in 1990 and in 1999 it was designated as a Special Protection Area and Special Area of Conservation (EU) and a Ramsar site (Global). Although saltmarsh extent has declined since Poole Harbour was designated, marsh extent is still larger than it was prior to colonisation. If sites are designated with little knowledge or understanding of the state of the system, how is the baseline defined and what should the goals and priorities be? It is likely that for many estuaries in Europe and particularly further afield, where data is limited, there is little understanding of what the baseline state is and hence there is no way of knowing if these sites are degrading or fulfilling their ecosystem role.

**What should the goals and priorities be?**

Often even anecdotal evidence does not exist so a clear baseline and understanding of the system is not feasible, in this case an idea of exactly what is required of an ecosystem and thus the form of designation is needed. For example often the conservation requirement and the ecosystem service that we value may be mutually compatible, but there may be cases where they are not. Natural temporal shifts from seagrasses to mudflats, where both are important habitats, may facilitate localised erosion due to an increase in wave exposure. Another example may be the eradication of an invasive species such as *Spartina anglica* that provides increased wave dissipation, yet is considered un-natural and a threat to native species. Current ecological designations rightly tend to focus on the conservation requirements of species, e.g. birds (Ramsar sites, Globally, SACs, Europe) or on habitat assemblages e.g. SPAs Europe and SSSIs UK. However, as ecosystem services are further examined and economically quantified the conflict between what is beneficial for the habitat or species vs required or exploited by humans may lead to conflicts and a re-examination of how we view these habitats. Furthermore this has implications for the current policy of maintaining stocks of habitat through managed realignment, the purpose of this practice is to recreate an equivalent habitat to the one damaged/lost, but this may not recreate the ecosystem service that was valued in the original site.

A fundamental question is whether the focus is to maximise ecosystem services or to conserve a natural state, in which case we must be prepared that habitats evolve and migrate, and flexibility to allow for this is needed, (Gardiner et al., 2007). Maximising ecosystems services of designated areas and the relative impacts on the original reason of designation, is beginning to be explored at some locations in the UK (Eastwood et al., 2013).

## 8.7 Further Research

This research has highlighted a number of different directions for further study, both for Poole Harbour, in micro-tidal estuaries and more widely. These are summarised within the following Section.

**Poole Harbour**

1. *Is Poole Harbour evolving back to a less ebb dominant/equilibrium state?*

   One of the main requirements for habitat change analysis, highlighted in this study is the need for consistent, long term monitoring of the estuarine system in order to clearly understand the spatial patterns of saltmarsh change (Section 8.2).Specifically within Poole Harbour, further LIDAR and bathymetry surveys of the saltmarsh, intertidal and sub-tidal areas, could be used to compare the morphology of the Harbour over time, in order to assess the long term changes in morphology and hence hypsometry. This could confirm whether the Harbours morphology is evolving to a less ebb dominant and potentially equilibrium state. Previous bathymetric data was collected in 2005 and LIDAR in 2006 and so data collected from 2016 onwards would have an adequate timescale of 10 years in order to observe broad scale morphological changes, considering the errors involved in collecting and processing these kinds of datasets.

2. *Sediment sampling to rule out/confirm other drivers and mechanisms*

   Sediment samples were taken from eroding and accreting regions within Poole Harbour, when tested in flume experiments the sediments had different critical shear thresholds and organic content. A larger sediment sampling campaign, involving systematic sampling from across the Harbour, adequately covering regions of saltmarsh loss and gain as well as sampling from regions where different settings of change have been identified, would be useful in examining other potential mechanisms of change. Alongside flume experiments to quantify shear velocity, analysis of organic content and sediment grain size, biological and chemical analysis could be performed, investigating the presence of sewage, bioturbators and other biota, chemicals likely to occur in run off, pesticides and herbicides, nitrogen content and other factors identified as potential drivers of change (Mason et al., 2003, Paramour, 2002, Paramour and Hughes, 2004, Beardall et al., 1988, Deegan et al., 2012) and outlined in Figure 2.10. Thus ruling out or potentially adding extra drivers and mechanisms of change within the Harbour, and as a result of this any current management of the systems could be reviewed.

3. *Is fishing a potential mechanism of change?*

   The impact of fisheries was identified within the Poole conceptual model, as being potentially relevant to saltmarsh changes in the region (Figure 8.1). During field work, deep grooves in some mudflats fronting the saltmarshes were observed. It was presumed that these were made during shellfish dredging by the local fishing fleet. As these mudflats are relatively high in the tidal frame, they would only be accessible at high tide and hence any sediment suspended into the water column during dredging could be redistributed during the following ebb tide. A study on the fishing practices within Poole Harbour and the impacts this may have on sediments could be useful in understanding some sediment transport pathways and identifying or dismissing further potential drivers of change.

4. *What is the driver of reedbed takeover?*

   At a local scale within Poole Harbour, reedbed takeover was observed as a mechanism of saltmarsh loss (Section 5.3.3 and Figure 8.1), future work to identify the drivers of this process could include monitoring the salinity of the upper marshes. This could be a result of local development, which may lead to more fresh water flow into the marshes or alternatively the marshes could have accreted out of the local tidal range. In which case the level of the upper marshes with relation to the local tidal levels could also be measured. Both processes would create a more favourable habitat for reedbeds to colonise which could then out-compete the saltmarsh species. Reedbed takeover accounted for a very small proportion of saltmarsh loss, however as it has also been potentially observed elsewhere as a driver of change (Branch Partnership, 2007) this process may be worth examining in more detail.

**Micro-tidal Estuaries**

1. *What are the drivers and mechanisms of change in other micro-tidal estuaries, are tides also important elsewhere?*

   Within micro-tidal estuaries the relatively small tidal range means that currents are generally weaker than might be found in a meso or macro-tidal estuary. These weaker tidal currents mean that other hydrodynamic factors, such as waves, may be proportionally more important in controlling coastal habitat extent. This study has illustrated that despite the small tidal ranges encountered within micro-tidal estuaries, tidal processes are still important in the development of coastal habitats within these regions (Chapter 7). Studying the relevant mechanisms and drivers of change in other micro-tidal estuaries will allow a greater understanding of the proportional effects tidal currents vs other hydrodynamic drivers have on habitat changes at a broader scale.

2. *Are micro-tidal estuaries more vulnerable to coastal squeeze?*

   Micro-tidal estuaries are cited as being more sensitive than other estuaries to sea-level rise, due to their inability to adjust and hence the coastal habitats within them are likely to be more susceptible to coastal squeeze, particularly where coastal development restricts their migration. Overall the lack of coastal squeeze identified within this study shows that sediment supply and favourable hydrodynamics allow the continued accretion of saltmarsh and the presence of seawalls does not necessarily result in habitat loss (Section 8.4). This could involve the examination of other case study locations or preferably with the support of an idealised modelling approach, using a range of basin geometries and a variety of tidal ranges in order to explore the amount of sediment required to allow the saltmarsh to maintain its position within the tidal frame. This would allow the quantification of the relative adaptability of different basins and different tidal regimes.

3. *Are micro-tidal estuaries more sensitive to invasive species such as Spartina?*

   Micro-tidal estuaries may also be more sensitive to the colonisation of invasive species; the results within this study illustrate the vast changes that can occur as a result of a new species introduced to a system (Figure 8.3). Further research could focus on the impacts caused by invasive species within estuaries, firstly by collating data already collected through coastal management programmes where relevant. Secondly identifying other suitable locations that have not previously been mapped, but have sufficient data to allow the rate of colonisation to be quantified. In understanding the susceptibility of micro-tidal estuaries to external influences, they can be better managed.

**General Estuaries**

1. *Does the conceptual model work elsewhere?*

   A conceptual model was created to identify and link the setting of the change, mechanisms of change and the over-arching drivers (Figure 2.11). Further work could be to apply this framework to other estuaries, (macro-tidal and meso-tidal), other intertidal habitats such as mangroves and seagrass beds and potentially to other marine ecosystems such as reefs or maerl beds. Testing the conceptual model in a range of environments would improve the models robustness.

2. *A re-examination of Spartina anglica colonisation using all available data*

   Historic trends of saltmarsh colonisation and subsequent decline have been shown to be substantial when put into perspective alongside more recent trends (Figure 8.3). In light of this a re-examination of saltmarsh colonisation within other estuaries where *Spartina anglica* has colonised, using historic charts and anecdotal evidence, could be undertaken in order to gain a better understanding of what the baseline was prior to *Spartina anglica* colonisation (Section 8.6). This is particularly relevant in estuaries that have yet to be formally designated, but it is also important where active management is being used to preserve coastal habitats that may be in a state of flux, due to perturbations due to species invasion.

3. *Why and how do regime shifts occur?*

   Further examples of documented regime shifts can be investigated, in order to understand the drivers that lead to them occurring. Within this study it is clear that the colonisation of *Spartina anglica* has led to dramatic changes within the case study site and likely contributed to a regime shift. With an increase in globalisation and worldwide marine traffic, combined with climate change and shifting ecological niches, the migration of invasive species is likely to increase. Elsewhere changing sediment supply created an estuarine regime shift (Kirwan et al.,2011). Future coastal management, where 'do nothing' or 'realignment' shoreline management strategies are adopted, may cause dramatic changes and widespread feedbacks resulting in unforeseen changes (Section 8.6). Hence observing where these regime shifts have been triggered previously, the drivers of them and the timescales over which they occur will enable better future coastal management.

# 9 Conclusions

Coastal habitat loss is a global issue, with many contributors including sea-level rise, exploitation, pollution and development leading to degradation and decline (Waycott et al., 2009, Valiela, 2006, Duarte et al., 2009). Micro-tidal regions containing coastal habitats are found throughout the world are more vulnerable to future changes, due to their limited ability to adjust to sea-level rise (cf(Nicholls et al., 1999)).

A multidisciplinary approach was taken to assess the drivers and physical mechanisms of saltmarsh change. Studying saltmarsh changes in a conceptual and spatial context allows an understanding of drivers and mechanisms of change and provides a broad overview of a system, identifying key aspects to investigate further or knowledge gaps that should be addressed. Studies of saltmarsh change often focus on one facet without considering the impacts of other mechanisms. In order to explore and assess the complex feedback systems involved in habitat change, including physical biological and chemical mechanisms, a conceptual framework was created (Figures 2.10 and 2.11).

The conceptual framework has applicability elsewhere, both in examining other saltmarsh systems as well as for other coastal habitats such as seagrass and mangroves, other climatic zones and meso or macro-tidal ranges. To apply the model at a case study level requires an understanding of the potential local drivers and requires both historic and contemporary data on the spatial extent of the habitats, which is often lacking. Within this study the conceptual model assisted in the identification of multiple mechanisms and drivers of saltmarsh change. The conceptual model was supported by a multidisciplinary analysis of historic saltmarsh trends using aerial photography, OS maps, bathymetric data and a hydrodynamic model. This method allowed the spatial settings of the change to be identified and hence the potential mechanisms and drivers. This approach was found to be advantageous due to the complexity of the biogeochemical feedback processes within intertidal habitat systems.

Multiple drivers and mechanism responsible for the changes observed were identified, small scale localised changes were caused by spit roll- back, realignment and reed bed conversion, alongside large scale hydrodynamic and morphological mechanisms. Flood dominant tidal flows were correlated with saltmarsh accretion, undoubtedly waves are important in shaping the morphology of micro-tidal environments (Fagherazzi et al., 2006, Fagherazzi and Wiberg, 2009). However this study shows that despite the small tidal ranges encountered within micro-tidal estuaries tidal processes are still often important in the development of coastal habitats.

The most prominent overall driver of saltmarsh change, both for losses and gains, was human influence, including the human facilitated invasive colonisation of *Spartina anglica*, and coastal development, consisting of marina development and land reclamation. The historical analysis suggests that *Spartina anglica* colonisation expanded saltmarsh area, at the case study site, substantially between 1900 and 1920 (Figure 8.3). As *Spartina anglica* colonised the intertidal area, the morphology and hydrodynamics would have been significantly modified shifting the estuary regime from an accretional to an erosional state and the erosion that continues to the present day results from the system adjusting to this perturbation, although the rate of saltmarsh loss as well as gain are slowing. Evidence shows that it only takes a small change in intertidal height and therefore sediment supply to potentially shift a regime.  Studies by Mariotti et al., (2010) have illustrated, using a wind-wave model, how a 15cm increase in elevation of the subtidal platform could reduce wave erosion by nearly 25%. In this case the shift was driven by an invasive species that could tolerate longer tidal submergence times, allowing it to colonise previously un-vegetated mudflats. Similar human-driven shifts, resulting in large scale wetland habitat expansion, have been observed in the United States, due to land use changes releasing large volumes of sediment into estuaries (Kirwan et al., 2011), creating habitats that have diverged from their natural equilibrium state. The changes seen are not likely to be unique to micro-tidal climates. Micro-tidal coastal regions are more sensitive to sea-level rise due to their inability to adjust and hence they are also more likely to be more sensitive to changes in sediment supply, this may have been a contributing factor to the dramatic extent to which *Spartina anglica* colonised the case study site. Historically *Spartina anglica* colonisation occurred throughout the south of the UK, as well as in many countries around the world, changes observed in these other estuaries may also be a result of the adjusting estuarine morphology that occurred as a result of colonisation, with estuaries now returning slowly back to a new equilibrium form.

At a broad scale, results from this thesis emphasise that saltmarsh changes occurring throughout the UK, and potentially elsewhere in the world, are more complex than often portrayed. Previous studies of saltmarsh change within the case study area, neglected to record the accretion that was occurring or fluctuations of the rates of change through time, with future saltmarsh area calculated assuming a linear loss with time. This is a gross over simplification and this is likely to be a widespread conclusion. This is particularly true when historic changes are calculated using limited data sources over short time scales, not allowing for a full understanding of dynamic and evolving habitats in a spatial context.

The case study chosen was considered to be an estuary that is relatively undeveloped; however the main drivers of change were related to human influence. From the direct destruction of habitats for coastal development and land reclamation, through to the introduction of invasive species. The wider implications of this finding is that any coastal activity that directly affects the distribution of coastal habitats should be assessed thoroughly with a full understanding of the complex driver and mechanisms feedbacks that can occur.

One of the main issues with quantifying this kind of study is the lack of baseline data and our perception of what the baseline should be. Humans have modified and developed the coastal zone for thousands of years and it is now difficult to envisage coastal habitats without human influence. Many coastal habitats worldwide are protected and within Europe coastal habitats are designated under the EC Habitats and Species Directive (Council Directive 92/43/EEC). Habitats were often originally designated for the conservation requirements of a particular species or for its habitat assemblage with little knowledge or understanding of the physical state of the system. As these habitats develop and change, naturally or un-naturally, with no valid baseline other than the state the system was in when it was designated, we will have no comprehension of whether the habitat is degrading or simply evolving.

This study illustrates the need to base future coastal management on accurate studies which use all the available information on a case by case basis. Many studies focus on the last 50 to 60 years when aerial photographs are available, but there is merit in using earlier sources, even if they are less accurate as they give a better sample of the range of conditions. With a lack of quantitative data available to understand the historic changes, anecdotal evidence can be used to gain an insight into the trends of change that have occurred in the past. Where no data exists then a concept of what role the habitat fulfils ecologically and therefore the requirement from the habitat should be assessed. However, in the future as ecosystem services are further assessed and economically quantified, conflict between what is beneficial for the habitat or species vs what is required or exploited by humans, may lead to questions as to whether the focus should be to maximise ecosystem services or to conserve a natural state.

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# A. Appendix A

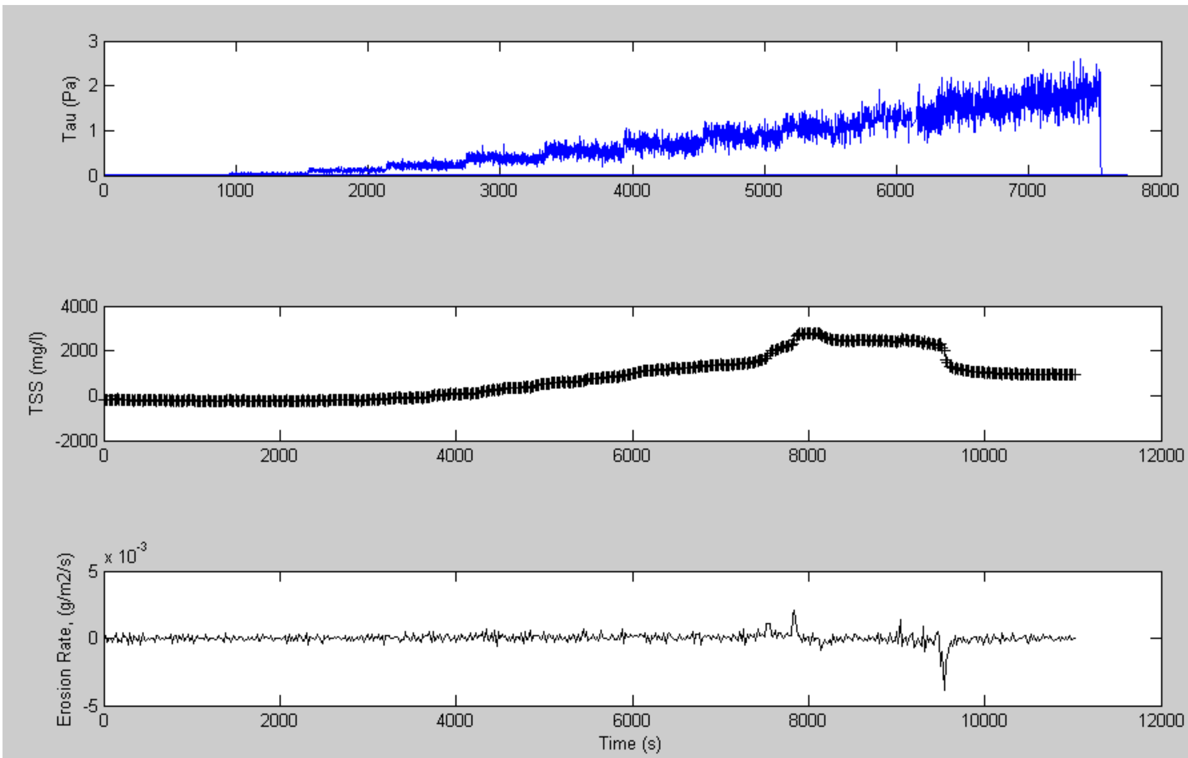


**Figure A.1 Time series plots of results from annular flume at site E1_1**

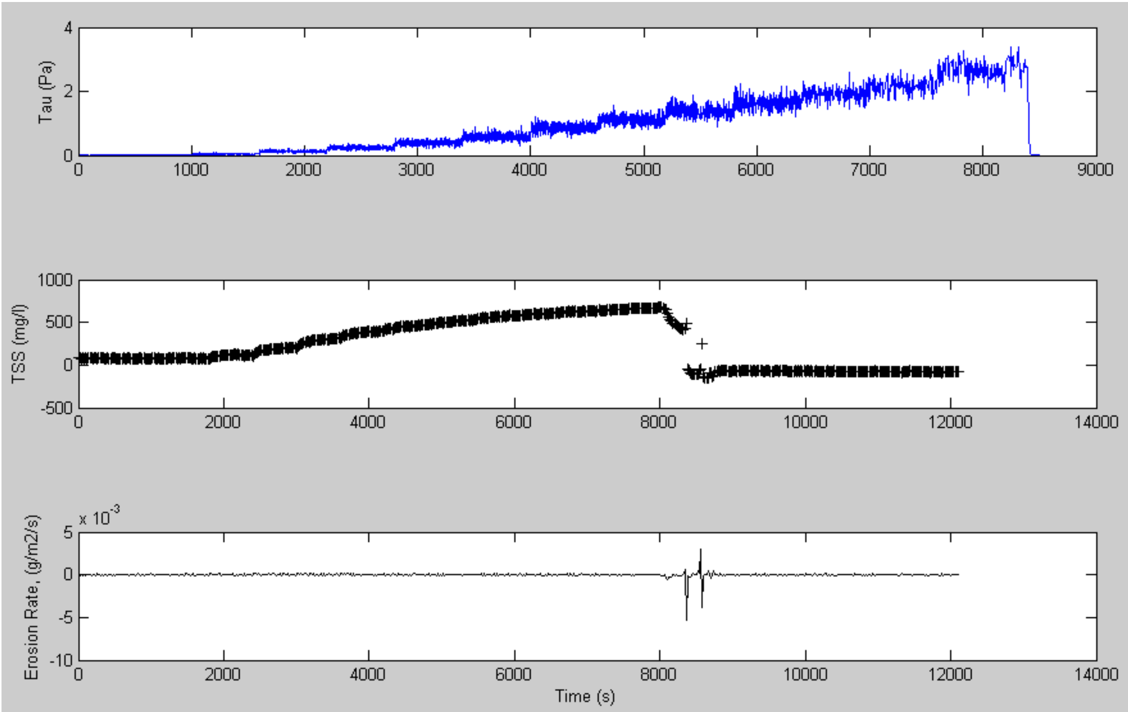


**Figure A.2 Time series plots of results from annular flume at site E1_2**

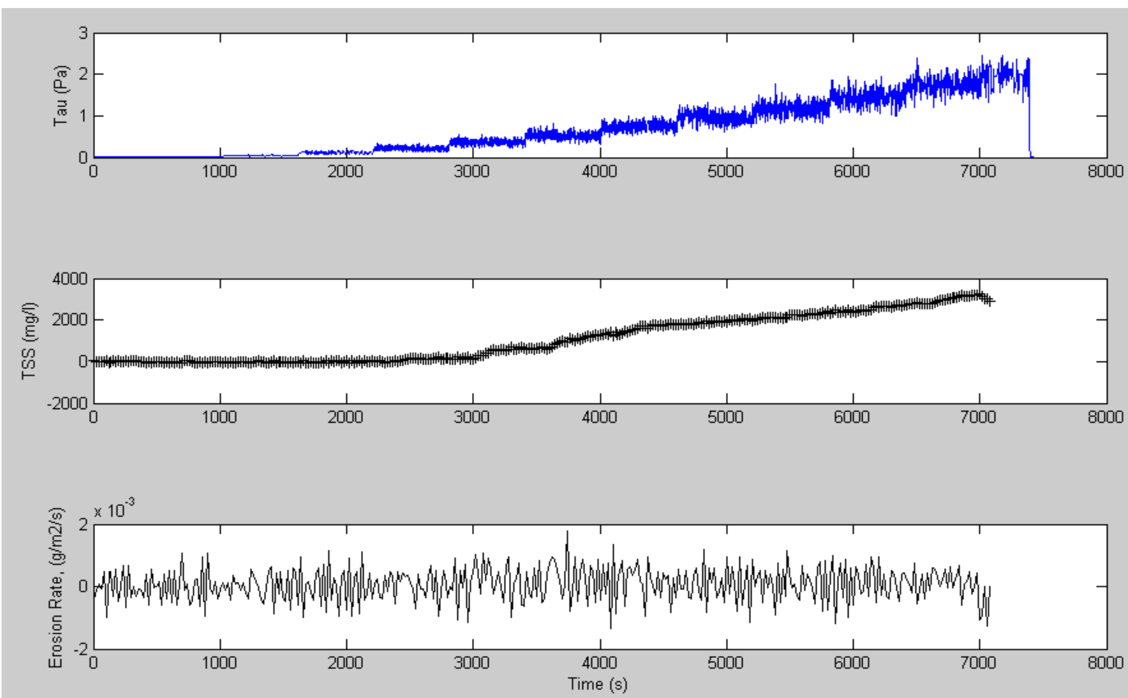


**Figure A.3 Time series plots of results from annular flume at site E2_1**

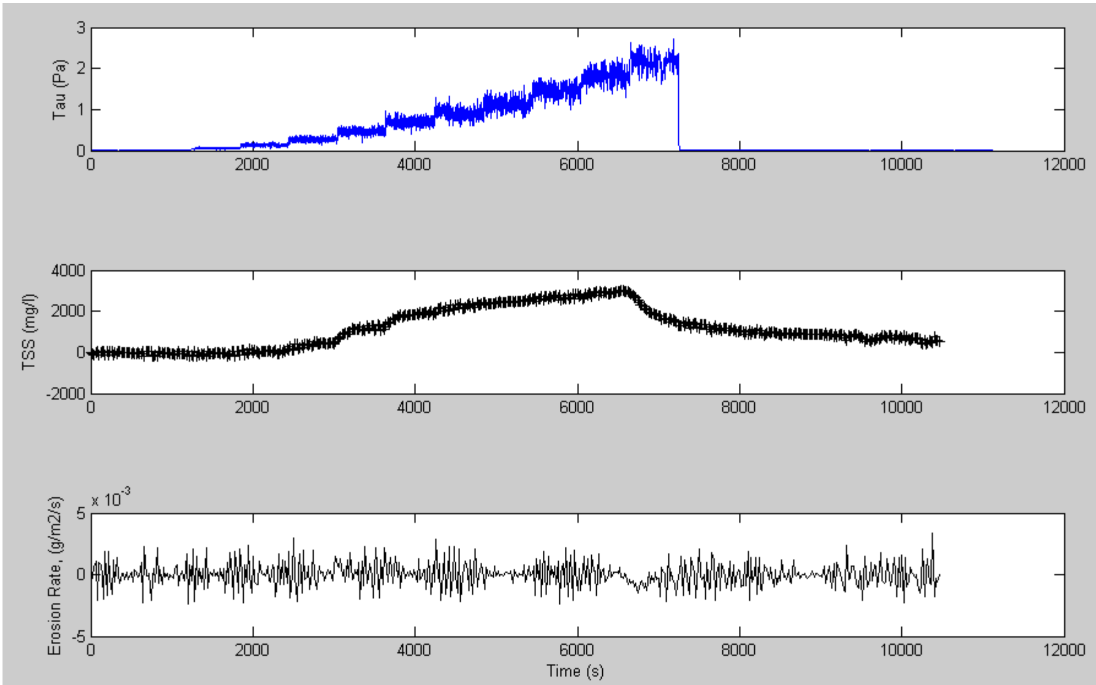


**Figure A.4 Time series plots of results from annular flume at site E2_2**

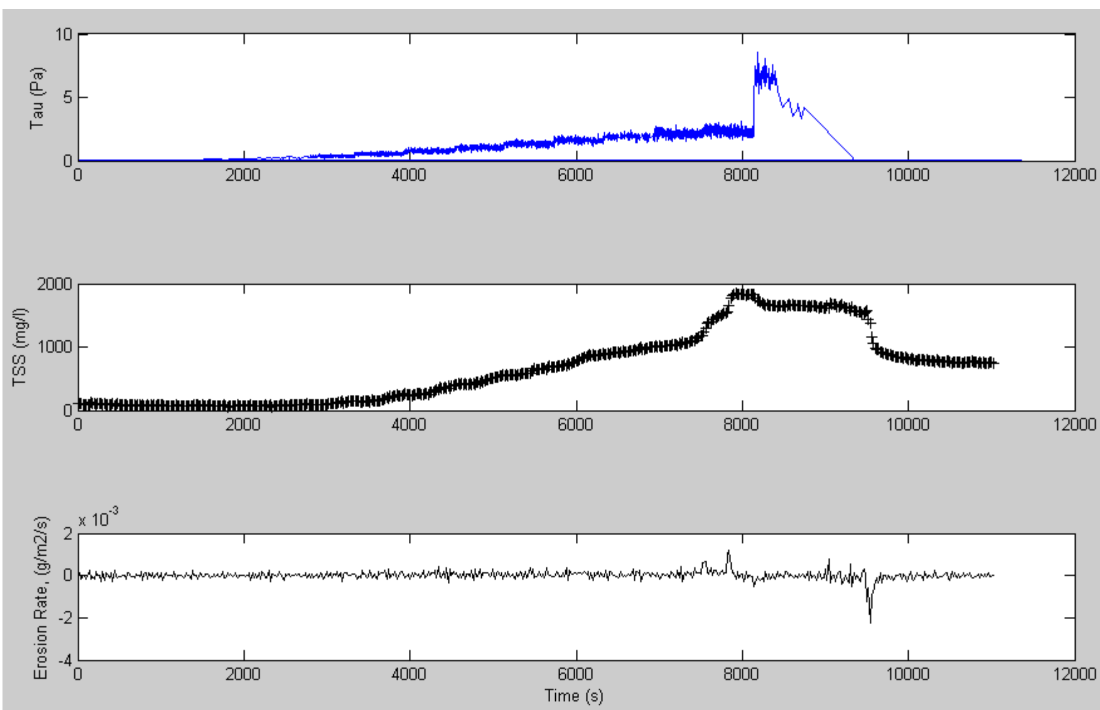


**Figure A.5 Time series plots of results from annular flume at site A1_1**

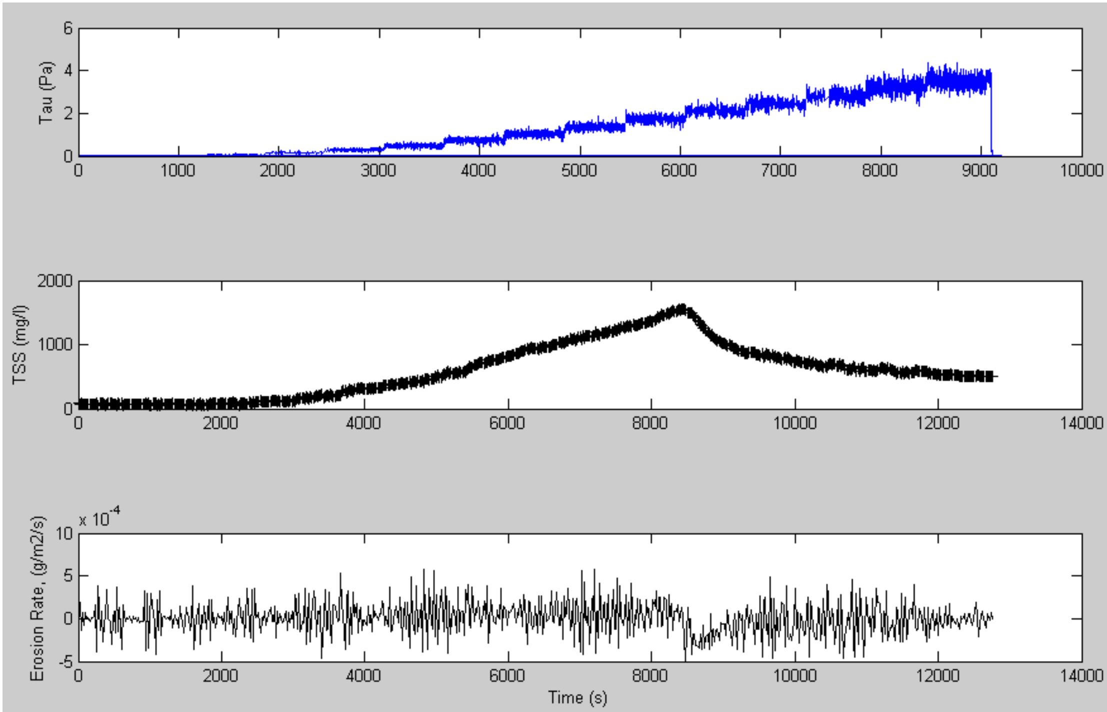


**Figure A.6 Time series plots of results from annular flume at site A1_2**

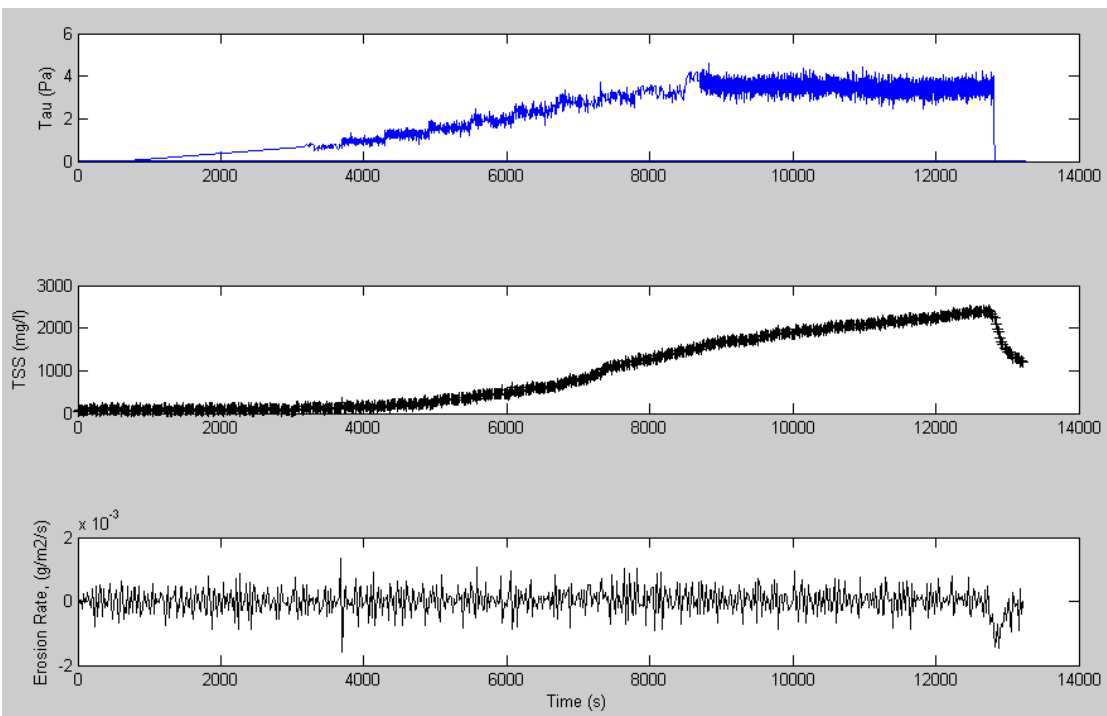


**Figure A.7 Time series plots of results from annular flume at site A2_1**

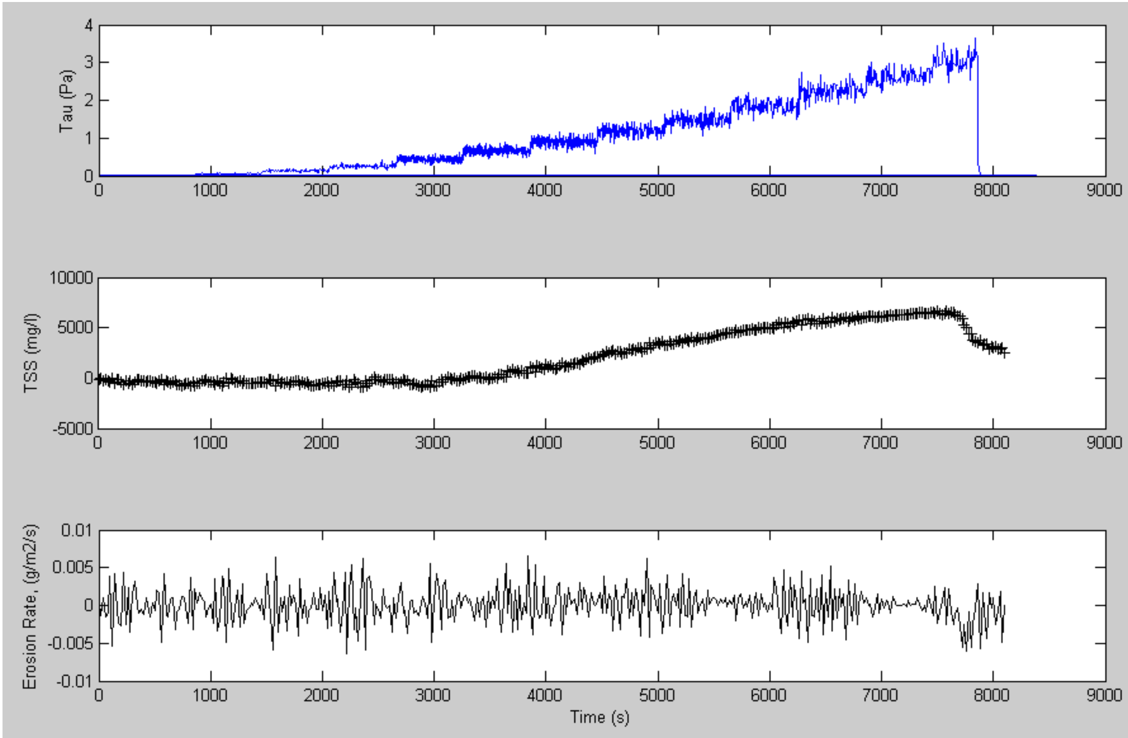


**Figure A.8 Time series plots of results from annular flume at site A2_2**

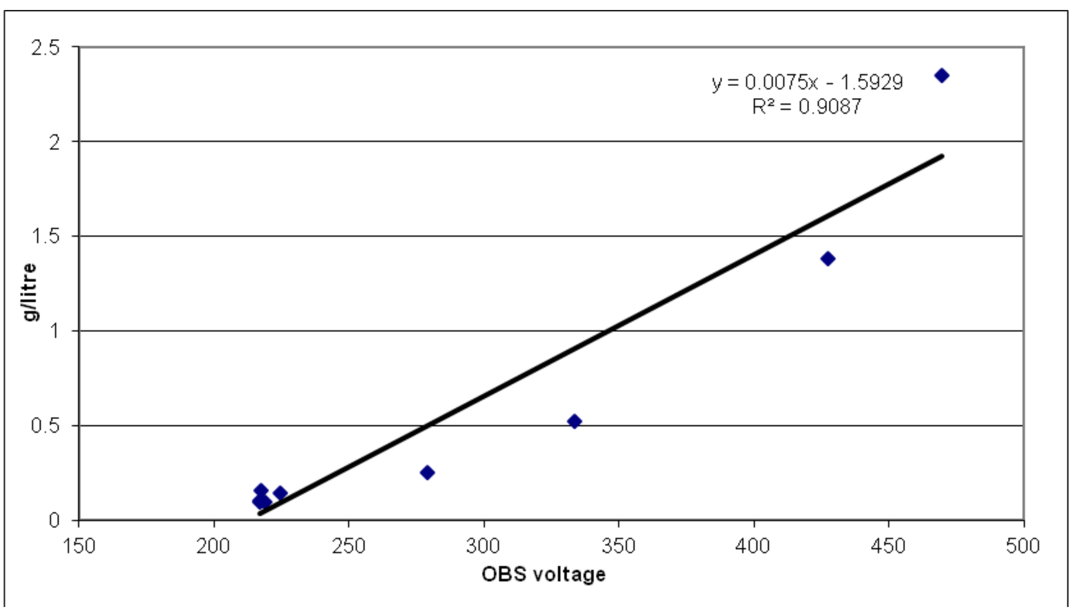


**Figure A.9 Calibration of OBS sensor to suspended sediment concentration measured in samples from the annular flume (E1_1).**

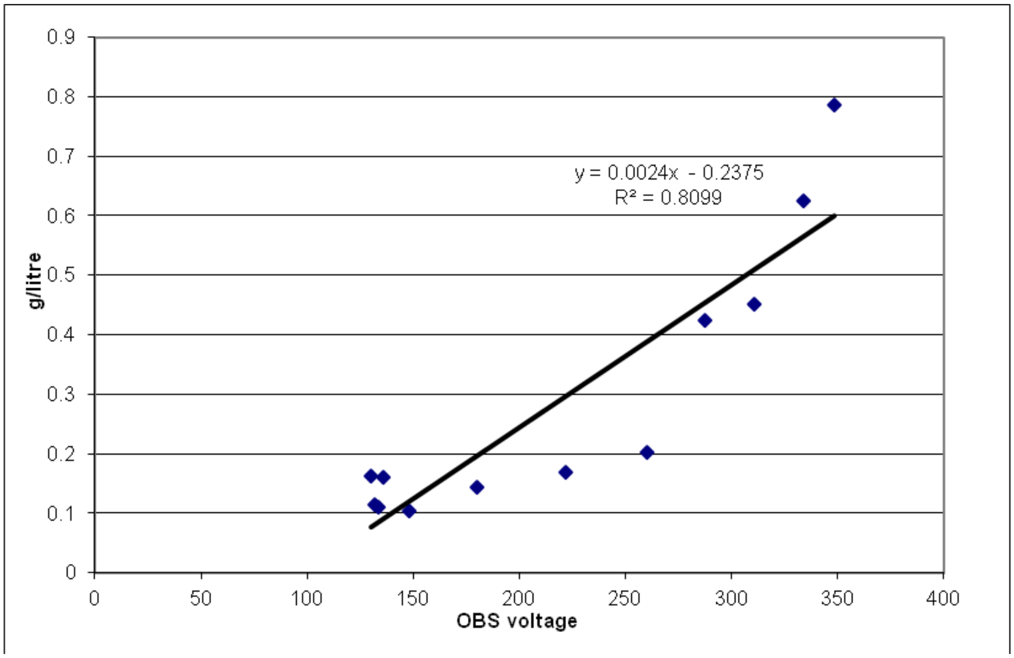


**Figure A.10 Calibration of OBS sensor to suspended sediment concentration measured in samples from the annular flume (E1_2).**

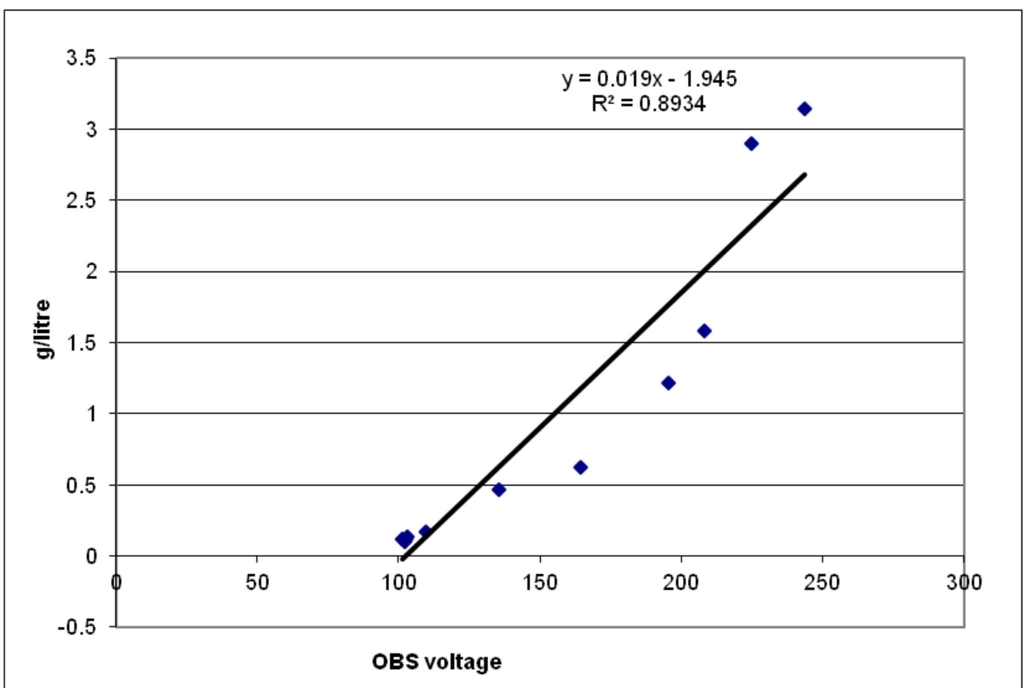


**Figure A.11 Calibration of OBS sensor to suspended sediment concentration measured in samples from the annular flume (E2_1).**

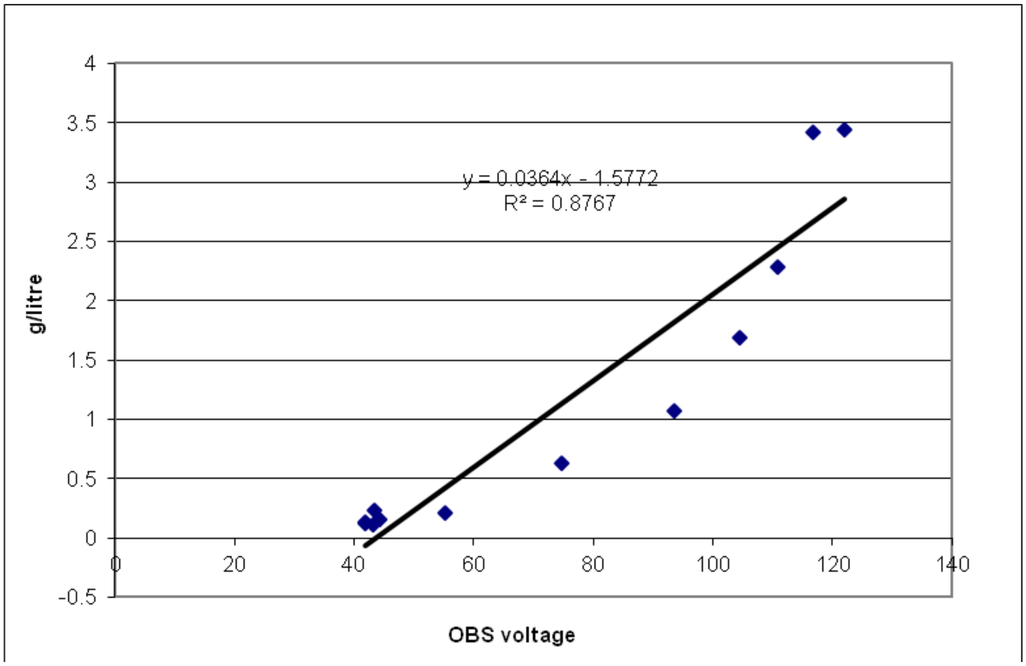


**Figure A.12 Calibration of OBS sensor to suspended sediment concentration measured in samples from the annular flume (E2_2).**

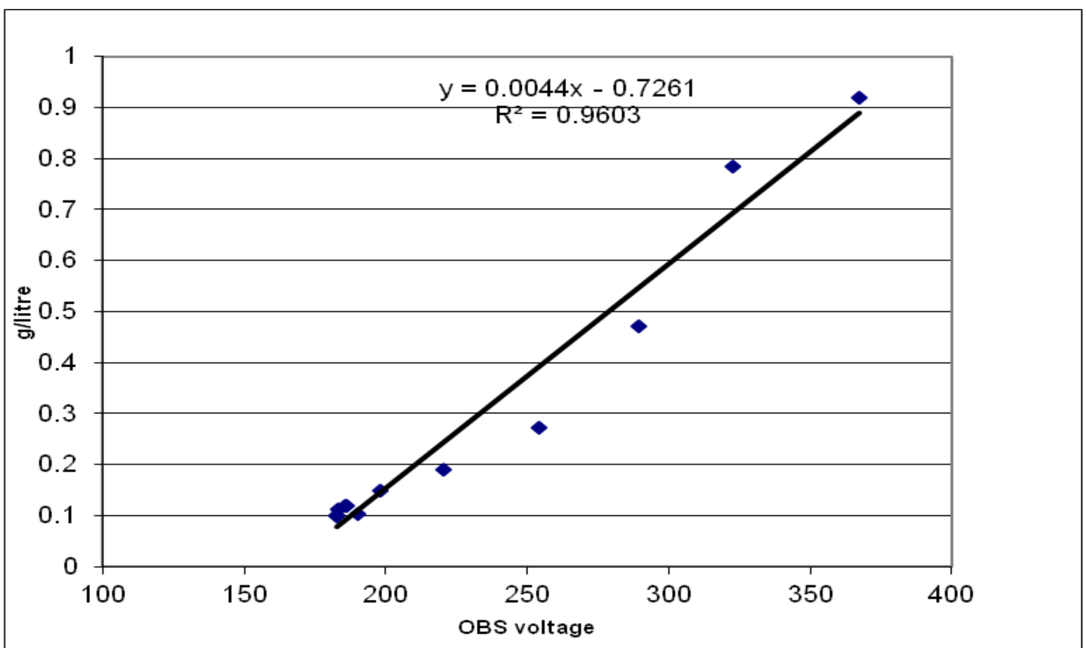


**Figure A.13 Calibration of OBS sensor to suspended sediment concentration measured in samples from the annular flume (A1_1).**

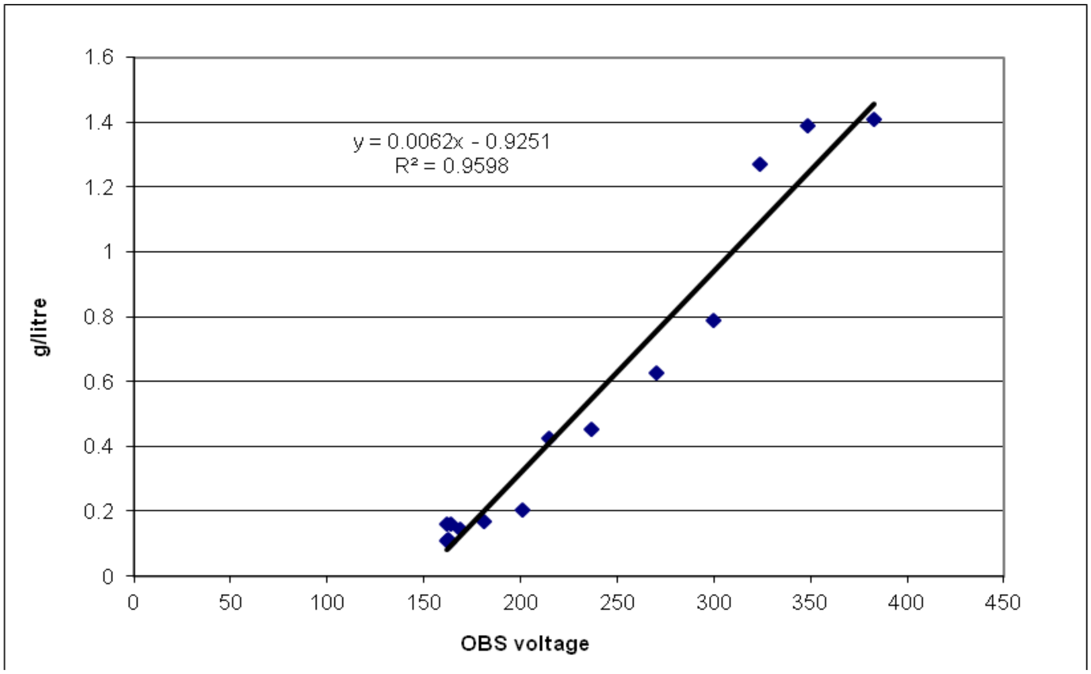


**Figure A.14 Calibration of OBS sensor to suspended sediment concentration measured in samples from the annular flume (A1_2).**

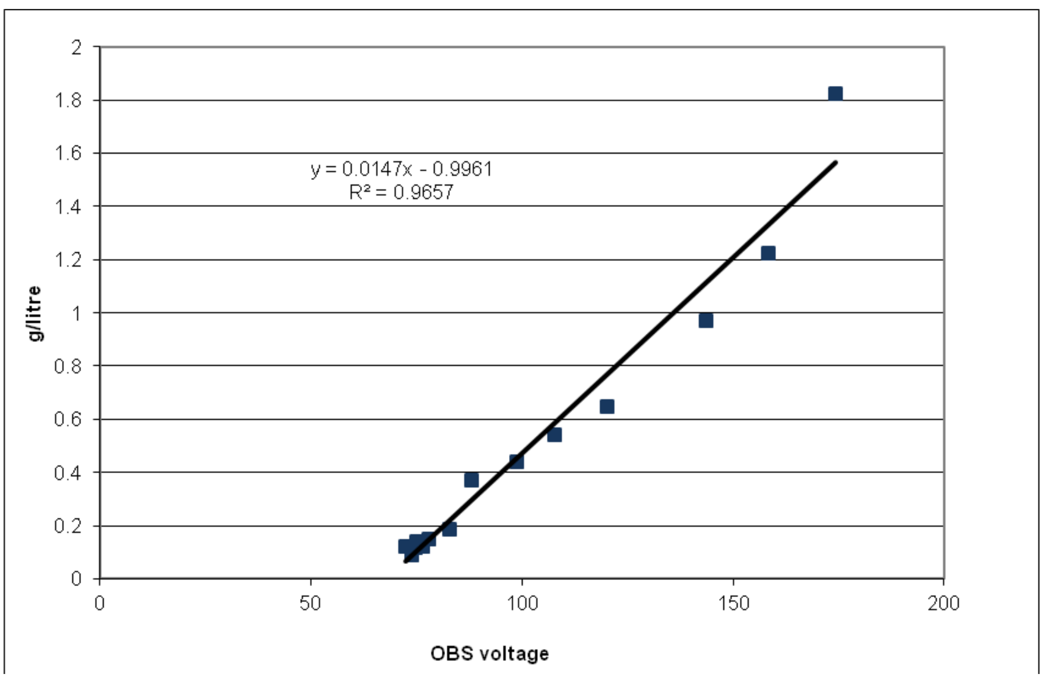


**Figure A.15 Calibration of OBS sensor to suspended sediment concentration measured in samples from the annular flume (A2_1).**

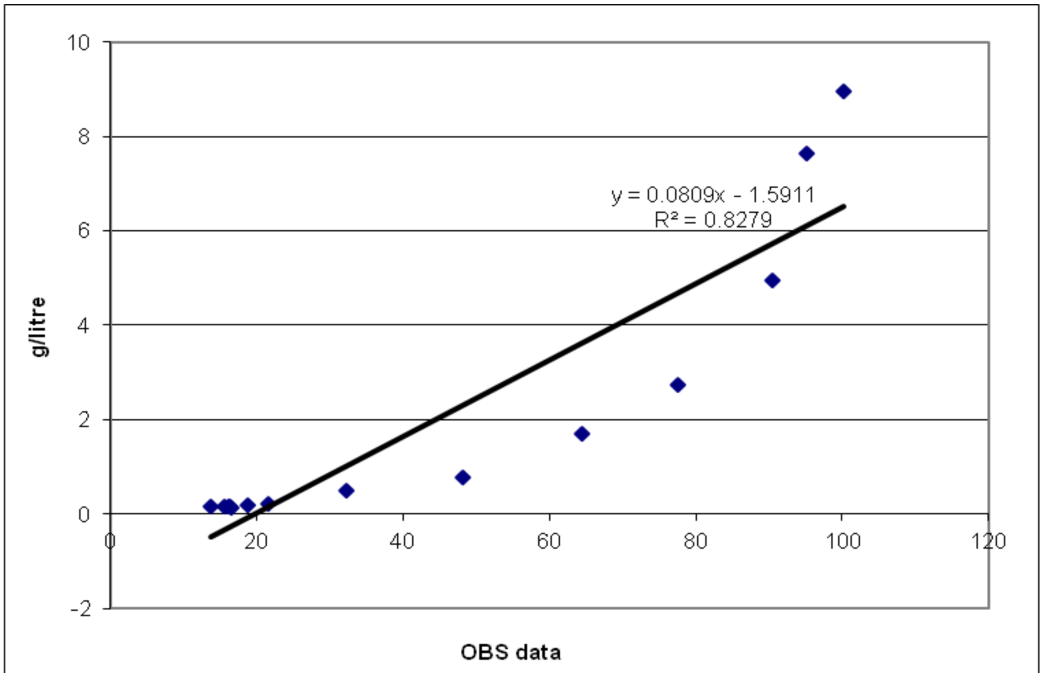


**Figure A.16 Calibration of OBS sensor to suspended sediment concentration measured in samples from the annular flume (A2_2).**

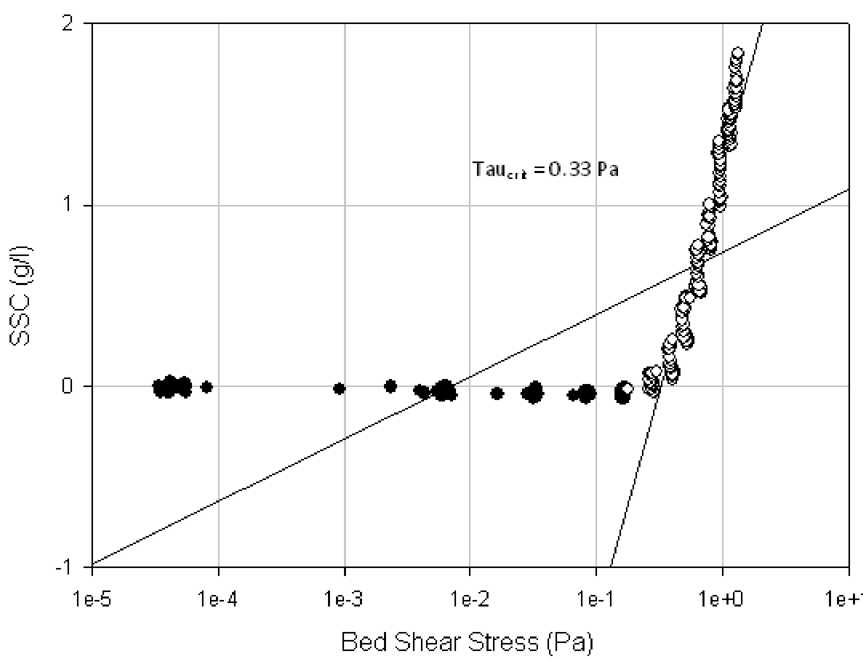


**Figure A.17 Estimations of the shear threshold for from the relationship between bed shear stress and suspended sediment concentration for site E1_1.**

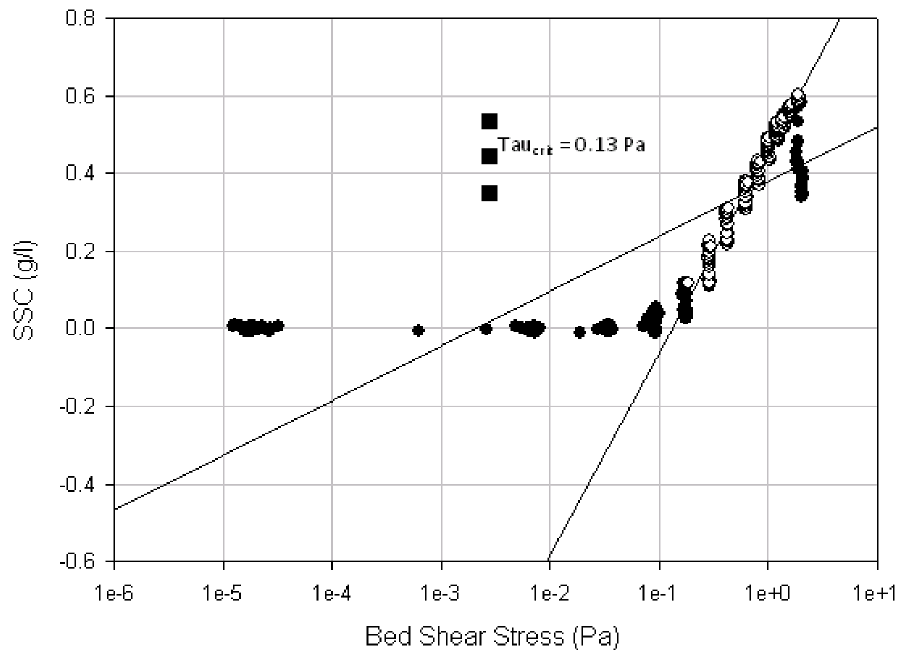


**Figure A.18 Estimations of the shear threshold for from the relationship between bed shear stress and suspended sediment concentration for site E1_2.**

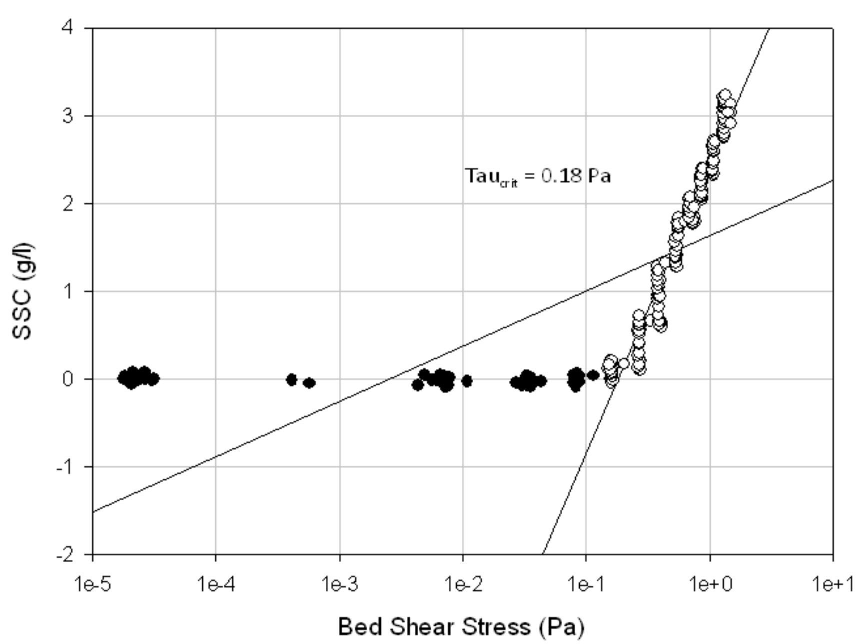


**Figure A.19 Estimations of the shear threshold for from the relationship between bed shear stress and suspended sediment concentration for site  E2_1.**

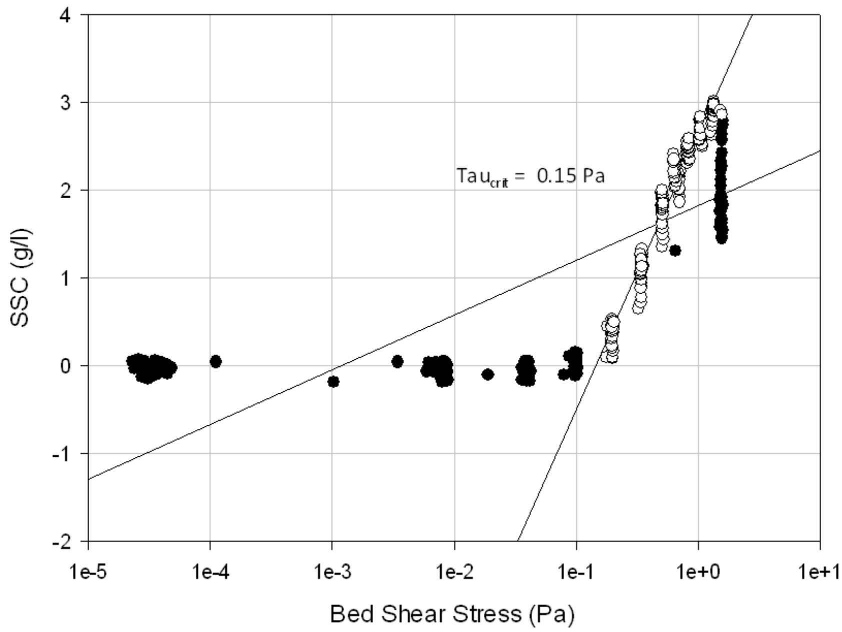


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**Figure A.20 Estimations of the shear threshold for from the relationship between bed shear stress and suspended sediment concentration for site E2_2.**

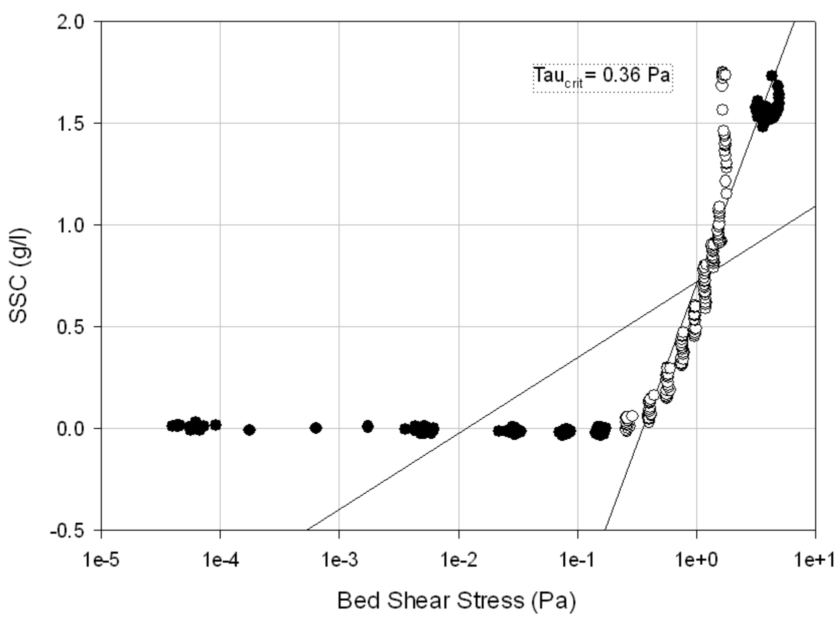


**Figure A.21 Estimations of the shear threshold for from the relationship between bed shear stress and suspended sediment concentration for site A1_1**

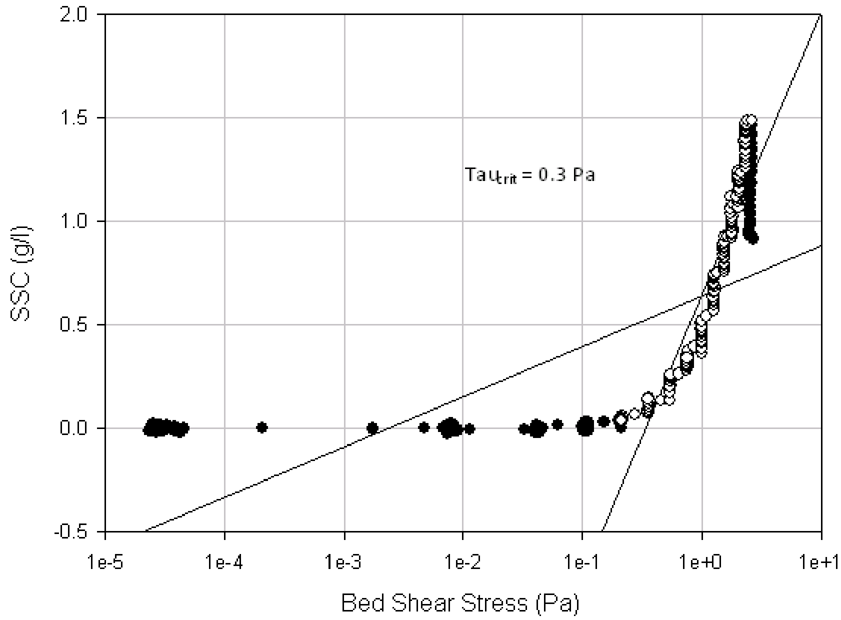


**Figure A.22 Estimations of the shear threshold for from the relationship between bed shear stress and suspended sediment concentration for site A1_2**

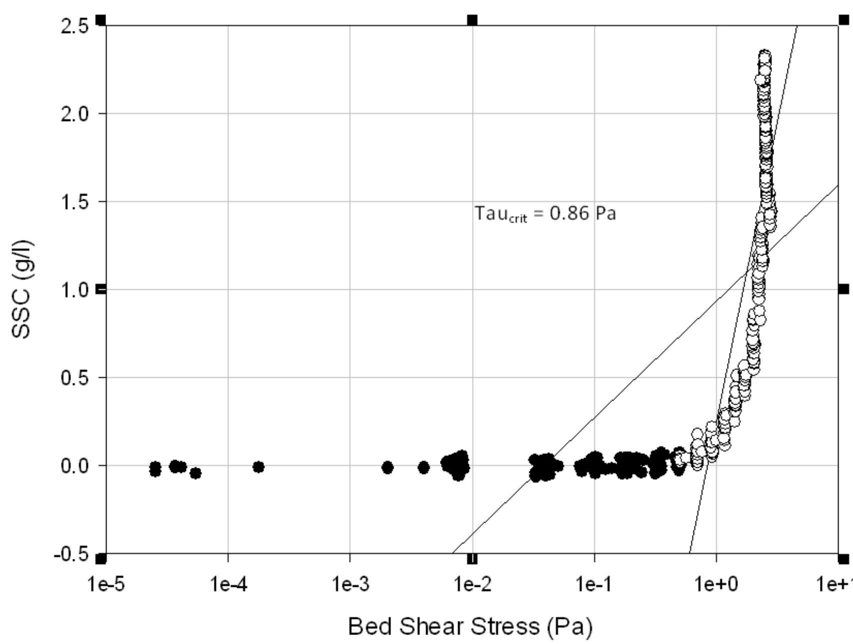


**Figure A.23 Estimations of the shear threshold for from the relationship between bed shear stress and suspended sediment concentration for site A2_1**

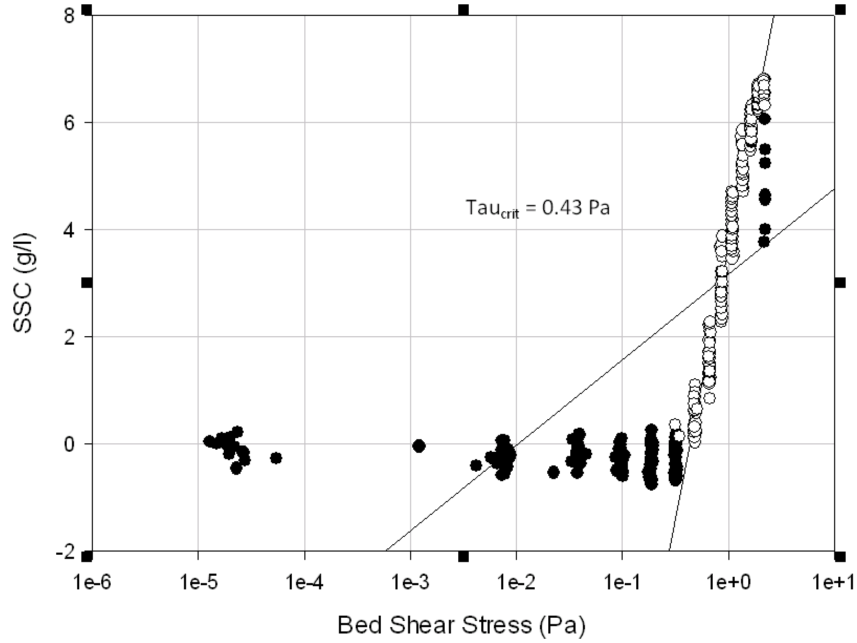


**Figure A.24 Estimations of the shear threshold for from the relationship between bed shear stress and suspended sediment concentration for site A2_2**

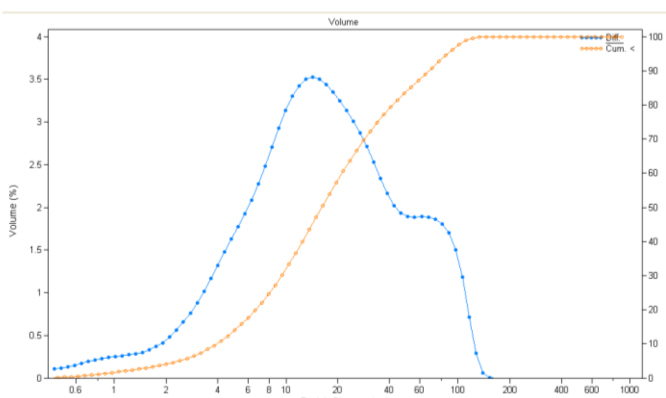


**Figure A.25 Sediment size distribution curve for site E1.( Diameter 50% 16.15µm)**

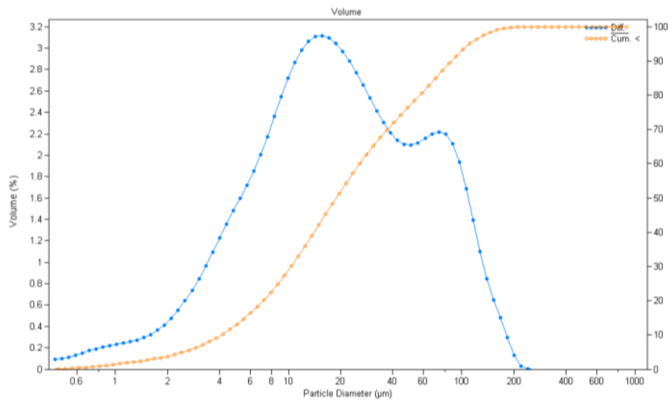


Figure A.26 Sediment size distribution curve for site E1_2 (Diameter 50% 18.87µm)

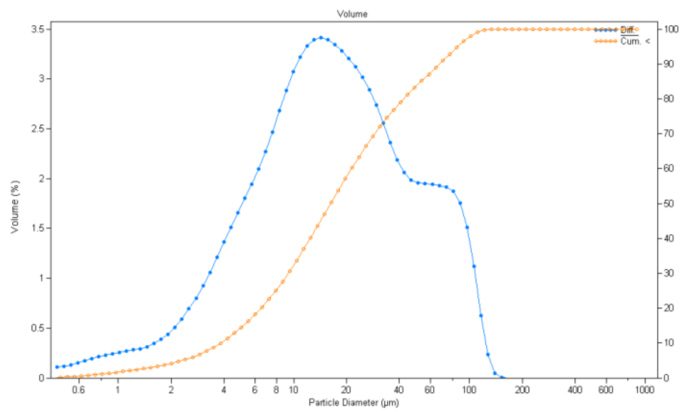


Figure A.27 Sediment size distribution curve for site E1_3(Diameter 50% 16.21µm)

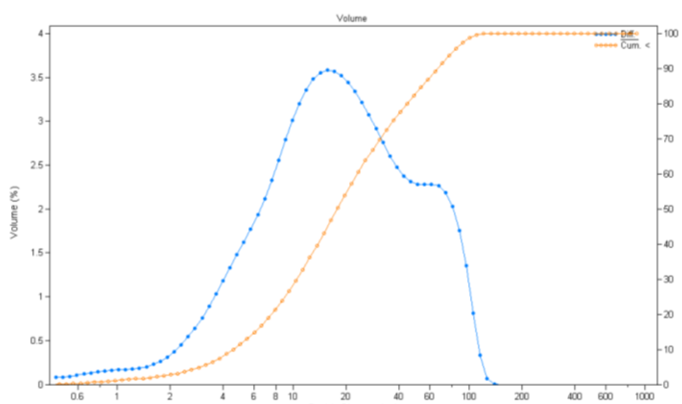


**Figure A.28 Sediment size distribution curve for site A1_1 (Diameter 50% 17.81µm)**

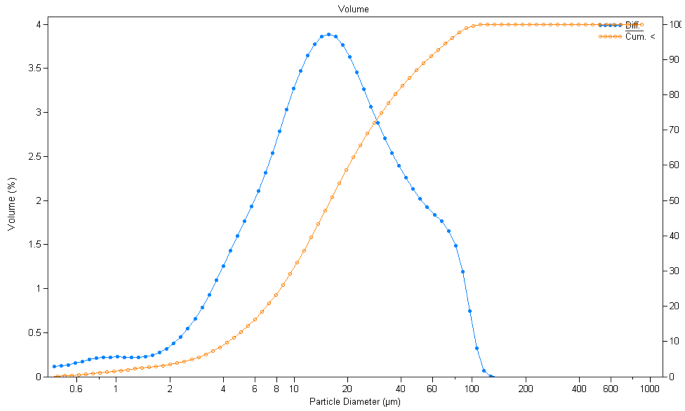


**Figure A.29 Sediment size distribution curve for site A1_2 (Diameter 50% 16.01µm)**

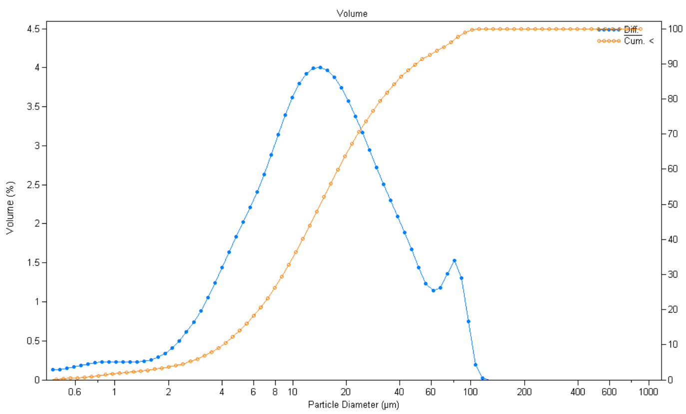


**Figure A.30 Sediment size distribution curve for site A1_3 (Diameter 50% 14.29µm)**

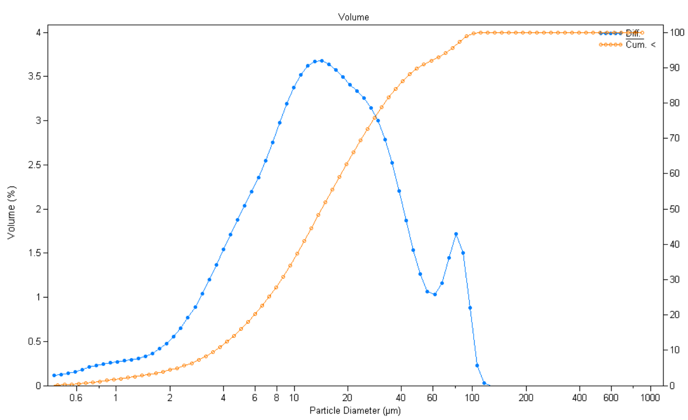


**Figure A.31 Sediment size distribution curve for site** A2_1 Diameter 50% 14.27µm

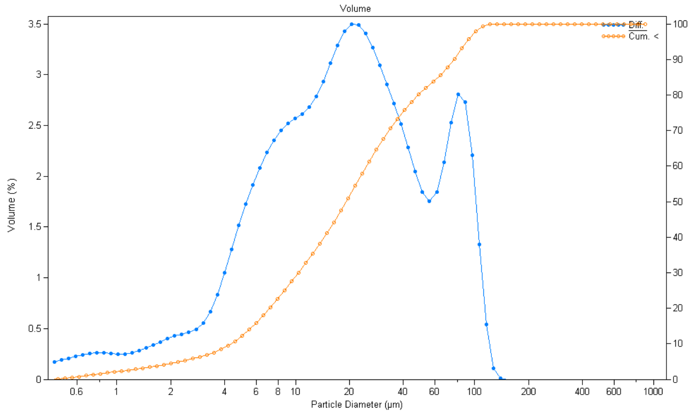


**Figure A.32 Sediment size distribution curve for site A2_2 Diameter 50% 19.81µm**

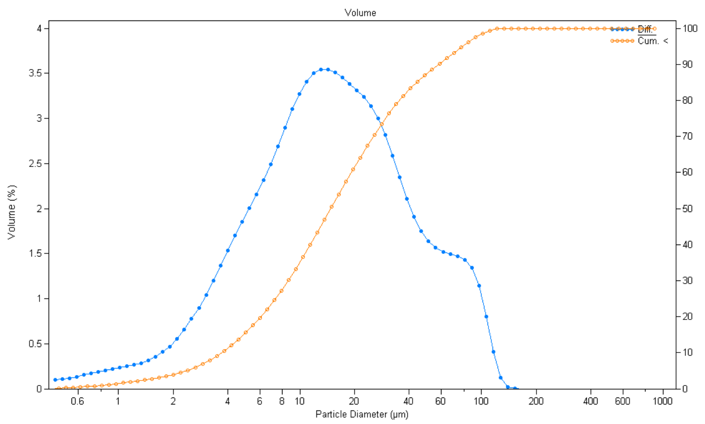


**Figure A.33 Sediment size distribution curve for site A2_3 Diameter 50% 14.77µm**