

**Estuary – coast interaction and  
morphodynamic evolution: a comparative  
analysis of three estuaries in southwest  
England**

By

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The thesis is submitted in partial fulfilment and conformity with the requirement for the degree of Doctor of Philosophy (PhD)

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## DECLARATION

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I, Temitope Dare Timothy **OYEDOTUN**, confirm and declare that the work presented in this thesis is my own. When information and data are derived from other sources, I confirm that such are indicated and acknowledged in the thesis.

*However, some parts of the work presented in this thesis are already published and presented in conferences (See Thesis output and appendices).*

Signed:  Date: 06/02/2015



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## THESIS OUTPUT

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### PEER REVIEWED PUBLICATIONS\*

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### CONFERENCE PRESENTATIONS

- 2014 5<sup>th</sup> CoastDoc Workshop at Center for Marine Environmental Sciences (MARUM) in Universität Bremen, Germany, from 29<sup>th</sup> – 30<sup>th</sup> September, 2014. Oral presentation: “*A comparative examination of historical morphodynamics of estuary-coast interaction in southwest England*”
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\*Papers published are included in the appendix.

**ABSTRACT**

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Investigations of geomorphology and morphodynamics within the coastal zone have tended to treat the open coast as an independent system to that of any neighbouring estuaries. This separation is also evident within shoreline management, which has traditionally been undertaken within the context of coastal cells or estuarine valleys. The focus of this research is a comparative analysis of morphodynamic behaviour and sedimentary characteristics of connected open-coast – estuary systems. The north coast of Cornwall, southwest England, is notably indented and dominated by bedrock cliff and shore platforms. However, it also comprises some broad embayments that accommodate estuarine valleys and open coast, typically sandy beaches. The region provides an ideal environment within which to assess broad-scale coastal change and the association between estuarine and open-coast morphodynamics. Furthermore, it provides an opportunity to consider regional coherence in coastal behaviour and to evaluate the relative importance of local physical context vs. regional climate forcing. The Hayle, the Gannel and the Camel estuaries that are located within St Ives, Crantock and Padstow bays respectively, have received considerable attention in terms of the impacts of mining on estuarine sedimentation. The impacts on sediment supply, sedimentology and mineralogy have been explored extensively in these past studies, however, very little consideration has been given to the nature of coastal geomorphology and coastal system dynamics. This PhD research explores mesoscale coastal dynamics, and evaluates coastal behaviour over decades to centuries in the context of climate and sea-level change.

Historical geomorphological evolution of these estuaries and their adjacent shorelines are examined to evaluate morphodynamic connectivity through the application of shoreline analysis tools (such as Digital Shoreline Analysis System (DSAS) and Location Probability Analysis). This study showed that low shoreline recession along the north Cornwall coast, where sediments are present, has attributed most to the significant sea-level rise in this region (no significant change was observed on rocky low water shorelines). The high water shoreline imposes a different pattern of change in response to constraining factors which are triggered by both environmental factors and historical human activities. Changes over contemporary time scales are focused on bedform movement into, within and landward of inlets and are primarily driven both by waves in the outer estuary/ebb delta region and by tides in the channels/flood delta region. The inlets, however, are largely fixed in position by the bedrock

valley, and channel dynamics within the estuary are dependent on the accommodation space provided by the valley.

Sedimentary linkages are also explored through the sedimentological and geochemical analysis of sediments sampled from the intertidal zone of these systems. Based on grain-size parameters, there is considerable homogeneity in the sediment populations specific to the sub-environments sampled and analysed. There is evidence of sediment mixing between estuarine and beach environments. Geochemical (XRF) and mineralogical composition of sediment indicate contamination by mine waste tailings in the estuaries resulting from major historical mining activities in the region with Sn, Cu, As and Zn as predominant in the Hayle, Pb and Zn in the Gannel and Sn, W, and Zr in the Camel estuaries.

This research presents a multidisciplinary approach that employs a range of computer and lab-based analyses to integrate geospatial resources (including published maps, chart archives, etc) and sedimentological characteristics (including grain size and XRF analyses). The thesis is the first comprehensive comparative investigation of the morphodynamic behaviour and sedimentology of these north Cornwall estuaries.

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**ABBREVIATIONS**

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BADC	-	British Atmospheric Data Centre
CCO	-	Channel Coast Observatory
DSAS	-	Digital Shoreline Analysis System
EGA	-	Expert Geomorphological Assessment
EPR	-	End Point Rate
ESRI	-	Environmental System Research Institute
GIS	-	Geographic Information Systems
GPS	-	Global Positioning System
HTA	-	Historical Trend Analysis
HWL	-	High Water Line
JNCC	-	Joint Nature Conservation Committee
LiDAR	-	Light Detection and Ranging
LPA	-	Location Probability Analysis
MHW	-	Mean High Water
MLW	-	Mean Low Water
NAO	-	North Atlantic Oscillation
NCC	-	Nature Conservancy Council
NSM	-	Net Shoreline Movement
ODN	-	Ordnance Datum Newlyn
OS	-	Ordnance Survey
PSMSL	-	Permanent Service for Mean Sea Level
SCE	-	Shoreline Change Envelope
SMPs	-	Shoreline Management Plans
SWAN	-	Simulating Waves Nearshore
SSSI	-	Sites of Special Scientific Interest
XRF	-	X-ray Fluorescence Spectrometry

# 1 INTRODUCTION

---

## 1.1 Coastal systems

The coastal environment, a triple conjunction of land, water and air, is a complex physical environment that requires a holistic / system approach (Carter, 1988). The seaward extent of coastal environment is characterised by the outer continental shelf (~200m depth) with the limit of territorial waters. This section of the coastal system can be referred to as the open-coast. It is mainly shaped by waves coming from the offshore zone and breaking at the nearshore zone (Dean and Dalrymple, 2002). Open coasts are impacted by issues such as beach and marine pollution (Jeftic *et al.*, 2009), shoreline recession and accretion (Oyegun, 1991; Albert and Jorge, 1998; Ado *et al.*, 2008; Brooks and Spencer, 2010; BaMasoud and Bryne, 2012), coastal erosion (Hanson *et al.*, 1984; Qu  lennec, 1987; Clayton, 1995; Cai *et al.*, 2009; Dhar and Nandargi, 2003; Galloway, 2009; Munji *et al.*, 2011; Lieske *et al.*, 2013; Koerth *et al.*, 2013), sea-level rise, saline intrusion and destabilisation (e.g. Bird, 1985; Dean and Dalrymple, 2002; Munji *et al.*, 2011; Teasdale *et al.*, 2011) and coastal flooding (Galloway, 2009; Munji *et al.*, 2011; Koerth *et al.*, 2013; Lieske *et al.*, 2013; Adamo *et al.*, 2014; Gallien, *et al.*, 2014). Coastal erosion and flooding are major global problems causing significant economic loss, ecological damage and various societal problems in coastal system environments. In Europe, these problems cause serious loss of properties, infrastructure and beach width annually costing millions of Euros in economic damage (European Commission, 2004; Marchand *et al.*, 2011).

Concerns is increasing over natural environmental forcing such as changes in storm surge frequency, sea-level and wave climate changes present acute ecological, environmental, morphological, sedimentological, and geochemical challenges within coastal environments (Komar, 1976; Davis, 1978; Carter, 1988; Pattiaratchi,(ed) 1996; Pye, 1996; Cabanes *et al.*, 2001; Dhar and Nandargi, 2003; Holgate and Woodworth, 2004; Blott *et al.*, 2006; Teasdale *et al.*, 2011). The implementation of hard coastal protective measures like flood defences on sandy coasts may be easy and long lasting (e.g. Anfuso *et al.*, 2011; Gallien, *et al.*, 2014); such may not be an easy task in a muddy coast (Saengsupavanich, 2013). However, the reality of a combination of increasing storminess (Donat *et al.*, 2011; Young *et al.*, 2011) and the continuous accelerating sea-level rise (Donnelly *et al.*, 2004) dictate the need to improve flood and erosion defences for the protection of coastal livelihoods and infrastructures (Bouma *et al.*, 2013). One recent proposal is the integration of nature into coastal defence schemes, that is, the integration of both the soft and hard options, which are observed to offer innovative and cost effective means of protecting the coast from the mirage of challenges and issues (Borsje *et al.*, 2011; Liqueste *et al.*, 2013; Temmerman *et al.*, 2013). Good examples of this innovation is exemplified by emphasising the role of coastal wetland and ecosystem

services in protecting shore lines (see Gedan *et al.*, 2011; Shepard *et al.*, 2011; Liqueste *et al.*, 2013). Current practices regarding flooding or erosion management show measures with local perspectives designs (Marchand, *et al.*, 2011). They are often in a reactive way without any regard for the larger temporal and spatial domination of coastal sediment or intrinsic processes which are at the root of the problem, especially in Europe (European Commission, 2004). Also, many countries lack or have weak coastal policy, lack sufficient funding, limited public understanding, consistent ad hoc arrangements at alleviating the impacts of erosion/flooding, data and field observations, etc is making it difficult for coastal managers/scientists to be able to address the coastal problems through the appropriate measures (Marchand, *et al.*, 2011; Gallien, *et al.*, 2014). As long as both anthropogenic and environmental forcing are ever present in coastal environments, studying them can never be exhaustive despite the challenges or problems confronting the system.

Similarly, estuaries, as the interface between the terrestrial and fluvial upland and the seaward wave- or tide- dominated regimes of the open coast (van Der Wal *et al.*, 2002) are complex system partly as a result of either the complexity of estuarine sediment dynamics and morphological evolution (Karunarathna *et al.*, 2008); their interaction with the physical dynamics of the open coast (Hibma *et al.*, 2004) or as a result of varied range of human activities (Pye, 1996). Estuaries are defined as a semi-enclosed or enclosed coastal water-body where marine waters are diluted by freshwater (Pritchard, 1967). Human needs for navigational purpose, training walls, port development, channel dredging, waste disposal into the estuarine environment and tidal power generation encourages pressing issues on estuaries, including flood defence, shoreline erosion, inlet instability as a result of sedimentation/morphodynamics, (Pye, 1996; van der Wal *et al.*, 2002; Blott *et al.*, 2006; Gallien, *et al.*, 2014). Most estuarine systems all over the world are under human-induced pressures which lead to a tension between economic activities and the integrity of the environment, for example, utilising estuaries for navigation routes (Schuttelaars *et al.*, 2013), mangrove destruction in paving way for agriculture, overexploitation for firewood and charcoal production (Barbier *et al.*, 2008; Clark, 1996; Granek and Ruttenberg, 2007; Masalu, 2000; Othman, 1994; Thampanya *et al.*, 2006; Saengsupavanich, 2013), excavation of ponds for aqua-cultural activities (Primavera, 2006), groundwater pumping and petroleum exploitation (Arthurton, 1998; Lin, 1996; Oyegun, 1993), or dredging/dam construction (Cooper *et al.*, 2001; Wang *et al.*, 2012). Loss of estuarine habitat (EEA, 2010), degradation in estuarine ecosystems like seagrasses (Bos *et al.*, 2008; Waycott *et al.*, 2009), salt marshes (Adam, 2002; Boorman, 1999), mangrove forests (Barbier *et al.*, 2008; Das and Vincent, 2009; Valiela *et al.*, 2001), saline water intrusion up rivers and estuaries (Cai, *et al.*, 2009), eutrophication and pollution of estuarine sediments and habitats (Chakraborty *et al.*, 2012; Rabalais *et al.*, 1996; Rabouille *et al.*, 2008; Seitzinger *et al.*, 2010), reclamation of estuarine wetlands (Costanza, *et al.*, 2008; Shepard *et al.*, 2011; Liqueste *et al.*, 2013), damage to wetland and biodiversity (Jing *et al.*, 2012), and destruction of sand dunes (Everard *et al.*,

2010). These are all examples of environmental and ecological problems associated with the estuarine environment.

The need to mitigate such problems lead to the development of estuarine protective measures. Options to protect and preserve the estuaries include soft and hard alternatives. The soft approach involves managing or protecting the estuaries through non-structural measures like artificially replanting of mangrove (mangrove reforestation) (Saengsupavanich, 2013), relocation of estuarine communities or creation of a set-back line (New South Wales Government, 1990; Sanò *et al.*, 2011), ecological engineering (Borsje *et al.*, 2011), and planned retreat (Abel *et al.*, 2011) among others. The arguments against soft options include the impracticality in reality of mangrove reforestation, for example, due to the longer time it takes for the mangrove to take roots, become strong and dense enough to withstand waves or protect intense coastal flooding (Saengsupavanich, 2013), even the mangrove may need hard coastal structures to dissipate waves, high currents and tides to increase their survival rate (Hashim *et al.*, 2010). The likely unwillingness of estuarine residents to move out of their homes in relocation is a challenge which hinder the soft options in many estuarine environments of the world. These challenges are obvious facts which encourage the implantation of hard alternatives that involve construction of hard fences and other engineering protective measures in order to immediately stop the estuarine erosion and flooding, while other management tools can be explored once the relative stability is achieved (Tamin *et al.*, 2011; Saengsupavanich, 2013).

### **1.1.1 The physical nature of coastal environments**

The key physical drivers of coastal processes and factors associated with coastal change are waves, tides, sea level change, sediment supply and the mediation of these by inherited or more slowly changing geological context/controls. Human intervention (coastal engineering such as coastal protection structures, marinas and commercial port development, land reclamation, river regulations works, unregulated dredging, etc) can impart significant control on these processes, particularly in terms of sediment budget. However, waves, storm surges, tides, wind parameters and oceanic circulations are the main processes that determine the physical nature of the coastal environment. These processes can co-exist either individually, in many cases, or in diverse interactions that drive the coastal processes (Longuet-Higgins and Stewart, 1960; Prandle and Wolf, 1978; Jansen, 1992; Bao, *et al.*, 2000; Welsh, *et al.*, 2000; Moon, 2005).

The changing nature of coastal environment is linked to significant shifts in wave and wind climates, which are key drivers of coastal change. Generation of storm surge, sea surface stress and coastal circulation are believed to be significantly influenced by wind and wave

(Janssen, 1992; Smith, *et al.*, 1992; Mastenbroek, *et al.*, 1993; Moon, 2005). Smith, *et al.*, (1992) show that the sea surface stress in the North Sea decreases as wave increases while Janssen (1991) and Moon *et al.*, (2003) show that increased ocean waves enhance the drag of airflow and surge in storm predictions and occurrences in a coastal environment. Similarly, significant surface coastal wave action is noted to influence the distribution of near-surface distributions of physical atmospheric and climatic properties such as temperature, velocity, salinity and ocean circulation (Kantha and Clayson, 2004; Mellor and Blumberg, 2004; Moon, 2005). Increased wave heights and the frequency of strong winds, especially in the North Atlantic to the north and west of the UK (Hadley, 2009) are reported in studies by Gulev and Hasse (1999), Gulev and Grigorieva (2004) and Alexander *et al.* (2005). Gulev and Hasse (1999) discovered that changes in swell height of the North Atlantic are consistent with increase in significant wave height. Gulev and Grigorieva (2004) note that the long-term changes in wind wave height of the North Atlantic is closely associated with both the North Atlantic and North Pacific Oscillation as well as El-Nino-Southern Oscillation in the Pacific. However, notable increases in wave height could not be attributed directly to influence of climate change or natural variability since other studies like Carretero *et al.* (1998) found comparability of the present wave and storm climate with what was obtainable at the beginning of the 20<sup>th</sup> Century (as reported in Hadley, 2009). What these findings suggest is that these physical processes are active in a coastal environment and their dynamics drive the changes in the system.

Diverse interaction in physical processes on the coastal environment are also obvious, especially the influence of physical parameters like tides, storm surges and oceanic currents. For example, tides and storms cause unsteady wind and wave propagation in the North Sea when the wave-current interactions are assessed (Tolman, 1991). These parameters are reported to also influence coastal wave scenarios in the Gulf Stream (Holthuijsen and Tolman, 1991; Komen *et al.*, 1994). Tides, wind waves, storms surges and oceanic circulations largely determine the nature of physical processes in the coastal system and drive morphodynamics (Moon, 2005). Although there have been efforts to separate and understand individual physical processes by a number of studies in the last few decades (e.g. Smith *et al.*, 1992; Janssen, 1989, 1991, 1992; Mastenbroek *et al.*, 1993; Zhang and Li, 1996, 1997, etc), however these processes interact and influence one another and also the coastal environment (Moon *et al.*, 2003; Moon, 2005). In another perspective, the non-linear interaction between tides and storm surges are demonstrated to affect the prediction of sea-levels in coastal environment (Tang *et al.* 1996) while Simmons, *et al.*, (2004) suggest that the interaction of tide and other physical parameters improve the coastal mixing processes in the coastal environment. This view is also supported by Schiller (2004) finding of the essential influence of tide in transportation and mixing processes in Indonesian coastal environment.

The 5<sup>th</sup> Assessment Report of Intergovernmental Panel on Climate Change (IPCC, 2013) reached a conclusion that the global average sea-level rose by an average of almost 2 mm yr<sup>-1</sup> in the 20th century, faster than preceding centuries, and also exhibiting evidence of continued acceleration during the 20th century. Also, evidence from coastal tide gauges and satellite radar altimetry has shown that the rate of sea-level rise has increased since the early 1990s to c. 3 mm yr<sup>-1</sup>. Sea-level rise remains one of the key driving mechanisms of coastal system over the mid- to long-term scale (Holgate and Woodworth, 2004; Church and White, 2006; and Hadley, 2009). In the last decade, as reported in Pickering, *et al.*, (2012), an accelerated rate of 3.1 mm yr<sup>-1</sup> is observed globally (Cazenave and Nerem, 2004; Holgate and Woodworth, 2004). These global trends are generally reflected in the UK-specific data (Hadley, 2009) with lower trends in Scotland principally as a result of impacts of uplift by post-glacial isostatic adjustment (Woodworth *et al.*, 1999). Post-glacial sea-level rise and eustasy are shown to experience long-term tectonic and isostatic vertical movements of coastal margins (Pirazzoli, 1976; Pitman, 1978; Flemmin, 1982; Leeder, 1988). Northern UK and Scandinavian coasts are reported to have longer geomorphological changes arising from these isostatic re-adjustments as a result of the Scottish and Scandinavian ice-sheets removal in the first half of the Holocene (e.g. Steers, 1946; Tooley, 1978). Such changes in sea-level have the potential to affect the tidal dynamics on coastlines, nearshore zone and shelf seas by possibly increasing the propagation speed and strength of tidal wave (Pickering *et al.*, 2013), although there may be different local responses in some coastal systems (see for example, Roos *et al.*, 2011; Pickering *et al.*, 2012; Shennan and Horton, 2002; Ward *et al.*, 2012).

Sediment dynamics in a coastal system is another physical nature of the coastal environments. The demand and supply, that is the transfer and the withdrawal, of sediments in a coastal system is rarely constant but continuous (Dean and Dalrymple, 2002). Coastal changes and morphodynamic evolution are determined, to an extent, by these sediment fluxes/movements. Recently, investigation of the rates and role of sediment transport processes are addressed in three studies: EUROSION (2004), Futurecoast (Burgess *et al.*, 2004) and Foresight Future Flooding (Evans *et al.*, 2004a). It is noted in the studies that the knowledge of the sediment fluxes and driving processes is very important not only for the management of flood and coastal defences, but also for the understanding and prediction of changes in coastal environment. The sediment flux determines the coastal changes and morphodynamic evolution of coastal features and environments. The transfer and the movement of sediments within the coastal system may be a result of many forcing mechanisms. The driving force behind these processes within a coastal system include: wave action, tidal currents, river and estuary flow and wind (Komar, 1976; Davis, 1978; Pethick, 1984; Carter, 1988). Though rivers may be supplying over 90% of the coastal sediment input (Pethick, 1984), dam construction is reducing this supply world-wide (Pye, 1997). The need to understand the physical processes governing the sediment erosion and deposition will always remain vital in the overall understanding of changes taking place in the coastal systems.

### 1.1.2 Scales of coastal morphodynamics

Many factors influence the shape, sediment transport, structure, morphological behaviour and dynamics in coastal environment – in response to changing environmental conditions and/or human interference (de Vriend, *et al.*, 1993). Notable of these factors are the physical process discussed in the previous section. Of importance to the morphodynamic processes in coastal environment is the adjustments in coastal system. Wright and Thom (1977) defined coastal morphodynamics as the ‘mutual adjustment of topography and fluid dynamics involving sediment transport’ while de Vriend (1991) defined it as the ‘dynamic behaviour of alluvial boundaries of fluid motion’. Combined effects of the processes in the evolution of coastal landforms are inherently non-linear and time dependent (Cowell and Thom, 1994). It is articulated by Wright and Thom (1977) that the mutual interaction between coastal landforms and coastal processes influence morphodynamic evolution over a broad range of spatial and temporal (time) scales (French, 1997).

Table 1.1 presents a summary of time-scales and processes that constantly shape and re-work coastal systems. These scales at which the coastal processes interplay and operate can be grouped into four classes or dimensions based on the considerations presented by Stive *et al.*, (1991), de Vriend (1991) and Cowell and Thom (1994). ‘*Instantaneous*’ time involves the morphodynamic processes of a cycle of primary physical forcing agents, such as tidal cycles, waves, currents. Absolute time-scale of the operating process is in seconds, minutes, hours and days, and this relate to coupling of morphology and fluid flows which can cause sediment grain movement. ‘*Event*’ scale operate at time span of single event which forces morphological changes in the coastal system. Such event could be storm surge or seasonal variations in physical conditions and can ‘comprise time-averaged effects of instantaneous process during a single fluctuation’ (Cowell and Thom, 1994:36). ‘*Engineering or historical*’ time-scales entail many cycles of processes causing sediment movements/transport, formation and loss of habitats, salt marshes or dunes, etc. Absolute time-scale of this period involves decades–centuries evolution or longer-term forcing, such as sea-level change (meso-scale dynamics). ‘*Geological*’ scales involve the continuous trends in environmental conditions with less dependence on individual or instantaneous fluctuations. The morphodynamic process (for example, relative sea-level response to glaciations) is at an absolute millennial time scale.

**Table 1.1 Time scale of coastal changes in relation to both absolute and human times-  
Source: French (1997: 9)**

Absolute time scale	Human time scale	Coastal processes
Millenia		Response of sea level to glaciation
Centuries	Shifts in settlement and industry	History coastal change- loss of towns and villages
Decades	Coastal engineering and protection	Formation and loss of habitats- marshes, dunes, etc
Years	Coastal engineering and protection	Effects of protection works, longshore drift
Months	Impacts of tourism	Seasonal adjustments, shore profiles
Weeks	Impacts of tourism, emergency coastal protection works, extraction	Shore profiles, spring-neap, tidal cycles
Days	Emergency flood protection works	Storm surges, defence breaches
Hours	Sewage, litter	Tidal cycles
Minutes		Wave and currents
Seconds		Sediment grain movement

### 1.1.3 Process framework

Sedimentary system, ‘as a set of deposits formed in one geomorphological environment (e.g. estuary, coastal embayment, or submarine canyon’ (Gao and Collins, 2014:268)) are beneficial in the understanding and establishment of process framework or environmental condition in a coastal system (Ijmker *et al.*, 2012). The nature of sediments in a coastal environment reflects the operation of sedimentary transport processes at spatial (local, regional) or temporal time scales (Anthony and Héquette, 2007). As the nature of processes such as tidal, wave and fluvial regimes are important in the understanding and classification of morphodynamics in coastal systems (e.g. Dalrymple *et al.*, 1992; Burningham, 2008), the significance of sediment structures and controls on coastal environment should not be ignored as they exhibit considerable dynamicity that are attributed to short-term events, long-term-forcing, historical/geological controls or anthropogenic modifications (e.g. Burningham, 2008).

There are many sources and sinks of coastal sediments, including those derived from cliff and shore erosion, supplied by/from the rivers, washed in from alongshore, blown from the land, washed in from the sea floor, from artificial nourishment and waster tipping, or from biogenic sources like from corals, sabellariids, diatoms, and other marine organisms that supply skeletal material to coastal sediments (e.g. Komar, 1976; Davis, 1978; Bird, 1996; Dyer, 1986; Carter, 1988; Dyer, 1986; Dean and Dalrymple, 2002). The sediment sources can be categorised into primary or secondary depending on the process leading to its source (Boggs, 2001). Generally, sediments are transported from the regions of higher to lower energy, suggesting that exposed sections of open-coast are more likely to experience consistent erosion unless supplied with sediments from other higher sources (Carter, 1988). Sheltered embayments and estuaries, on the other hand, are expected to be sediment sinks for eroded materials as a result of minimal energy in such system (e.g. Brew *et al.*, 2000).



Apart from the key drivers of coastal processes which exert control on estuarine and coastal morphology, the inherited antecedent framework such as drainage patterns (e.g. Fitzgerald, *et al.*, 2002; Bertin, *et al.*, 2004), valley character (e.g. Roy *et al.*, 2001), accommodation space (e.g. Heap and Nichol, 1997), and sea-bed geology (e.g. McNinch, 2004) also exert control on the geomorphic evolution on the estuarine system. These examples demonstrate that more than physical processes are important in the process-response and geomorphic sensitivity in coastal system framework.

Consequently, coastal seas and estuaries have had a long and varied history of anthropogenic interference. They have served as a viable source of many valuable resources for economic, social and recreational activities (Pattiaratchi, 1996). In the distant past, the coastal environment provided food and security (Carter, 1988) but as human needs advanced, the demands and use of the coasts increase and become more varied. Most of the world's largest and economically active cities are located in the coastal zone and it is also the region to which anthropogenic wastes are discharged (Jeftic *et al.*, 2009). Goldberg (1994) states that 50% of the world's population lives within 1km of the coastal zone, and this population is predicted to grow at a rate of about 1.5% during the next decade. An alternative analysis by Cai *et al.* (2009) places two-thirds of the world's major cities with over 60% of the population and significantly higher levels of economic activity within in the coastal zone. The works of Reclus (1873), Wheeler (1902), Owens and Case (1908), Johnson (1919), Stamp (1939) and Steers (1946) are examples of early investigations into the complex development of coastal environments and their complicated relationship with human society. It is argued that if humans had not sought to make use of the coastal environment/zone, there would have been few environmental problems (Clayton, 1995). Thus the presence of humans in the coastal environment is argued to interfere and modify the coastal systems and causing many environmental challenges in many parts of the world (Viles and Spencer, 1995). One of the pressing challenges is coastal erosion (e.g. Dhar and Nandargi, 2003; Galloway, 2009; Munji *et al.*, 2011; Lieske *et al.*, 2013; Koerth *et al.*, 2013). However, in term of process framework, anthropogenic interference in coastal system control manifests itself in modification of wave, tidal and fluvial regimes and alteration of sediment supply (e.g. Nordstrom and Roman, 1996; Albert and Jorge, 1998; Pye, 1996; Blott, *et al.*, 2006; Royo, *et al.*, 2009; Komar, 2010).

## 1.2 Estuary-coast interaction

Estuaries are generally considered as sinks or sources (in timescales, mechanisms, etc) for sediment and associated particle-reactive pollutants in their role as they interface between rivers and ocean (Pethick, 1984; Perillo, 1995; Rees *et al.*, 2000; Rogers and Woodroffe, 2012; Viguri *et al.*, 2002; Yang, *et al.*, 2006). Estuarine interaction with the open-coast occurs

on different levels: this can be hydrodynamic (prism effects, asymmetry, littoral drift etc – for example, Bruun and Gerritsen, 1960; Uncles *et al.*, 2006; Manning *et al.*, 2010) but can also involve sediments (e.g. Allen *et al.*, 1980; Coulombier *et al.*, 2013; Lawler, 2005; Mitchell *et al.*, 2003; Rees *et al.*, 2000; Rogers and Woodroffe, 2012; Ruhl *et al.*, 2001; Townend and Whitehead, 2003). Tidal deltas, and associated sediment bypassing processes and exchanges with adjacent beaches exert significant influence on the morphodynamics of estuary-coast processes (Hayes, 1975; FitzGerald, 1988; Hicks and Hume, 1996; Hicks *et al.*, 1999; FitzGerald *et al.*, 2000b; Gaudio and Kana, 2001; Burningham and French, 2006). There are, however, complex responses and the challenge of separating intrinsic from extrinsic controls on system behaviour. For example, extrinsic forcing is of importance in estuaries, especially as it affects the residence time of materials in the estuary and the estuarine morphological development (Pattiaratchi, 1996). In Jervis Bay (East Coast of Australia), the flow structure and water exchange through the estuary entrance is dominated by low frequency circulations during exchange processes, thus enhancing the flushing of the coastal embayment (Holloway, 1996). At Mobile Bay, Texas USA, on other hand, upwelling occurs at the landward extent as a result of wind-driven estuarine-coast exchange processes which leads to the deposition of warm saline water in the estuary (Schroede *et al.*, 1996). The internal tidal asymmetry plays an important role in sediment and salt balance that cause the landward, near-bed transport at the residual and over-tide frequencies in the Columbia River estuary (Jay and Musiak, 1996). These examples indicate that the mixing and transport processes during water and sediment exchanges between estuary and open-coast affect conservative materials within the system. These linkages can therefore play important roles in the morphological development of landforms within the coastal system.

Estuaries are important component of coastal systems, themselves often comprising a significant suite of coastal landforms. Coastal research is replete with studies of estuarine environments, but often in isolation from the neighbouring open-coast environments. Geomorphologically, estuaries are a significant component of the coastal system due to their importance as sediment source and sink (Pethick, 1984; Perillo, 1995). Estuaries worldwide are exposed to an increasingly complex suite of environmental perturbations originating within their watershed and externally from climatic forcings (Wetz and Yoskowitz, 2013). They are also heavily used and, in most regions, contain larger proportions of land at risk from flood risk than the open-coast. Typically, estuaries are sensitive to change, combining threats from the terrestrial and the ocean side (Monbaliu *et al.*, 2014). Certainly the potential in estuaries for sediment mobilisation (e.g. wave breaking, fluidisation of the bed, erosion by currents, pick up by wind, fluvial input, side slope subsidence, etc), advection (e.g. tidal current, near bed flow, density current, wave-driven flow, meteorological induced flow, vessel induced currents, etc) and deposition (e.g. reduction of wave breaking and wave-driven flows, deposition from suspension and interception of side slope subsidence) mechanisms make them sensitive to changes in the broader coastal environment (Monbaliu *et al.*, 2014).

The topographic features of a coastal valley and the vertical distribution of the accommodation space influence the sedimentary evolution of an estuary (e.g. Heap and Nichol, 1997). This suggests that estuary behaviour is not always a strict product of wave-tidal-fluvial regimes alone (Burningham, 2008). Burningham (2008), for example, demonstrated that there is a complex response to the historical behaviour of the mixed energy and mixed sediment estuaries while examining the ebb channel dynamics in the Loughros estuaries of northwest Ireland. Three phases of geomorphic response were identified for the 172 year history: - a steady state of equilibrium which characterised the 19<sup>th</sup> century, - a subsequent period of dynamic response to sudden extrinsic forcing, and, - adjustments to intrinsically forced changes in the structural control of the estuary. It was argued that the combinations of 'extrinsic forcing mechanism' and 'intrinsic structural controls' drive historical controls on estuary morphodynamics. The author concluded by advising that the systems largely unaffected by human impacts be examined so as to form a wider understanding of coastal morphodynamics in an age dominated by discussion on anthropogenic influence on coastal environments.

The examples presented in this section illustrate the complexities of estuary-coast connectivity and justify the reason for further work to advance our knowledge of the processes governing estuarine morphodynamic behaviour, especially at historical and contemporary timescales. The inherent complexities of estuary-coast systems, especially in relation to the physical processes, sediment movement and geomorphological changes present a range of challenges. The present understanding that the sea-level has risen since the mid-20<sup>th</sup> Century (Cabanes *et al.*, 2001; Holgate and Woodworth, 2004; Woodworth *et al.*, 2009; Teasdale *et al.*, 2011) is also adding to the debate on how this phenomenon is having effects on contemporary coastal systems.

There is thus a need for a more integrated approach whereby the connectivity between adjacent estuarine systems is explicitly considered. Hitherto, specific estuaries and adjacent coasts have tended to be studied in isolation rather than as interacting phenomena at a regional scale. This piecemeal approach tends to neglect the potential for coeval behaviour of adjacent estuaries. No meaningful appreciation of system behaviour, or predictions of future morphological changes, can be made if the processes which led to the present form are poorly understood. There is a need for adequate understanding of the evolution of the present form as well as the present-day physical processes operating across and between estuaries and open-coast. This research, therefore, seeks to provide an avenue to explore the morphological changes occasioned by the relationship/interactions between adjacent systems as a way of separating externally-forced changes from their internal dynamics.

### **1.2.1 Process linkages**

Geomorphological dynamics and physical processes affecting the interaction between open-coast and estuaries are unique and have therefore received attention of recent researchers. The scientific attention is partly as a result of the complexity of estuarine dynamics (Karunaratna *et al.*, 2008) and their interaction with the physical dynamics of the open coast (Hibma *et al.*, 2004) and varied range of human activities (Pye, 1996). Sediment exchange between the estuary and open-coast depends critically on many factors; for example, on the dynamics of inlets and the processes within/around the inlets (Aubrey, *et al.*, 1993); the intermittent estuary-coast entrances (Haines, *et al.*, 2006; Morris and Turner, 2010; and Natesan, *et al.*, 2014); the pattern of inlet movement and stability (Walton and Adams, 1976; Chandramohan and Nayak, 1994); the transport forcing or process circulation pattern that drive the geomorphologic changes and the connected processes around the inlets which drive linkages between the estuary and the coast (Panda, *et al.*, 2013).

The process linkage between estuary and open-coast is maintained by tides (e.g. Escoffier, 1940), dynamic equilibrium of inlet (e.g. Natesan, *et al.*, 2014), littoral drift (e.g. Chandramohan and Nayak, 1994), wave regimes through the inlet in a wave-dominated coastal environments (e.g. FitzGerald, 1988), and, through exchange of sediment supply to the open-coast/adjacent beaches and the backbarrier systems (FitzGerald, 1988). Estuary-coast system linkages are stated by many authors to be impacted by tidal flow or wave dominance in the system (e.g. Oertel, 1972; Hayes, 1979; FitzGerald, 1996; FitzGerald, *et al.*, 2002; Morris, *et al.*, 2001, 2004). Evaluation of this linkage is fundamental in understanding the function and evolution of estuary-coast interaction in the overall coastal system in many ways. Firstly, this process determines the exchange of sediment between the open-coast and estuaries (Smith, *et al.*, 2008). Secondly, it determines the influence of coastal processes in the vicinity of the inlet (e.g. Davis and Fox, 1981; Dallas and Barnard, 2011). Thirdly, it can influence the partial or total wave sheltering of adjacent coastline, and thereby indirectly/directly reduce shoreline erosion and increase shoreline accretion (e.g. Marino and Mehta, 1987). Fourthly, the evaluation of the linkage process can show the dynamic balance between the dominant tidal regime within estuarine system and wave processes at the open coast. This kind of evaluation can determine the ebb-delta morphology and the impacts/effects of ebb-tidal currents, which can lead to the inducement of either net-onshore or net-offshore directed sediments movement (e.g. Hayes, 1975; Walton and Adams, 1976; Dallas and Barnard, 2011). Fifthly, the morphodynamic coupling between ebb-tidal delta, back-barrier system (estuaries) and inlet throats – all of which remain in constant and dynamic equilibrium in response to large scale hydraulic forcing, collectively or individually, make the estuary-coast process linkage key element in behaviour and evolution of coastal system (e.g. Dean, 1988; Stive, *et al.*, 1998; Stive and Wang, 2003; Elias and van der Spek, 2006).

Elias and van der Spek (2006), while writing on the tidal inlet morphodynamics, note that the change in the equilibrium state in any of the estuary-coast components will effect sediment

exchange within and between the other parts of the components. The change can cause small scale/temporary delivery or storage of sediments in compensating the equilibrium or it may be impacted by the large scale natural forcing such as sea-level rise, storm surges, tsunamis, etc or by the anthropogenic intervention such as damming part of the estuarine system, construction of ports/jetties in the system – the impact of which can cause the entire inlet system to evolve a new equilibrium. Other studies also note that the relative wave vs. tidal energy are mostly important in changing the equilibrium morphology in the system. It is noted that the wave dominated ebb tidal system pushes coastal system towards the inlet throat while the tide-dominated energy pushes the system offshore (e.g. Brunn and Gerritsen, 1959; FitzGerald, 1982, 1988, 2000a). This form of sediment by-passing and sediment exchanges under mixed energy condition explain the morphodynamic and stability of inlet throat, the movement of ebb channels, and the evolution of coastlines. Other factors which play prominent role in this linkage process and behaviour in equilibrium maintenance include: amount and nature of sediment supply, sedimentation history, bedrock layers, basing geometry, freshwater discharges by the rivers, increase in water extractions upstream for irrigation purposes, etc (FitzGerald, 1996; Shuttleworth, *et al.*, 2005; Elias and van der Spek, 2006).

Stability of forcing in the system and estuary-coast equilibrium relationship can also be related to the concept of tidal prism. Average velocity over a tidal cycle (e.g. O'Brien, 1931, 1969), the longshore transport (e.g. Brunn, *et al.*, 1978), and the effectiveness of the relationship between average velocity, longshore transport, throat area and peak discharge (after Hume and Herdendorf, 1992) are effective indicators of equilibrium and stability of tidal prism (that is, the volumes of fluid into the inlet that are generally between the mean high and low tides). According to Fontolan, *et al.* (2007), in consideration of the relationship between tidal inlets and dynamics of estuarine-coastal system, the hydrodynamic equilibrium of tidal inlets predicts and determines ebb-delta growth, especially in cases where there is no significant alteration of morphology of the inlet. This study showed that the tidal discharge is closely related to the size, structure and modification of tidal inlet, which directly/indirectly correlates with the driving force in the dynamics of the linkages/interactions.

Therefore, in terms of process linkage, tidal inlets that are hydronomically controlled by interaction of tides, waves and rivers as the driving process (Boothroyd, 1985; Burningham and French, 2006) and the nature of sediment in movement (FitzGerald, *et al.*, 2002) exert significant influence on the morphodynamics of the estuary-coast systems.

### **1.2.2 Estuary mouth and inlet dynamics**

Inlets, as the common features in the estuarine coastal system, are highly important and significant in sediment exchange in estuary-coast system as they have great influence on the environment and ecological components of the system (Siegle *et al.*, 2007). Inlets are defined

as ‘the passage between the ocean and adjacent estuary or lagoon, encompassing the channel and associated sediment bodies’ (Hayes, 1980; Siegle *et al.*, 2007). Specifically, the tidal inlet is defined as the narrow waterway that connects an estuary, a bay, a lagoon to open-coast or the ocean and is maintained by tidal currents (Watt, 1905; Chapman, 1923; Brown, 1928; O’Brien, 1931; Escoffier, 1940; Dissanayake *et al.*, 2009; Natesan *et al.*, 2014). It is principally the opening by which water, sediments, nutrients, etc are exchanged between the open-coast/sea and the backbarrier basin (Elias and van der Spek, 2006). The investigation of inlet has been a subject in coastal research since the 1930s with the study of stability of inlets in the USA by O’Brien (1931, 1969). Inlet channels are very important in the supply and accumulation of eroded sediments at the seaward (coastal section) and the landward section of the system where the flow velocities subside after passing through the often narrow inlet throat (that is at the ebb- and flood- tidal delta respectively) (Elias and van der Spek, 2006). Tidal inlets, according to Hayes (1979), usually occur in meso-tidal environments and they are noted for a moderate wave energy of c. 0.6 – 1.5m (Castelle, *et al.*, 2007) and they are found in major part of the world’s sediment coastlines (Elias and van der Spek, 2006).

Cross-sectional area of inlets and the state of forcing parameters significantly influence the linkage process in coastal system. Therefore, inlet remains significant in estuary-coast interaction because of the physical processes acting in the system (Komar, 1996). Past studies have explored the influence the inlet system exerts on various driving processes in the context of estuary-coast interaction. Examples of the earlier studies include: Fitzgerald, *et al.* (1979) which suggest that the tidal inlet body shelter wave propagation in the estuary; Hayes and Kana (1976)’s observation of littoral drift which are trapped at the downdrift side of the ebb delta as a result of wave refraction. Other influence of inlet reported include the trapping of beach sand on the estuaries and delta as a result of littoral drift bypassing (e.g. Fitzgerald and Hayes, 1980; Fitzgerald, 1984). The growth of sediment complexes at the ebb delta platform as well as its characteristics erosion and deposition cycles that emphasise the influence of temporal and spatial scale in inlet processes are other findings from Fitzgerald and Hayes, (1980); Fitzgerald (1988). Hicks, *et al.* (1999) monitored the mixed energy (principally tide dominated) inlets and observed the quasi-annual signal as a result of the reflection of cross-shore sediments forced by storm waves and the reversal of longshore transport processes at the inter-annual time scales. While the longshore process is observed to cause the sediment oscillation between the two headlands along the open coast, the refraction-induced transport processes cause the divergence of erosion and accretion at the inlet system (or ebb-delta system).

Further importance of inlet in estuary-coastal system is the possibility of choking. As waves propagate from the open coast through the inlet into the estuary, there is possibility of decrease in tidal-wave amplitudes which can result into the development of phase lags relative to the coastal sea-surface fluctuations (MacMahan, *et al.*, 2014). Such tidal choking

influences the ability of estuary in transportation and flushing (Kjerfve, 1986; Hill, 1994); in the damping of high-frequency tidal energy (Keulegan, 1967); in varying ebb channel water depths (Hill, 1994); in acting as a hydraulic low-pass filter and responses between the estuary and the ocean (Di Lorenzo, 1988; Kjerfve and Knoppers, 1991; MacMahan, *et al.*, 2014), and in the decay of amplitudes of semi-diurnal tidal fluctuations (MacMahan, *et al.*, 2014).

The seasonality of some inlets in enforcing geomorphological response in estuary-coast interaction are also reported in the literature. Examples of such seasonal inlet systems reportage are in Brunn, (1986) for Krishnapantnam/Ponnai inlets in India; Hodgkin and Clark (1988) on the inlets in Western Australia; Gordon (1990) on Wollumboola inlets of New South Wales in Australia. Other works include Cooper (1994), Newton and Mudge (2005), Bertin, *et al.* (2005), and Sennes, *et al.*, (2007), etc. These inlets are sealed by the formation of sand bar at the coastal entrance of the estuaries during the summer time when the stream flow into the estuaries is very low or non-existence, or when the swell waves dominate the open coast for a long period without its penetration into the estuaries or as a result of the increase in the rate of sediment transport longshore-ward. During this seasonal dynamics, there is deterioration in the use of estuaries for ecological or anthropogenic purpose - except it is maintained through the intervention like dredging so as to sustain the navigability purpose of the inlet (the cost of which are mostly high). Other effects of this sort of seasonal inlet dynamics on the estuary-coastal system are: the reservation of sediments for beach nourishments (e.g. Castelle, *et al.*, 2006, 2007), encouragement of littoral stability adjacent to the inlets (e.g. Elias, *et al.*, 2006), the need for replacement of water in the estuaries/lagoons in an environment where they are being used for aquaculture (e.g. Bertin, *et al.*, 2005), and the problem of water quality maintenance in the system (e.g. Newton and Mudge, 2005). Dynamicity of inlet system shows that inlets are very important in the overall estuary-coast interaction and the overall coastal system dominant processes.

The complexities of the processes at the inlet have been emphasised in this section based principally on the transport, sedimentological, morphological and hydrological parameters. Importance of the inlets in understanding the estuary-coast interaction processes remain primarily in the area where waves, tides and rivers interact (Boothroyd, 1985; Burningham and French, 2006) while also acting as the conduit for the movement of sediments. The inlet exerts significant influence on the morphodynamics of adjacent shorelines (FitzGerald, 1988; Hicks *et al.*, 1999), the interruption of the continuity of longshore sediment transport and exchange of sediments between both landward and seaward shoals (Burningham and French, 2006), therefore constitute important small system within the overall coastal system consideration.

### 1.3 Management perspectives - UK coasts and estuaries

The United Kingdom (UK) is a coast-dominated country and is relatively well endowed with estuaries on the account of its varied geology. From the coastline of England and Wales, the furthest point is only 110 km while the large proportion of the UK population lives within the 10 km of the coast (Environmental Agency, 1999; Hadley, 2009). The varied geology of the UK imparts varying degrees of structural control and varied sediment regimes (mud, sand, gravel, etc). The distribution of different rock types, the direction of tectonic movements and the rate of tectonic activities account for the much of the varied nature of physical processes and morphodynamic changes at the coast (Pye, 1997). The combination of these activities has a significant influence on the quantity and type of sediments supplied to the coastal zone (Pye and Neal, 1994). Geologically, Britain can be divided into two major parts based on its lithological features and relief 'along a line drawn approximately from the Tees to Lyme Bay' (Pye, 1997). To the west and north, lithologies are dominated by hard rock of igneous and metamorphic composition ranging from Precambrian to Triassic. To the east and south of this divide, sedimentary rocks are mainly Cretaceous to Holocene in age (Pye, 1997). This geological framework, to a large degree, accounts for a broad scale of widespread subsidence in southeast England from the beginning of the Mesozoic era, causing submergence of river valleys and estuaries, such as that of Severn (Pye and Neal, 1994).

As the coasts are constantly changing in a variety of ways through the interaction of land and sea, this has given rise to dynamic and diverse geomorphological and geographical features including soft shores, rocky shores and cliffs, narrow and wide coastal shelves, hilly or flat coastal plains and a wide variety of wetlands (Hadley, 2009). The varied coastal processes and climate in the UK cause the complexity of tidal regimes (amphidromes), wave climate and regional variation in sea level history.

The UK has a particularly large number of estuaries (in excess of a hundred), equating to more than a quarter of northwest European estuaries by area (HR Wallingford *et al.*, 2006). In all, 163 estuaries were identified and classified (ABPMER *et al.*, 2008: 25-28). Many research works are reported on the estuaries and coastlines of the UK. Examples of the research on some of the estuaries include the works of Pye (1996), van der Wal *et al.* (2002), Blott *et al.* (2006), van der Wal & Pye, 2004; Nicholls *et al.*, 2000; Burningham and French, 2008, etc. Of all the estuaries in the UK, Thames estuary is one of the few which is extensively studied (see, for example, van der Wal & Pye, 2004; Nicholls *et al.*, 2000; Burningham and French, 2008). Key issues which are widely reported in literatures about UK estuaries include shoreline change; shifts in bank and channel configurations; changes in sediment volumes; changes in sediment transportation between the inner estuary and outer estuary; the constant and continuous subjection of estuaries to both spatial and temporal sequence of changes in response to both physical and human activities; channels infilling; that anthropogenic



activities are outstripping natural forcing factors in causing the morphological changes in some of the estuaries; etc. Also, the combined forces of sea-level rise (Woodworth *et al.*, 1999; Holgate and Woodworth, 2004; Church and White, 2006), storminess (Alexander *et al.*, 2005) and anthropogenic activities are another cogent issues which also drive interest in UK estuaries.

Similarly, some research on UK coasts is well reported in the literature. Examples of the research on some of the coastlines include Esteves, *et al.*, (2009), Burgess *et al.*, 2004; Evans *et al.*, 2004b. Quantification and management of shoreline changes along the Sefton Coast in UK is the focus of Esteves *et al.* (2009). The Sefton coast, which is between Mersey and Ribble estuaries in northwest England, is stated to be rapidly eroding in the last century, although the rate of erosion are differ at one point to another. Coastline erosion in the UK has had several recent major studies (Halcrow Group Ltd *et al.*, 2001; EUROVISION, 2004; Burgess *et al.*, 2004; Evans *et al.*, 2004b). These confirmed that about 28% of the coastline in England and Wales are currently undergoing erosion rates which are greater than 10 cm year<sup>-1</sup> based on the detailed and substantial analyses of rates and location of erosion around the UK.

Although open-coastal and estuarine areas can be ecologically, environmentally, socially and economically rich, sea-level rise (causing higher and extreme water levels), adverse atmospheric situation causing coastal flooding, storm surge propagation, extreme wave conditions and intense anthropogenic conditions, are threatening these systems (Monbaliu, *et al.*, 2014). These challenges facing the UK coasts and estuaries have led to various strategies and interventions in managing the UK coastline and estuaries.

### **1.3.1 Strategy context**

The historical importance of estuaries for navigation and commerce has led to a plethora of research. For example, Beardall *et al.* (1991) reported that many estuaries in the UK (for instance the Blyth Estuary in Suffolk) experienced major reclamation in the Roman, Norman and 16<sup>th</sup>/17<sup>th</sup> Century periods. There is significant potential for this sort of large-scale anthropogenic intervention in many UK estuaries, especially larger systems. Research interest tends to follow, and the Thames estuary is a good example of a large, human-impacted system (e.g. *The Thames Estuary Project 1996 and 1999*; van der Wal & Pye, 2004; Nicholls *et al.*, 2000; Burningham and French, 2008). The attention other large systems receive is partly due to a long history of dredging, reclamation, port development, training wall construction, and especially from both a flood defence and habitats protection perspective (e.g. Cooper *et al.*, 2001).

The historic separation of coast from estuary in the UK is illustrated in the national coastal management strategy and policy. Shoreline Management Plans (SMPs) are based on coastal

cells that do not extend into estuaries. The open coasts around England and Wales were initially classified into a framework of coastal cells, comprising 11 cells and 48 sub-cells (Figure 1.1). The major cells were considered to be more-or-less closed systems, with sediment transfers occurring between cells only under extreme conditions (Motyka and Beven, 1986). Cell divisions and sub-divisions were based on coarse (i.e. sand and gravel) sediment paths with boundaries at major headlands and estuaries (referred to as sediment sinks). These have served as a basis for strategic and future-planning in Shoreline Management Plans (Motyka and Brampton, 1993).

Cooper and Pontee (2006) criticised the coastal cell concept as a framework for shoreline management on the basis that, whilst it works very well at compartmentalised coasts that are dominated by transport of beach-grade material, it does not make provision for cohesive sediments very well. Moreover, important aspects of estuary-coast interaction are ignored. Time variation in coastal behaviour is also ignored in the classification (Motyka and Brampton, 1993), yet cell boundaries can clearly change over longer time intervals. Finally, the underlying sediment budget model neglects other aspects of landform processes and also wave dissipation. With the expectation of rising sea-levels and ever increasing population in England and Wales, it was therefore recommended that the full spatial and temporal range of coastal elements, estuary processes, offshore features and the over-all interactions between the elements should be incorporated for effective and sustainable management of the coastal environment (Cooper and Pontee, 2006).

As a result of the review of the cells concept, it is clear that the initial concept (first generation of SMP) is not perfect neither is it consistent. It was, therefore, recommended that a new guidance plan be established, to rely on more recent science data that emerged from FutureCoast, Regional Atmospheric Soaring Predictions (RASP), Regional Monitoring, etc projects. As a result, the Environment Agency commissioned Halcrow Ltd to carry out the FutureCoast project that now provides a framework for the second generation of SMPs, which include a 100 years' timeframe that considers behaviour and management over three epochs (20, 50 and 100 years). The plans include a modification of boundaries, more consideration of policy units and increased opportunities for local Coastal Groups to undertake groundwork. Units of management are rationalised from 49 coastal cells to 22 SMP units (Figure 1.2). The 2<sup>nd</sup> generation SMPs are expected to deliver a high level of improved baseline understanding and full integration of adjoining SMPs. They have the advantage of greater involvement of stakeholders and improvement of Action Plan integration, to increase confidence in the plan.



Figure 1.1 Sediment cells around the coast of England and Wales (adapted from Motyka and Brampton (1993), Cooper and Pontee (2006)).

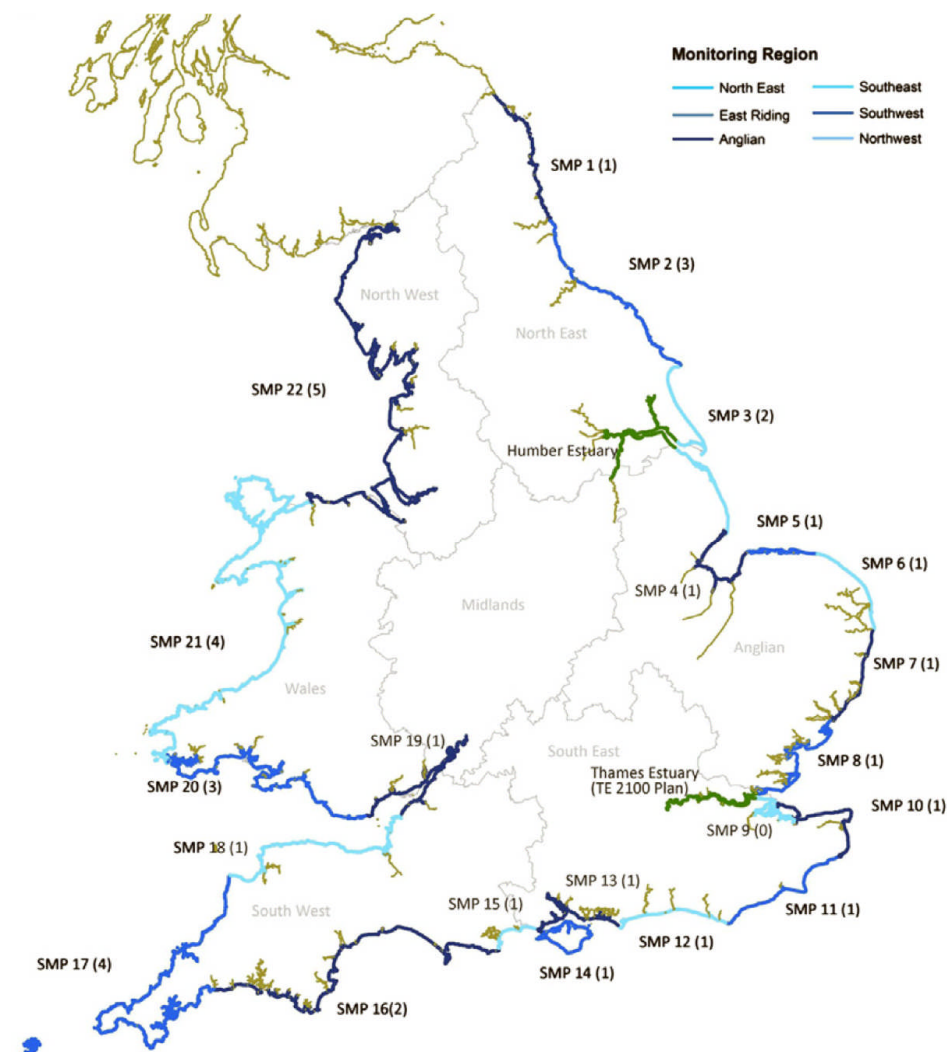


Figure 1.2 2<sup>nd</sup> Generation of SMPs around the coast of England and Wales (adapted from Nicholls *et al.* (2013)).

### 1.3.2 Intervention

In contrast to the organisation of the England and Wales coastline into sediment cells and SMPs as strategy for coast and estuarine management, efforts have been made to also classify UK estuaries according to their geomorphological origins and/or contemporary physical process regimes – another key intervention in management practices. Examples of such classifications include Davidson and Buck (1997), DEFRA (2002) and ABPMER *et al.* (2008). The FutureCoast (DEFRA, 2002) scheme, modified by ABPMER *et al.* (2008), classified UK estuaries in the manner shown in Table 1.2 according to a set of simple rules (summarised in Table 1.3).

**Table 1.2 Estuary typology (after ABPmer *et al.* (2008), modified from Defra (2002))**

Type	Origin	Behavioural Type	Spits'	Barrier Beach	Dune	Delta	Linear Banks <sup>2</sup>	Channels <sup>3</sup>	Rock Platform	Sand Flats	Mud Flats	Salt marsh	Cliff	Flood Plain <sup>4s</sup>	Drainage Basin
1	Glacial valley	Fjord	X					X	X	X			X		X
2		Fjard	0/1/2					X	X	X	X	X		X	X
3		Ria	0/1/2					X	X		X	X	X		X
4	Drowned river valley	Spit-enclosed	1/2	X	E/F		X/N		X	X	X	X	X	X	X
5		Funnel-shaped	X	X	E/F		X		X	X	X			X	X
6	Marine/fluviial	Embayment		X		X	X	X	X	X	X			X	
7	Drowned coastal plain	Tidal inlet	1/2	X	X	E/F		X		X	X	X		X	

Notes: X indicates a significant presence.

<sup>1</sup> Spits: 0/1/2 refers to number of spits; E/F refers to ebb/flood deltas; N refers to no low water channel;

<sup>2</sup> Linear Banks: considered as alternative form of delta.

<sup>3</sup> Channels: refers to presence of ebb/flood channels associated with deltas or an estuary subtidal channel.

<sup>4</sup> Flood Plain: refers to presence of accommodation space on estuary hinterland.

**Table 1.3 Development and demonstration of systems based estuary simulators (EstSim) rules to identify estuary type using the UK estuaries database**

Type	Behavioural	Rule
1	Fjord	Glacial origin, exposed rock platform set within steep-sided relief and with no significant mud or sand flats
2	Fjard	Glacial origin, low lying relief, with significant area of sand or mud flats
3	Ria	Drowned river valley in origin, with exposed rock platform and no linear banks
4	Spit-enclosed	Drowned river valley in origin, with one or more spits and not an embayment
5	Funnel-shaped	Drowned river valley in origin, with linear banks or no ebb/flood delta and not an embayment
6	Embayment	River or marine in origin (i.e. not glacial), with multiple tidal rivers meeting at or near mouth and a bay width/length ratio <sup>1</sup> of 1 or greater, and no exposed rock platform
7	Tidal inlet	Drowned coastal plain in origin, with barrier beaches or spits

<sup>1</sup> Where bay extends from sea opening to the confluence of the rivers (From Page 24, ABPMER *et al.*

(2008))

In the UK, one of the intervention strategies of conserving and managing the network of national and international important sites of geological, geomorphological and environmental heritage/features is the establishment of such as Sites of Special Scientific Interests (SSSIs), including coastal environments - meaning that such sites are managed by conservation bodies (Thomas and Cleal, 2005; Prosser, 2008; Prosser, *et al.*, 2011). Fletcher, *et al.* (2014) review the principal marine and coastal intervention/policy in England since 1999 and conclude that the changes in coastal governance framework in England (and UK by extension) are in the establishment of key and strategic national policy, legislation, emergence of institutions, establishment of Marine Protected Area network, for marine and coastal issues. On coastal management, the responsibilities for marine and coastal management are divided among varieties of administrative bodies and government agencies (Ballinger, 2005; Smith, *et al.*, 2008; Stojanovic and Ballinger, 2009). A key feature of intervention on this is the development of regional coastal initiatives that are aimed at improving decision making for the overall governance of the coastal system. However, based on various management interventions in the coastal system management in the UK, some issues are noted. These include: decline in partnerships among the various initiatives, complexity in coastal affairs, the division of estuary and open-coast management in Marine and Coastal governance down the years, and conflicting management objectives by different government departments (e.g. see Fuller and Randall, 1988; Ballinger, 1999; Sellers, 2010; Fletcher, *et al.* 2014).

The EUROVISION (2004) report suggested that of the 17,380 km UK coastline, 3008 km are currently undergoing erosion while a further 3,185 km are being protected by engineering structures. A complex interaction of physical factors (sea-level change, geomorphology, storminess, waves, tides, near shore current) and human factors (land reclamation, river regulation works, unregulated dredging, etc) are shaping the UK coastline through the dynamic process of erosion and accretion. However, it is also clear, in this section, that estuaries have tended to be studied and considered for management purpose separately from open-coasts and also from each other. This is despite evidence to suggest that this potentially neglect important processes, correlated and connected behaviour. There is therefore a need for a more integrated approach whereby estuaries and open coast environments are considered as a set of adjacent – and potentially coupled-systems. Analysis of estuary-coast connectivity at a regional scale has the potential to provide insights into the relative importance of internal estuary morphodynamics and externally-imposed forcing.

#### **1.4 Aims and objectives**

The main aim of this thesis is to investigate the morphological evolution of coupled estuary - open coast systems, focusing on the relative importance of intrinsic estuary

morphodynamics and regional coastal forcing. This aim is addressed via a number of specific objectives:

- To examine the comparative historical and contemporary behaviour of estuary - open coast systems. The key hypothesis here is that coastal systems within the same region, experiencing regional similarities in forcing, display consistent behaviour over the mesoscale (years to several decades). This objective seeks to describe and understand the historical and contemporary geomorphology of regionally co-located coastal systems drawing from past and recent maps, aerial photography and LiDAR data.
- To explore the nature of sedimentary environments throughout estuary - open coast systems. The underlying hypothesis being tested here is that sediments across connected estuary - open coast systems are interchanged, and that spatial variations in sedimentary character are a product of local changes in the process energy regime. Key questions being addressed through this objective are: whether sediment sources are common between estuary and open coast environments, and what is the evidence for sediment pathways connecting the estuaries and open coast?
- To evaluate the importance of regional wave climate forcing as a driver of contemporary coastal and estuarine change. It is hypothesised that wave climate is a fundamental control on coastal processes, particularly in terms of sediment delivery and transport, and morphological change. This third objective is to briefly examine the role of seabed morphology in modifying nearshore wave climate, and thereby driving localised variance in these coastal processes.
- To consider the relative importance and wider implications of local versus regional controls on coastal system dynamics.

## **1.5 Thesis structure**

This chapter has highlighted the importance of estuaries in the broader context of coastal change and outlined the nature of some of the most pressing coastal system challenges. A brief overview of estuary-coast interaction, and the management concepts in relation to the UK, provide a context for the aim and objectives of the present research.

Chapter two of this thesis sets out the scientific research design and methodologies adopted in achieving the aim and objectives. This chapter also summarises the various data sources and discusses some critical data quality issues.

Chapter three discusses the geological/physiography, geomorphological context and sedimentary environment of the southwest region of England and the three case study estuaries: the Hayle, Camel and Gannel. The geological and geomorphologic context of each estuary is summarised, together with the physical processes, sedimentary regime, climate and anthropogenic factors.

Chapter four examines the historical and contemporary coastal behaviour of the case study systems. This focuses on shoreline change analyses, locational probability mapping of the principal ebb channels, the ebb channel morphodynamics. Recent airborne LiDAR (Light Detection and Ranging) datasets are used to infer contemporary morphodynamic behaviour.

Chapter five presents the result of the analysis of metocean data focusing on investigation of historical and contemporary coastal forcings as drivers of coastal processes.

Chapter six analyses surface sediments sampled during a field campaign undertaken in 2011. Sedimentological and geochemical analyses are presented, and discussed in the context of source, supply, mixing and dynamics. These are considered with respect to spatial and morphological dynamics of the estuaries/systems.

In Chapter seven, bathymetric change analyses and numerical wave modelling are used to evaluate the importance of extrinsic forcing of wave and sea-bed morphology on the coast and the estuaries in the region.

Chapter eight discusses the implications of results presented in previous chapters in view of the interaction between estuary and adjacent open coast environments in southwest England, and considers the importance of these results more generally in line with the objectives set out in this research. The chapter summarises the main conclusions of the research, and makes recommendations for further work.

A series of appendices of the papers published and posters presented out of this work are included, while the separate CD includes summaries of the main datasets used. Data are provided on the enclosed CD, arranged in four main folders (Ordnance Survey historical data, historical bathymetrical data, LiDAR data, sedimentological data and metocean data).

## 2 METHODOLOGY

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### 2.1 Research design - overview of research methodology

Historical trend analysis (HTA) is one of the key methods utilised in the first step of analyses undertaken in this research. This approach involves change analysis over historical (decade to century) timescales (Blott, *et al.*, 2006; HR Wallingford, *et al.*, 2006) that is used to assess past behaviour, and patterns of erosion and deposition. Secondary data (maps, charts, aerial photographs, topographical and bathymetric surveys, and so on) are vital in the historical, and also the recent (contemporary), trend analysis. This analysis is aimed at addressing the first objective of this research enumerated in chapter 1. Therefore the research starts with sourcing of secondary geospatial resources (historical and recent), which are integrated as part of consideration of meso-scale coastal dynamics and contemporary behaviour (see chapters four and five).

Another key objective of this research is the exploration of sediment dynamics and sedimentary evolution at the study sites. Of importance to the achievement of this objective is the utilisation of primary data. Therefore geomorphological field surveys (for sediment sampling) and progressive laboratory/sedimentological analyses (including grain size analysis and XRF for geochemistry of a small sub-sample analysis) are the second key stage of this research.

The third step is the consideration of coastal climate and sea-level changes as drivers of the open-coast and estuarine behaviour. Investigation of spatial and regional climate/physical data (waves, wind, sea-level) is the main component of this step. Interpretation of the key findings from these three strands of research undertaken at the study sites is then projected to wider understanding of the estuary-coast systems', interactions and responses to internal dynamics and regional processes.

Figure 2.1 presents the summary diagrammatic flow chart of the research steps and methodology utilised in this research.



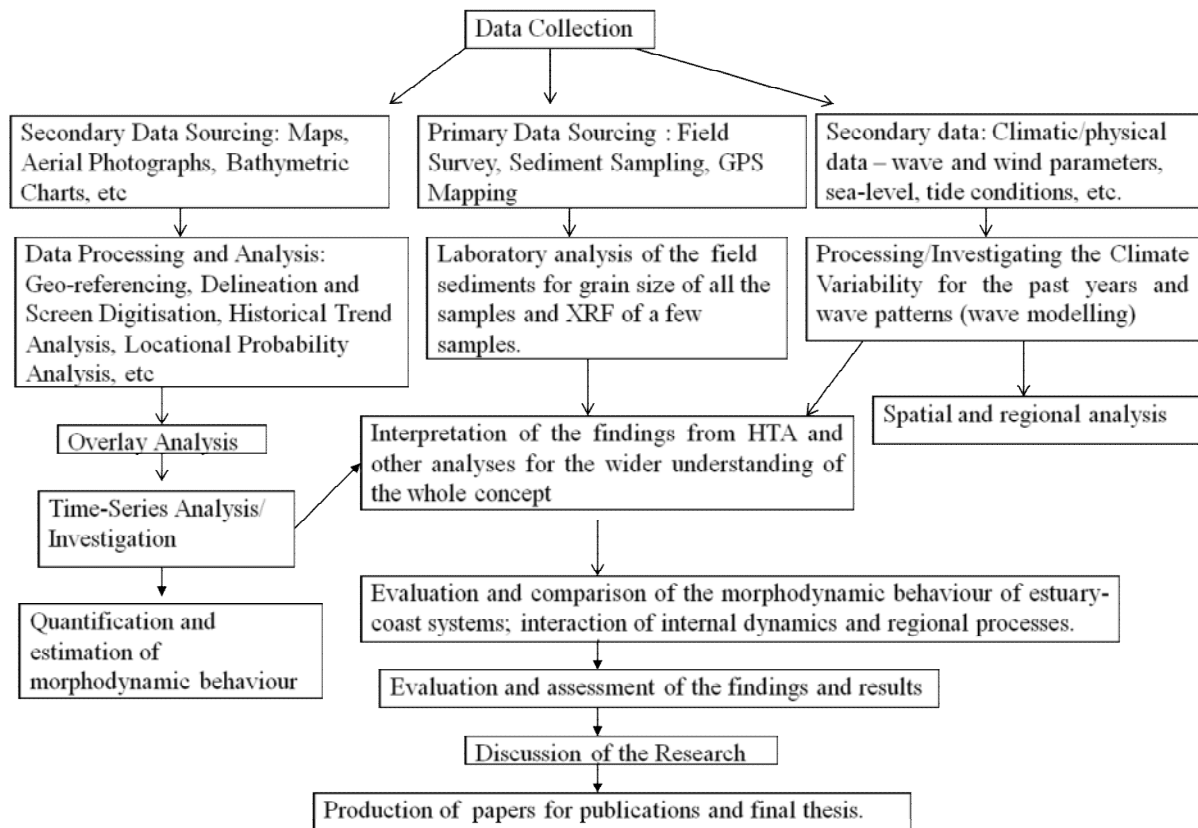


Figure 2.1 Flow chart summarising the work flow of this study.

## 2.2 Historic trend analysis

### 2.2.1 Data sources

The analysis of historic shoreline change underpins the first research objective (Chapter 1.4), concerned with the extent to which coastal evolution exhibits any regional coherence. It has been stated that the “patterns of shoreline erosion and deposition are often indicative of changes in the sedimentary budget of a coastline” (Viles and Spencer, 1995:6). In most investigations of shoreline change, the mean low and high water marks (MLW and MHW respectively) are used to represent the shoreline, representing both a coastline position and also a simple expression of shoreline morphology. The quantitative analysis of shoreline change over historic timescales is very important for understanding processes which drive coastal erosion and accretion (Sherman and Bauer, 1993), for computing regional sediment budgets (Zuzek *et al.*, 2003), identification of hazard zones (Al Bakri, 1996) or as the basis for the modelling of morphodynamics (Maiti and Bhattacharya, 2009). The dynamic processes of shoreline erosion and accretion are often attributed to hydrodynamic forces (e.g. river cycles, sea-level rise), geomorphological changes (e.g. spit development), anthropogenic actions (e.g. port development, tidal power generation, construction, dredging) or other episodic forcing (e.g. sudden storm events, earthquakes and tsunamis, rapid seismic events) (Scott, 2005; Maiti and Bhattacharya, 2009). To this end, major effort

was made to identify and secure relevant maps and charts. Table 2.1 lists the data acquired and utilised in this analysis.

### 2.2.2 Geospatial techniques

Historical Trend Analysis, referred to as HTA henceforth, is the principal geospatial technique adopted here to investigate changes in the shoreline of these estuary-coast systems (Blott *et al.*, 2006; HR Wallingford *et al.*, 2006). A GIS (Environmental System Research Institute (ESRI) ArcGIS v9.3.1) is used to delineate shorelines and evaluate dynamics in channel positions, channel morphology, erosion and deposition over specific time epochs. HTA has been widely used in the UK. For example, Pye and van der Wal (2000) report on the application of HTA to four estuaries, the Ribble, Mersey, Southampton Water and Humber. Blott *et al.* (2006) applied both the HTA and Expert Geomorphological Assessment (EGA) methods to investigate the long-term morphological change and its causes in the Mersey estuary, NW England. In a similar vein, Cashin (1949), Price and Kendrick (1963), Thomas (2000) and Thomas (2002) applied HTA to investigate the cause of morphological dynamics in the Mersey estuary. This shows the application of HTA has spanned almost 50 years. HR Wallingford (2001) undertook a series of HTA studies on the Stour Estuary between 1997 and 2001 to develop an understanding of the changes in the system occasioned by successive port development over the period of 1965-1999.

**Table 2.1 Datasets used for the analysis of historical shoreline change**

Source	Date	Data	Scale	Accuracy
<i>Hayle</i>				
Ordnance	1845	Old series, 1 <sup>st</sup> Edition	1:2,500	+/-10m
Survey	1908	County Series: 3 <sup>rd</sup> Revision	1:2,500	+/-10m
	1936	County Series: 3 <sup>rd</sup> Revision	1:2,500	+/-10m
	1948	National Grid: 1 <sup>st</sup> Imperial edition	1:10,560	+/-10m
	1963	National Grid: National Survey	1:2,500	+/-10m
	1989	Latest National Grid edition	1:10,000	+/-5m
	2010	Master Map Vector data (Tiles)	1:2000	+/-5m
<i>Gannel</i>				
Ordnance	1888	County Series	1:10560	+/-10m
Survey	1977	National Survey	1:2500	+/-10m
	1996	1 <sup>st</sup> Metric Edition	1:10,000	+/-10m
	2012	MasterMap Edition	1:2000	+/-5m
<i>Camel</i>				
Ordnance	1880	Padstow First Revision County series	1:2,500	+/-10m
Survey	1907/8	County Series: 1 <sup>st</sup> Revision	1:10,560	+/-10m
	1962	National Grid Padstow	1:10,560	+/-10m
	1973	National Grid Padstow	1:2,500	+/-10m
	1979	National Grid Padstow	1:10,000	+/-10m
	2010	Master Map Vector data (Tiles)	1:25,000	+/-5m

HTA is aided by the use of the Digital Shoreline Analysis System. The Digital Shoreline Analysis System (DSAS) is a GIS tool that can be used in HTA to examine past or present shoreline positions or geometry. One of the main benefits of using DSAS in coastal change analysis is its ability to compute the rate-of-change statistics for a time series of shoreline positions. The statistics allow the nature of shoreline dynamics and trends in change to be evaluated and addressed. DSAS is developed as a freely available extension to ESRI's ArcGIS (Thieler *et al.*, 2009). It has been updated and upgraded over time, so multiple versions exist allowing its use with ArcView 3.2 through to ArcGIS v10. In 2013, a web-based version (DSASweb) was released (USGS, 2013). Download and further information on the installation and use of DSAS can be accessed at <http://woodshole.er.usgs.gov/project-pages/dsas/>. Instructions, usage of the software and the configuration of input and output parameters are well documented in Thieler *et al.* (1994a, 1994b and 2009).

There has been increasing concern regarding the likely long-term impacts of changes in the natural physical and environmental forcing factors (hydrodynamic, geomorphologic and rapid seismic forces) as well as anthropogenic activities and human interventions (Sherman and Bauer, 1993; Al Bakri, 1996; Zuzek *et al.*, 2003; Blott *et al.*, 2006; Maiti and Bhattacharya, 2009). However, before any predictions of future morphological responses can be made with confidence, there is the need to understand the past changes as well as determine the envelope of natural variability associated with long-term trends or cycles. On sedimentary coastlines, the shoreline (and changes in erosion and deposition) is perhaps the most basic indicator of changes in sediment dynamics, budgets and forcing. Shoreline change analysis is hence one of the multiple approaches in monitoring and understanding the changes in coastal/estuarine systems.

There are numerous examples of the use of DSAS in the study of coastal behaviour and shoreline dynamics. Table 2.2 reviews examples of recent studies that have utilised DSAS in Historical Trend Analysis and the examination of coastal system dynamics, shoreline and cliff geometry, modelling and estimations. In the present study, DSAS is used to compute various rates of change statistics for the Mean Low Water (MLW) and Mean High Water (MHW) shorelines. More specifically, in this study DSAS is used to undertake:

- i. The mapping of historic configurations of shoreline position over the period covered by the available historical spatial data (listed in Table 2.1);
- ii. The evaluation of historic changes and trends of individual or selected transects (discrete alongshore positions). Within DSAS, shoreline change is calculated at specific transects, and the time-series of change at specific locations are evaluated using the DSAS output;

iii. The analysis of shoreline geometry, including foreshore steepening (using the distance between mean high and low water marks (after Taylor *et al.*, 2004)) and orientation (for example, to examine rotational tendencies (e.g. Nebel *et al.*, 2012)).

**Table 2.2 Recent studies on shoreline and cliff geometry which made use of DSAS**

Coastline feature studied	Articles
Historical record of coastline dynamics	Carrasco, <i>et al.</i> , 2012; Montreuil and Bullard, 2012; González-Villanueva, <i>et al.</i> , 2013; Jabaloy-Sánchez, <i>et al.</i> , 2013.
Shoreline variation, shoreline erosion and coastal changes	Houser, <i>et al.</i> , 2008; Brooks and Spencer, 2010; Restrepo A, 2012; Beetham and Kench, 2013; Hapke, <i>et al.</i> , 2013; Rio, <i>et al.</i> , 2013; Houser and Mathew, 2011.
Gully development and evolution	Draut, <i>et al.</i> , 2011; Leyland and Darby, 2008.
Cliff retreat and erosion	Rio and Gracia, 2009; Brooks, <i>et al.</i> , 2012; Katz and Mushkin, 2013; Young, <i>et al.</i> , 2014.
Cliff measurement and modelling	Hackney, <i>et al.</i> , 2013; Thébaudeau, <i>et al.</i> , 2013.

### 2.2.3 Shoreline digitisation and data quality consideration

The main stages in the shoreline analysis workflow, as undertaken using DSAS within ArcGIS, are summarised in Table 2.3. Shoreline positions are important features defined in DSAS analysis. Specific features of interest - here, the Mean Low Water (MLW) and Mean High Water (MHW) marks - are extracted through digitisation. These shoreline positions are explicitly indicated on Ordnance Survey (OS) and other national mapping agency publications which make for simple digitisation and analysis within a GIS, thereby reducing some complications associated with automatic shoreline detections (Ryu *et al.*, 2002; Loos and Niemann, 2002; Maiti and Bhattacharya, 2009). When digitising from other sources (e.g. satellite images, aerial photographs etc), accurate and careful digitisation of shoreline position, possibly with constant reference to the same feature, is recommended before the computations of DSAS are initiated. This form of analysis is not immune to the usual limitations associated with digitisation and synthesis of variable quality and resolution data derived from various sources as a result of irregular time sampling interval. For example, reliance on Ordnance Survey (OS) mapping relies on the accurate and consistent interpretation of surveyors and cartographers over decades and centuries (Fenster *et al.*, 1993; Burningham, 2005). Older surveys were usually land-based whilst later ones are often derived from aerial photography (Fenster *et al.*, 1993).

Care was undertaken to ensure that accurate digitisation and critical review of features are considered in the source materials. The calculated measures of change provided by DSAS are only as reliable as the sampling and measurement accuracy associated with the source materials. Therefore, in this study mapping errors were estimated as  $\pm 10$  m for the pre-2000 maps and  $\pm 5$  m for post-2000 maps (Anders and Byrnes, 1991; Crowel *et al.*, 1991; Thieler

and Danforth, 1994a; Moore, 2000). Any form of spatial or laboratory analysis is always aimed at finding solutions to certain spatial problems or to understand certain processes (Uluocha, 2007). In order to achieve this focus, the significance of data quality cannot be over-stressed. The issue of data quality was therefore given prominence. Care was taken to determine the integrity, quality and relevance of any data used in the analyses. The indices which were used in data quality check include logical consistency, completeness, positional accuracy and precision, scale, spatial resolution and currency (temporal accuracy and precision), (Faiz and Boursier, 1996; Jones, 1997; Dobson, 2002; Uluocha, 2007).

**Table 2.3 Workflow for using DSAS in shoreline change analysis (after Thieler *et al.*, 2009)**

---

*Inputting data*

- creation of shorelines, mostly through digitisation as polyline in shapefile/feature class;
  - creation of baseline, mostly through digitisation as shapefile/feature class;
  - setting of default parameters in DSAS extension, which include transect settings; shoreline calculations parameters setting; metadata settings and log file output options;
  - setting of the cast transect parameters, whether simple or smooth as well as transect metadata.
- 

*Outputting to geodatabase*

- transect generation is exported to the geodatabase;
  - editing of individual transects where needed
  - within the geodatabase, calculation of change statistics by selecting the desired statistics to be calculated in DSAS;
  - specification of confidence interval and shoreline intersections thresholds, etc
  - DSAS processes the submitted information and validates the user's selections before outputting the results to the personal geodatabase
- 

*Output statistics*

- the generated statistical results are then presented/analysed within ArcGIS or exported to other packages like Microsoft Excel for further analyses and processing
  - the output are also modified to visually represent the change in statistics in ArcGIS, etc.
- 

#### 2.2.4 Shoreline analysis and interpretation

The DSAS approach calculates shoreline rates of change based on the measured differences between the shoreline positions associated with specific time periods. The following statistical measures (from Thieler *et al.*, 2009) were computed for this research:

- (i) Shoreline Change Envelope (SCE): a measure of the total change in shoreline movement considering all available shoreline positions and reporting their distances, without reference to their specific dates.
- (ii) Net Shoreline Movement (NSM): reports the distance between the oldest and the youngest shorelines. It is useful to compare the SCE and NSM metrics to gauge the extent to which shoreline changes throughout the period considered are reflected in the net change.
- (iii) End Point Rate (EPR): derived by dividing the distance of shoreline movement by the time elapsed between the oldest and the youngest shoreline positions. This metric has been shown to provide an accurate measure of the net rate of change over longer term and it is relatively easy to apply in shoreline analyses. Further justification

for the choice of this method over other methods of estimate is its ability to reliably indicate shore change irrespective of the availability of intermediate shoreline dates (see Milligan *et al.* (2010a, 2010b, 2010c, 2010d for example). Unlike the Linear Regression Rate (LRR), it is unaffected by variations in the temporal resolution of data, and instead summarise change based on the net change (NSM) over the full time period considered.

The transect spacing adopted along the coastline of each of the study site was 5 m with 20 m simple baseline smoothing distance while the change statistics was based on 95% Confidence Interval. The above parameters were evaluated for coastlines (bays) of the estuaries to show the spatial patterns of movements of the shorelines. To quantitatively measure the amount of shoreline shift along each transect, the oldest shoreline position was chosen as the baseline to which all other shorelines were referred. With reference to that baseline, positive and negative changes indicate shoreline progradation and recession respectively. To quantitatively examine the temporal characteristics of the transects, the cumulative rate of change at some locations in the system were selected and examined. The cumulative change in the shoreline positions along the same transects are plotted in graphs with 'year' plotted along the X-axis and the corresponding cumulative change in shoreline positions with respect to 1845 shoreline plotted on the Y-axis for St Ives- Hayle and respect to 1888 shoreline for Crantock-Gannel and 1881 for Padstow-Camel systems respectively. The locational probability analysis was used to investigate the ebb channel migration within the estuary.

### 2.2.5 Locational probability analysis

Analysis of the historical morphodynamic evolution of estuarine ebb channels was undertaken using Locational Probability Analysis (LPA) (Graf, 2000; Wasklewicz *et al.*, 2004). This involved digitisation of individual estuarine channels from the historical maps as feature layers before being converted to raster layers. Channel data for each time period was classified such that cells representing the ebb channel was assigned a value of 1 and other cells as 0. Following Graf (2000), weights were assigned to each *rasterised* layer according to the relation

$$W_n = t_n/m$$

where  $W_n$  = is the weighting value assigned to map  $n$ ,  $t_n$  is the number of years represented by map  $n$ , and  $m$  is the total number of years for the historic record. The *rasterised* data layers are then overlaid in date order based on the Graf's algebraic equation and the overlay methodology by Burrough (1986) and Tomlin (1991). The main purpose of adopting this method is to evaluate the evolution, persistence and consistency of channel position over time.

Accordingly, the data were carefully scrutinised for logical consistency, completeness, positional accuracy and precision (after Faiz and Boursier, 1996; Jones, 1997; Agumya and Hunter, 1997; Dobson, 2002; Uluocha, 2007). This process enabled payment of particular attention to geo-referencing, which was repeated where necessary to achieve Root Mean Square (RMS) errors better than  $< 5$  m in most cases.

### 2.2.6 Bathymetric change analysis

Historic bathymetric data are acquired from UKHO chart 1686, which were surveyed and published in 1931 and obtained from British Library (shelfmark BAC 1686). The chart is scanned at 300 dpi. The scanned raster image is then georeferenced to British National Grid (OSGB 36) in ArcGIS 9.3 using the Ordnance Survey georeferenced data. The Root Mean Square (RMS) spatial error for the geo-rectification/geo-referencing process was  $< 30$ m. The most recent bathymetric charts covering the north Cornwall coast are published in 2008: charts 1178, 1149 and 1156 are obtained through the Seazone Marine Data Supply (accessed through the EDINA Marine Digimap Service).

Soundings, contours and shorelines are digitised from all charts into point layers with depths initially referenced to the chart datum. As chart datum varies spatially, and its associated tidal reference changed over time (e.g. MLWS vs. LAT), depths are converted to Ordnance Datum. A Natural Neighbour interpolation is performed using the Spatial Analyst tool in ArcGIS 9.3 to generate regular grids for the each digitised bathymetric layers. A region of interest that is covered by all available charts is defined for further analyses. Change in bathymetry is then computed for the period between 1931 and 2008 using a simple raster calculation.

This research methodology is documented in detail by Burningham and French (2011), and sources of errors in the analyses are well established. Potential analytical errors in this work include digitisation errors and gridding techniques (Gibbs, 1999). Quantifying these errors is difficult, and a cautious interpretation of the results presented in Chapter 7 is recommended.

## 2.3 Contemporary morphology

The techniques mostly used in mapping intertidal topography focused on the analysis of airborne stereo-photogrammetry, optical satellite imagery, airborne and satellite interferometry, Light Detection and Ranging (LiDAR) data (after Lillesand and Keifer, 2000; Mason, *et al.*, 2006; Gallay, 2013). In the present study, the LiDAR data obtained from Channel Coast Observatory (CCO) are extensively utilised. The main purpose of using the LiDAR surveys for the study sites is to assess the recent morphological change within the estuarine intertidal zone. Aerial photographs, supplemented by Google and Bing aerial

images provide a shorter-term perspective on planform morphological changes, especially in the vicinity of the inlet channels.

### 2.3.1 Data sources

Airborne LiDAR surveys covering the sites of interest were obtained from the Channel Coast Observatory and the dates of the LiDAR flights for the data used in the research are summarised in Table 2.4. The LiDAR datasets provide information with which to investigate the recent morphological behaviour of the systems. The zones of notable change of vertical erosion, deposition and no change are obtained by undertaking a difference calculation between temporally consecutive surveys: this is achieved in ArcGIS 9.3. A measure of  $\pm 0.025\text{m}$  is used to differentiate areas of minimal change from those exhibiting notable morphological change. Transects are also extracted from these spatial surfaces in order to explore the morphological features associated with the changes observed. This is undertaken in Matlab. Some LiDAR data could not be used due to data distribution in integer, not float, format (for example, 2009 Hayle LiDAR).

**Table 2.4 LiDAR datasets used for Hayle, Gannel and Camel systems.**

Source	Map Date	Data	Datum	Uncertainty Value
<i>Hayle</i>	15/09/2007	LiDAR	ODN	+/-15cm+
Channel	Coast 09/09/2008	LiDAR		+/-40cm+
Observatory	10/09/2009	LiDAR		+/-15cm+
	10/04/2010	LiDAR		+/-15cm+
<i>Gannel</i>	02/27/2008	LiDAR	ODN	+/-15cm
Channel	Coast 16/04/2009	LiDAR		+/-30cm
Observatory	09/02/2010	LiDAR		+/-15cm
	10/03/2011	LiDAR		+/-40cm
<i>Camel</i>	02/27/2008	LiDAR	ODN	+/-15cm*
Channel	Coast 16/04/2009	LiDAR		+/-30cm*
Observatory	09/02/2010	LiDAR		+/-15cm+
	10/03/2011	LiDAR		+/-15cm+

\*-Attribute Accuracy Value

+ - Positional Accuracy (Vertical)

#### Further details about LiDAR Data:

LiDAR instrument manufacturer	OPTECH
Instrument model	ALTM Gemini 06SEN191
Average flight height (metres)	1000 mAGL (approximate)
Swath width (metres)	1025
Grid size (metres)	1
Units of elevation reading for ASCII grid file	mAOD
Units of elevation reading for text file	mAOD

## 2.4 Sediment sampling and analyses

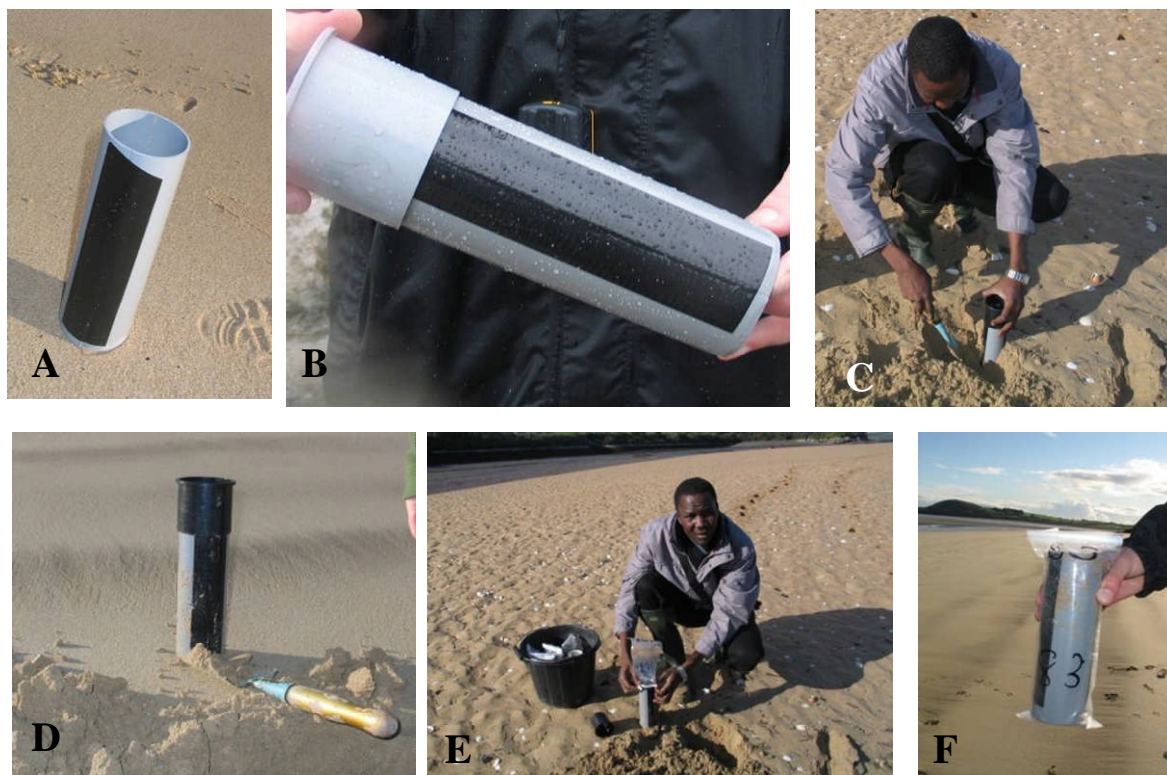
Sampling of surface sediments within the intertidal zone of each system was undertaken with a view to characterise their sediment regimes and, potentially, identifying estuary-coast



sediment pathways. Sampling was carried out between 24 - 27<sup>th</sup> October 2011 within the estuaries and also along the adjacent stretches of open coast. Sediments were sampled from the surface through to a depth of 15 cm in order to evaluate short- versus long-term sediment trends.

#### 2.4.1 Field sampling and descriptive sedimentology

A total of 143 short cores (length <15 cm) were collected from the intertidal zone of the estuaries and along the beaches using a 65 mm diameter tube (Figure 2.3 a-f). The main reason for sampling a 15 cm short-core was to obtain a more complete understanding of changes in the instantaneous (surface) sedimentology. The immediate surface may reflect only process dynamics associated with the most recent high tide, but sampling to a greater depth can increase the temporal reference of the sedimentary environment. Sample locations were located randomly within individual and key sedimentary sites in each system, and positioned using a hand-held Global Positioning System (GPS), ( $\pm 3$  m rms error). Chapter 6 provides full detail of the sampling locations and positions for each of the study sites, which is summarised here in Table 2.5. An effort was made to ensure that sufficient samples were collected from within the estuaries and along the beach areas, across the full intertidal zones. Cores acquired at low tide, were sealed, tagged and returned to the laboratory intact.



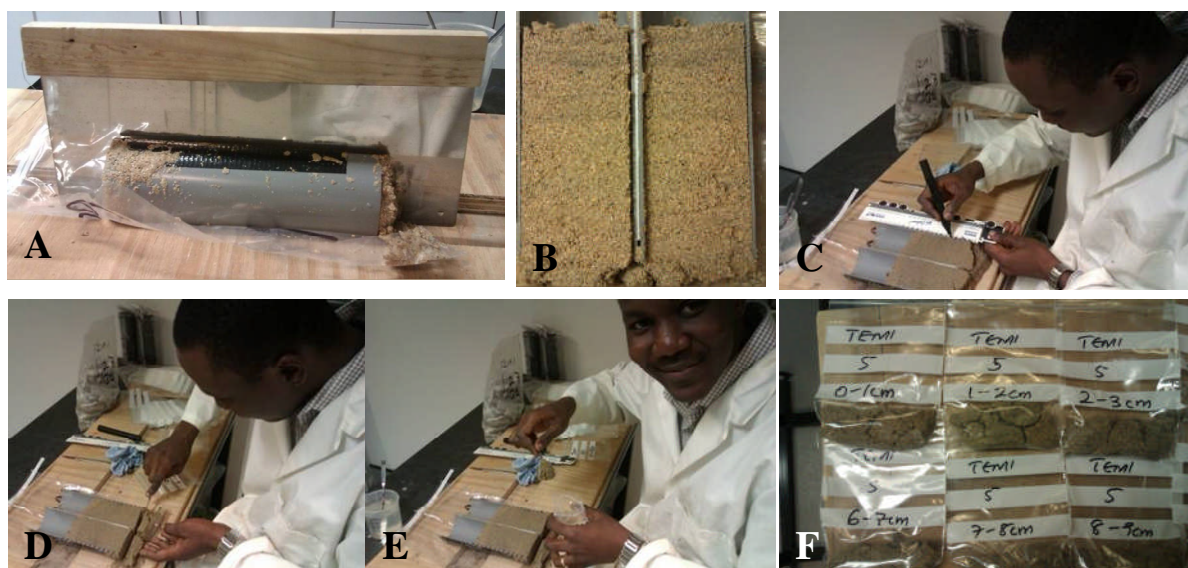
**Figure 2.2.** (A) & (B)-the 15cm pipe used in the core sampling, (C), (D), (E) and (F)-hammering, retrieving and bagging of sediment core.

Cores were sliced at 1 cm intervals (down-core) (Figure 2.4 a - f) and grain size distribution of these subsamples were analysed using a *Malvern MasterSizer 2000* particle analyser, which uses a laser diffraction principle (Figure 2.5), detecting sizes across the range of 0.02 – 2000  $\mu\text{m}$  (Malvern, 1999). No sediment coarser than sand ( $>2,000 \mu\text{m}$ ) was present. Folk and Ward (1957) grain size statistics (median ( $D_{50}$ ), sorting (spread of the distribution) and skewness (asymmetry of distribution)) were calculated using GRADISTAT (Blott and Pye, 2001). Multivariate analyses of the grain size distributions were undertaken in Matlab.

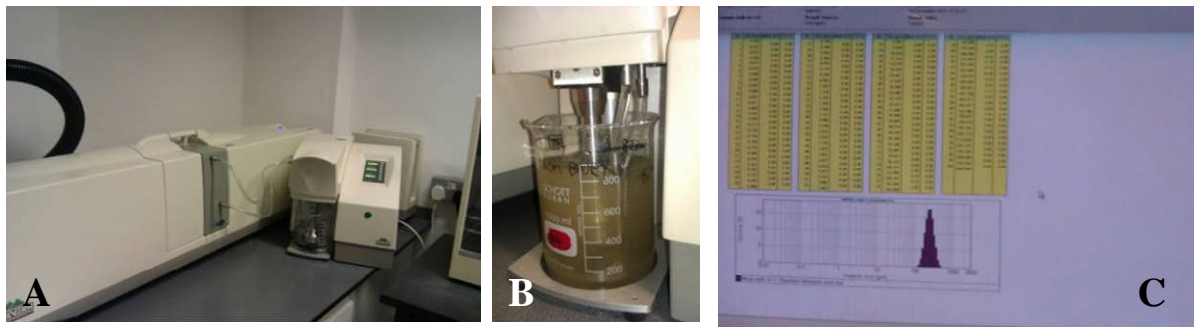
**Table 2.5 Summary of sediment samples acquired at the study sites**

Site	Number of estuarine samples	Number of open coast samples	*Underlying reasons
Hayle - St Ives	40	40	SSSIs locations are not covered because of the restriction in the site.
Gannel - Crantock	10	9	A smaller site, sampling density was maintained, which generated a smaller number of samples when compared to the other systems.
Camel - Padstow	22	22	SSSIs restrictions in the sampling sites limited the anticipated random sampling to areas freely accessible to the public
Total	72	71	
<b>Grand total</b>		<b>143</b>	

SSSIs – Site of Special Scientific Interests



**Figure 2.3 Preparation of sediment samples: (A) splitting the core, (B) split and open core, (C) % D) slicing the core sediment into 1cm layers, (E) bagging the sediment, (F) bagged and labelled sediments.**



**Figure 2.4 (A) Malvern optical unit, (B) the wet dispersion and stirring accessory, and (C) the computer display of particle size distribution.**

Various configurations, settings and runs for the same sample were considered for *Malvern MasterSizer 2000* equipment while preparing the sediment for analysis. Tables 2.6, 2.7 and 2.8 are examples of results obtained when the equipment was set up and tested for the grain size measurement runs. The most consistent results were obtained when the time of the processing was set to 45 seconds and the pump stirrer speed to 2,500 rpm for the three cycles of runs (Table 2.8). The result for sample 3 (Table 2.8) was so consistent with all of the variables (obscuration, residuals, span, Malvern statistical parameters) considered for data analysis and quality. Tables 2.6 and 2.7 are examples of results which were obtained at the testing stage of the analysis of the same sediment samples. The results of these tests (Tables 2.6 and 2.7 for examples) were not consistent at three cycles of runs for the same sample when Malvern equipment was set to 2000 and 2250rpm (pump speed) and 12” and 30” (time) respectively. From the consideration of quality of the results generated based on different equipment test settings, the time (45 seconds) and pump speed (2500 rpm) configuration/settings that yield the 99.9% consistent results during the trial of the main Malvern setting parameters used in the grain size analysis presented in this research. Tables 2.6 – 2.8 represent the results of different settings for the same sample.

**Table 2.6 Setting 1- Time- 12”, Pump Speed: 2000rpm**

Sample (Cycle)	Obscuration (%)	Residual (%)	Span	D [4,3] Volume weighted mean	Specific surface area	D [3 2] Surface weighted mean	d (10) $\mu\text{m}$	d (50) $\mu\text{m}$	d (90) $\mu\text{m}$
1(1)	9.97	1.152	1.66	549.867	0.0266	225.4	231.6	466.4	1006
1(2)	12.9	2.373	1.33	702.653	0.0107	561.9	336.9	631.8	1174
1(3)	14.96	2.925	1.22	873.884	0.00872	687.8	427.3	817.3	1422
1(Average)	12.61	2.15	1.49	708.801	0.0153	391.1	297.4	633.8	1244

**Table 2.7 Setting 2- Time- 30", Pump Speed: 2250rpm**

Sample (Cycle)	Obscuration (%)	Residual (%)	Span	D [4,3] Volume weighted mean	Specific surface area	D [3 2] Surface weighted mean	d (10) $\mu\text{m}$	d (50) $\mu\text{m}$	d (90) $\mu\text{m}$
2(1)	6.42	2.273	1.62	612.4	0.0212	283.3	248.7	531.7	1107
2(2)	6.94	2.377	1.59	682.504	0.0176	341.6	271.3	601.8	1230
2(3)	7.5	2.868	1.19	600.056	0.012	499.3	309.1	550.2	961.4
2(Average)	6.95	2.506	1.47	631.653	0.0169	354.6	276	559.2	1099

**Table 2.8 Setting 3- Time- 45", Pump Speed: 2500rpm**

Sample (Cycle)	Obscuration (%)	Residual (%)	Span	D [4,3] Volume weighted mean	Specific surface area	D [3 2] Surface weighted mean	d (10) $\mu\text{m}$	d (50) $\mu\text{m}$	d (90) $\mu\text{m}$
3(1)	12.67	0.424	0.84	319.815	0.0207	290.387	203.1	304.6	457.4
3(2)	12.56	0.453	0.83	318.706	0.0207	289.664	202.9	303.8	455.1
3(3)	12.58	0.461	0.83	319.497	0.0207	290.359	203.3	304.6	456.3
3(Average)	12.6	0.446	0.83	319.339	0.0207	290.136	203.1	304.3	456.3

#### 2.4.2 Sediment size analysis

Grain size analysis has been widely used to statistically examine spatial changes in sediment size properties. It was pioneered by McLaren (1981), improved by McLaren and Bowles (1985), and further modified by Gao and Collins (1992). Applications include the studies by McLaren *et al.* (1993); Masselink (1992); Gao and Collins (1994); Gao *et al.* (1994); Flemming (2007); Le roux and Rojas (2007); McLaren *et al.* (2007); McLaren and Singer (2008); Plomartis *et al.* (2008); and Poulos and Ballay (2010).

Grain-size trends, which may be primarily related to abrasion and selective sorting effects (Le Roux and Rojas, 2007), are naturally the result of sediment transport processes (Krumbein, 1938; Russell, 1939; Swift *et al.*, 1972; Stapor and Tanner, 1975; McCave, 1978; Harris *et al.*, 1990; Le Roux and Rojas, 2007). Key grain-size statistics (e.g. those relating to the average, sorting, skewness and kurtosis) have traditionally been obtained by sieve or settling techniques (Blott and Pye, 2001; Le Roux and Rojas, 2007). However, modern laser diffraction sediment size analysers permit much more rapid processing of large numbers of samples (Eshel *et al.*, 2004; Blott and Pye, 2006).

Despite its importance in understanding sediment provenance, sediment grain sizes are difficult to characterize because of the range in the order of magnitude (Friedman and Sanders, 1978; McLaren and Bowles, 1985). However, over the years most sedimentologists have used or adopted the logarithmic Udden-Wentworth grade scale (Udden, 1914; Wentworth, 1922) with classification based on the boundaries differentiated by the factors of two (Table 6.1). Krumbein (1934), on the other hand, took the Udden-Wentworth classification further by developing a phi scale ( $\phi$ ) and proposing that the Udden-Wentworth grade scale value be logarithmically transformed into phi ( $\phi$ ) values using the expression:

$$\phi = -\log_2 d$$

where  $d$  is the grain size in mm. With the geometric series, the  $\log_2$  can be used to linearise the logarithmic grain size distribution to fit Udden-Wentworth scale. These *log-normal distributions* were conventionally used by Visher (1969), Middleton (1976) and Wrywoll and Smith (1985; 1988) for example. Many sedimentologists have, however, advocated comparisons which has led to a rise in the consideration of alternative distributions. For example, the works of Bagnold and Barndorff-Nielsen (1980) and Hartmann and Christiansen (1992) advocated the application of logarithmic transformation of both grain size and frequency scales. Despite various propositions to sediment distribution measurements, the log-normal distribution continues to be in use to date.

Blott and Pye (2001) developed a series of computational routines for the rapid analysis of grain size statistics regardless of any standard measuring techniques. The macros, written in Microsoft Visual Basic for use within Microsoft Excel and distributed within the spreadsheet package GRADISTAT, allow the calculation of statistical variables arithmetically, geometrically (in metric units) and logarithmically (in phi units) using Folk and Ward (1957) graphical methods. The authors discovered that results in metric units through Folk and Ward (1957) measures appear to provide the most robust basis for routine comparisons of variable sediment composition. In GRADISTAT, the statistical method of moment analysed geometrically based on the log-normal distribution metric size values is the result presented this section. Table 6.2 shows the grain size metrics classification groups of sorting and skewness discussed in this chapter.

**Table 2.9** Size scale adopted in the GRADISTAT program, compared with those previously used by Udden (1914), Wentworth (1922), and Friedman and Sanders (1978). From Blott and Pye (2001: page 1239).

Grain size		Descriptive Terminology			
Phi	Metric	Udden (1914) and Wentworth (1922)	Friedman and Sanders (1978)	Blott and Pye (2001) and GRADISTAT program	
-11 $\phi$	2048 mm		Very large boulders	Boulders	
-10	1024	Cobbles	Large boulders		Very large
-9	512		Medium boulders		Large
-8	256		Small boulders		Medium Boulders
-7	128		Large cobbles		Small
-6	64		Small cobbles		Very small
-5	32		Pebbles	Very coarse pebbles	Very coarse
-4	16	Coarse pebbles		Coarse	
-3	8	Medium pebbles		Medium Gravel	
-2	4	Fine pebbles		Fine	
-1	2	Granules	Very fine pebbles	Very fine	Sand
0	1	Very coarse sand	Very coarse sand	Very coarse	
1	500 $\mu\text{m}$	Coarse sand	Coarse sand	Coarse	
2	250	Medium sand	Medium sand	Medium Sand	
3	125	Fine sand	Fine sand	Fine	
4	63	Very fine sand	Very fine sand	Very fine	
5	31	Silt	Very coarse silt	Very coarse	Silt
6	16		Coarse silt	Coarse	
7	8		Medium silt	Medium Silt	
8	4		Fine silt	Fine	
9	2	Clay	Very fine silt Clay	Very fine Clay	

**Table 2.10** Geometric method of moment graphical measures, after Folk and Ward (1957) (from Blott and Pye, 2001: 1240)

Mean	Standard deviation	Skewness	Kurtosis		
$\bar{x}_g = \exp \frac{\sum f \ln m_m}{100}$	$\sigma_g = \exp \sqrt{\frac{\sum f (\ln m_m - \ln \bar{x}_g)^2}{100}}$	$Sk_g = \frac{\sum f (\ln m_m - \ln \bar{x}_g)^3}{100 \ln \sigma_g^3}$	$K_g = \frac{\sum f (\ln m_m - \ln \bar{x}_g)^4}{100 \ln \sigma_g^4}$		
Sorting ( $\sigma_g$ )	Skewness ( $Sk_g$ )	Kurtosis ( $K_g$ )			
Very well sorted	<1.27	Very fine skewed	<-1.30	Very platykurtic	<1.70
Well sorted	1.27-1.41	Fine skewed	-1.30 to -0.43	Platykurtic	1.70-2.55
Moderately well sorted	1.41-1.62	Symmetrical	-0.43 to +0.43	Mesokurtic	2.55-3.70
Moderately sorted	1.62-2.00	Coarse skewed	+0.43 to +1.30	Leptokurtic	3.70-7.40
Poorly sorted	2.00-4.00	Very coarse skewed	>+1.30	Very leptokurtic	>7.40
Very poorly sorted	4.00-16.00				
Extremely poorly sorted	>16.00				

Greenwood (1969) found that the basic frequency distribution in grain size statistics could be used to differentiate sediments from different sedimentary environments, the assertion of Temitope Oyedotun

which was disputed by Muiola and Weister (1968) in another study, although clearer delineation exists when distinctly different environments are compared. Difficulties in differentiation arise most commonly when the sedimentary environments considered are all sourced from a single sediment population, and in these cases, subtle differences in the distribution are likely the most effective delimiters.

Folk and Ward (1957) grain size statistics (median ( $D_{50}$ ), sorting (spread of the distribution) and skewness (asymmetry of distribution) were calculated from the raw Malvern-derived grain size distribution using the GRADISTAT macro for Microsoft Excel (Blott and Pye, 2001). The grain size distribution of the multiple samples from each site were also explored using principal component analysis (PCA) to reduce the data into a smaller number of key variables. Hierarchical cluster analysis (using Euclidean distance and average linkage) was applied to the grain size distribution to organise samples into groups comprising similar sedimentological characteristics, specifically for each of the system. These calculations were undertaken in Matlab.

### 2.4.3 XRF analysis

The sedimentological characteristics of sedimentary environments in the coastal systems studied were also examined in terms of elemental composition. This geochemistry is hypothesised to characterise sediment source composition, of the parent rock, climatic-environmental conditions determining sediment formation and transportation, and possible anthropogenic interactions with the sediment supply chain (Pettijohn, *et al.*, 1987; Johnsson, 1993; Basu, 2003; Weltje and von Eynatten, 2004; Bloemsa, *et al.*, 2012). The XRF is used here to complement the grain size analyses in the sedimentological characterisation of sedimentary environments within, and connectivity between, the estuary and open coast system. X-ray Fluorescence Spectrometry (XRF) is used to determine the major oxide and trace element composition of sediment samples. The major and trace elements in their oxidised state are determined as percentage of composition. They comprise Na, Mg, Al, Si, P, S, Cl, K, Ca, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, Ga, Ge, As, Se, Br, Rb, Sr, Y, Zr, Nb, Mo, Ag, Cd, In, Sn, Sb, Te, I, Cs, Ba, La, Ce, Hf, Ta, W, Hg, Tl, Pb, Bi, Th and U. The samples used in the XRF analyses were obtained from 0-5 cm sediment depth from a range of estuarine and open coastal sample locations.

The samples were freeze-dried at  $\sim 60^{\circ}\text{C}$  in MODULO 4k Freeze Drier (Figure 2.7a) for five days before the dried samples were pulverised into a fine powder using an agate mortar and pestle (Figure 2.7b). To avoid contamination and the mixture of sub-environment samples during preparation stage, both faces of the compression die for each of the samples for the analysis were well covered (Figure 2.7c). Each pulverised ground sample was then weighed prior to analysis (Figure 2.7d) and the weight for each of the 21 samples ranged from 4 to 6

grams. These subsamples were analysed using a Spectro XLab Pro 2000 to produce the high X-ray intensity, that permits the quantitative analysis of elements in the ng-range (after Jenkins, *et al.*, 1995).

The generated data were then analysed in Matlab and Paleontological Statistics (PAST) software (Hammer, *et al.*, 2001) for comparison of major and minor/trace element composition across the three systems while the geospatial comparison of some major and minor elements composition were explored in ArcGIS. Major elements were measured in percentage (%) while trace elements were measured in  $\mu\text{g/g}$ . The evidence for the sediment sources at the study sites are already covered in some works, therefore the investigation of the source of elemental composition are considered in line with what has been established in the literature (for example, Reid and Scrivenor, 1906; Bryan *et al.*, 1980; Pirrie *et al.*, 1999; Pirrie *et al.*, 2000a, b; Rollinson *et al.*, 2007; Pirrie *et al.*, 2009, etc).





**Figure 2.5 (A) MODULO 4k Freeze drier (B) pulverising into using agate mortar and pestle (C) storing the pulverised sample in compression die and (D) weighing the sample.**

## 2.5 Metocean analyses

### 2.5.1 Metocean characteristics

Meteorological and oceanographic community (metocean) are always concerned with the supply of environmental data and models for accurate approximation of ocean's physics (Bitner-Gregersen, *et al.*, 2014). Time series (1823 – 2012) of winter NAOi, wind climate, tidal conditions and recent sea-level rise were analysed and plotted in Microsoft Excel. These analyses are aimed at addressing the third objective of this research. The intention here is to evaluate the importance of physical environmental forcings as agents of change within the coastal system. Historical time-series of wind climate based on indices for St Mawgan, and the winter NAOi with 50<sup>th</sup> and 99<sup>th</sup> percentile correlation were collated to the N, E, S, W, NW and SW quadrants as the correlation at NE and SE were found to be insignificant. Also, usage of all directions, especially each 10<sup>0</sup> sector, was able to show very specific changes in directions (without obstruction of significant signature), and this is why the historical analyses presented in chapter 4 do not follow the 90<sup>0</sup> bin. The contemporary wave climate conditions using the 20 year (1999 – 2009) hindcast hourly wave parameters supplied by ABPmer, are analysed in Matlab. Specifically, the wave parameters at West (Long. -5.67, Lat. 50.65) and Central West (Long. -5.33, Lat. 50.55), which are within the study areas, are considered for contemporary wave condition analysis. Key variables explored were: frequency of wave direction and significant wave height, frequency distribution of wave direction and wave period, time-series of significant wave height and wave approach. For the tidal conditions and sea-levels at Newlyn, the time-series of minimum and maximum tidal residuals are considered while the monthly and annual sea-level were investigated in Microsoft Excel. Chapter 5 presents the results of these metocean analysis and exploration.

Forcing of coastal change was explored through the analysis of key metocean data, focusing on wind and wave climate and sea-level change (Table 2.9). Wind data acquired through the Meteorological Office Integrated Data Archive System (MIDAS) Land and Marine Surface Stations Data was obtained from the British Atmospheric Data Centre (BADC) ([http://badc.nerc.ac.uk/view/badc.nerc.ac.uk\\_ATOM\\_dataent\\_ukmo-midas](http://badc.nerc.ac.uk/view/badc.nerc.ac.uk_ATOM_dataent_ukmo-midas)). Due to the limitations of the temporal extent of this data, which extends back to the 1950s, the North Atlantic Oscillation index (NAOi) was also considered to provide a measure of wind climate extending over the full history covered by the coastal change datasets (late 1800s to present). NAO monthly indices were downloaded from the University of East Anglia Climate Research Unit (<http://www.cru.uea.ac.uk/cru/data/nao>), and associations between the winter NAOi and wind climate measures were analysed following Burningham and French (2013). Hindcast wave measures (1991 - 2009) derived (using SEASTATES modelling suites) for the north coast of Cornwall were supplied for the purpose of this research by ABPmer.

Annual and monthly mean sea-level data for Newlyn, the location where tidal data are collated for the region, were acquired from the Permanent Service for Mean Sea Level (<http://www.psmsl.org/>). These data are used in the assessment of historical coastal forcing (Section 4.2) and contemporary coastal climate (Section 5.2).

**Table 2.11** Metocean datasets used in this study

Dataset	Location	Dates	Resolution
<i>Surface wind climate</i> BADC	St Mawgan 5.013°W, 50.435°N	1957-2008	Hourly
<i>NAO index</i> CRU	n/a	1823-2013	Monthly
<i>Hindcast wave climate</i> ABPmer	4.92°W, 50.67°N	1991-2009	Hourly
<i>Mean sea level</i> PSMSL	Newlyn 5.543°W, 50.103°N	1916-2012	Monthly Annual

### 2.5.2 Wave modelling

Simulating Waves Nearshore (SWAN, henceforth) is a sophisticated and widely used third generation Eulerian spectral wave model that computes growth, decay and transformation of the discrete wave action balance equation (Booji *et al.*, 1999; Neill *et al.*, 2009). It is specifically designed for modelling irregular waves in coastal regions/environments, using the deep water regime and seabed bathymetry (Booji *et al.*, 1999; Ris *et al.*, 1999; Wolf *et al.*, 2000; Neill *et al.*, 2009). SWAN (version 40.91A) was run, using both the 1931 and 2008 bathymetries, to investigate the variation in coastal and estuarine wave climate. The simulation of wave propagation was carried out for two different periods (1931 and 2008) of the wave climate in the region. The objective here is to briefly examine the role of seabed dynamics on the nearshore open coast processes. It is hypothesised that the upper shoreface has control on nearshore morphology through modification of the incoming wave climate. Two representative of moderate - wave energy conditions were used in the simulation of influence of bathymetric controls on the nearshore and offshore wave climate (Table 2.10). Offshore wave conditions were derived from wave buoy and hindcast data, and focused on higher energy wave climates. The first scenario applied used wave conditions from February, 2013 (wave buoy data of 26 February, 2013 at Sevenstones Lightship from National Data Buoy Centre (NDBC) - [www.ndbc.noaa.gov](http://www.ndbc.noaa.gov), accessed on 26/02/2013). The significant wave height ( $H_s$ ) of 4.5 m having a period of 10.0s was simulated on the two bathymetries (1931 and 2008); these conditions represent a typical winter wave climate. The second simulation focused on extreme conditions, and used the 99<sup>th</sup> percentile wave climate derived from analysis of ABPmer hindcast wave model for a position to the northwest of the study area, giving the measures 6.52 m ( $H_s$ ), 9.3s (period) and 28.5° (spread). The results of this modelling are presented in Chapter 7 to illustrates the influence of the bathymetry on the wave climate. The SWAN model was run in time-dependent mode on the two bathymetric

data and was set up with an extent of about 40 km in the offshore directions and about 60 km in the long-shore direction (after Wolf *et al.*, 2000).

**Table 2.12 Wave climate scenarios used in SWAN modelling**

Source	Location	Dates	$H_s$ (m)	T0 (s)	Spread (°)
NDBC	<u>Stevenstones</u> <u>Lightship</u> 6.100°W, 50.103°N	26/02/2013	4.5	10.0	30.5
<u>Hindcast</u> <u>climate</u> ABPmer	<u>wave</u> <u>West point</u> 5.67°W, 50.65°N	12/02/2007	6.52	9.3	28.5

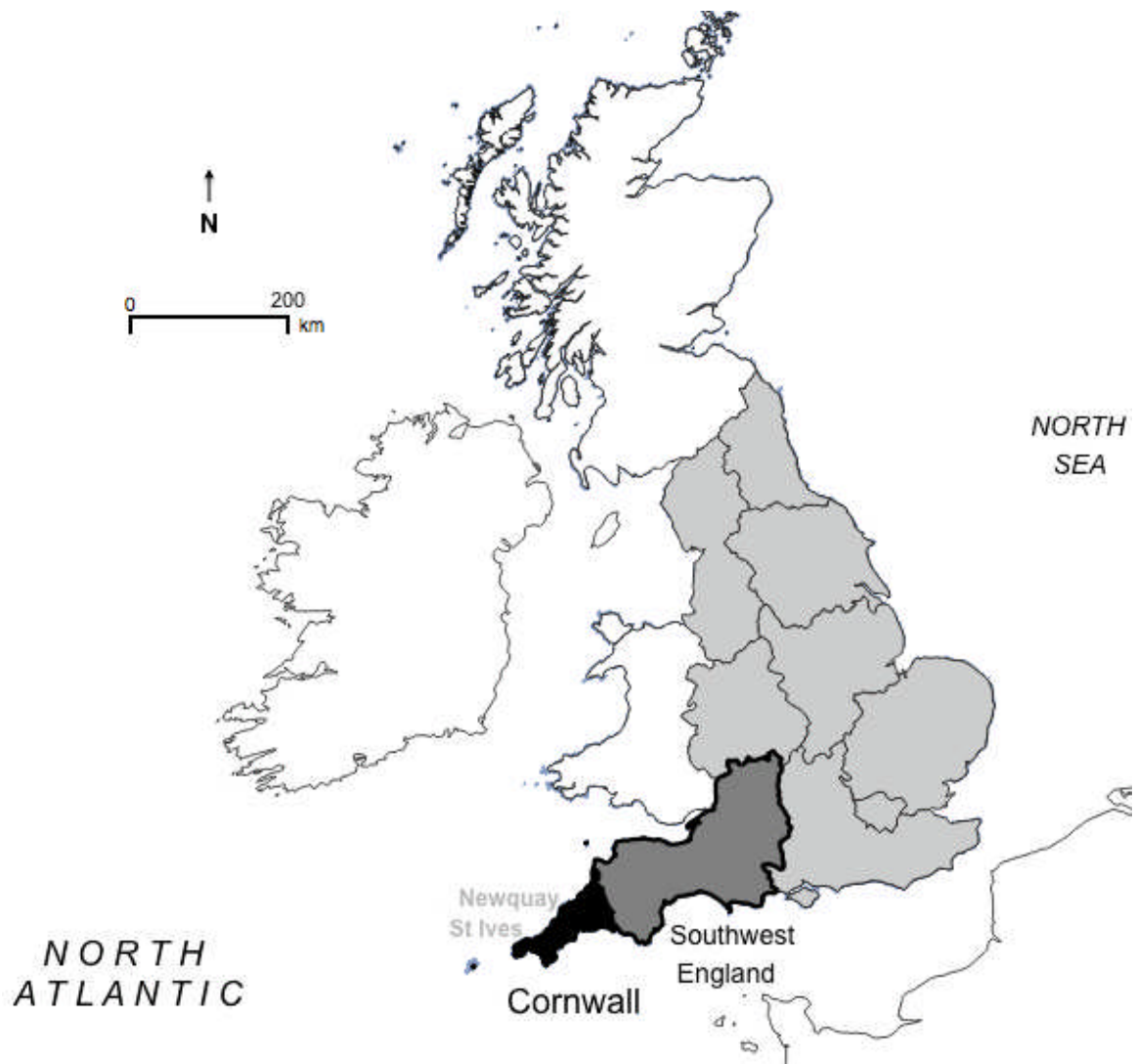
## 3 STUDY AREA

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### 3.1 Geological setting

Southwest England is one of the nine (9) sub-national regions of England, with an estimated area of 9,200 square miles (23,828 km<sup>2</sup>), formed of a peninsula between the English and Bristol channels (SWRDA, 2006) in the northeast Atlantic (Figure 3.1). The coastal zone of Southwest England is regarded as the longest of England's regions with a total of 702 square miles (1,130 km<sup>2</sup>) (SWRDA, 2006). The county of Cornwall occupies the western-most extent of this region. Geologically, the region is largely igneous and metamorphic to the west, and mainly sedimentary in the east of River Exe. Granite and slate, that underlie Cornwall and the west, have exerted significant geological control on the coastal system, which is rock-dominated with moorland hinterland, unlike in the wide, flat clay vales, chalk and limestone lowland to the east (SWRDA, 2006). The climate of the region has been classified as oceanic (Cfb) according to Köppen climate classification, with cool and wet winters and warmer summer. The annual rainfall ranges between 900 – 1000 millimetres (39 in) in the lowlands and up to 2,000 millimetres (39 in) on higher ground (Met Office, URL). The summer average temperature ranges from 18<sup>0</sup>C (64<sup>0</sup> F) to 22<sup>0</sup> C (72<sup>0</sup> F) while the winter minimum averages range from 1<sup>0</sup> C (34<sup>0</sup> F) to 4<sup>0</sup> C (39<sup>0</sup> F) across the region (Met Office, URL).

The geology of north Cornwall is classified as resistant (Clayton and Shamoan, 1998) and it is formed of Devonian (345-395 MaBP) sandstones, shales, conglomerates and limestones (Buscombe and Scott, 2008). To the west, between St Ives and Newquay, is dominated by the Porthtowan formation consisting of slates inter-bedded with sandstones and siltstones (Buscombe and Scott, 2008). More details about the formation in the region are described by Campbell (1998); Bird (1998), Scourse and Furtze (1999), Halcrow (2002) and Buscombe & Scott (2008).



**Figure 3.1 The Southwest Region of England position in Great Britain**

### **3.2 Holocene context**

Evidence of early Holocene (ca. 11,400 – 6800 cal. yr BP) coastal systems for Southern England is limited (Waller and Long, 2003). However, the bathymetric maps investigation suggests a probability of marine flooding of British Channels in the earliest Holocene (Wrywoll and Smith, 1985, 1988) while palaeographical maps evidence indicates flood occurrence at western area of the Channel around the 11,400 calendar year before present (cal. yr BP) forming a marine waterway which is connected with and through the southern North Sea basin around 8300 cal. yr BP (Lambeck, 1995; Shennan *et al.*, 2000; Waller and Long, 2003). Further evidence of early Holocene of coastal evolution is recorded within Southampton Water with the record of marine silts deposition at around *ca* – 20 m Ordnance Datum (OD, the mean sea-level Newlyn) depth of Clashot Spit (Hodson and West, 1972). Godwin and Godwin (1940) pollen analysis of basal organic deposits at Southampton Water suggests deposition commenced before 10,000 cal. yr BP and at

around 5 m below the modern surface, confirming a deposit which must have started accumulating above Relative Sea-Level (RSL). The accessibility and analysis of sedimentary deposits after 6,800 cal. yr BP show that largely fine-grained sediments (of minerogenic and organogenic source) accumulated against the circumstance of prevailing rising RSL which contributed to the wider development of coastal barriers (Waller and Long, 2003). During this period, around *ca.* 6,200 – 5,000 cal. yr BP, Healy (1995) discovers the peat insertion within coarse sand and a further formation of basal peats in Cornwall (specifically at Marazion Marsh) to the depth of between -6.21 and -4.71mOD. Also, Morey (1983) notes the migration and formation of organogenic sediments in response to landward barrier at Slapton Ley during the mid-Holocene (*ca.* 6,800 – 3,700 cal. yr BP). The late Holocene (*ca.* 3,700 cal. yr BP onwards) witnessed widespread inundation and minerogenic sedimentation that contributed to a relative low rates of long-term RSL, barrier instability and sediment reworking especially in the southern coast of England (Waller and Long, 2003). Within the last 1,000 year or thereabout, the “coastal land reclamation and sea-defence construction has accelerated” in southern England (Waller and Long, 2003:354). A contrasting situation appears to be observed in Cornwall as the evidence here suggests more extensive deposition of organogenic sediments, although not a continuous process, during the Holocene (Waller and Long, 2003).

The different analyses of crustal movements within Great Britain based on geologic, geodetic and tide gauge information revealed patterns of relative uplift in (highland) Scotland and relative subsidence in the south of England (Valentin, 1954; Churchill, 1965; Kelsey, 1972; Rossiter, 1972; Shennan, 1983, 1989; Woodworth, 1987; Shennan and Horton, 2002). During the Holocene, crustal downwarping occurred throughout southern England and most of Wales with southeast and southwest England experiencing a net subsidence rate of over 1 mm yr<sup>-1</sup> since 4000 BP (Shennan, 1989; See Figure 3.2). This uneven spatial distribution of uplift and subsidence is attributed, in part, to the isostatic recovery from Pleistocene ice melt that led to the crustal upward movement of land in northwest Britain during the Holocene and the net subsidence (downwarping) in southern England as a result of the combination of regional-scale subsidence and the collapse of proglacial ‘forebulge’ after the Pleistocene ice melt (Pye, 1997).

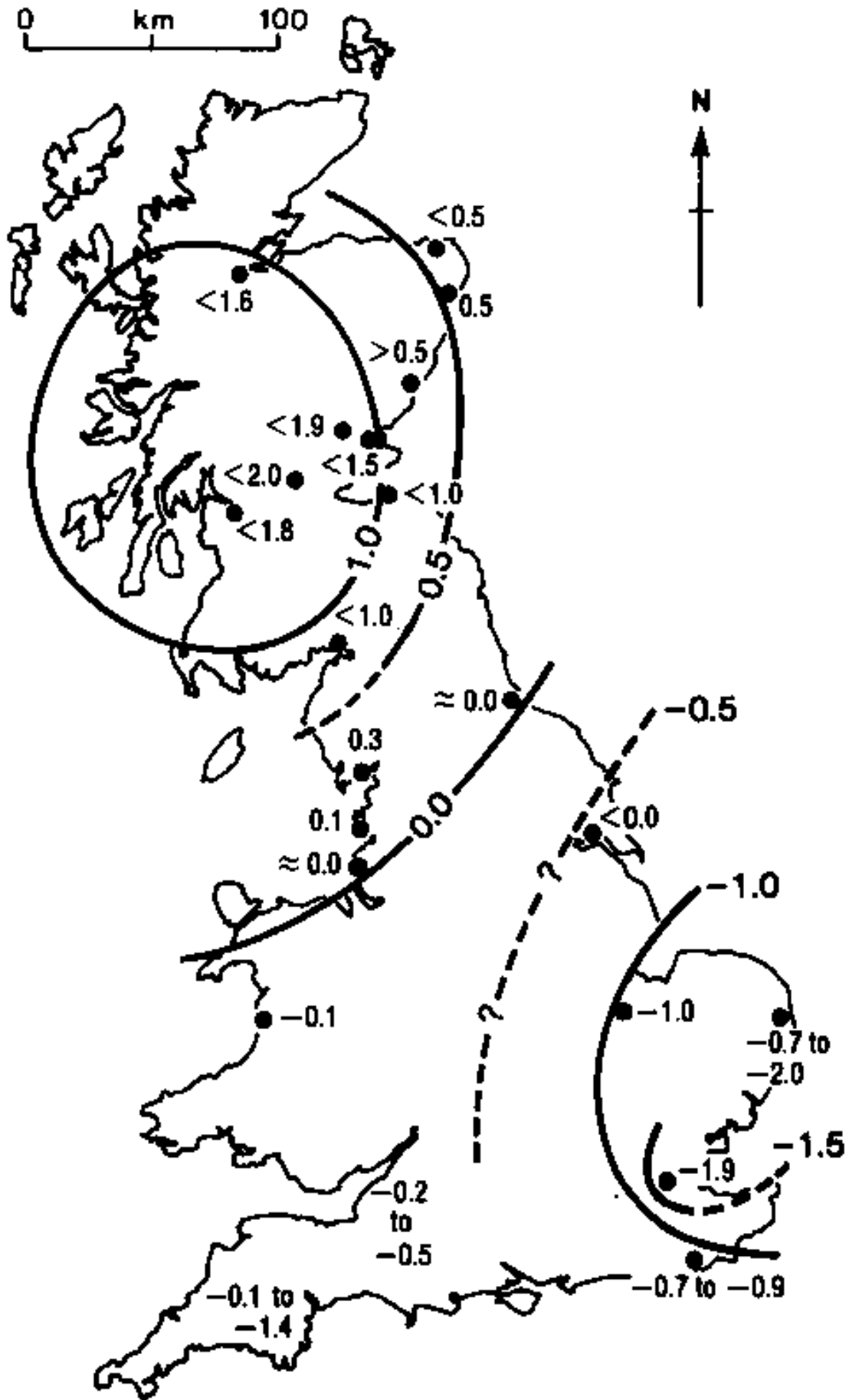


Figure 3.2 The estimated rates ( $\text{mm yr}^{-1}$ ) of crustal movement in Great Britain. (From Shennan, 1989: page 87)



### 3.2.1 Holocene and Sea-level change

The Southwest of England was observed to be ice-free during the Last Glacial Maximum (LGM) with its post-glacial RSL history having implications for proglacial forebulge dynamics, the flexing of outer part of the earth (crust and upper mantle) near the ice margin that eventually migrated and collapsed as 'the land-based ice retreats' (Massey, *et al.*, 2008). There was global 'eustatic' sea level rise during the Holocene as a result of the combination of melting glaciers/ice sheets, and the thermal expansion of the upper layer of the ocean (Mörner, 1971; Shennan 1989; Shennan and Horton, 2002). The effect of which led to the rise in sea-level to 40 m in approximation. However, different parts of the world, Great Britain inclusive, experienced quite distinct and contrasting responses to the 'relative' sea-level rise during the course of Holocene as a result of 'isostatic' tectonic movement (Milne, *et al.*, 2008). As far as south-west Britain is concerned, Kidson and Heyworth (1978) suggested that the region was tectonically stable, therefore the local relative sea level rise in this region could be an indication of eustatic change (Edwards, 2006). While the relative sea-level rose more or less continuously between 13,000 and 6,000 BP in North-west England, it has been suggested that the rise began in the region by 14,000 BP, then continued at a rapid rate until 6,000 BP (Pye, 1997) but reached its current altitude at about 4,000BP (Edwards, 2006) since when it has continued at a slower rate of  $c. 2 - 3 \text{ mm year}^{-1}$  (Pye, 1997).

However, the coastline of southwest England is determined to be currently undergoing relative subsidence at faster rate (approximately at  $0.9 - 1.4 \text{ mm yr}^{-1}$ ) than any other coasts in Great Britain (Shennan and Horton, 2002; Massey *et al.*, 2008). The recent gravity measurements by Teferle, *et al.* (2006) determines absolute subsidence rates of  $0.1 \pm 0.9 \text{ mm yr}^{-1}$  while recent GPS measurements suggest a subsidence rate of  $0.0 \pm 0.5 \text{ mm yr}^{-1}$  (Massey *et al.*, 2008). Compared to global anomalous subsidence average, the rate of sea-level rise of  $\sim 1.6 \text{ mm yr}^{-1}$  in Southwest England (using the tide gauge measurement in Newlyn, Cornwall since 1916) does not differ significantly (Woodworth, *et al.*, 1999). A higher rate of relative sea-level rise of  $1.0 - 2.3 \text{ mm yr}^{-1}$  contributes to widespread loss of intertidal flats and saltmarshes, erosion of coastal cliff and landward retreat of shingle barriers (Woodworth *et al.*, 1999). Figure 3.3 shows the calculation of RSL change using the present tidal range values and the modelled changes for both inner- and outer- estuarine deposits by Shennan and Horton (2002). The channel coasts of Cornwall produced only 7 scattered sea-level index points (SLIPS) with the relative  $-1.27 \text{ mm yr}^{-1}$  rate since 4,000 cal yr BP and the best estimate rate of  $-1.21 \text{ mm yr}^{-1}$  (Healy, 1995; Shennan and Horton, 2002). The current recommended rate of sea-level rise for southwest England is now  $c. 1.8 \text{ mm yr}^{-1}$  (PSMSL, 2013).

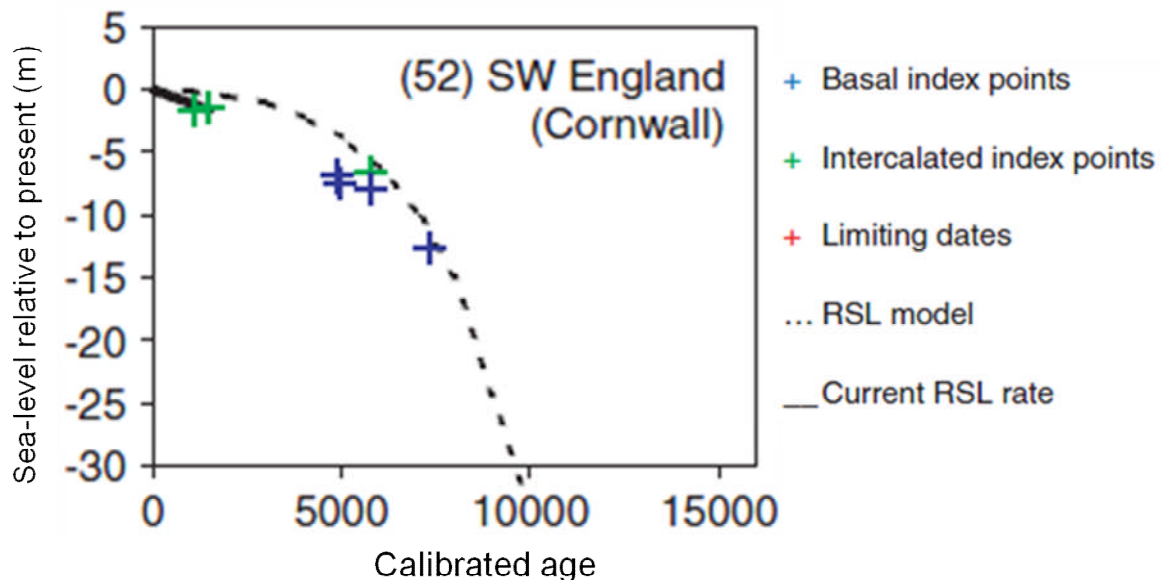


Figure 3.3 Sea-level index point for location 52 in Great Britain plotted as calibrated age against change in sea-level relative to present (m). The best estimate of the late Holocene trend for the location is plotted as solid line. The dashed line shows the predicted RSL from model described by Shennan, *et al.*, (2002). [The figure is adapted from Shennan and Horton, 2002: 518]

### 3.2.2 Coastal evolution

The different patterns of sea-level changes through mid- to late- Holocene age have had profound effects on coastal evolution. Analysis of more than 1200 sea-level index points and 180 limiting dates for the 52 locations in Great Britain by Shennan and Horton (2002), covering the last 16 000 years show maximum relative uplift in central and western Scotland of *c.* 1.6 mm yr<sup>-1</sup> and maximum subsidence of *c.* 1.6 mm yr<sup>-1</sup> in southwest England (Shennan and Horton, 2002). Raised marshes, barrier systems, abandoned shore platforms and beach ridge plains from the mid- to late- Holocene are common in Scotland and northwest England. In southern England, however, sediment consolidation increases the subsidence in areas with thick sequences of Holocene sediments, contributing an average of *c.* 0.2 mm yr<sup>-1</sup> to land subsidence (Shennan and Horton, 2002). The continuing trend of subsidence and submergence in the southwest region has formed a coastline of drowned river valleys and estuaries. The contrasting relative sea-level histories have had (and still have) profound effects on coastal landforms and evolution.

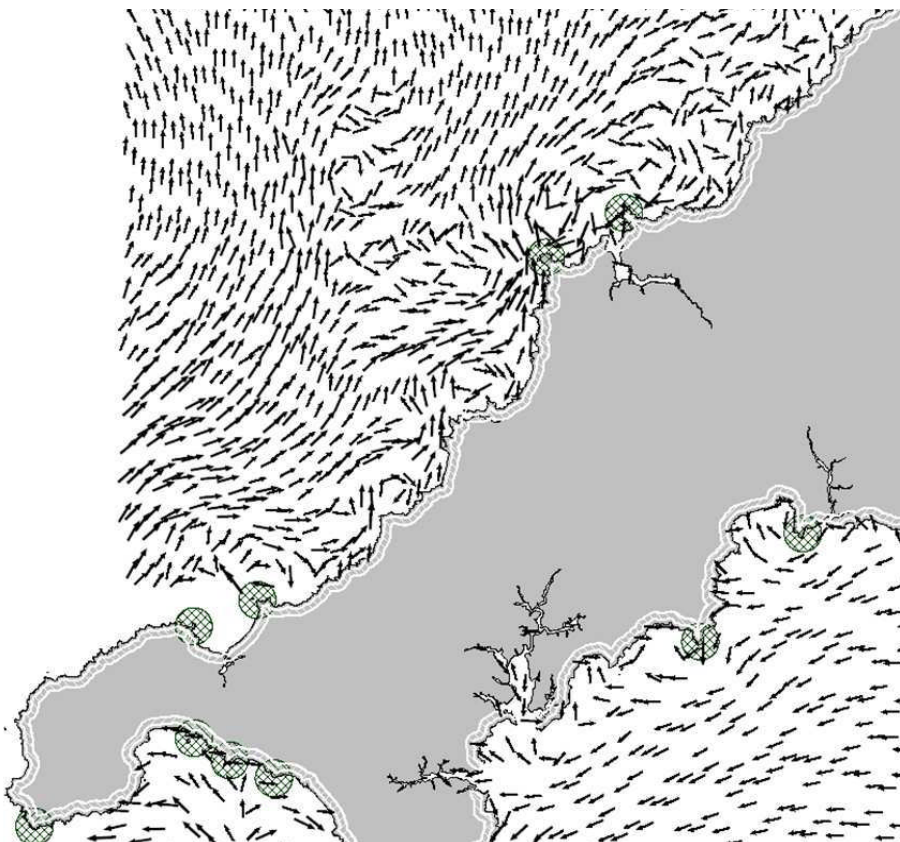
## 3.3 Contemporary coastal processes

### 3.3.1 Process regime

The wind and wave climate of the southwest of England is dominated by North Atlantic weather systems and storm activity. The 10% exceedance significant wave height ( $H_{s,10\%}$ ) is 2.5 – 3 m (Draper, 1991; NERC, 1998) characterised by a mixture of Atlantic swell and Temitope Oyedotun

locally generated fetch-limited wind waves (Buscombe and Scott, 2008) that exhibit a Mean Spring tide Ranges (MSR) of 4.2 to 8.6 m (UK Hydrographic Office, 2003; Scot, *et al.*, 2007). The annual mean offshore wave power, was estimated to be between 21kW/m and 25kW/m (DTI, 2004; SWRDA, 2004). Wave energies along the north Cornwall coast are sufficiently high to be used in the development and piloting of wave energy convertors (Millar *et al.*, 2007; Smith *et al.*, 2012; Stokes *et al.*, 2014).

The spring tidal range along the north coast of Cornwall is around 5 – 6 m (UKHO, 2003). Tidal currents are generally weak ( $\leq \sim 0.75\text{ms}^{-1}$ ) except in local areas around headlands (Figure 3.4) (Halcrow, 2002) and at tidal inlets. Southwest England is the second most exposed area of Great Britain after the Western England, therefore strong winds are active in this region. The bulk of the strongest winds are from southwest and northeast caused by the passing of West - East Atlantic depression over the Great Britain with a change in west–northwest direction when depression ceases/leaves. The winds in Southwest England are stronger in winter as the strength of frequencies and depression increase while the lightest mean wind speeds occur in summer, – gusty wind also follow this pattern of scenarios (Metcalf, *et al.*, 2003). To the North-east of the region and in the the inland areas, the mean wind speed are generally low. For example in places like Yeovilton (the Somerset lowland), the mean wind speed is two-thirds of that of St Mawgan of Cornwall (Metcalf, *et al.*, 2003).



**Figure 3.4** Tidal residuals within the study area, according to Halcrow (2002) and Buscombe and Scott (2008:8). Arrow size is relative to the magnitude of tidal flux. The map extent is 100 km<sup>2</sup>.

### 3.3.2 Sediment and sediment transport in the region.

The early works of Stride (1963) and Pingree and Griffiths (1979) present contrasting patterns of sediment movement in southwest England. While Pingree and Griffiths (1979) suggest the region experiences a net northwesterly sediment transport under the westerly/southwesterly prevailing waves, Stride (1963) suggests opposite based on the bedform symmetry, stating that the sediment moves out of southern bight of the North Sea in northward direction. It is currently believed that waves cause the seasonal onshore/offshore movement of sediments along the shoreline (Scott *et al.*, 2007; Buscombe and Scott, 2008). However, sediment movement is thought to be limited due to water depths, the pattern of the inlets in the region, the structure of the headlands and limited volume of sediments (Halcrow, 2002; Buscombe and Scott, 2008). Figure 3.5 shows an overview of the bathymetry of the study area. The areas around the shorelines are obviously shallower than those further away offshore. The nearshore sediment circulations patterns in the region is thought to stay close to the coasts as the sediments in southwest England are driven by north/easterly waves and south-westerly swell during the storms (Buscombe and Scott, 2008).

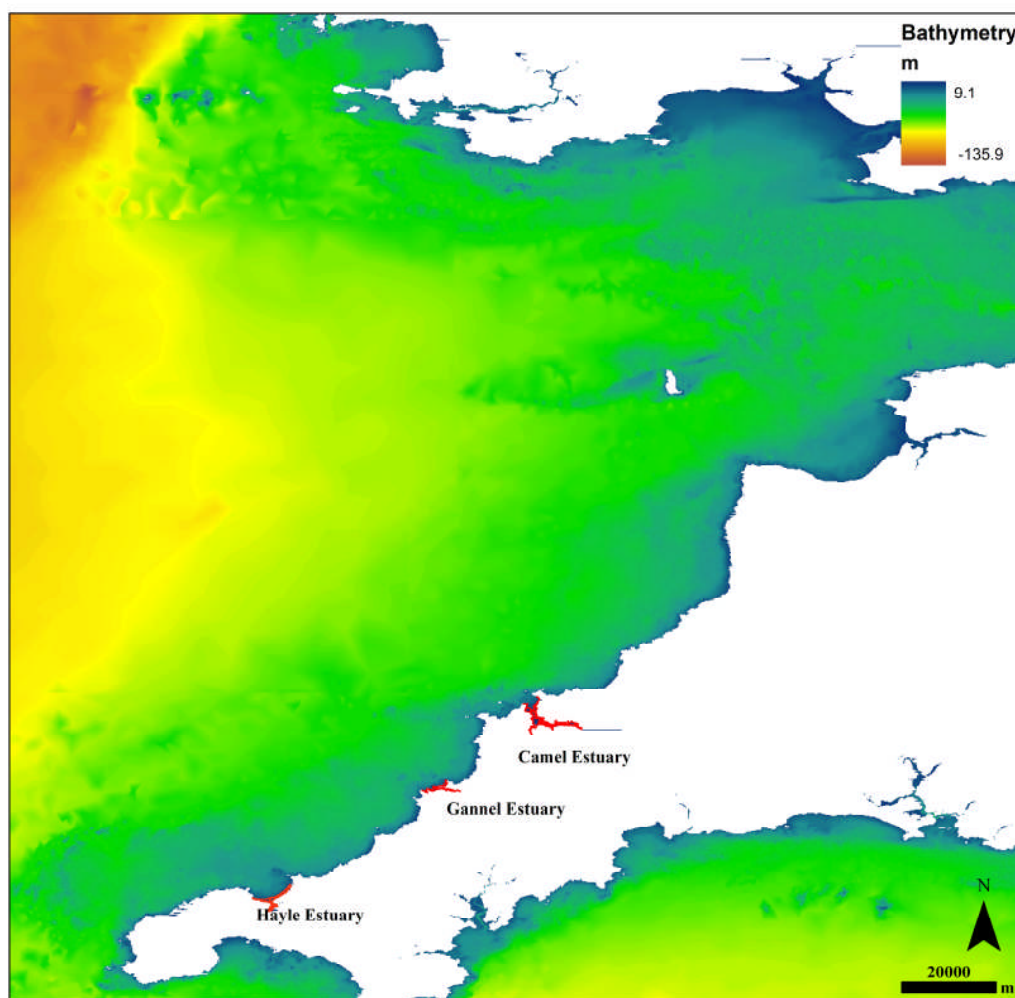
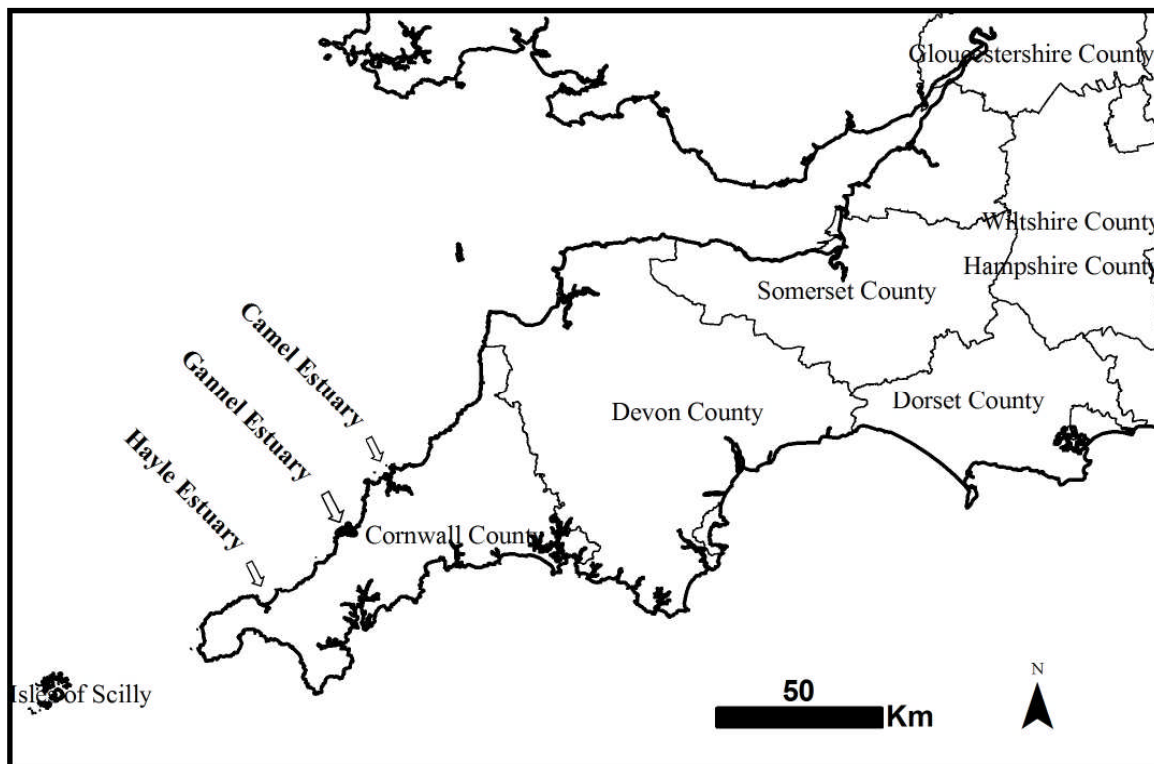


Figure 3.5 Bathymetry of the southwest England shoreface.

### 3.4 Study sites

#### 3.4.1 Southwest England case study

As noted in the preceding chapter, the UK is very rich in estuaries (over 160 according to Defra, 2006) with more than a quarter of the northwestern European estuaries occurring in the UK (Defra, 2006). Many of these have been studied separately from their adjoining coasts, often in isolation from the broader coastal context. In contrast, the present study is based on a more integrated analysis of a regional cluster of estuaries, focusing on the north coast of Cornwall, southwest England. The Hayle, Gannel and Camel estuaries and their adjacent open-coast shorelines (Figure 3.6) have been the subject of various studies in the past, but no regional synthesis of the historical behaviour has yet been attempted. Also important, is the availability of various datasets to support characterisation of coastal and estuarine geomorphology and analysis of shoreline change, not least the airborne LiDAR datasets available through the Channel Coast Observatory ([www.channelcoast.org](http://www.channelcoast.org)). These three neighbouring systems also provide an excellent opportunity to examine the sedimentary linkages between coast and estuary, and to investigate the extent to which their historical behaviour exhibits any regional coherence.



**Figure 3.6** Location of the selected study sites on the north coast of Cornwall, southwest England.

The north Cornwall coast is exposed to a predominantly westerly wave climate with a 10% annual exceedance wave height of 2.5 – 3 m and a 1 in 50 year extreme offshore wave

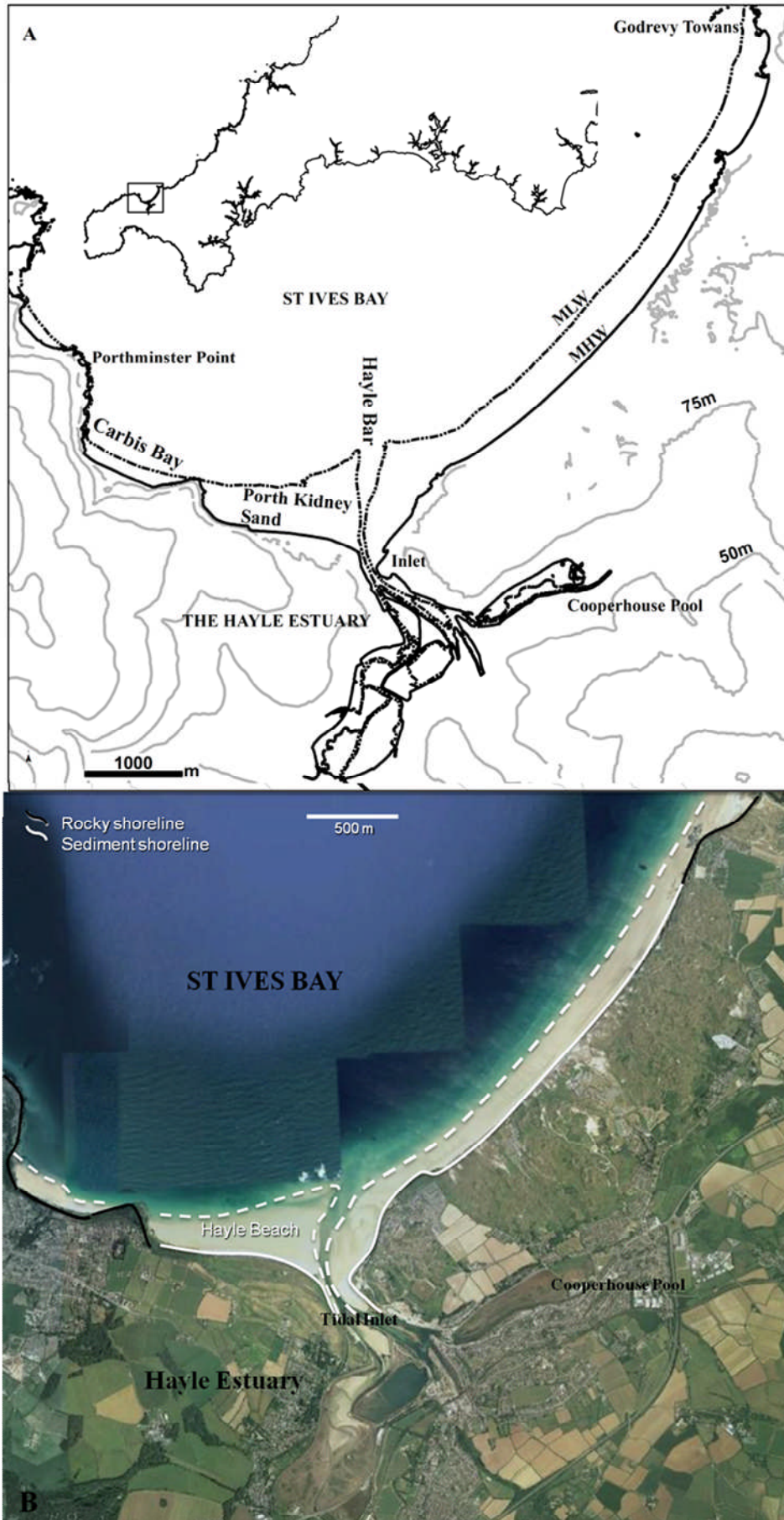
height of 20 m, with the possibility of wave heights regularly exceeding 5 m during the winter months. This is the season when long period swells of 15 seconds wave or more are common (Royal Haskoning, 2011). The Hayle, Gannel and Camel estuaries and their adjacent open-coast shorelines (bays) are discussed extensively in this section.

### **3.4.2 St Ives Bay and the Hayle Estuary**

The Hayle estuary lies within St Ives Bay in the Penwith District of Cornwall (Figures 3.7). The Hayle estuary comprises approximately 1.2 km<sup>2</sup> of largely intertidal sand flats, mud flats and saltmarsh. St Ives Bay extends *c.* 8 km between the headlands of Porthminster and Godrevy Points: the Hayle Estuary enters the Bay west of centre. The estuary lies within the drowned valleys of the Rivers Hayle and Angarrack. The Hayle Estuary has been classified as bar built estuary in the Joint Nature Conservation Committee (JNCC) inventory while ABPMER *et al.* (2008) classified it as ‘spit enclosed’ (ERP2 Geomorphological Type). It means the estuary is formed in a drowned river valley with one or more spits bounding the estuary mouth. The aerial photograph of Hayle estuary is presented in Figure 3.7 showing rocky and sediment shoreline.

St Ives Bay contains 10 distinct beach systems (covering a total area of 2,802,500 m<sup>2</sup>), coastal dunes and the Hayle inlet (Buscombe and Scott, 2008). It can be considered as a closed sedimentary system whereby little or no exchange of sediment (sand or coarser) to neighbouring bays occurs. This implies that local patterns of erosion and deposition are likely to be balanced within the embayment and redistribution of reworked sediment is common. It is thought that sediment linkage between offshore and the shoreline is limited (Babtie, 2002; Buscombe and Scott, 2008). The sedimentary cover overlies a rock floor, which lies at an average of 3.40 m below Ordnance Datum Newlyn (ODN). The tidal regime in St Ives Bay is macro-tidal (mean range at spring tides 5.8 m; Table 3.1) and storm surges may add 1 m or more to predicted tidal levels (Pugh, 1987; Table 3.2).

The bedrock geology of St Ives Bay and the Hayle catchment is largely composed of Devonian metasediments (mudstones, siltstones, slates and sandstones). Permian granitic intrusions bound the bay to the west (at St Ives), and border the Hayle catchment to the south and southeast. Elsewhere, Devonian intrusions and lavas form resistant headlands (e.g. St Ives Head). Permian and Devonian intrusive dykes maintain a strong southwest-northeast alignment, whilst primary faults are aligned northwest-southeast. Structurally, the Hayle estuary comprises two river valley basins extending southwest (River Hayle) and northeast (River Angarrack).



**Figure 3.7 (A) The St Ives Bay and Hayle Estuary. Inset: Its location in Southwest England, and (B) the 30/08/2012 Google aerial photograph showing the sediment and rocky shoreline.**



**Figure 3.8 Photographs showing A) the Hayle Estuary by Lelant Rail Station and B) the Barrepta Cove/ Carbis Bay (Field picture, 25/10/2011)**



**Table 3.1 Summary of typical water levels at St Ives (Lat. 50.21<sup>0</sup>N Long. 5.43<sup>0</sup>W). Data taken from Admiralty Chart, © Crown Copyright / SeaZone Solutions Ltd [2008]**

<b>Tidal State</b>	<b>Water Level (m ODN)</b>	<b>Height (m CD)</b>
Mean High Water Spring (MHWS)	+3.2	6.6
Mean High Water Neap (MHWN)	+1.5	4.9
Mean Low Water Neap (MLWN)	-1.0	2.4
Mean Low Water Spring (MLWS)	-2.6	0.8

**Table 3.2 Summary of extreme water levels at St Ives (Lat. 50.21<sup>0</sup>N Long. 5.43<sup>0</sup>W) [Source: Defra/EA (2004)]**

<b>Return Period (years)</b>	<b>Water Level (m ODN)</b>
1 in 2	3.55
1 in 5	3.63
1 in 10	3.66
1 in 20	3.69
1 in 50	3.72
1 in 100	3.75
1 in 200	3.76

*Note: Figures in Table 3.2 above exclude surge or long term sea level rise; m ODN refers to metres above Ordnance Datum Newlyn.*

Settlement and use within the Hayle valley has an extended history due to the role of the river and estuary as an important harbour. The name ‘Hayle’ was derived from the Cornish word ‘hayl’ or ‘heyl’, which means ‘tidal flats’ or ‘estuary’. The development of the copper and tin mining industry in Cornwall led to the advancement of a mining community around Hayle in the 18<sup>th</sup> century. The intense industrial and commercial activities led to the establishment of Hayle harbour which handled many thousands of tonnes of coastal and transatlantic shipping during the 19<sup>th</sup> century. The further development of Hayle harbour involved the construction of training walls, quays, slicing of ponds and dredging. Also, in order to maintain a navigable channel for shipping, there has been a long history of sand extraction from the estuary (Noall, 1984; Pascoe, 2005). Related to this, there are several commissioned studies on the Hayle:

- Harvey’s Hayle’s Report on engineering works and maritime activities, by Harvey & Co in 1966 (Vale, 1966);
- Port of Hayle - aspects to be considered in relation to future requirements. Consultant Report by Hydraulics Research Station (1976);
- An investigation of sediment dynamics in the Hayle Estuary Cornwall by Sea Sediments (1983);
- Water Level Control in Hayle Harbour by Sir Alexander Gibb & Partners (1989);
- Hayle Harbour- Hydraulic and siltation studies by HR Wallingford (1989);

- Cornwall & Isles of Scilly Coastal Group, Lands End to Hartland Point Shoreline Management Plan by Halcrow Group (1999); and,
- Hayle Harbour Hydrodynamic Modelling Report by Babtie Group Limited (2002).

Newman (1976), with his team at the Hydraulics Research Station, visited Hayle Harbour and subsequently carried out a desk review on the hydraulic problems of the port area, on the request of Penwith District Council. The Newman's report referred to capital dredging in the harbour entrance where about 49,000 tonnes of sands were dredged between 1972 and 1975, and concluded that: (i) the estuary and the bar areas would be accumulating sand on a small scale especially with the then current sluicing operations; (ii) the maintenance of the water depths in the channel and over the bar would require the artificial removal of sediments and sand accumulations; and (iii) the increased shoaling in the channel and the bar area is as a result of reduction in tidal volume at Copperhouse Pool due to progressive siltation from land areas. The report concluded by recommending hydraulic investigations of the estuary in case of future developments. It should, however, be noted that the report was limited by lack of detailed survey data.

An investigation of sediment dynamics in Hayle was carried out in 1983 for the owners of Port of Hayle Ltd with following objectives: (i) determination of water and sediment movement due to tidal, river and wind/wave induced flows; (ii) determination of the long-term stability of the estuary should no change be implemented; and (iii) the possibility of maintaining deepened channels or pools within the estuary by sluicing. Field measurements were carried out, sediments sampled and analysed, while the historical survey charts were also reviewed and the possible transport scenarios discussed in a bid to achieve the objectives. The main conclusion of the report centred on the conceptual sand transport processes and dynamics within the estuary. The Sea Sediments study contained useful field information and reference on sediment and water interaction in the Hayle estuary. Sea Sediments (1983) used the figure 3.8 to diagrammatically explain how the constructive waves, during their south-westerly direction (before refraction) approach to Hayle beach, supply sand to the foreshore especially at the westernmost points. The wave rays model for the situations for 1848, 1930 and 1983 show that the landward movement of sand continues until when the waves 'feel the-bottom' and then allow the tidal currents to act on the sand flowing in parallel to the channel axis before being ultimately transported seawards. It was observed that during the early period, the net supply of sand to the system during the flood tide decrease the tidal prism. This example from Sea Sediments (1983) investigation shows that the system responds sensitively to changes in wave patterns and sand transport systems.

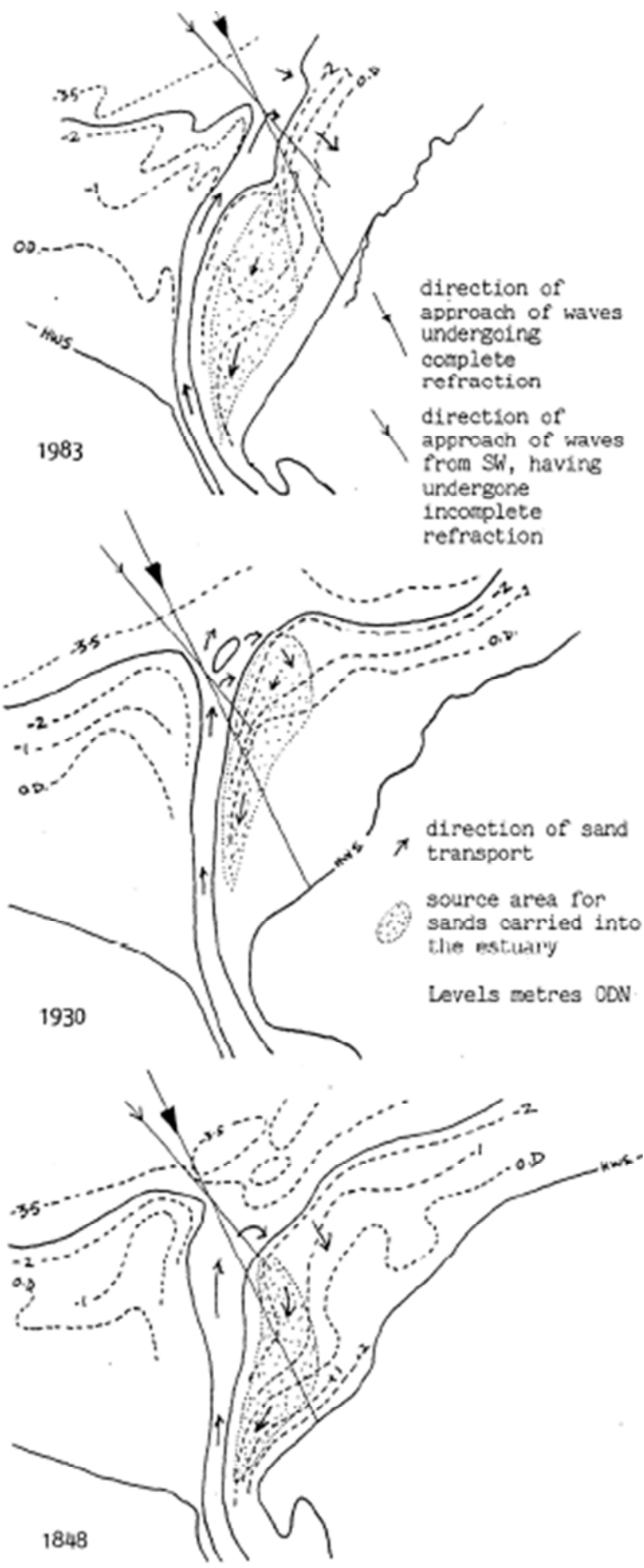


Figure 3.9 Historical sand supply model for the entrance into Hayle Estuary [Courtesy of Sea Sediments, 1983: 119].

The 1989 field surveys by Sir Alexander Gibb & Partners and HR Wallingford, on the other hand, were focused on monitoring tidal levels and water/sediment movements in the Hayle Harbour respectively. While Sir Alexander Gibb & Partners' report focused on tidal/water levels, the HR Wallingford project was on sediment, hydraulics and siltation in the harbour. The two reports concluded that the proposed harbour village development would not have any adverse effects on both water and sand movements.

Babtie Group Ltd (2002) assessed the estuarine and coastal processes of Hayle Harbour through numerical hydrodynamic modelling. The objectives of the project ranged from investigating the rapid accretion/erosion of sediments in the harbour, the effects of dredging on sediment transport processes and reductions in beach levels to investigating interaction between the retreating dunes and dredging activities. The findings of the investigation indicated that waves play a significant role in the transport and redistribution of sediments within the intertidal zone; and that the dominance of the flood tide over Hayle beach resulted in the transport of sediments towards the mouth of the estuary during the spring tide. The reports recommended a simple monitoring scheme whereby positions of dune crest and toe are measured at three month interval to assist in the determination of dune recession or sediment accretion in the estuary.

The previous works, as summarised and discussed above, focused on the developments and maintenance of the estuary for harbour development with the exception of Sea Sediment and Babtie Group's reports which investigated sediment dynamics and hydrodynamics of Hayle harbour, its effect on sediment accretion and transport processes, respectively. The reports, however, have not considered the impacts of both natural forcing and human activities on coastal-estuarine processes, and the morphodynamic connection/interaction, because the objectives of those projects were restricted to the scope of their commissions. Nevertheless, it is very pertinent to understand how the impacts of the natural processes and barrage of human activities have influenced the major evolution and development of the estuaries.

Rollinson *et al.* (2007) investigated the sediment geochemistry and mineralogy of shallow cores in the Hayle as a result of mining activities that took place in the estuary. A high level of tin and copper were discovered in the sediment samples, associated with contributions from historic mine and smelt wastes. Importantly, the authors established that much of the surface sediment within the main southwest basin of the Hayle had been deposited prior to 1880 and that more recent sedimentation had been removed by recent and continuous erosion. The impact of this metal pollution is considered further by Bury and Durrant (2009) who examined the role of metal pollution on population traits of brown trout (***Salmo trutta L.***) living in the river Hayle, Cornwall, UK. Although major mining activities ceased in late 19<sup>th</sup> century, it was shown that metal pollution affects the genetic

diversity and inbreeding of the brown trout, despite the fact that the brown trout in the rivers are highly adapted to the elevated metals. The Hayle and other Cornish systems have received considerable attention in terms of the impact of mining (principally for Sb and Sn) on sedimentation. Although pollution and chemistry indicators are considered extensively in past studies, very little consideration is given to the nature of estuary-coast linkages in terms of sedimentary processes and morphodynamic evolution.

Issues relating to the changing beach levels around the Hayle estuary inlet received some community and media attention over recent years. A local campaign group, Save our Sands (SOS) successfully raised awareness of beach dynamics, which also featured in the national news (BBC, 2011; Figure 3.9). There is a consensus among the groups that there is an urgent need to protect the beaches in order to avert their disappearance. The report quoted one Mr Egan as saying that the Hayle beach, as at 2011, was 5 m (16 ft) lower than it was in 2005. This is an indication of the attention that such dynamic systems are gaining among the research interest groups, the media and concerned organisations/individuals (Figure 3.10).



The image is a screenshot of a BBC News Cornwall website page. At the top, there is a red navigation bar with the BBC logo and 'Mobile' text on the left, and 'News | Sport | Weather | Travel | TV' on the right. Below this is a large white banner with 'NEWS CORNWALL' in red. A secondary navigation bar contains links for 'Home', 'UK', 'Africa', 'Asia-Pac', 'Europe', 'Latin America', 'Mid-East', 'South Asia', 'US & Canada', 'Business', and 'Health'. A third bar lists regional links: 'England', 'Northern Ireland', 'Scotland', 'Wales', 'UK Politics', and 'Education'. The article's date and time are '11 August 2011 Last updated at 06:03 GMT'. A share button shows '52' shares and icons for Facebook, Twitter, Email, and Print. The main headline is 'Fears for the future of Hayle Beach'. The sub-headline reads: 'Campaigners are calling for urgent efforts to restore a west Cornwall beach.' The text states: 'Save Our Sands (SOS) has warned that beaches round the popular St Ives Bay could start to disappear unless urgent action was taken.' It further notes: 'SOS said the removal of a million tonnes of sand by dredging over 30 years had nearly destroyed Hayle Beach.' A final line says: 'They want sluicing to be introduced to keep clear the channel used by fishing boats.' To the right of the text is a photograph of two people, Anne Marie Rance and Ged Egan, standing on a sandy bank next to a body of water. Below the photo is a caption: 'Anne Marie Rance and Ged Egan said dredging over 30 years had damaged Hayle Beach'.

Figure 3.10 The headline caption about Hayle beach on the BBC website (<http://www.bbc.co.uk/news/uk-england-cornwall-14415539>. Accessed on 11/08/2011).



**Figure 3.11** Some rocks fragments and stones left at Black Cliff by some residents or concerned organisations in a bid to check erosion at the beach (Field picture, 25/10/2011).

### **3.4.3 Crantock beach and the Gannel estuary**

The Gannel estuary lies between Pentire Point East and Pentire Point West, on the north coast of Cornwall, southwest England (Figures 3.12 and 3.13). The estuary is a ria estuarine system comprising sandy intertidal flats within a narrow valley merging with a large sandy beach-dune system (Crantock) at the seaward extent, and saltmarshes at the landward extent. Around 70% of the estuarine valley is intertidal (Davidson *et al.*, 1991). It is suggested that the estuarine system (between the Devonian slate/sandstone headlands of Pentire Points East and West (Hollick *et al.*, 2006)) functions as a self-contained sediment cell (Dyer, 2002). However, there may be weak and intermittent alongshore transport and some limited exchange of sediments between the bay and open-coast, especially across the broad intertidal zone, and during storm conditions (Royal Haskoning, 2011; see also Figure 3.12).

The estuary is the tidal outlet for the River Gannel. Similar to Hayle, the mouth of Gannel was extensively used for shipping and other maritime activities until the late 20<sup>th</sup> Century when trading decreased as a result of development of Newquay harbour and the siltation of the River Gannel (Royal Haskoning, 2011). This coastline is macrotidal (mean spring tide range 6.4 m) (Table 3.3), and is exposed to a predominantly westerly wave climate with a

10% annual exceedance wave height of 2.5 – 3 m and a 1 in 50 year extreme offshore wave height of 20 m. Wave heights regularly exceed 5m during the winter months and swells of 15 seconds or more are common (Royal Haskoning, 2011).

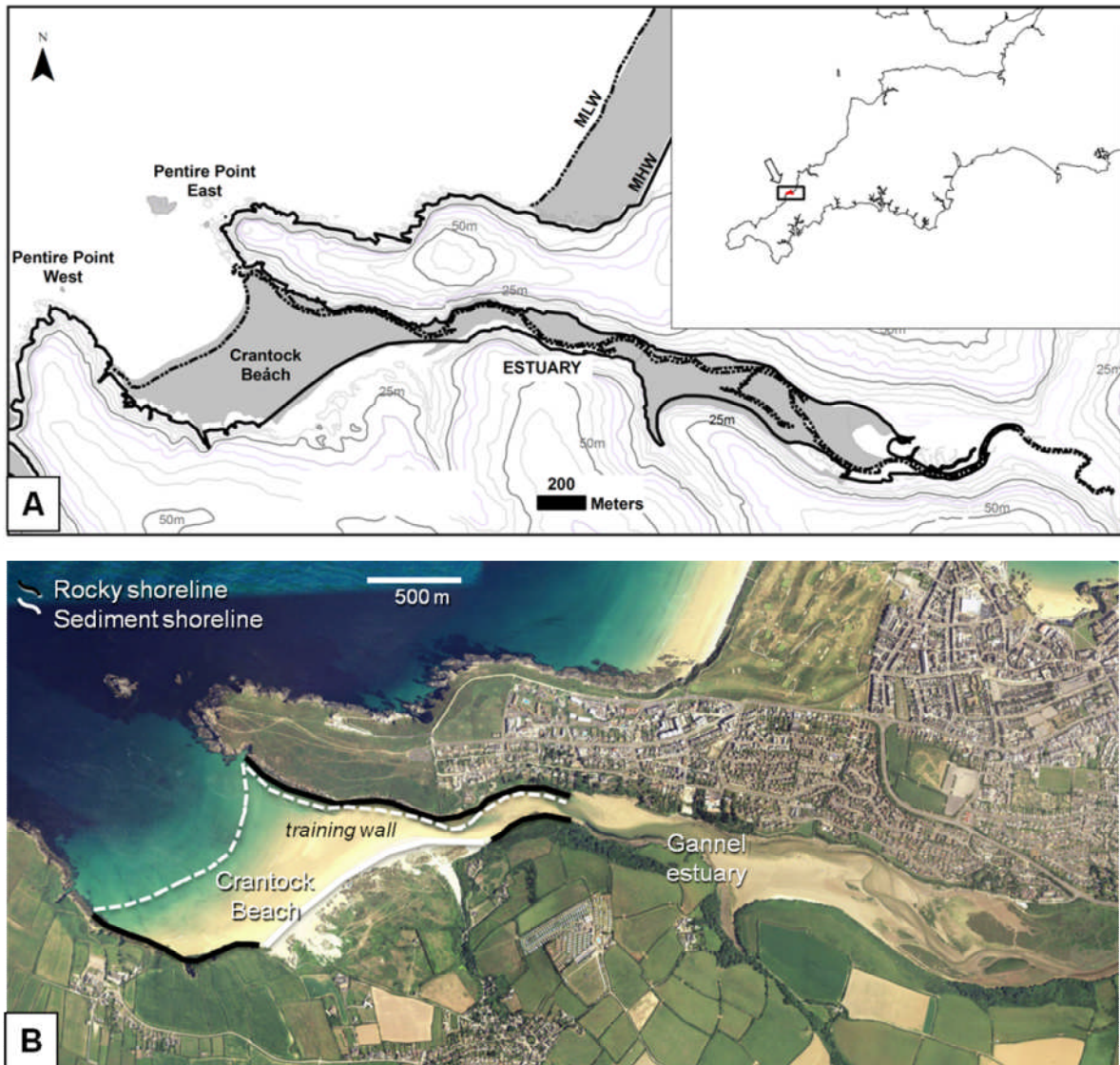


Figure 3.12 (A) Crantock Beach and the Gannel Estuary, Cornwall, located in the southwest England, and (B) the 20/08/2012 Google aerial photography showing the rocky and sediment shoreline.

Table 3.3 Summary of typical water levels at Newquay (Lat. 50° 25' Long. 5° 05')

Tidal State	Water Level (mODN)	Heights in metres above datum
Mean High Water Spring (MHWS)	+3.4	7.0
Mean High Water Neap (MHWN)	+1.7	5.3
Mean Low Water Neap (MLWN)	-1.1	2.5
Mean Low Water Spring (MLWS)	-3.0	0.6

(Data taken from Admiralty Chart, © Crown Copyright / SeaZone Solutions Ltd [2008])



**Figure 3.13 The Crantock beach from Pentire Point West (Field Picture, 29/10/2011).**

Pirrie *et al.* (2000) investigated the impacts of mining on sedimentation in the Camel and Gannel estuaries. Sedimentological, mineralogical and geochemical tests were carried out on sediments sampled from the intertidal zone so as to determine the importance of mining on sediment supply. Very high concentrations of Pb and Zn were observed within estuarine sediments, and significant enrichment of Zr, Ce, La, Y and Ag. The probable deposition of these minerals could be linked to the release of particulate mine waste as a result of mine closure in the late 19th or early 20th Century. The impact of mining on sedimentation in the Gannel estuary had earlier been recognised by Reid and Scrivenor (1906) when it was commented that “the washings from these mines, combined with the shell-sand, drifted in by the sea, have almost silted up the estuary of the Gannel, which can no longer be used for shipping” (cited in Pirrie *et al.*, 2000:22). As with other Cornish estuaries, the past studies on the Gannel focused on the impact of mining on sedimentation, and no consideration has been given to the nature of morphodynamic evolution, sedimentary processes, and linkages between estuary and open coast.

#### **3.4.4 Padstow bay and the Camel estuary**

The Camel estuary in Padstow bay is a shallow and sandy valley ria estuary which has been drowned by post-glacial rising sea level (Brew and Gibberd, 2009). It is also a macro-



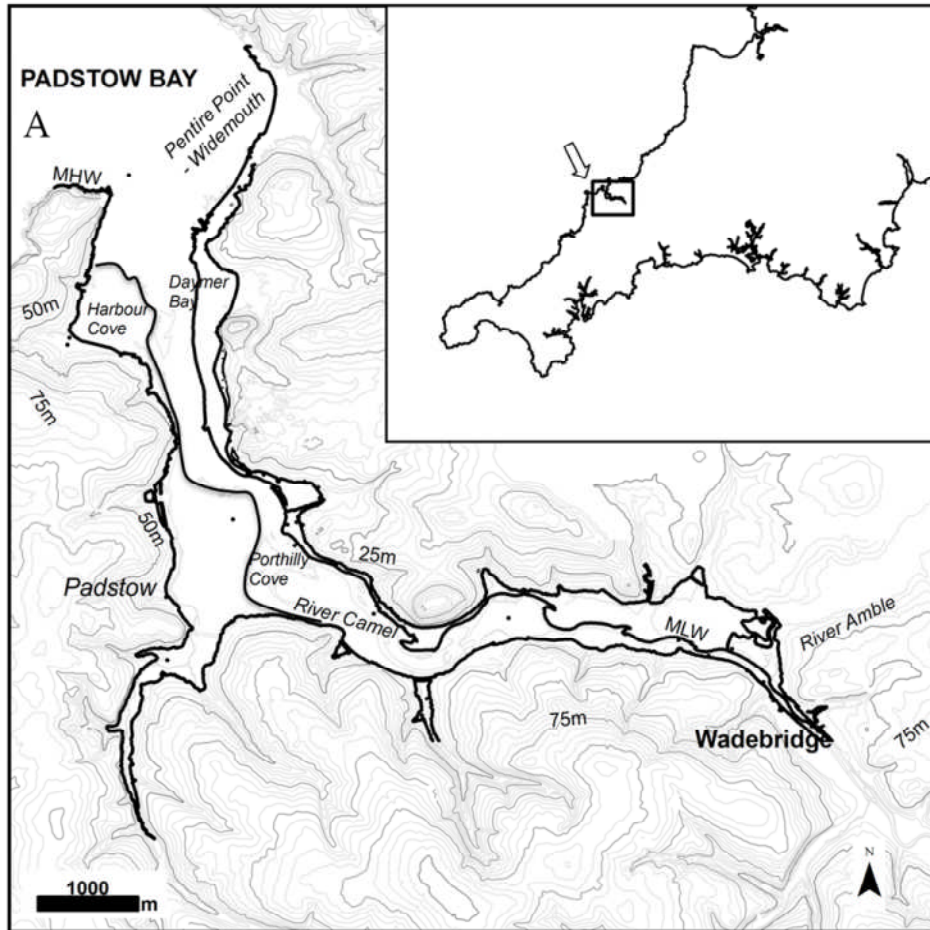
tidal estuary (Table 3.4), with a mean spring tide range of 6.3 m at Padstow, decreasing to 2.8 m near the estuary head c. 12 km up the valley. The system has a narrow meandering channel which shifts across the estuary but with a core area of 8.39 km<sup>2</sup>, inter-tidal area of 6.10 km<sup>2</sup> and tidal range of 5.9 m. It is located on JNCC grid reference SW 935755 (Davidson *et al.*, 1991; EMPHASYS, 2000; Dyer, 2002; Townend, 2005).

The system is more than 0.8 km wide at Padstow Bay and stretches inland for approximately 8.1 km into Wadesbridge where it starts narrowing (Murray, 1984; Figure 3.15). The estuarine environments include saltmarsh, mud-flats, sand-flats, sub-tidal channels, sand dunes and grazing marsh (Brew and Gibberd, 2009; Figures 3.14B). The total intertidal area is around 6 km<sup>2</sup>, with 92% of this being intertidal flats (Buck, 1993; Brew and Gibberd, 2009). There are various geological structures in Camel system, although the rocks are described principally as slates which are of Middle (Trevone) and Upper (Pentire succession) Devonian age (Gauss and House, 1972). In southern zone of the estuary between Padstow and Wadesbridge (the mid- and Inner- Estuary) (Figure 3.15), the formation is of Trevoise Slate (older) Formation which are thrust over the younger Harbour Cove Slate Formation while the northern zone are of the juxtaposing/mixture of older and younger Polzeath Slate Formation (Durning, 1989). The north and east of the outer estuary succession shows greater tectonic complexity with a southward facing recumbent fold style (Gauss and House, 1972). The total catchment area for the estuary comprises the rivers which drain the Devonian metasediments of the Harbour Cove, Polzeath, Trevoise and the Tredorn Slate formations (Selwood *et al.*, 1998; Pirrie *et al.*, 2000). Pirrie *et al.* (2000) reports that basaltic lavas commonly occur within the Harbour Cove and Trevoise Slate formations on the north side of the estuary while River Camel drains the western margin of the Moor granite. In summary, the catchment geology for the Camel system comprises mainly Devonian slates and granite with some shales and sandstones.

**Table 3.4 Summary of typical water levels at Padstow (Lat. 50° 33' Long. 4° 56')**

<b>Tidal State</b>	<b>Water Level (mODN)</b>	<b>Heights in metres above datum</b>
Mean High Water Spring (MHWS)	+3.5	7.3
Mean High Water Neap (MHWN)	+1.8	5.6
Mean Low Water Neap (MLWN)	-1.2	2.6
Mean Low Water Spring (MLWS)	-3.0	0.8

(Data taken from Admiralty Chart, © Crown Copyright / SeaZone Solutions Ltd [2008])



**Figure 3.14 (A) The Padstow bay and Camel Estuary. Inset: Location in Southwest England, and (B) the the 20/08/2012 Google aerial photograph showing the sediment and rocky shoreline.**



**Figure 3.15 Photographs of Padstow Bay at Low Tide (top, 31/10/ 2011) and Camel estuary at Low Tide (bottom, 31/10/2011)**

Brew and Gibberd (2009) divided the Camel estuary into three reaches: outer, middle and inner. The outer Camel is approximately 1 km wide and dominated by a large intertidal sandflat connected to the west bank of the north-facing mouth. The sub-tidal channel flows from the bar and Daymer intertidal sandflats in a narrow upstream (Figures 3.12 and 3.13) passing close to the Rocky shoreline (Brew and Gibberd, 2009). The inner estuary is dominated by large intertidal sandflats and salt marsh. The headlands of Steeper Point and Pentire Point - Widemouth provide sufficient shelter which enable the Camel estuary to be the most important sediment sink in the Padstow bay (Halcrow, 2002; Defra, 2002). Brew and Gibberd (2009) suggested that in the late 1920s, the main sub-tidal channel in the

estuary switched from the western to the eastern side of the outer estuary, causing changes in sand-flat and sand dune distribution, although had little impact on local saltmarshes. The study concluded by observing that Camel Estuary appeared to have a dynamic 'positive sediment budget' with the capacity to regularise sediment removed (as a result of dredging activities) through mainly marine sediment supply and a limited fluvial sediment supply.

Pirrie *et al.* (2000), in another study, discovered that there is a clear stratigraphical geochemical anomaly for Sn, W and Zr, which corresponds with abundant cassiterite, wolframite and zircon. The release of particulate mine waste as a result of mine closure in the late 19th or early 20th century was asserted to be responsible for downstream estuarine sedimentation. These findings are indications that both human and physical processes have impacted the sedimentology and mineralogical configuration in the estuary. It is also an indication that one singular action may have a long-term effect on estuarine morphology and geochemistry.

## 4 SHORELINE AND ESTUARINE CHANGE ANALYSIS

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### 4.1 Mesoscale morphodynamics

One of the objectives of this research is to examine the comparative historical behaviour of estuary - open coast systems. Historical trend analysis (HTA) methods (as described in section 2.3) were used to investigate the historical coastal behaviour of the study sites. Each of the selected systems were analysed, and the findings compared in a bid to assess the regional coherence in coastal morphodynamics. The investigation of shoreline change was undertaken for the period covered by the mid-19th century to early 21st century. The historical movement in the position of mean low and mean high water (MLW/MHW) were investigated in GIS using the Digital Shoreline Analysis System (DSAS) toolbox developed by the USGS. Estuary ebb channel dynamics were examined using the locational probability analysis approach (Graf, 2000). The historical datasets utilised include multiple map editions from Ordnance Survey (Section 2.3.1). In addition, recent LiDAR data (2008-2012) were analysed using topographic profiles and surface change analysis.

#### 4.1.1 Shoreline change analysis

This section presents findings relating to the historical evolution of shorelines and the geomorphology of the bays and estuaries of southwest England in a bid to address the first object of this research. It documents and characterises the historic behaviour of the shorelines of St Ives Bay, between Porthminster Point and Godrevy Point (where the Hayle Estuary is located); at Crantock Beach between Pentire Point West and Pentire Point East (where the Gannel Estuary is located); and at Padstow Bay between Steeper Point and Pentire Point - Widemouth (where Camel Estuary is located) (see Figure 2.1 and Chapter 3.4 for the location and detailed description of the sites), using Geographical Information Systems (GIS).

##### 4.1.1.1 Changes in Mean Low Water (MLW) and Mean High Water (MHW)

In most applications, the measures of shoreline change are used to make a cumulative summary of the processes that have impacted the coast through time (Dolan *et al.*, 1991). The spatial distribution of measures of change [Shoreline Change Envelope (SCE), Net Shoreline Movement (NSM) pattern and End Point Rate (EPR)] associated with the MLW and MHW marks, as computed using DSAS in the ArcGIS environment, are presented in Figures 4.2, 4.3 and 4.4 for St Ives Bay, Crantock Beach and Padstow Bay respectively.

*St Ives Bay*

The envelope of variability in the high water shoreline (MHW) throughout the bay is relatively consistent, ranging 50-100 m at over 60% of transects (Figure 4.1A (i)). Changes are noticeably greater around Port Kidney Sand, on the west bank of the Hayle inlet and ebb delta, which is where the maximum movement in the low water (MLW) shoreline occurs. Net shoreline change, reflecting patterns of erosion and accretion are, however spatially varied (Figure 4.1Aii). The MLW shoreline is predominately erosional between the Carbis Bay and Port Kidney Sand, where 30 m to 320 m recession has occurred over 165 years. In contrast, the MHW shoreline along this stretch has been primarily accretional, though it exhibits smaller scale shifts. The eastern part of St Ives Bay is more varied in scale and direction of change. In and around the Hayle inlet, changes of the order  $\pm 50$ -100 m are shown in the MHW, but the scale of change in MLW is about half of this ( $\pm 0$ -50 m). The MHW shoreline is more consistent (stable) along the Black Cliff to Godrevy Towans shoreline which predominately shows small-scale accretion. The MLW here is more mixed, with pockets of accretion, but rather more evidence of small-scale erosion. Rates of change (as shown by the end point rate (EPR) in Figure 4.1iii) are relatively small for large stretches of the bay ( $\pm 0.25$  m yr<sup>-1</sup>), but increase significantly within the inlet region, and are also particularly high in the MLW between Carbis Bay and Port Kidney Sand. Interestingly, the west bank of the inlet exhibits greater rates of change than the east bank.

Small scale changes ( $-0.24$  –  $0.25$  m yr<sup>-1</sup>) dominate the historical dynamics, experienced by 76.4% of MLW transects and 90.8% of MHW transects (Table 4.1). In general, greater rates of recession are expressed in the shift in MLW (22.2%) than MHW (12%), broadly suggesting that the intertidal zone has experienced some degree of narrowing, and assuming no change in tidal regime, has presumably steepened. However, there is no any direct spatial association between changes in the two shorelines.

The association between the Shoreline Change Envelope (SCE) and Net Shoreline Movement (NSM) for the MLW and MHW shorelines is explore in Figure 4.2. As shown, there is no correlation between SCE and NSM in St Ives Bay. The magnitude of NSM increases with increasing SCE implying that the net change over the history considered is a good reflection of the overall envelope of variability in the system. But it is clear a range of magnitudes of shoreline change are experienced in both those parts of the system that are erosion-dominated and those parts that are accretion-dominated.

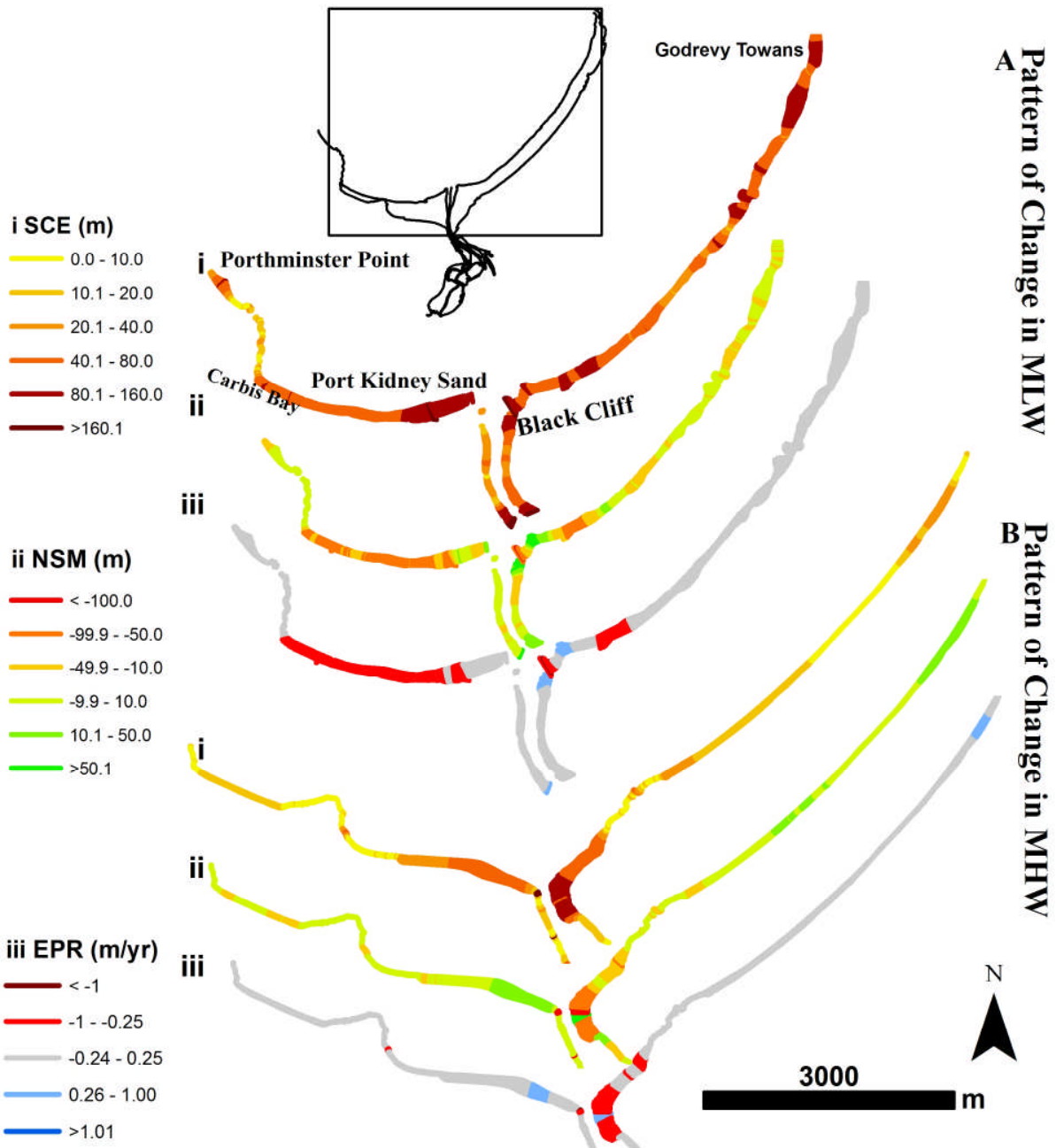


Figure 4.1 St Ives Bay – Hayle estuary pattern of change (1845 – 2010): i) Shoreline Change Envelope (SCE), ii) Net Shoreline Movement (NSM) and iii) rate of change based on the earliest and most recent surveys (EPR) for Mean Low Water (MLW) and Mean High Water (MHW). Inset: location of the shorelines.

Table 4.1 Summary of MHW and MLW movements and trends in St Ives Bay

Change rate (m yr <sup>-1</sup> )	No. of MLW transects	% of MLW shoreline	No. of MHW transects	% of MHW shoreline
< -1	6	0.28	3	0.2
-1 - -0.25	473	22.2	69	4.4
-0.24 – 0.25	1,628	76.4	1,411	90.8
0.26 – 1.00	23	1.1	72	4.6
> 1.01	1	0.05	0	0.0

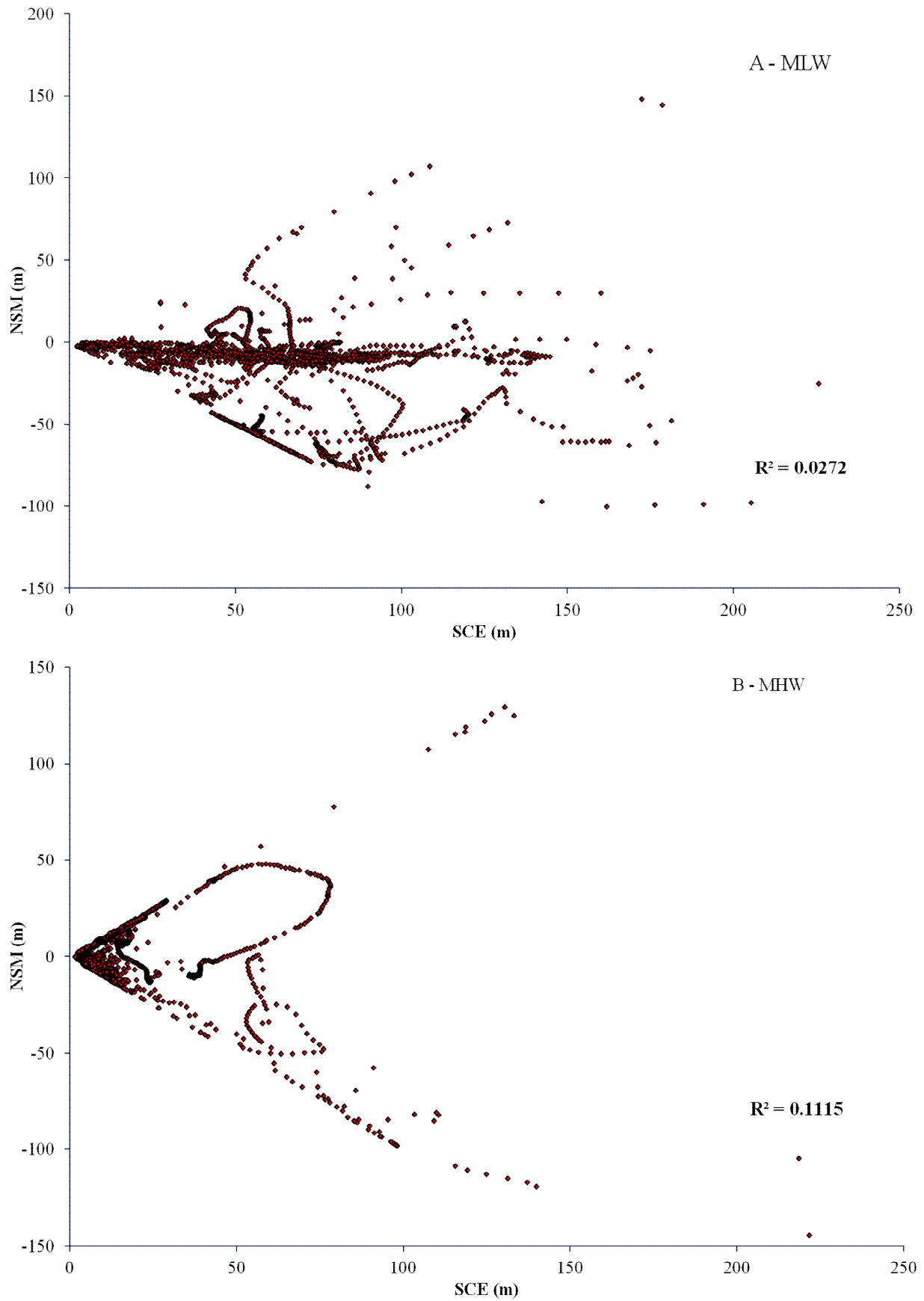


Figure 4.2 Correlation between SCE and NSM for MLW (A) and MHW (B) in Hayle System.



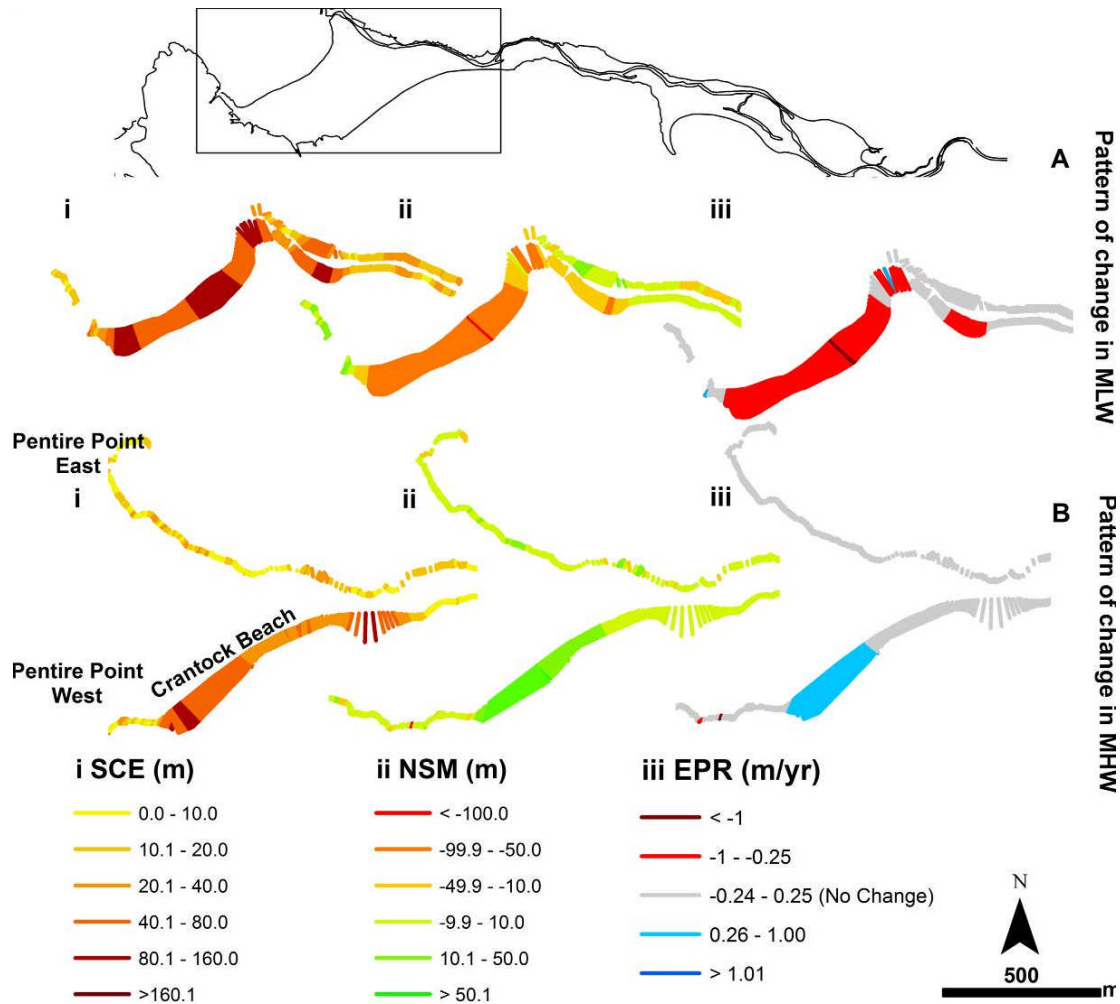
*Crantock Beach*

Figure 4.2 summarises the scales and rates of change in shoreline position at Crantock Beach. Scales of change in the position of MLW are maximum in the centre of the bay and minimum in the inlet (Figure 4.2Ai). The changes are almost entirely the consequence of recession (landward movement) of the low water shoreline at a rate of 0.1 - 0.8  $\text{m yr}^{-1}$  (Figure 4.2Aiii). The only place in the lower foreshore where significant erosion is not taking place is along the ebb channel margins within the inlet. Comparison of the SCE with NSM shows that the majority of change in the position of MLW change exhibited here is equivalent to the difference between the earliest (1888) and most recent (2012) shorelines. The shifts in MLW position are predominately erosional, at rates of between -0.81 to -0.10  $\text{m yr}^{-1}$  in the 124 historical years (Figure 4.2 Aiii). The only place in the bay where there has been negligible change in MLW shoreline positions are in the rocky outcrops of Pentire Point West and East respectively. The inlet to the Gannel estuary shows a more variable response of minimal erosion and accretion. This may be as a result of the location which would be influenced by the short-time interference of dynamic activities of River Gannel and tidal fluctuations.

The scales of change in the position of high water (MHW) are somewhat reduced by comparison. First, it is clear that the rock-dominated shorelines along Pentire Points West and East have changed very little (<20 m) over the 124 year period (Figure 4.2B). Second, the high water shoreline of Crantock Beach has shifted in position by up to around 140 m, but is largely characterised by change of the order of 30-60 m. Shifts in MHW are generally the product of shoreline advance (deposition), and there is evidence that gross change (SCE) is greater than net change (NSM). In the absence of significant changes in tidal regime, the product of a retreating low water and advancing high water is the steepening of the intertidal profile. The SCE associated with the Crantock dune system MHW is greater to the west than the east, suggesting that the orientation of the shoreline shifts from distinctly parallel to MLW to being at a slight angle. However, the net consequence of these changes appears to be minimal as the NSM is relatively consistent along the dune shoreline.

The analyses show that most transects experience less than 0.25  $\text{m yr}^{-1}$  retreat or advance (88.7% of MHW and 62.2% of MLW), largely dominated by the bedrock shorelines along the inlet and in the outer bay (Table 4.2). However, > 36.7% of MLW shorelines are erosion-dominated (i.e. these have experienced a net landward retreat in position) compared to 0.4% for the MHW. Rates of change in MLW are greater than rates of change in MHW. Fewer transects show evidence of deposition, with only less than 1% experiencing advance in the MLW and 11% showing seaward shifts in the MHW. Here too, there is no direct spatial association between changes in the two shorelines.

Statistically, there is evidence of a good correlation between SCE and NSM (Figure 4.4) both MLW and MHW. The more mobile shorelines (largest SCE) are associated with negative accretion at 78% for the MLW and at 64% to positive NSM for the MHW (Figure 4.4). The correlation performance for these measures are clearly much better (0.74 and 0.64 respectively) than for the other study sites (St Ives Bay and Padstow Bay) as the correlation between the measures in the other sites indicate poor relationship between largest SCE and NSM.



**Figure 4.3 Crantock Beach – Gannel estuary pattern of change (1845 – 2010): i) Shoreline Change Envelope (SCE), ii) Net Shoreline Movement (NSM) and iii) rate of change based on the earliest and most recent surveys (EPR) for Mean Low Water (MLW) and Mean High Water (MHW). Inset: location of the shorelines.**

**Table 4.2 Summary of MHW and MLW movements and trends at Crantock beach**

Change rate (m yr <sup>-1</sup> )	No. of MLW transects	% of MLW shoreline	No. of MHW transects	% of MHW shoreline
< -1	2	0.4	1	0.1
-1 - -0.25	167	36.7	3	0.4
-0.24 – 0.25	283	62.2	647	88.7
0.26 – 1.00	3	0.7	80	11
> 1.01	0	0	1	0.1

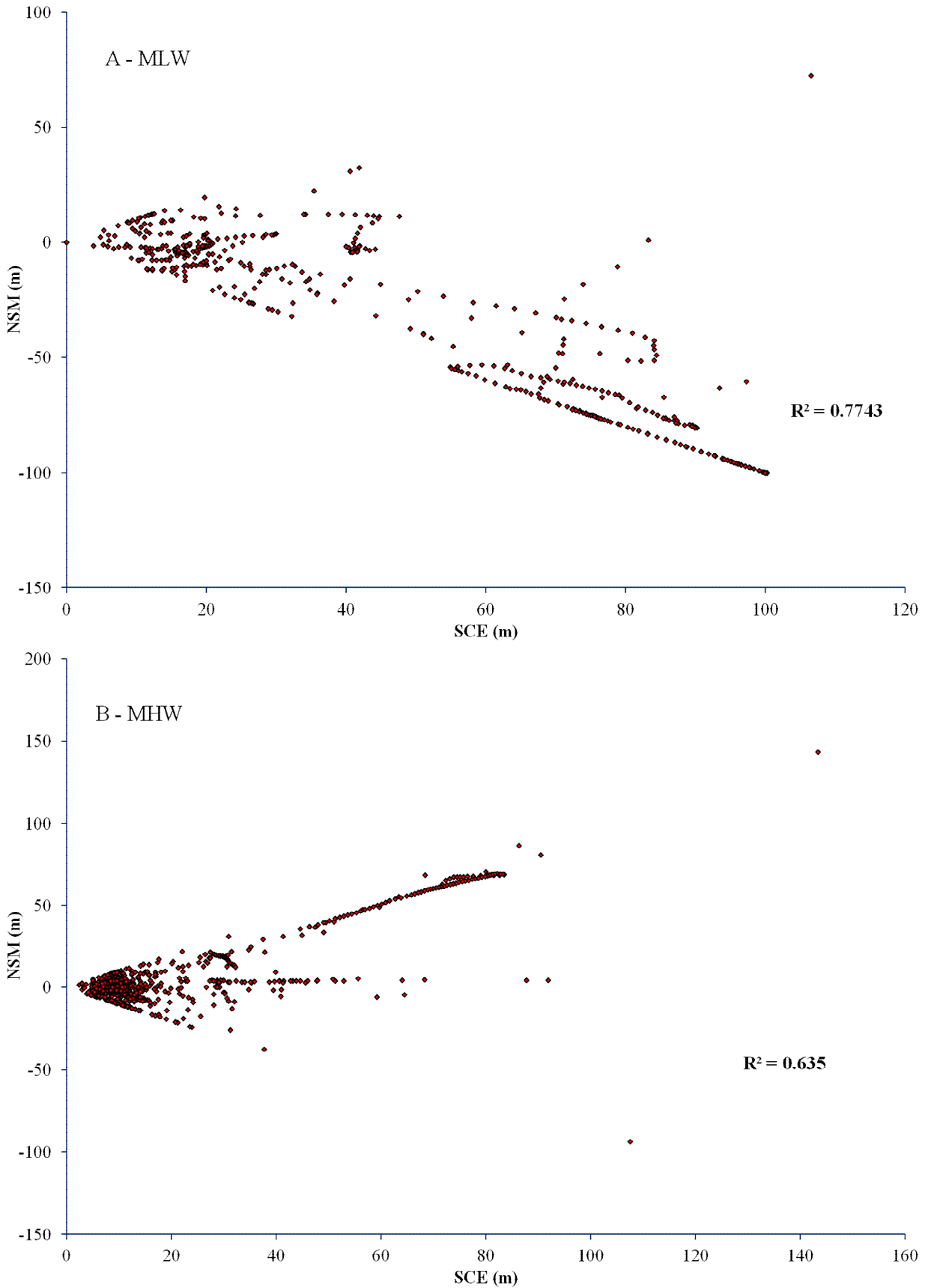
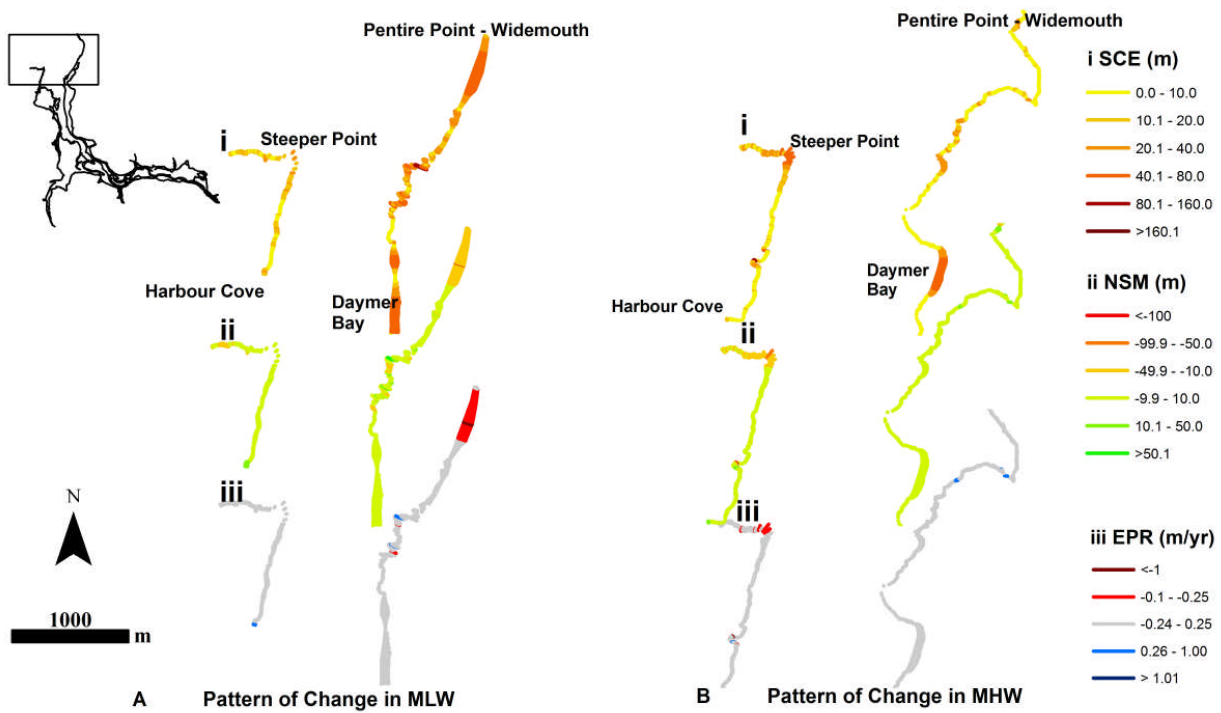


Figure 4.4 Correlation between SCE and NSM for MLW (A) and MHW (B) in Gannel System.

*Padstow Bay*

Historical changes in shoreline position within Padstow Bay (associated with the Camel estuary) are notably different to those illustrated in St Ives Bay and Crantock Beach. The Padstow Bay low water shoreline has a limited envelope of variability when compared with the other systems considered here (0-20m). Figure 4.3 summarises the scales and rates of change in shoreline position at Padstow Bay. Changes of around 20-40m are evident along the eastern shoreline, around Pentire Point - Widemouth and Daymer Bay (Figure 4.3Ai). Transects between Steeper Point and Harbour Cove remain relatively stable with varied rates of erosion and minimal total accretion of low water position (Figure 4.3 Aiii). Rates of change reach a maxima at Pentire Point - Widemouth where shifts of between  $-0.10$  and  $-0.25 \text{ m yr}^{-1}$  are observed (Figure 4.3Aiii). Padstow Bay is relatively confined in comparison to St Ives and Crantock, and Widemouth to Steeper Point represents the open-coast before the narrower inlet of the Camel estuary just south of Daymer. Rock platform dominates the shorelines of the open coast around Steeper Point and Pentire Point - Widemouth and this is likely responsible for the relative stability in the MLW shoreline when compared with St Ives and Crantock bays.

There is a relative stability in the shoreline change envelope of the MHW shoreline (Figure 4.3B), where only Daymer Bay stands out as showing any dynamics. But net accretion here of  $\sim 10 \text{ m}$  illustrates the minimal shoreline movement during the 132 year period considered. Rates of change ( $\pm 0.24 \text{ m yr}^{-1}$ ) in all of the bay for the high water shoreline indicates a relative stability. Rocky shorelines that border the bay are certainly less responsive than sedimentary shorelines, but here also seem to provide a stabilising role, perhaps either through sheltering from the impacts of tides and waves, or simply constraining morphodynamic behaviour. It is also possible that the orientation of the bay and estuary may facilitate a more enhanced sheltering role of the Pentire Point and Steeper Point headlands. Overall, the direction of change is rather more balanced here than in the St Ives or Crantock bays. However, there is no correlation between largest SCE and NSM within Padstow Bay. The more mobile shorelines (largest SCE) are not related to negative accretion for the MLW (5%) nor to positive NSM for the MHW (20%) (Figure 4.6). Stability is experienced along 87.6% of the MLW and 99.2% of the MHW shorelines, although 12% of the MLW experiences retreat (Table 4.3). Sediments are broadly recycled within the open coast system here, certainly much more so than in the systems further west.



**Figure 4.5 Padstow Bay – Camel estuary pattern of change (1845 – 2010): i) Shoreline Change Envelope (SCE), ii) Net Shoreline Movement (NSM) and iii) rate of change based on the earliest and most recent surveys (EPR) for Mean Low Water (MLW) and Mean High Water (MHW). Inset: location of the shorelines.**

**Table 4.3 Summary of MHW and MLW movements and trends in Padstow Bay**

Change rate (m yr <sup>-1</sup> )	No. of MLW transects	% of MLW shoreline	No. of MHW transects	% of MHW shoreline
< -1	0	0	1	0.
-1 - -0.25	93	12	8	1.0
-0.24 – 0.25	679	87.6	1260	99.1
0.26 – 1.00	3	0.4	2	0.2
> 1.01	0	0	0	0

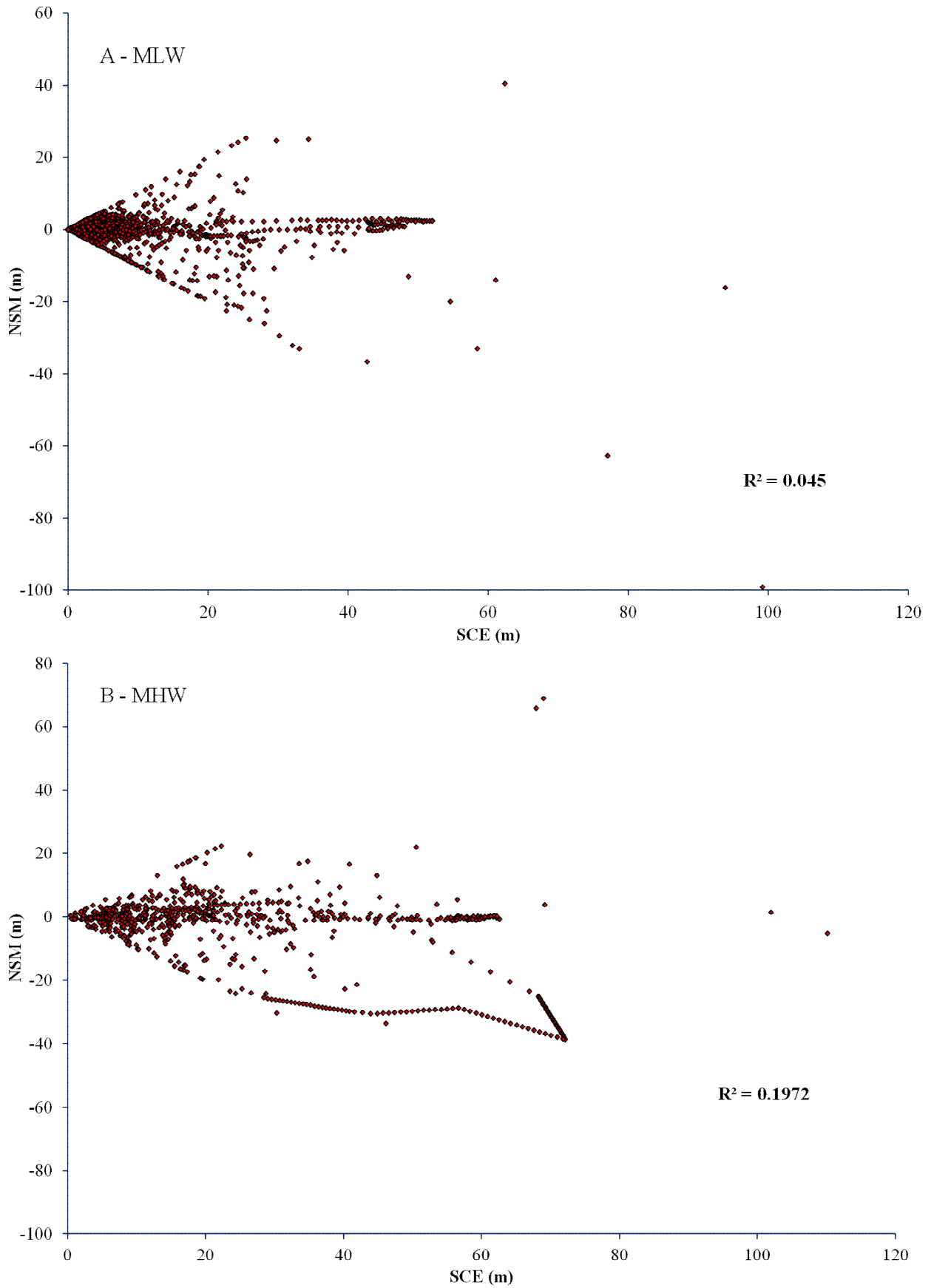


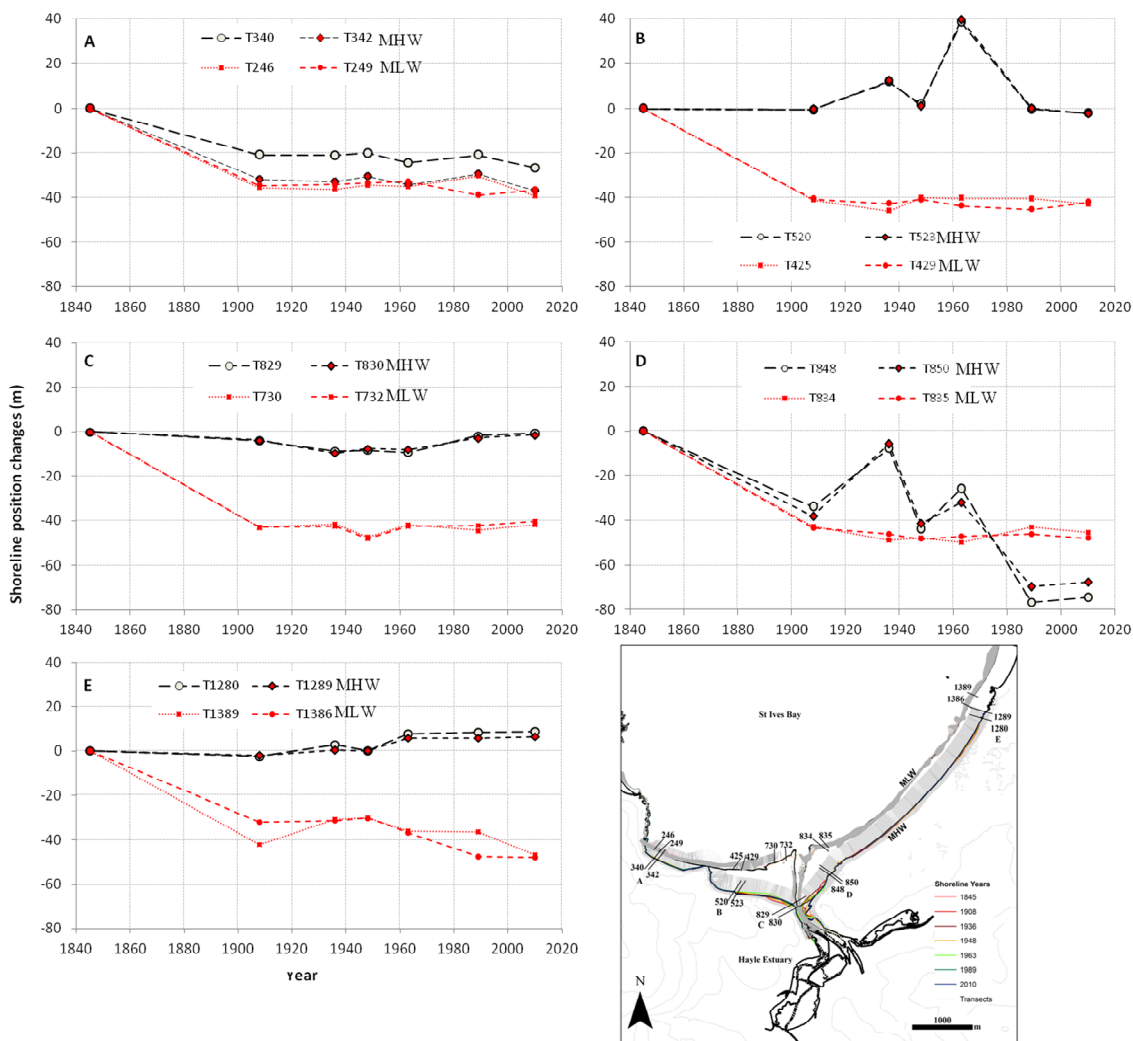
Figure 4.6 Correlation between SCE and NSM for MLW (A) and MHW (B) in Camel System.

4.1.1.2 Temporal characteristics of shoreline change

Investigation of single or individual transects are utilized here in order to evaluate more fully the shoreline change statistics associated with shoreline change analysis (for example, Fletcher *et al.*, 2003; Hapke *et al.*, 2006; and Romine *et al.* 2009).

*St Ives Bay*

Shoreline changes are spatially and temporally varied (Figure 4.4). There is a very little change in MHW at the Port Kidney Sand (B), inlet (C) and the northern beaches (Godrevy Towans) (E) but a landward retreat of MLW of over 30m throughout the history explored here. However, progressive recession (> -40m) of both MHW and MLW is evident at Carbis Bay (A) and more so at Black Cliff (D) over the same time scale in the mid-1900s.



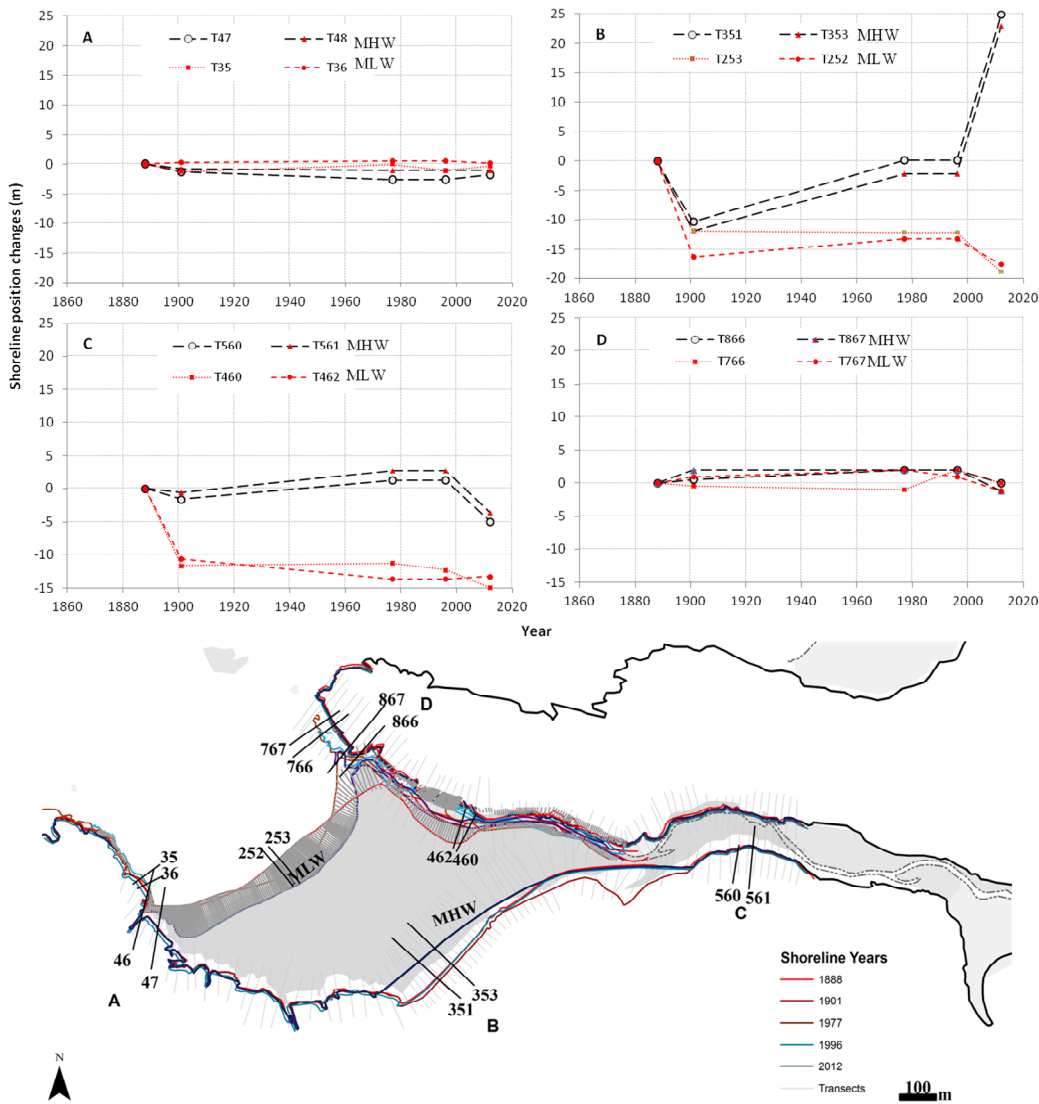
**Figure 4.7** Cumulative change in shoreline position along transects (A) T340 & T342 (MHW) and T246 & 249 (MLW) (Carbis Bay), (B) T520 & T523 (MHW) and T425 & T429 (MLW) (Port Kidney Sand), (C) T829 – T830 (MHW) and T730 & T732 (MLW) (Inlet), (D) T848 & T850 (MHW) and T834 & T835 (MLW) (Black Cliff) and (E) T1280 & T1289 (MHW) and T1389 & T1386 (MLW) (Godrevy Towans), followed by location of transects in St Ives Bay. Positive change shows accretion; negative change reflects erosion. {Within graph presentation: MHW – Black colour line, MLW – Red colour line}.

The western shorelines in Carbis Bay (A) show general retreat, but this is mostly associated with 20-30 m of erosion between 1845 and the subsequent survey in 1909. Here most transects show a landward shift, but close to the inlet at Port Kidney Sand (B), although the net change is negligible, this masks episodes of advance and retreat in the 1920s and the 1960s. This pattern of movement is also evident in transects on the western margin of the inlet at Black Cliff (D), but is almost inverse of the small-scale shifts in the Inlet (C), where small erosion-accretion episodes are shown. At Black Cliff (D) the mid-century dynamics are superimposed on a general trend of retreat. At Godrevy Towans (E), again very small-scale change in the MHW position comprises slight retreat until the early 1900s followed by minor advance in the mid-1900s. Rates of change in the position of MLW are in the range  $\pm 0-5.8 \text{ m yr}^{-1}$ , but are smaller ( $\pm 0-1.5 \text{ m yr}^{-1}$ ) for MHW (Figure 4.1). This equates to a total shift of -0.35 to +838 m in the position of MLW over the 165 year period analysed here, and -0.65 to +241 m in the position of MHW. These shifts vary throughout the bay, where regions of stability are found in close proximity to areas of significant change, as illustrated by the shoreline change envelopes shown in Figure 4.1. The scales of change evidenced here are often well within the uncertainty of the historic mapping products, which makes it difficult to ascertain and evaluate coastal change. It is clear though that in some places, significant change has taken place (e.g. Black Cliff), and that the behaviour is characterised by both episodic change (e.g. periods/cycles of erosion and accretion) and progressive change where temporally and spatially localised shifts are superimposed on an underlying erosional or accretional trend.

#### *Crantock Beach*

Comparison of the time series of changing shoreline position in Crantock (Figure 4.6) shows how important it is to consider both the envelope of variability (SCE) and the net change (NSM and EPR). Transects at Pentire Points West (A, T47 and T48, T35 and T36 for MHW and MLW respectively) and East (D, T866 and T867, T766 and T767 for MHW and MLW respectively) show consistency in shoreline positions, principally because they represent the rocky shorelines (indicated in aerial photograph of Figure 3.12). Changes along the Pentire Points are small, but the inlet shoreline also shows small-scale shifts, and these are likely within the accuracy margin (C, T560 and T561 for MHW, T460 and T462 for MLW). There is some suggestion here though that the MHW shoreline goes through periods of slight recession followed by advance, which might be linked to migration and meandering of the low tide channel. At Crantock Beach (B, T351 and T353, T252 and T253 for MHW and MLW respectively) however, the high water shoreline has advanced more substantially (c. 25 m), but this net positive change masks an episode of erosion during the late 19th century while the low shoreline consistently retreat landward through out the considered historical timescale. Plots of the sedimentary shorelines (B and C) show that the most recent shoreline is a significant departure from those from previous years. In most cases, the change between the late 1990s and 2012 is greater than change at any other time.

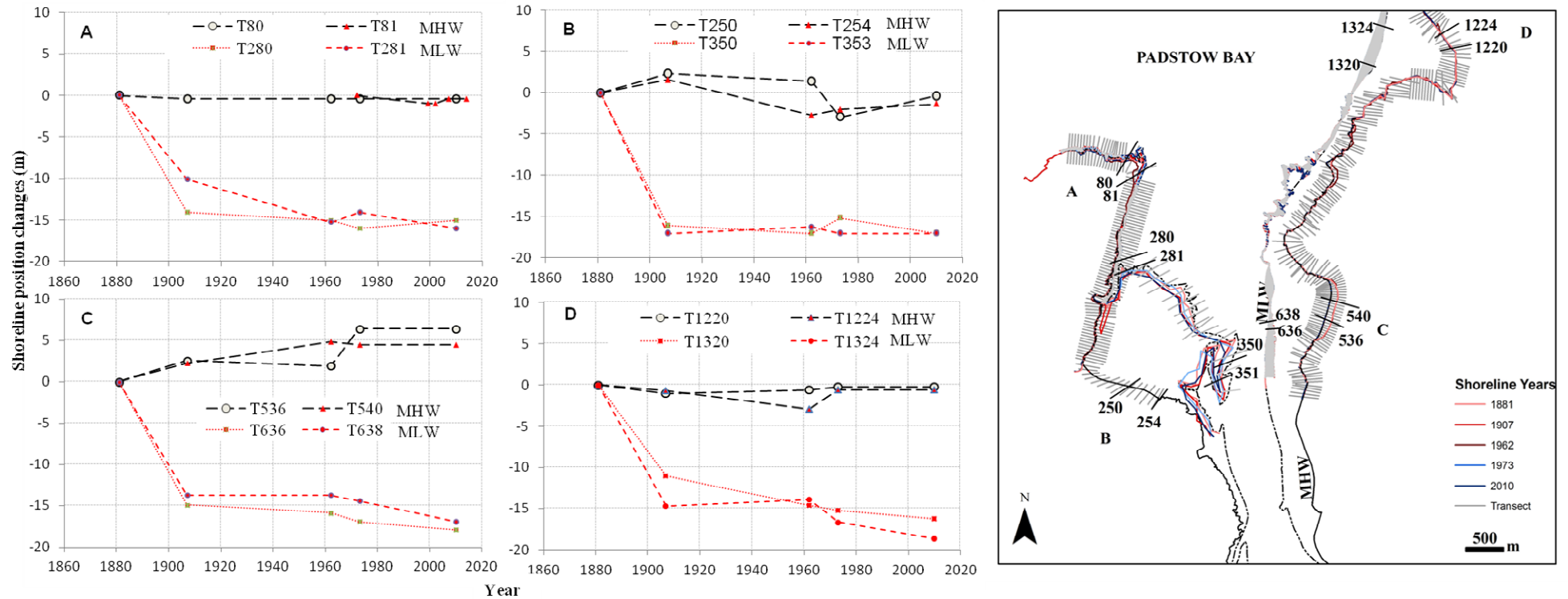




**Figure 4.8** Cumulative change in shoreline position along transects (T) (A) T47 & T48 (MHW) and T35 & T36 (MLW) (Pentire Point West), (B) T351 & T353 (MHW) and T252 & 253 (MLW) (Crantock Beach), (C) T560 & T561 (MHW) and T460 & T462 (MLW) (Inlet) and (D) T866 & T867 (MHW) and T766 & T767 (MLW) (Pentire Point East) at Crantock Beach, followed by location of the selected transects. Positive change shows accretion; negative change reflects erosion. {Within graph presentation: MHW – Black colour line, MLW – Red colour line}.

*Padstow Bay*

In Padstow Bay, transects at Steeper Point (A, T81 and T82) and Harbour Cove (B, T251 and T255) on the west margin exhibit relative stability in the high water shoreline throughout the historical timescale considered (Figure 4.9). On the eastern margin, the high water shoreline at Daymer Bay (C, T537 and T538), closer to the inlet, advanced minimally from the 1920s while Pentire Point - Widemouth (D, T1220 and T1224) shows little movement throughout the 129 years considered. The stability of the high water positions, over space and time, throughout the rocky shorelines of Padstow Bay is clearly a product of the bedrock nature of these shorelines. The MLW shorelines, on the other hand, retreated in the bay. Depositional shorelines here are limited to local sinks, such as at Daymer Bay, where greater change is evident for the high water shorelines.



**Figure 4.9** Cumulative change in shoreline position along transects (A) T80 & T81 (MHW) and T280 & T281 (MLW) (Steeper Point), (B) T250 & T254 (MHW) and T350 & T353 (MLW) (Harbour Cove), (C) T1229 & T1230 (MHW) and T636 & T638 (MLW) (Daymer Bay) and (D) T1220 – T1224 (MHW) and T1320 & T1324 (MLW) (Pentire Point - Widemouth) in Padstow Bay, followed by location of these selected transects in the bay. Positive change shows accretion; negative change reflects erosion. {Within graph presentation: MHW – Black colour line, MLW – Red colour line}.

## 4.1.1.3 Intertidal steepening through MHW and MLW movement

The analyses of MHW movements revealed varied responses within and between the coastal systems considered here. Almost half of the high water shoreline in Padstow Bay and Crantock show signs of historical retreat (42%) compared to 75% of the high water shoreline in St Ives Bay. Changes in the low water shoreline are rather different, with recession occurring along more than half of the Padstow Bay shoreline (51%), and extended reaches of St Ives Bay and Crantock Beach (83% and 71% respectively) (Figures 4.1, 4.3, and 4.5 respectively). The scenario observed in this study could be compared to what Taylor *et al.* (2004: 181) referred to as “lateral landward retreat through non equilibrium profile”. The pattern of change shown indicates an overall dominance of erosion along the sediment shorelines while the rates of retreat and advancement are occurring at unequal levels between MHW and MLW leads to a change in foreshore geometry (beach width and beach slope) (Figures 4.10 – 4.12). Analysis of intertidal widths and slopes here again reveals considerable spatial variation in the response of the intertidal foreshore over this historical timescale. Landward shift in MLW, and seaward advance (or even relative stability) in MHW produces a narrower and steeper intertidal zone (Figures 4.7-4.9), and this is evidenced at some specific locations. Sites within St Ives Bay are perhaps the most convincing, but this is largely related to the continuity of the beach environment within this system; specifically, Carbis Bay and Port-Kidney Sand show historical foreshore narrowing and steepening (Figure 4.10). Crantock Beach also shows a selection of transects where steepening has occurred (Figure 4.11), but the picture is more muddled in Padstow Bay (Figure 4.12).

Shoreline change analysis suggests an overall dominance of erosion, the landward movement of the sediment shoreline positions with the rates of retreat occurring at unequal rates between MHW and MLW. The overall historical beach width (c. 1845) at Carbis Bay was approximately 180m while that of Porth Kidney Sand and Black Cliff areas were around 400m and 800m, with a slope of  $<3^\circ$ . However, the modern beach width in Carbis Bay is currently around 120m indicating a reduction of around 50-60m. Beach width in Porth Kidney Sand and Black Cliff areas have remained stable while there is a reduction of around 10m at the Hayle ebb delta. Intertidal width at Crantock has reduced from around 300-400m in 1888 to around 150m in 2012 (Figure 4.11). Landward shifts in MLW, evident in St Ives Bay and Crantock, has resulted in a narrower and steeper intertidal zone. These broad, dissipative beaches still retain a low gradient morphology, so it may be likely that the morphodynamics of these systems has shown limited changes as they still function as dissipative intertidal zones. Steepening is evident where the MHW shoreline is rock-dominated, which precludes the recession of the high water shoreline. There is evidence at Crantock however, of retreating MLW coincident with an advancing MHW, which leads to increased steepening. The source of sediment accumulation in the supratidal zone is unknown, but it is possible that shifts in the nearshore, low water shoreline might release sediment that could, under conditions conducive to onshore accretion, result in backshore deposition. In this area, small foredunes are now present across the region where the upper

foreshore existed in the late 1800s. Areas where both MLW and MHW are retreating tend to be located where both shorelines are sediment-dominated, and here foreshore steepening is less clear as rates of change are similar.

The overall recession in MLW could be attributed to a rise in sea-level, which this region has certainly experienced over the historical time scale. Relative sea-level rise in southwest England is c.  $1.8 \text{ mmyr}^{-1}$  (PSMSL, 2013). In many locations, sediment shorelines are known to undergo a complete landward shift in response to sea-level rise (e.g. the Bruun rule), but the presence of bedrock or other fixed upper foreshore or supratidal feature forces the profile to respond out of equilibrium, leading to an overall steepening of the foreshore (for example, at Widemouth in Padstow, Figure 4.12). In the three study sites, a rather more complex signature of retreating MLW and advancing MHW suggests decreased sediment supply to the beach system, in addition to the vertical shift associated with sea-level rise. Tidal bays are known to be complex systems subject to various marine and terrestrial influences. They are controlled by a combination of hydrodynamic processes, sea-level change, sediment supply, the antecedent geological framework and anthropogenic activities (Blott *et al*, 2006; Moore *et al*, 2006). Landward shifts in MLW could, therefore, be as a result of more factors than the sea-level rise alone. The high water shoreline (MHW) on the other hand, exhibits a more complex pattern of variability. The transects which exhibit accretion or seaward movement were found on the western extent of the Hayle ebb delta (Porth Kidney Sand) and the northeast beaches of St Ives Bay (Godrevy Towans), Crantock Beach and the western margins of Padstow Bay (Steeper Point to Harbour Cove). Retreat occurred at the Carbis Bay (western St Ives Bay beaches) and Black Cliff (eastern extent of the Hayle ebb delta), close to the inlet to Gannel inlet (Crantock), and, east Padstow Bay (Daymer Bay and Pentire Point-Widemouth).

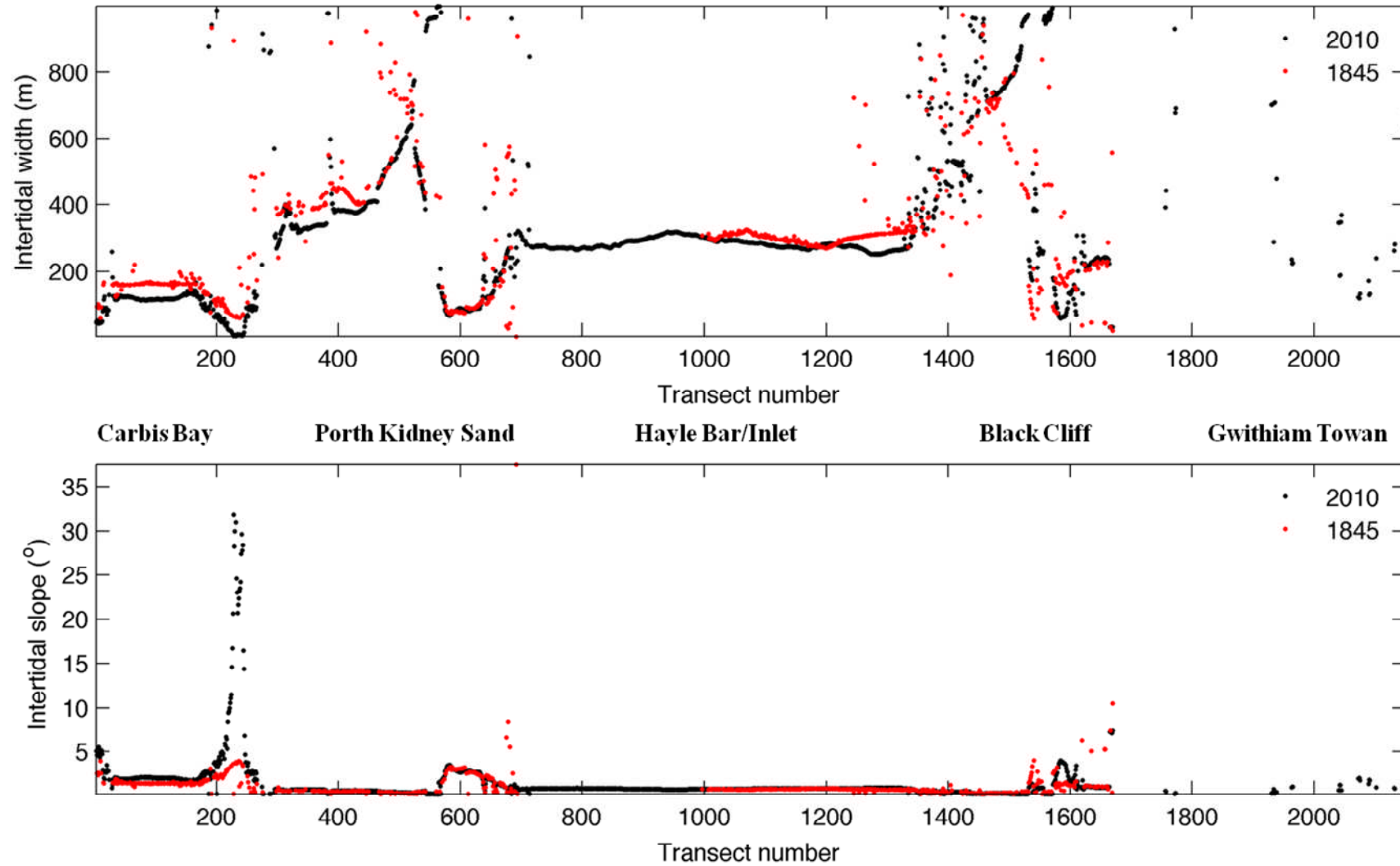


Figure 4.10 Beach width (expressed as the distance between MHW and MLW) and slope (width/mean tide range) in the earliest (1845 – colour red) and most recent (2012 – colour black) mapping available for St Ives Bay and the Hayle inlet. (See Figure 3.7 for location).

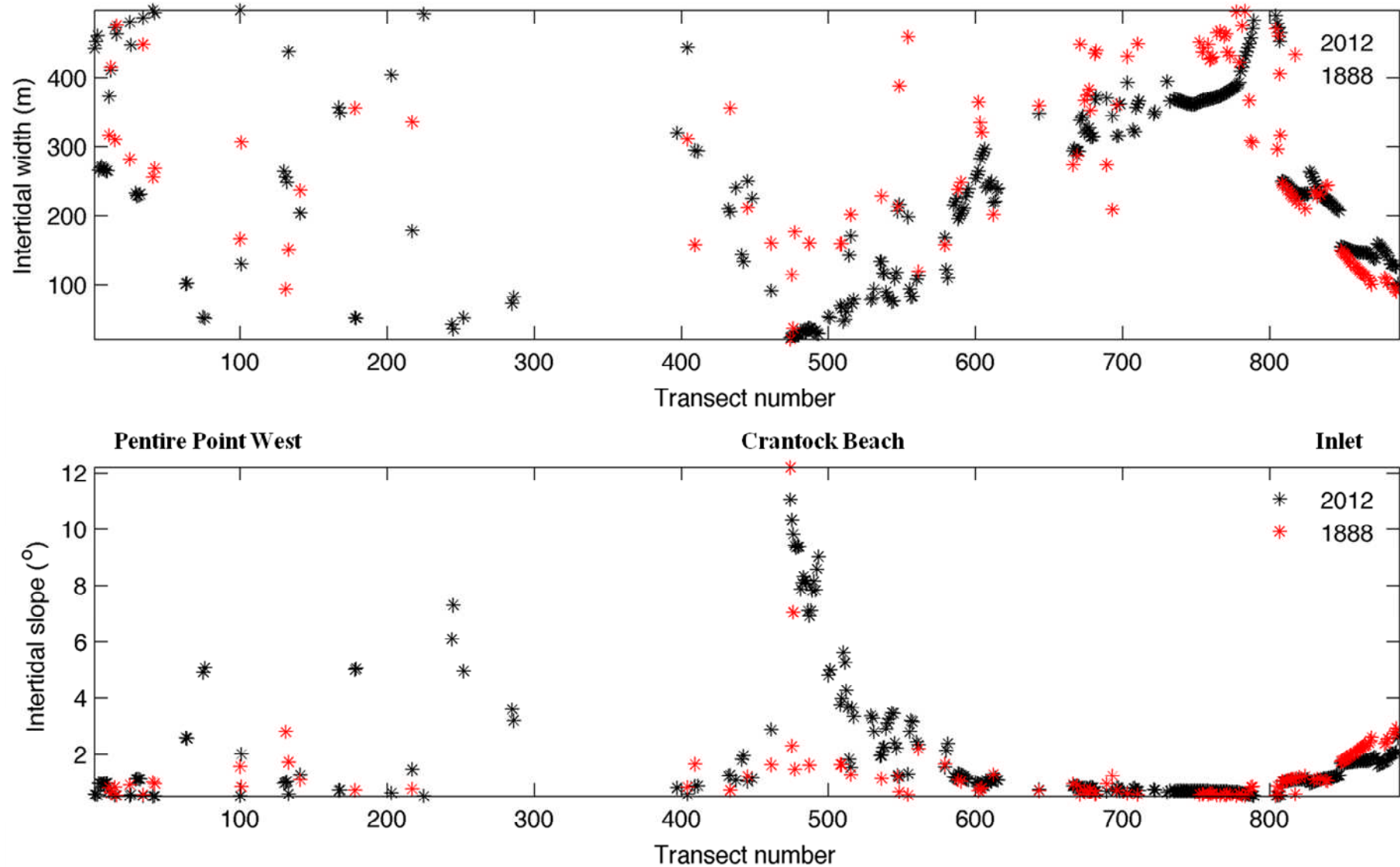


Figure 4.11 Beach width (expressed as the distance between MHW and MLW) and slope (width/mean tide range) in the earliest (1888 – colour red) and most recent (2012 – colour black) mapping available for Crantock Beach and the Gannel inlet. (See Figure 3.12 for location).

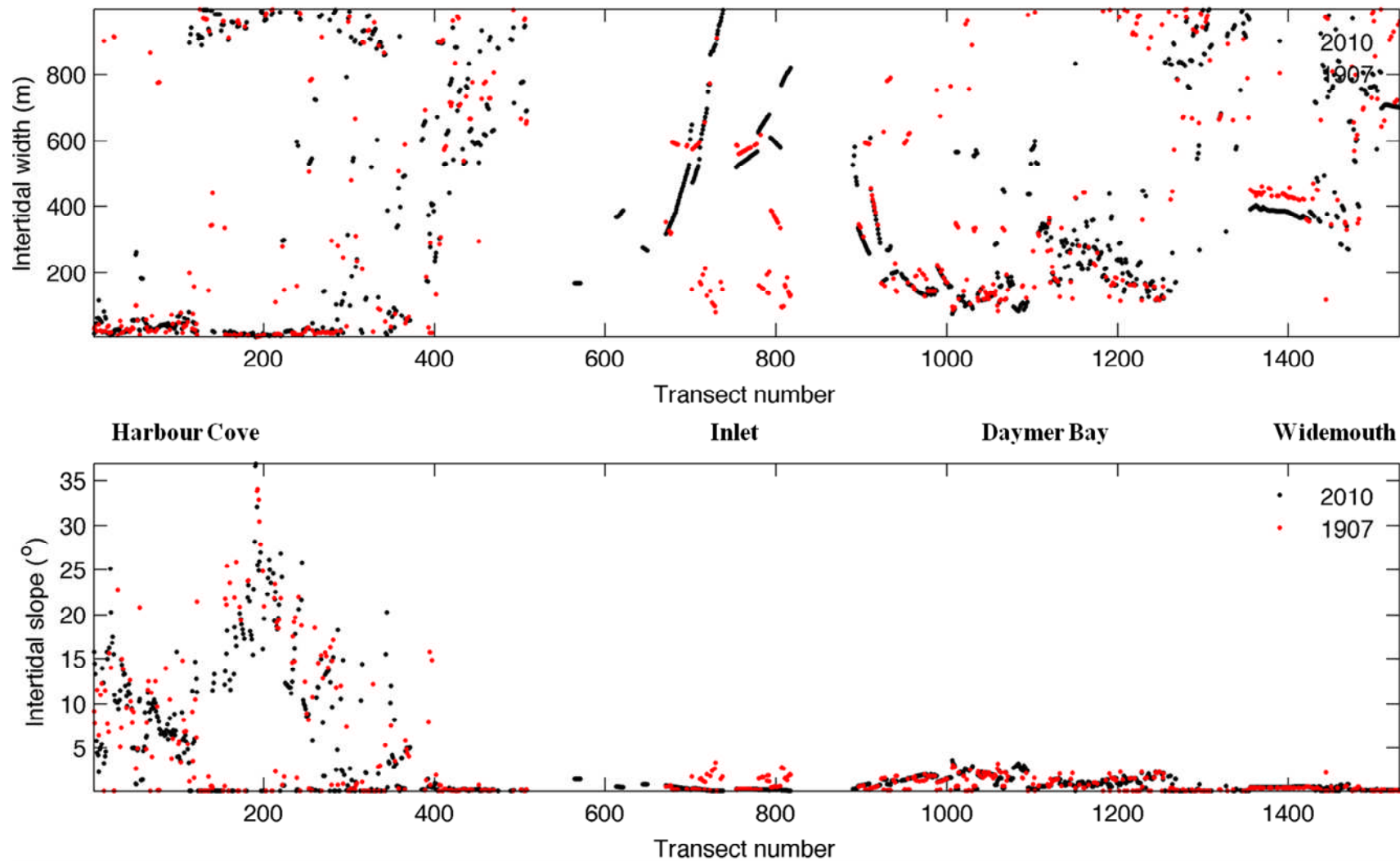


Figure 4.12 Beach width (expressed as the distance between MHW and ) and slope (width/mean tide range) in the earliest (1907 – colour red) and most recent (2012 – colour black) - mapping available for Padstow Bay and the Camel inlet. (See Figure 3.14 for location).

#### 4.1.2 Locational probability analysis

The variations in the ebb channel positions in each of the estuaries associated with these bays can be characterised on the basis of planform morphology through time (Wasklewicz *et al.*, 2004). This integrative approach enhances the analysis of historic channel change and ebb migration within the estuaries. The weighting values based on Graf's (2000) formula  $W_n = t_n/m$ , where  $W_n$  is the weighting applied,  $t_n$  is the time period associated with a specific record or survey, and  $m$  is the total time period covered by all records/surveys considered) assigned to each of the ebb channel layers from the historic archives of the estuaries are presented in Table 4.4. The weights are based on the years covered by the historical maps for each of the estuary.

**Table 4.4 Weighting values for the MLW Channel Location Probability Value for estuaries**

Year	Length of record (years)	Equation ( $W_n = t_n/m$ )	Weight ( $\Sigma = 100\%$ )*
<i>Hayle (St Ives Bay)</i>			
1845	63	63/168	37
1908	28	28/168	17
1936	12	12/168	7
1948	15	15/168	9
1963	26	26/168	15
1989	21	21/168	13
2010	3	3/168	2
<i>Gannel (Crantock)</i>			
1888	89	89/125	71.2
1901	13	13/125	9.6
1977	76	76/125	6.1
1996	16	16/125	12.8
2012	1	1/125	1
<i>Camel (Padstow Bay)</i>			
1881	26	26/132	19.6
1907	55	55/132	41.6
1962	11	11/132	8
1973	37	37/132	28
2010	3	3/132	2.3

\*Highly dependent on data availability

The ebb channel networks within the three estuaries comprise a main low tide channel, which is sustained as a continuous feature through the historical record, and some temporally and spatially variable branching and braided channels (Figure 4.13). The morphometric overview of the changing channel planform shows that channel width decreases upstream in all three estuaries. This scenario has been well-documented in previous works on fluvial systems (see for examples Leopold, *et al.*, 1964; Leopold, *et al.*, 1993; Marani, *et al.*, 2002 and Burningham, 2008). Consideration of channel shape indicates that there are relatively marked differences in meander structure between the inner and outer estuary/inlet. In the Hayle (Figure 4.13A) and Camel (Figure 4.13C) estuaries, clear meandering is present within the mid-/inner estuary, but close to the outer estuary/inlet region, the meander enlarges significantly to almost exhibit no meander at all. The meanders within the Gannel estuary are spatially limited and appeared to be relatively mobile (Figure 4.13B). Broadly, there is a limited shifts in length and width of the ebb channel in these estuaries.



The most stable areas of the ebb channel system seem to be the inlet and outer-estuary. Consistency in ebb channel positions between the estuaries suggests controls or forcings that is regionally coherent. The historical sequence of planforms presented in Figure 4.13 have shown that there is little movement at the most seaward and landward extents of the estuary (the inlet and head) although there appear to be gradual shifts in the position of the ebb channels throughout the main region of the estuary.

Locational probability analysis highlights the spatial variation in ebb channel dynamics, and can also be used to express the degrees of morphodynamic activity within each system. Within the Hayle (Figure 4.14), around a third of the area that has historically accommodated the channel system is in the 26-50% probability class, indicating that within this part of the system, the channel has been present for at least a quarter to a half of the historical period considered here. High probability values dominate the inlet region, indicating that this is relatively stable in comparison to other parts of the system, such as the inner estuary (Figure 4.14). Around 46% of the historically occupied channel area has accommodated the ebb channel more than 50% of the time (28% of the area has 76-100% probability and 18% has 51-75% probability). Areas showing evidence of increased variability (where probabilities of channel occurrence are low) represent less than a quarter of the channel area (12% of the area is 1-10% probability; 10% is in the 11-25% class). These are mostly within the inner estuary and Copperhouse Pool areas (Figure 4.14). Spatial changes in ebb channel position can be summarised as lower probabilities within inner estuary (both west and east valleys) and higher probabilities in the inlet and central section. This implies that the inlet/central axis of the estuary has been more stable over the historical period, possibly aided by anthropogenic activities, whereas inner reaches are more dynamic, and possibly less constrained.

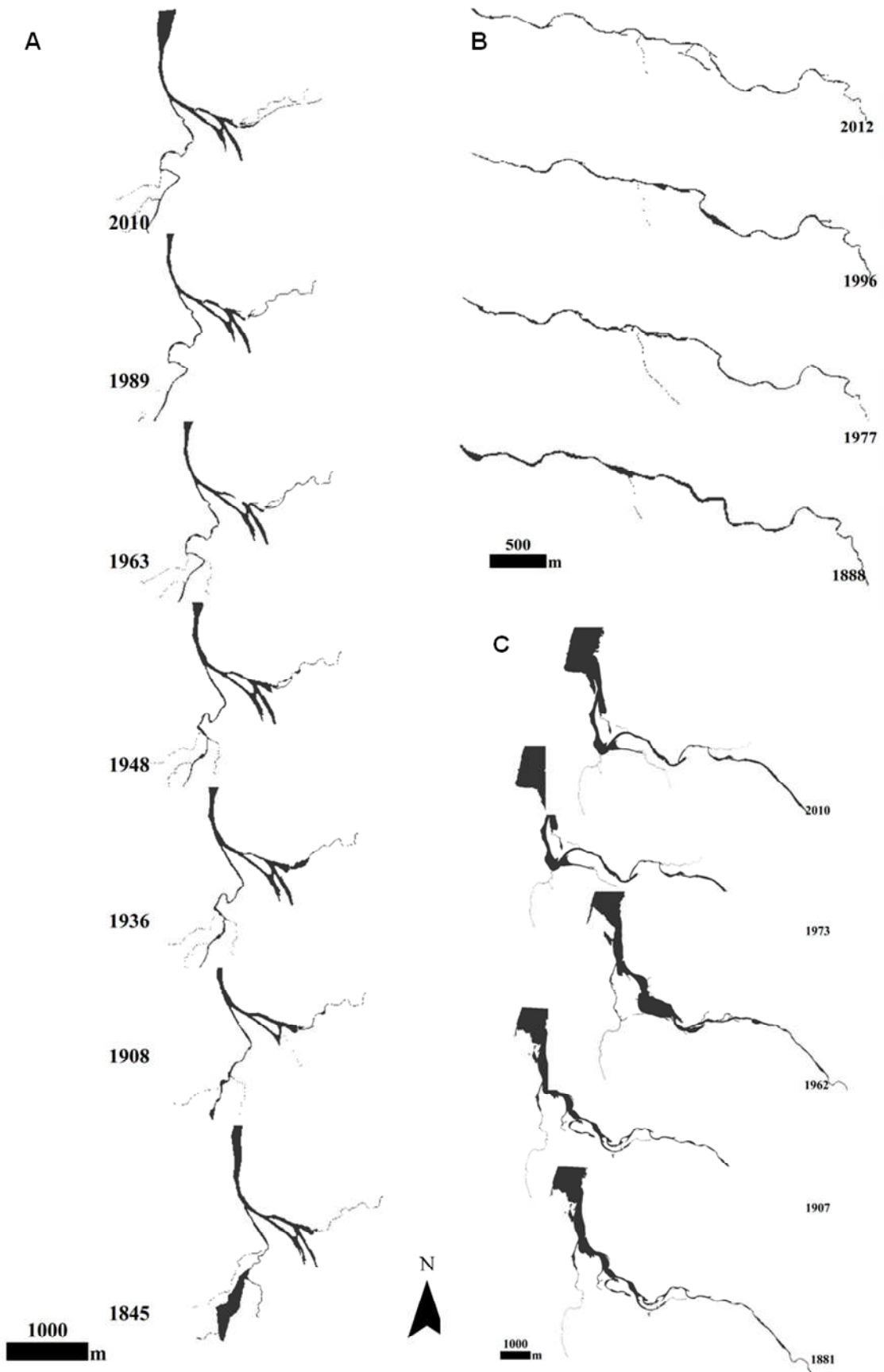
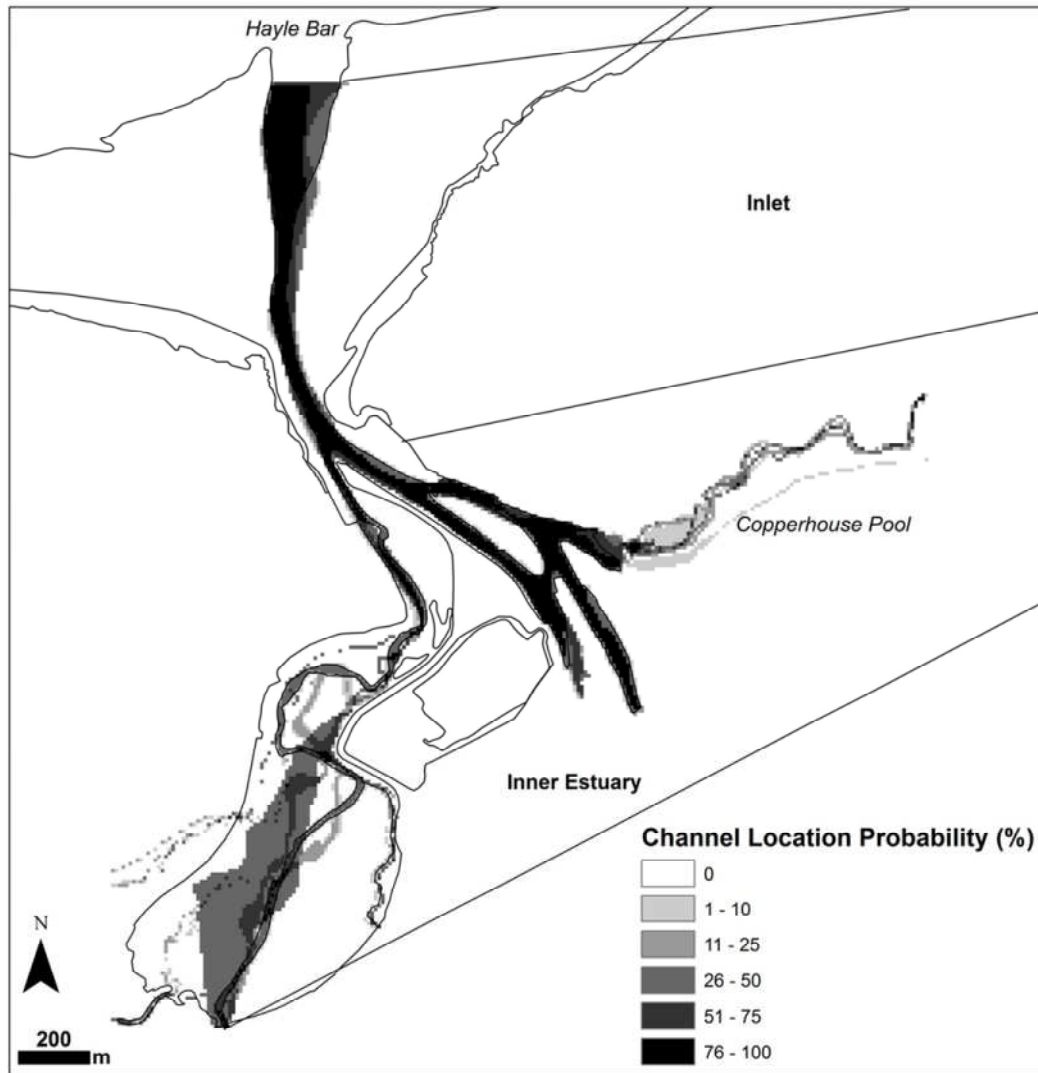


Figure 4.13 Changing planforms of the estuarine ebb (low tide – MLW) channels in the (A) Hayle, (B) Gannel and (C) Camel respectively.



**Figure 4.14** Historical channel location probability mapping of the ebb channel in Hayle Estuary.

The location probability analysis for the Gannel ebb channel network reveals stability and activity along the entire length of the estuary (Figure 4.15). Within the estuary, shifts in the ebb channel are focused on progressive extensions in low channel meanders. The highest probability classes, representing greater stability in channel position, cover around two-thirds of the estuary channel area (18% of the channel area is in the 76-100% class, 47% in the 51-75% class). This suggests that the low-tide system is largely consistent. Only localised patches of mobility are evident. There is clearly a dominant ebb channel position along the northern margin of the estuary, and this has changed very little in the history considered here. The more dynamic parts of the ebb channel are found in the mid- and inner- estuary, associated with meandering, exhibiting reduction in channel width and the cut-offs of channel length in the mid-estuary.

Similar patterns of channel shifts are also observed in Camel estuary (Figure 4.16). The zones of high probability of occurrence over the 132 historical years are again the inlet

region within the outer estuary. The zones of variable or low probabilities are within the mid- and inner estuary. Channel meandering is apparent here, although some positions remain relatively stable through the entire 132- historical year record, the most notable of which is the outer-estuary. The highest probability class (76-100%) accounts for just over a third of the estuary channel area (38%) mainly in the inlet, while the high probability class (51-75%) accounts for 30% of the area, and runs through the mid- to outer sections of the estuary (Figure 4.16). The dynamic parts of the system (low probability class) class are concentrated in the inner and part of the mid section of Camel Estuary, and seem to relate to channel migration.

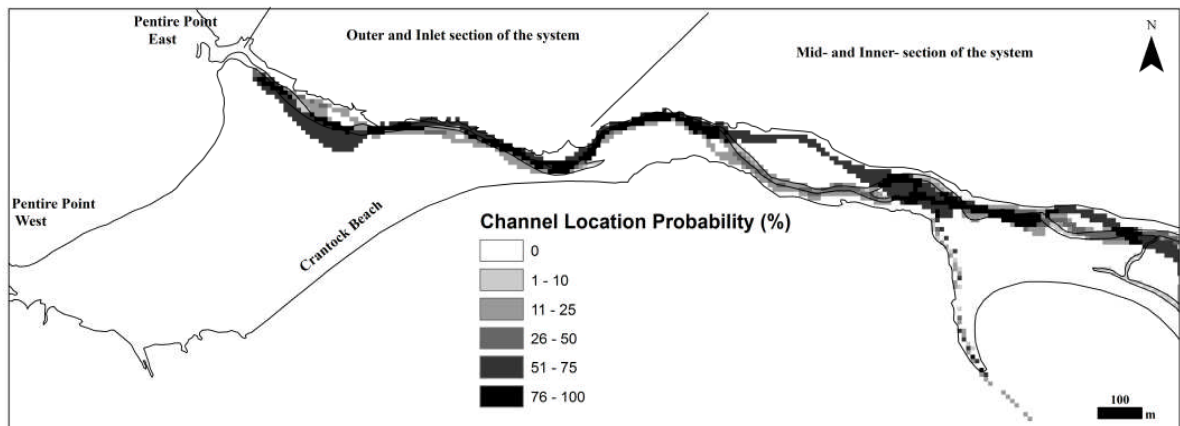


Figure 4.15 Historical channel location probability mapping of the ebb channel in Gannel Estuary.

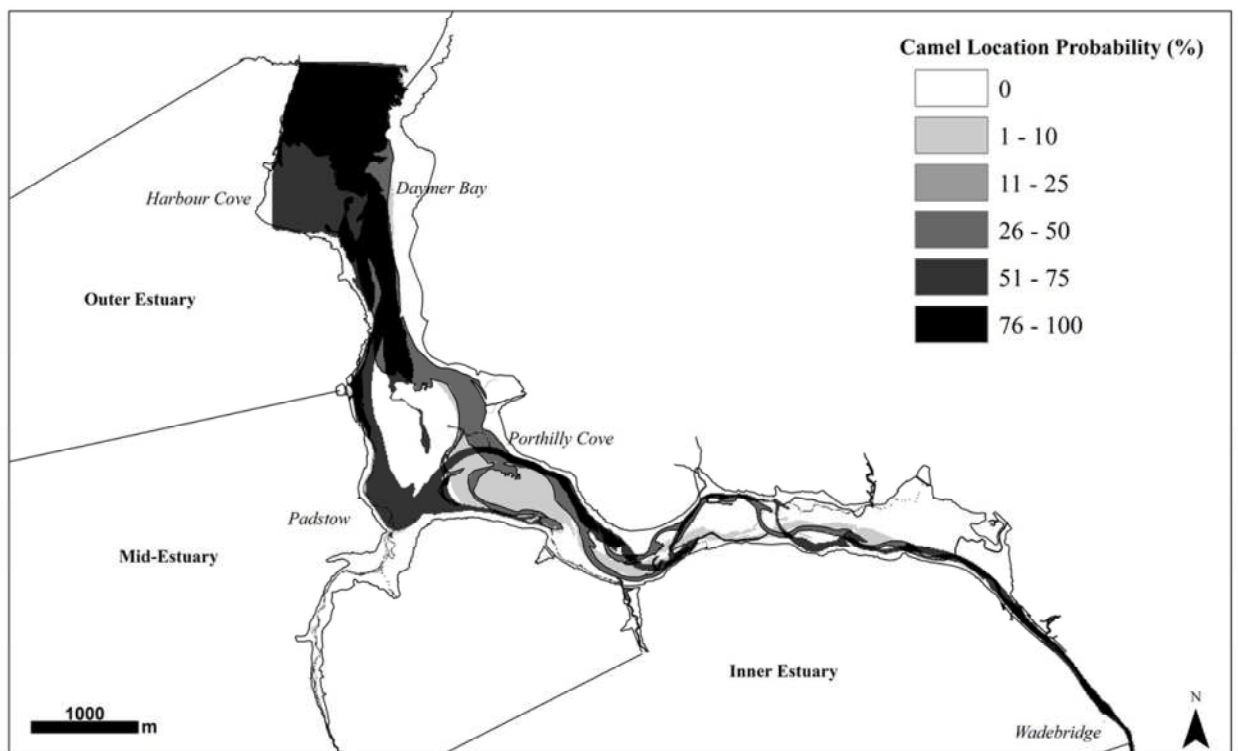
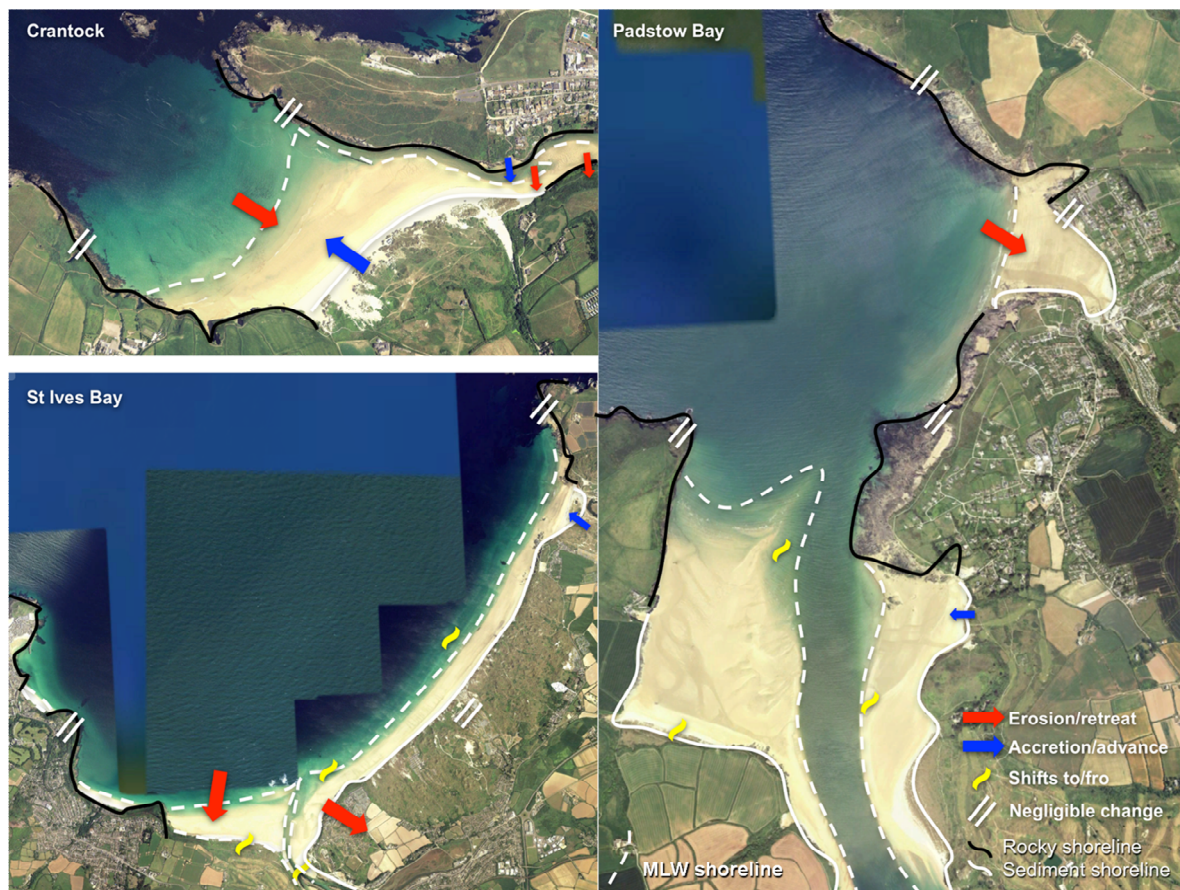


Figure 4.16 Historical channel location probability mapping of the ebb channel in Camel Estuary.

### 4.1.3 Summary of historical morphological change

The behaviour of the high and low water shorelines is spatially and temporally complex. Figure 4.17 summarises the historical trends observed, and illustrates the strong control of the bedrock on shoreline dynamics. Rock-dominated shorelines have experienced little change over the last 120 years, whereas sediment-dominated shorelines exhibit both advance and retreat, but also small-scale changes, and are therefore far more dynamic. In all the systems, the low water shoreline has experienced retreat, or no significant net change. None of the low water shorelines have advanced. In contrast, the high water shoreline experienced a much more varied behaviour - in Crantock, the dune-associated high water shoreline prograded seaward but in St Ives Bay, the dune-topped shoreline near the Hayle inlet eroded significantly. Elsewhere, rocky shorelines displayed negligible change and sediment shorelines show variable change. The consequence of this pattern of change is a broad-scale steepening of the foreshore over the historical time-scale, and some localised reshaping of the coastline.

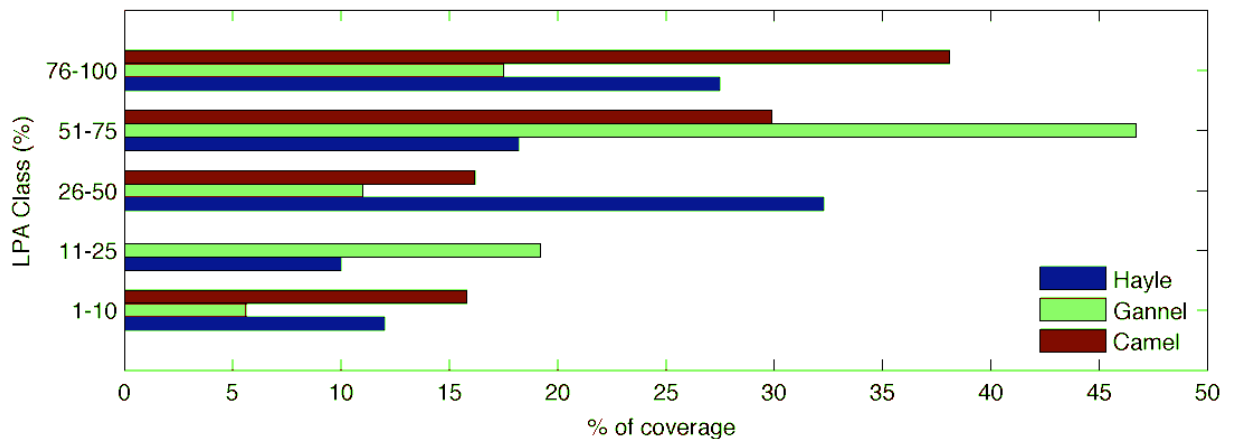


**Figure 4.17 Summary of historical shoreline changes in the St Ives, Crantock and Padstow bays.**

This analysis has shown that some parts of the estuarine systems behave differently, with some being more dynamic than others. Although the channels have shown some mobility, the spatial constraints imparted by the valleys, and the limitations on accommodation space that this imposes, has ensured that the channels have maintained a broadly similar position

throughout the history presented here. Increased channel dynamics are locally evident, particularly in the mid- and inner estuary locations, but these do not show any consistent or persistent behaviour, suggesting channel migration is an ongoing process driven more by hydrodynamic response to the physical structure of the estuarine valley and sediment infill. Perhaps surprisingly, the inlet and outer-estuary regions display high channel stability with high/highest probability class.

The LPA results are compared in Figure 4.18, which shows the proportion of the estuarine channel environment covered by each stability (probability) class. The important results to draw from this are: 1) two-thirds of the historical envelope of ebb channel area in each estuary has accommodated the low tide channel for at least 50% of the last 100+ years and 2) although differences exist between the three systems, the skew of the distribution to the higher probability (increased stability) classes implies that the ebb channel is not a particularly dynamic feature of these estuaries.



**Figure 4.18** Summary of LPA results for all estuaries considered here, based on the proportion of the channel environment covered by each probability class.

## 4.2 Contemporary coastal behaviour

The previous chapter has focused on the historical coastal behaviour and morphodynamics in the study sites. The short-term, contemporary morphodynamic behaviour of the systems is now considered, and focuses on a four-year investigation of the recent morphological behaviour and short-term morphodynamics.

### 4.2.1 Recent morphological change

Recent LiDAR data (2008-2012) from Channel Coast Observatory were analysed using topographic profiles and surface change analysis. The 2009 Hayle LiDAR data could not be used due to data distribution in integer format, and not as float. The change analysis of repeat LiDAR surveys for St Ives Bay and the Hayle (Figure 4.19) show small lateral shifts in channel position, but the analysis shows that movement of low amplitude bars and high tide berms dominate the

short term beach dynamics. Much of the topographic change shown in LiDAR change analysis is balanced across the system as expected with onshore/offshore bar/berm movement. Between 2008 and 2011, the vast proportion of beaches (36.4% of the proportion) to the north of the Hayle inlet showed evidence of accretion, and in fact the primary signature of change is accretional (positive), as the average net change was 0.013m. Erosion was almost entirely associated with the ebb tidal delta (Porth Kidney Sands) (~1.7%), except for some erosion in Carbis Bay (~1%) and some along the high water shorelines of the inlet. It is worth noting that there is some asymmetry to the change in Carbis Bay where erosion dominates to the east and accretion dominates to the west. This could reflect small-scale rotation in the beach deposit in this small bay. The patterns of positive and negative change across the ebb-tidal delta are best explained by the migration of swash bars across the broad intertidal flat: the location of the bars in the earlier time frame is shown as a significant erosional patch, and where they are present in the latter time frame is shown as a large accretional patch. Within the estuary, change is limited to two clear patches of accretion, one in the central basin, and one within the western arm. In both cases, between 0.5 and 1m of accretion has taken place across large banks within and alongside the channel. Although some of this change could be attributed to channel migration (there are certainly some linear erosional features alongside the channels, it seems likely that most of this sediment has been brought into the estuary through the inlet, and these features are comparable to flood-tidal deltas. Table 4.5 presents the frequency volume of classes of magnitude of change in Figure 4.19.

In Carbis Bay however, the rotational change evidenced between 2008 and 2011 is reversed, where erosion now dominates the west, and accretion to the east. This seems to suggest that Carbis Bay switches between westerly and easterly skewed orientation. Due to problems with the 2009 data, it is not possible to establish whether this is an annual rotation, but consideration of the total change between 2008 and 2012 shows that the changes of 2011-2012 have dominated over the slightly longer period. Conversely, it is the accretional signature in beach change from 2008-2011 that is maintained as a signature in the slightly longer term (2008-2012).

The change between 2011 and 2012 (with average net change of  $0.043 \text{ m}^3$ ) is to some extent comparable to that shown for 2008-2011 (with average net change of  $0.013 \text{ m}^3$ ). The majority of change is focused on the ebb delta region, but in this time frame, very little change is evident for beaches to the east and west of the inlet. There are patches of both small-scale accretion and erosion within the estuary, some of which looks to be the result of small shifts in channel position.

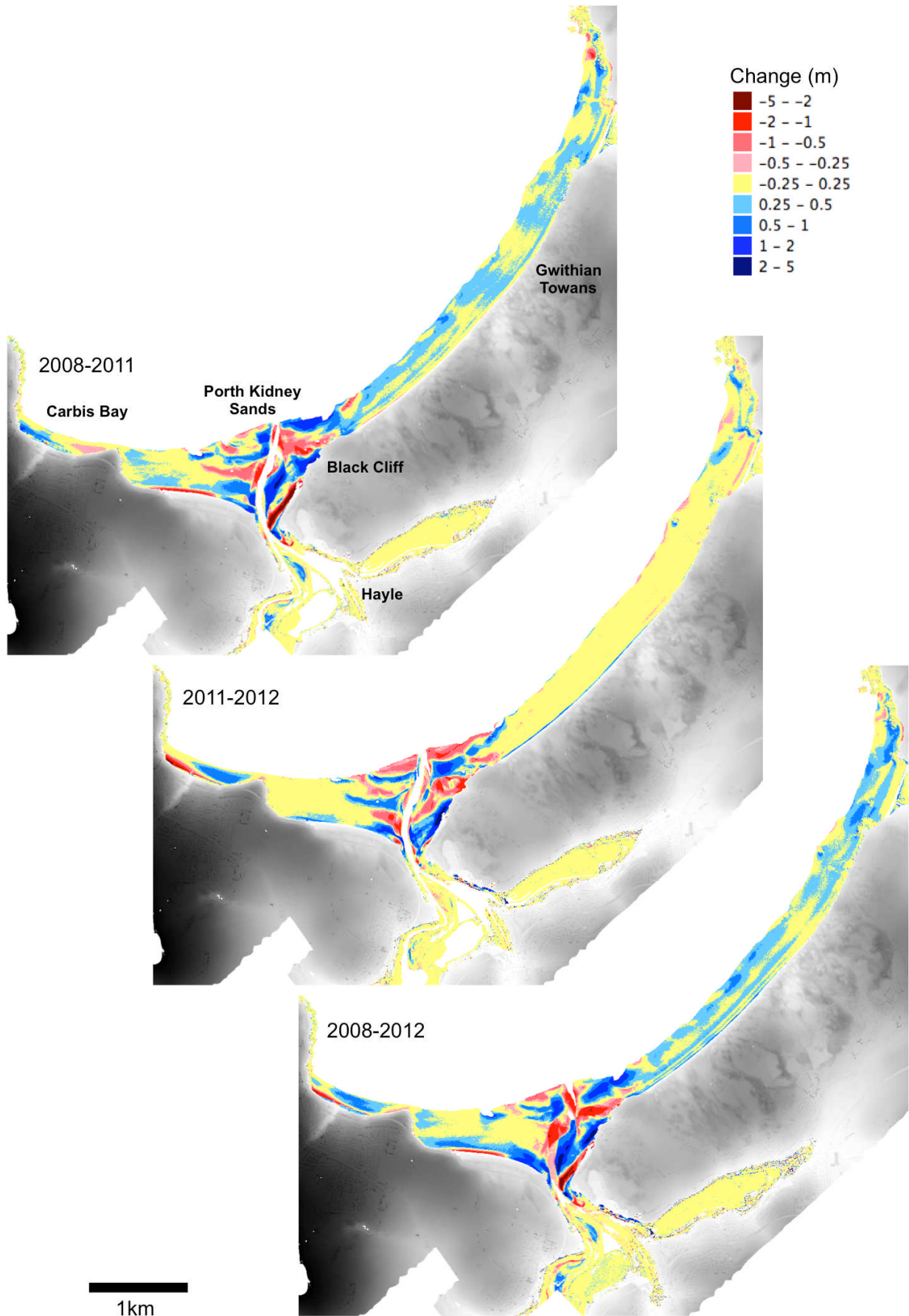


Figure 4.19 Recent morphological change in Hayle Estuary.



**Table 4.5 Frequency analysis for classes of magnitude of change in the Hayle system**

Average net change (m <sup>3</sup> )	Volume of sediment movement (change) (m <sup>3</sup> )		2008 - 2012			
	2008 - 2011	2011 - 2012				
	0.013	0.043	0.15			
Classes of Magnitude (m)	Absolute (m <sup>3</sup> )	*% of proportion	Absolute (m <sup>3</sup> )	*% of proportion	Absolute (m <sup>3</sup> )	*% of proportion
-5 - -2	3384	1	3705	0.11	21321	0.6
-2 - -1	57361	1.7	39114	1.11	88669	2.4
-0.5 - -0.25	283517	8.4	353479	10.04	250964	6.9
-0.25 - 0.25	1919625	56.6	2757723	78.4	2047100	56.1
0.25 - 0.5	898832	26.5	262276	7.5	939314	25.8
0.5 - 1	229112	6.8	226041	6.4	329703	9.0
1 - 2	106276	3.1	66396	1.9	119340	3.3
2 - 5	24	0.001	29	0.001	166	0.004

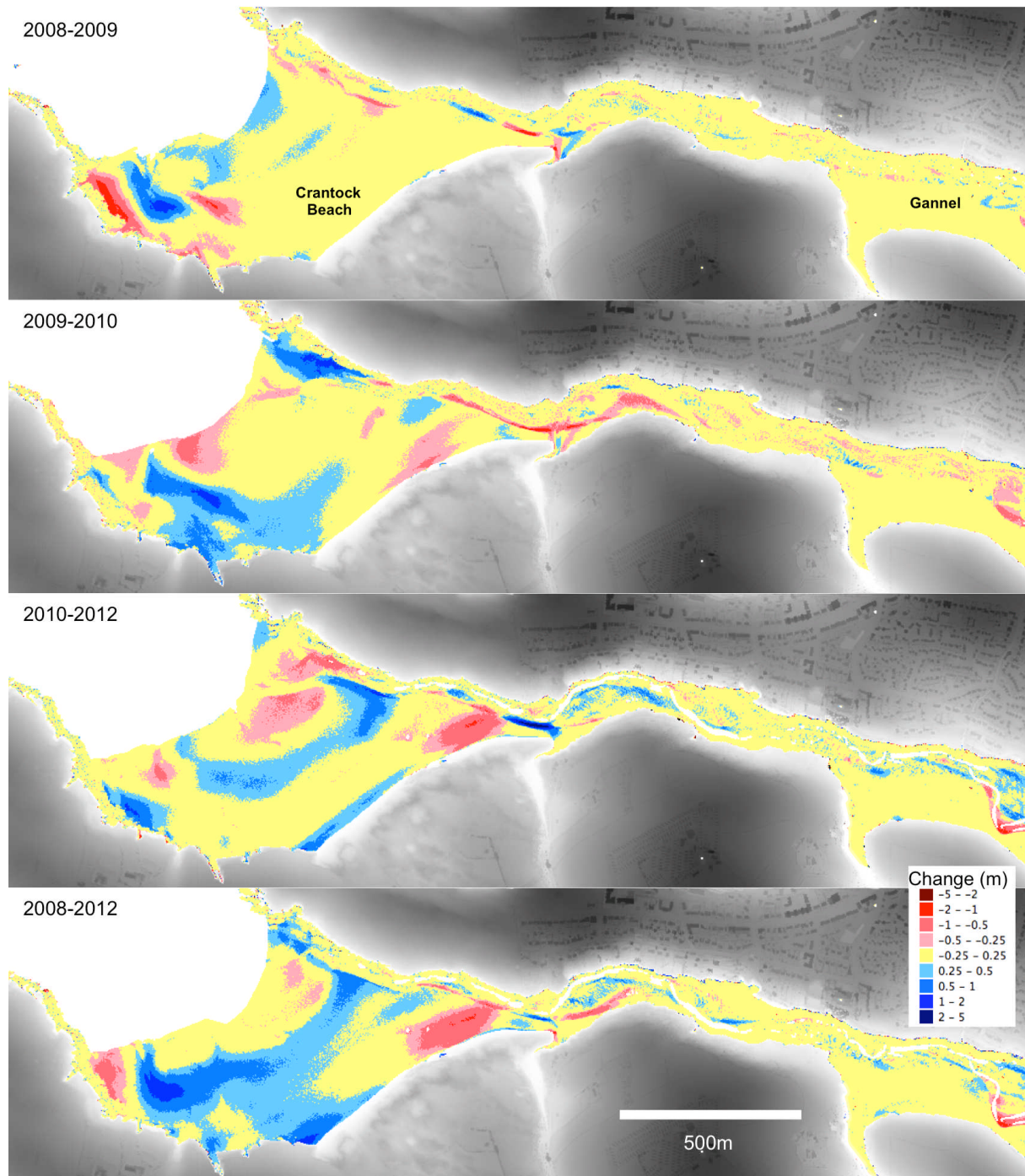
*\*Instead of comparing directly here - the number of cells in classes of magnitude of change is represented as a % (proportion) rather than an absolute.*

The Crantock-Gannel system shows perhaps slightly smaller scales of change to those evidenced in St Ives Bay (Figure 4.20). Here though, changes within the estuary part of the system are of comparable magnitude. Between 2008 and 2009, the most significant patterns of erosional and accretion occur on the beach, aligned in a cross-shore pattern. Along the southwest margin, a large area of erosion dominates, but further north on the beach, accretion dominates. The patterns suggest that sediment movement on this beach is in the form of large-scale migratory bedforms, but that these are neither shore-parallel nor shore-normal in structure or movement. Closer to the inlet, it is clear small lateral shifts in channel position have resulted in a succession of linear erosional and accretional signatures. This continues into the estuary, but here there is also evidence of larger, more diffuse areas of erosion and accretion that would be associated with bedform movement over the intertidal flats.

Between 2009 and 2010, somewhat interesting patterns of erosion and accretion continue to take place across the Crantock foreshore. Again, they are more generally concentrated to the southwest, but there is also further change alongside the channel and inlet. In this case, quite significant erosion is evident along most of the southern margin of the inlet, but perhaps in balance to this, a large deposit is shown around the seaward extent of the channel. Between 2010 and 2012, accretion is evident across most of the mid-foreshore, extending shore-parallel across most of the bay. To the seaward of this, some erosion is shown, and erosion is along evident in the upper foreshore closer to the inlet. Within the estuary, the rather erosional expression shown in the 2009-2010 change map is replaced by a distinctly accretional signature.

When considering the sequence of events between 2008 and 2012, perhaps what is most striking about the series of changes shown here is the behaviour of depositional features on Crantock beach. Quite a significant volume of material accumulated on the lower foreshore on the southwest side of the Bay between 2008 and 2009 that subsequently dispersed cross-shore (landward), and then moved alongshore (northeastward). This suggests that sediment is delivered

to the west part of the beach, and is then redistributed north- and eastward over the following 2 or 3 years across the rest of the foreshore. Table 4.6 presents the frequency volume of classes of magnitude of change in Figure 4.20.



**Figure 4.20 Recent morphological change in Gannel Estuary.**

Within the estuary however, there appear to be different cycles of erosion and deposition that might relate specifically to channel meandering, but also seem to suggest quite significant delivery of sediment into the estuary from the inlet region. Certainly, over the 4 year period, the margins of the inlet show significant erosion and reshaping, whilst the estuary shows a complex

mosaic of accretion and erosion, possibly associated with the movement of megaripples (See figure 6.9) through the system.

**Table 4.6 Frequency analysis for classes of magnitude of change in the Gannel system**

		Volume of sediment movement (change) (m <sup>3</sup> )							
		2008 – 2009		2009 – 2010		2010 – 2012		2008 - 2012	
Average net change (m <sup>3</sup> )		0.02		0.032		0.077		0.12	
Classes of Magnitude (m)	Absolute (m <sup>3</sup> )	% of proportion	Absolute (m <sup>3</sup> )	% of proportion	Absolute (m <sup>3</sup> )	% of proportion	Absolute (m <sup>3</sup> )	% of proportion	
-5 - -2	86	0.01	63	0.001	219	0.02	119	0.01	
-2 - -1	3943	0.54	1177	0.2	3046	0.3	1503	0.2	
-0.5 - -0.25	49960	6.84	92674	12.5	82112	8.15	62466	6.3	
-0.25 – 0.25	649718	89.02	585558	79.1	816249	81	731398	73.7	
0.25 – 0.5	48786	6.68	100180	13.5	127757	12.7	164153	16.6	
0.5 – 1	10853	1.49	33304	4.5	30991	3.1	59342	6.0	
1 – 2	2152	0.29	4484	0.61	3527	0.35	8579	0.9	
2 – 5	7	0.001	16	0.002	2	0.0001	8	0.00	

*\*Instead of comparing directly here - the number of cells in classes of magnitude of change is represented as a % (proportion) rather than an absolute.*

Patterns of change in Padstow Bay and the Camel estuary are complicated, with multiple patches of erosion and accretion evident throughout the system, and throughout the time periods considered here (Figure 4.21). Only surveys from 2008 and 2011 extend across the outer estuary and open coast. Focusing initially on the estuary, between 2008 and 2009, the change was primarily characterised by accretion – large areas of intertidal flat experienced 0.25-2m vertical accretion. To some extent, quite a lot of this change was associated with channel margins, and evidenced for migration is shown in the presence of spatially-matched, narrow patches of erosion and accretion either side of the main channels. From 2009 to 2011, the general patterns of change are spatially comparable, but the signature is reversed and erosion dominated. Channel migration clearly continues, most notably along the stretch to the east of Padstow where the west bank is eroded and the east bank exhibits accretion. Changes between 2011 and 2012 appear very similar to those between 2008 and 2009, where again, erosion is largely aligned with channel margins, and large surfaces of intertidal flat show an accretionary signature. Table 4.7 presents the frequency volume of classes of magnitude of change in Figure 4.21.

Channel migration driving erosion and accretion is not evident in the outer bays of Harbour Cove and Daymer Bay. These intertidal flats form the ebb-delta, and here deposition and erosion seem to follow the formation of large sedimentary deposits such as sand waves and their migration across the flats. This is clearer in Daymer Bay, where the deposits are shore-parallel, but in Harbour Cove, features are more complex and variable in structure, though the dynamic zone is clearly the lower, rather than upper foreshore.

#### 4. Shoreline and Estuarine Change Analysis

The net consequence of these changes (2008 to 2012) reveals quite substantial changes have occurred over the vast majority of the intertidal environment of the Camel. In comparison, the open coast beach in Padstow Bay exhibits very little change over a similar period (2008 to 2011). Although the lack of lidar data for the open coast site precludes a direct comparison, it is clear that the small patches of accretion evident are insignificant in comparison to the dynamics shown in the estuary, inlet and ebb-delta regions.

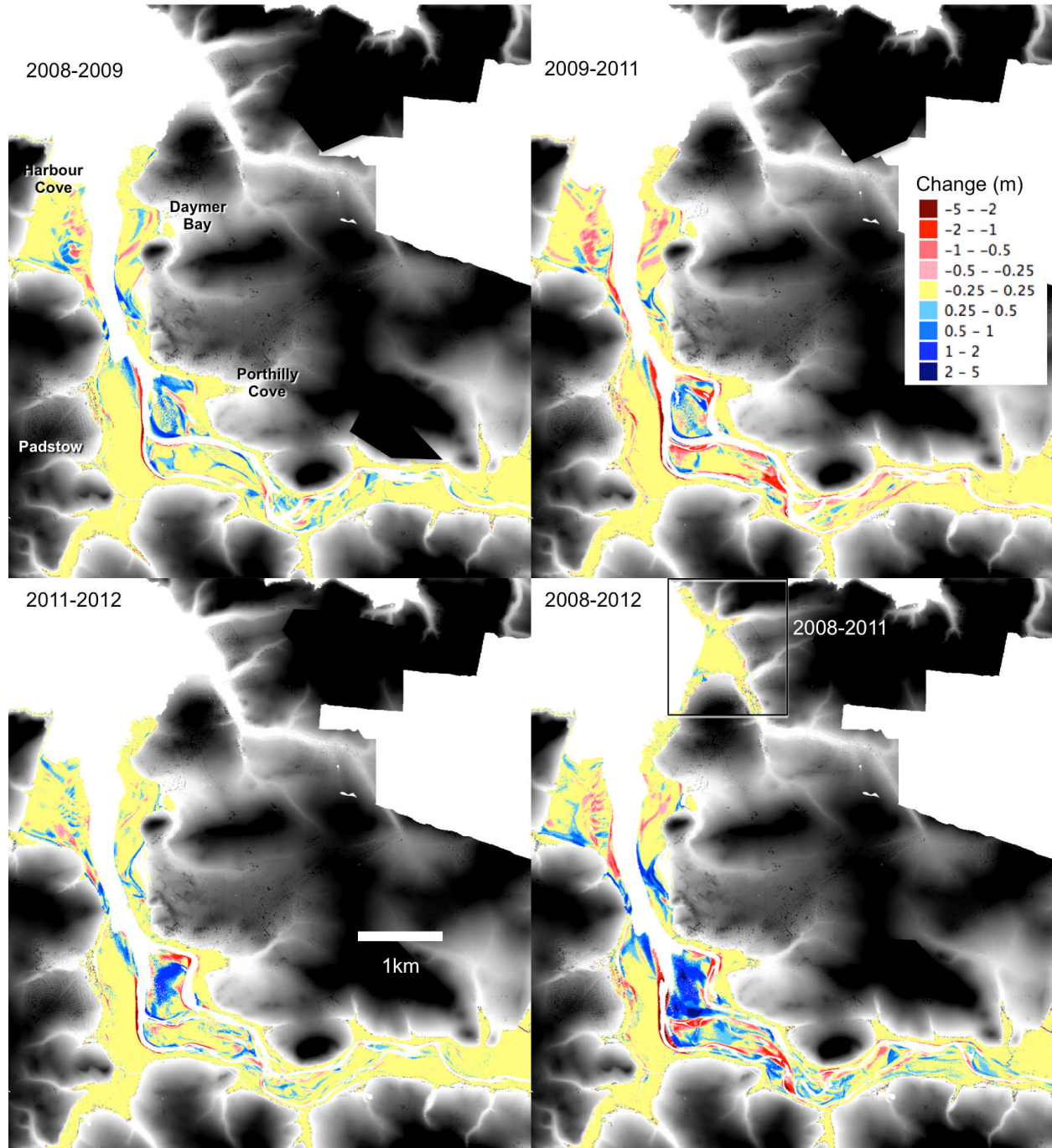


Figure 4.21 Recent morphological change in Camel Estuary.

**Table 4.7** Frequency analysis for classes of magnitude of change in the Camel System

		Volume of sediment movement (change) (m <sup>3</sup> )										
		2008 – 2009		2008 – 2011		2009 – 2011		2011 – 2012		2008 - 2012		
Average net change (m <sup>3</sup> )		0.092		0.017		-0.094		0.083		0.10		
Classes of Magnitude (m)	Absolute (m <sup>3</sup> )	*% of proportion	Absolute (m <sup>3</sup> )	*% of proportion	Absolute (m <sup>3</sup> )	*% of proportion	Absolute (m <sup>3</sup> )	*% of proportion	Absolute (m <sup>3</sup> )	*% of proportion	Absolute (m <sup>3</sup> )	*% of proportion
-5 - -2	9036	0.14	27569	0.41	24593	0.4	15173	0.2	32492	0.52		
-2 - -1	24215	0.38	112448	1.66	106625	1.7	28175	0.5	103650	1.65		
-0.5 - -0.25	77626	1.22	574998	8.5	758198	12.3	269715	4.4	518505	8.24		
-0.25 – 0.25	5450930	85.5	5464654	80.7	5369911	87.1	5349288	86.4	4608093	73.3		
0.25 – 0.5	541003	8.5	507484	7.5	276593	4.5	455679	7.4	699224	11.1		
0.5 – 1	222355	3.5	303270	4.5	130640	2.1	190315	3.1	378332	6.0		
1 – 2	47727	0.75	141760	2.1	31260	0.5	80505	1.3	261670	4.2		
2 – 5	276	0.01	356	0.01	311	0.001	332	0.001	351	0.001		

*\*Instead of comparing directly here - the number of cells in classes of magnitude of change is represented as a % (proportion) rather than an absolute.*

#### 4.1.1 Short-term morphodynamics

Cross-sectional profiles can be investigated using the LiDAR data (Moore, *et al.*, 2009) in order to examine the behaviour of specific cross-shore features. Cross-sections extracted from LiDAR data for St Ives Bay (2008 – 2011) are shown in Figure 4.22. The western transects (T1, T2, T3) show varied shifts around the high water mark – some accretion at T1 and T3, and more significant erosion at T2. The northern beach transects (T5, T6) show very small changes in the position of MHW. Beach level fluctuates by up to 75 cm (as shown in the vertical accretion at T3 and erosion at T5), but again the story is not consistent across the bay. Transect T4 crosses the main ebb channel in the inlet. Here, significant vertical change has occurred over the 2 - 3 year period, but only on the eastern margin: the west bank has changed little in comparison. Referring back to the spatial mapping of change, the deposits here (of >2 m) are associated with the migration of sand waves/spits into the inlet from the upper foreshore of the beach.

At Crantock, the shoreface cross sections (T1 and T2) reveal only small changes in the position of MHW and MLW, and small-scale shifts in the beach level during the four year (2008 – 2011) (Figure 4.23). The estuarine transects (T3 – T5) which crosses the main ebb channel in the inlet and inner estuary reveal year to year localised erosion and deposition, which appears to be linked to sandbank movement and channel migration/shifting in the Gannel estuary. The inlet transects (T3) shows variable change over the 4 year period, whilst T4 (extending over the flood-delta just landward of the inlet) illustrates the role of mobile and migrating sandwaves (wavelength 8 – 10cm, height 10 – 30cm) in the re-organisation of sediment over the larger intertidal forms. These bedforms progressively move over the broad intertidal flood-delta platform into the estuary. As expected, the flood-delta is forced primarily by tidal currents, but the changes also suggest that this supply of sediment into the estuary might drive shifts in channel position.

Transects within the Camel estuary (Figure 4.24) reveal variable shifts in surface levels over the intertidal flats, with year to year localised erosion and deposition. On the open coast (T1), there is some suggestion of overall accretion between 2008 and 2011, particularly across the upper foreshore, but the changes are quite minimal. Within the ebb-delta and inlet region, larger scales of change are more evident. Broad, but low features move across the lower foreshore in both T2 and T3: these do not show progressive change, and the envelope of variability is consistent across the foreshore. Within the inlet however, there is distinct evidence of accretion on both margins of the inlet. In particular, the east bank displays progressive accumulation across the mid and upper foreshore. In places, the vertical accretion is *c.* 1m, and this has led to a narrowing of the mid-tide inlet by around 25m. Given the presence of intertidal bars across the foreshore to the north (T3), it is likely that this accretion has benefitted from sediment supply via these mobile foreshore bars.

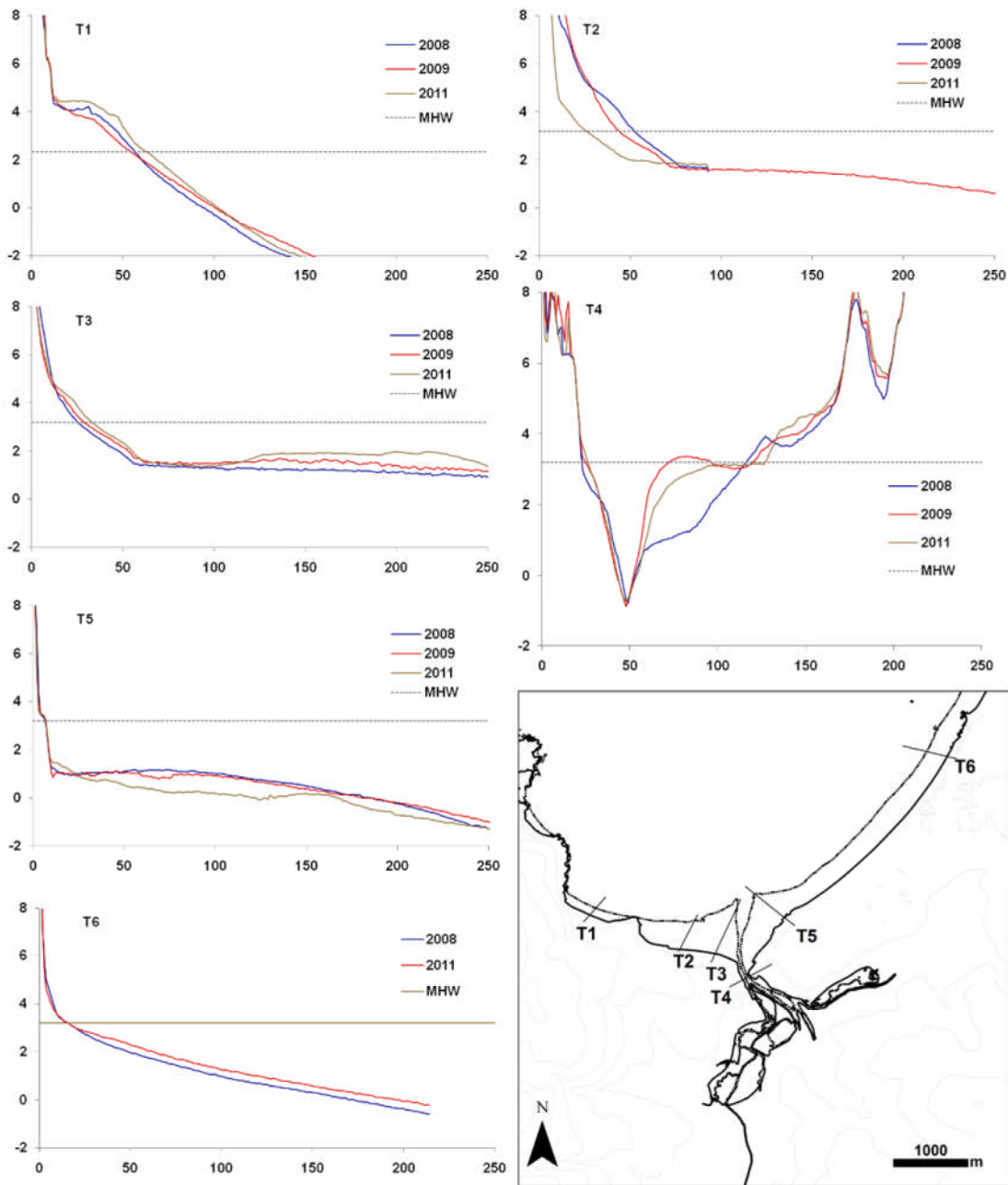


Figure 4.22 LiDAR cross-sections for transects 1 – 6 (T1 - T8) in St Ives Bay (Inset: transects positions of the LiDAR cross-sections in the estuary).

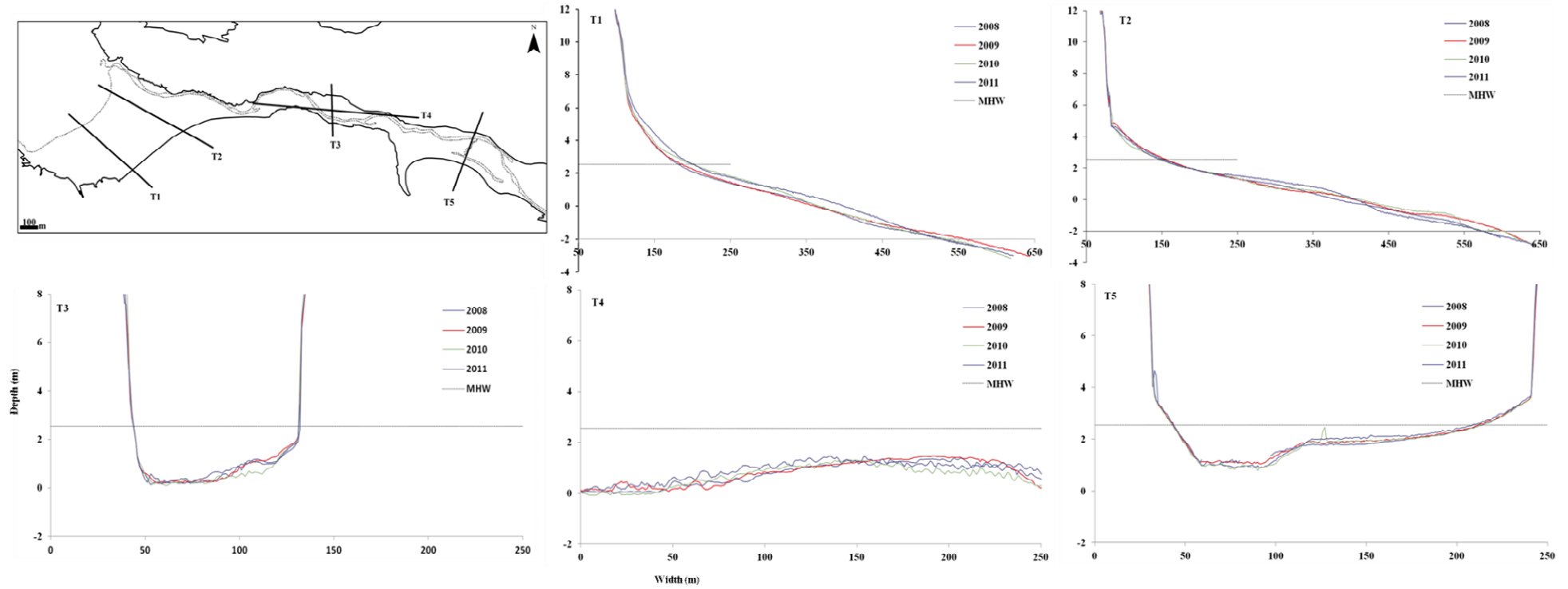


Figure 4.23 Transects positions of the LiDAR cross-sections in Gannel Estuary (Inset: transects positions of the cross-sections). Please note different elevation (y-axis) and distance scales (x-axis).



Into the estuary, the wide transect at T5 shows the lateral extent of the channel network through the estuary. This transect in particular seems to suggest that changes in elevation of the intertidal flat surface are less distinct than changes associated with channel movement. A small static channel exists close to the west bank, but there are several substantially larger channels within the mid-estuary where there is evidence of progressive migration (shown by the gradual retreat or advance of the channel margin) and channel switching (where channels seem to appear and disappear). Channel switching is particularly clear around 900m into the transect, where a substantial channel was present in 2009 but completely gone by 2011. It is not clear whether shoals either side prograded and therefore enclosed and infilled this channel or whether sediment was delivered from up/down stream. But it is clear that channels in the mid-Camel estuary are significantly more active than in the Hayle or Gannel. As the valley begins to narrow, the intertidal structure becomes less variable. At T6, the intertidal surface shows both erosion and accretion over the 4 years, but channel position has remained relatively stable, and this is furthermore the case at T7.

#### 4.1.2 Inlet dynamics

The dynamics of tidal inlet aids in the understanding of the morphodynamics and interaction between components of open coast – estuarine systems (O'Connor *et al.*, 2011). The inlets in this study have all shown significant positional stability over the historical timescale. A review of the channel position through the inlet and ebb delta shows that although notably stable in all cases, inlet channel variability is more apparent in the Hayle and Gannel estuaries than the Camel (Figure 4.25). The central section of the Hayle inlet channel is static, but the position envelope increases in both the seaward and estuary directions. Exploring the detail within this, the channel moved eastward until the 1960s since when it has been west: the channel still lies to the west of its 1845 position (Figure 4.25C). Inlet channel dynamics in the Gannel estuary are similar (Figure 4.25D), however the timing of change in direction of movement was much later (mid-1900s). The scales of movement in the Camel are much reduced (Figures 5.7B), and they follow small shifts rather than continued migration. These differences in historical scale inlet behaviour appear to suggest that despite exposure to the same regional processes, estuary inlets respond differently. This is the result of antecedent differences between the systems, such as geomorphology, geological configuration, intrinsic tidal forcing specific to the individual estuary physical structure, or sedimentary characteristics that determine the mobility of sediments within each system. Of course, the other probable influence is the intensity of the past anthropogenic influences in each of the estuaries.

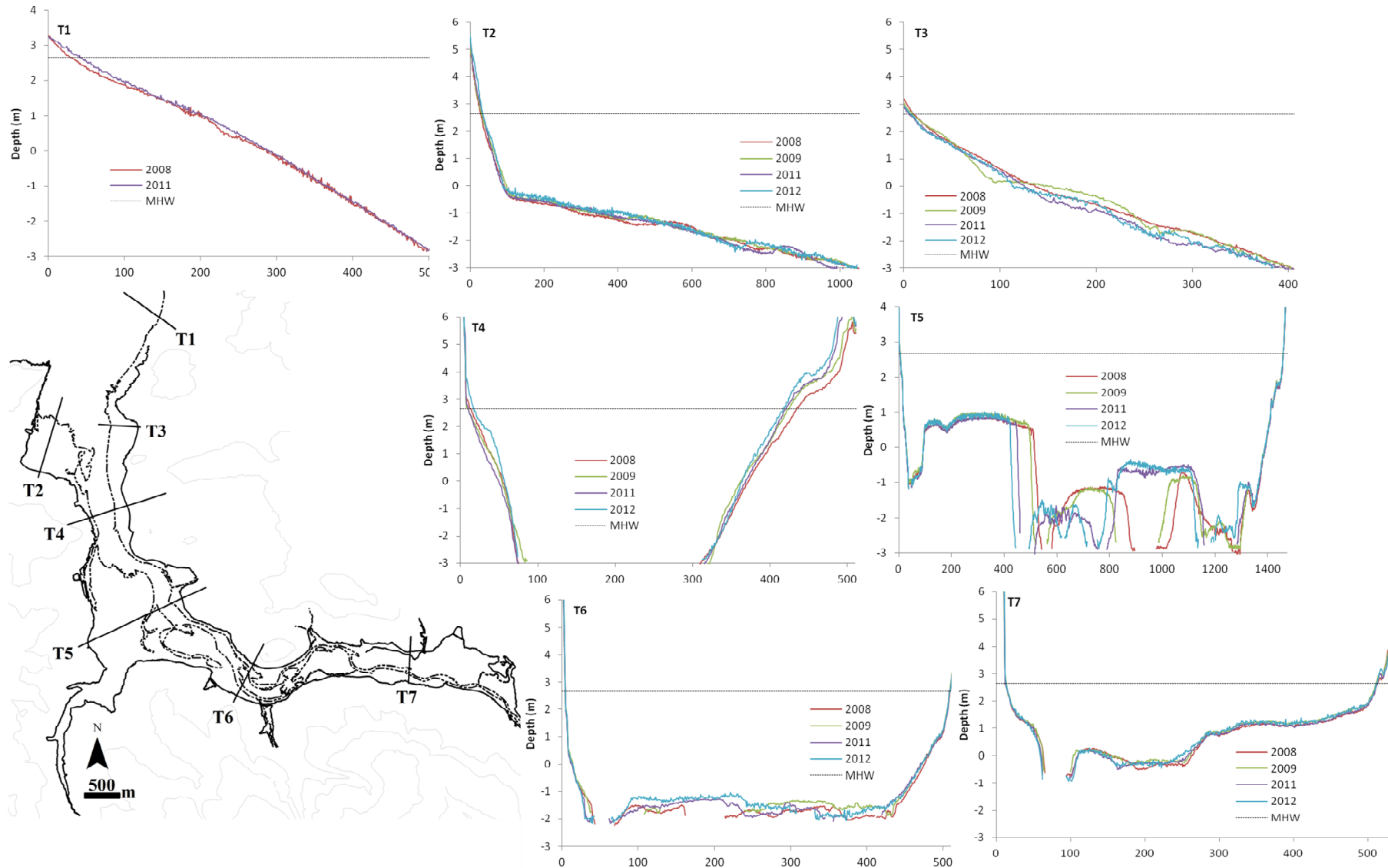
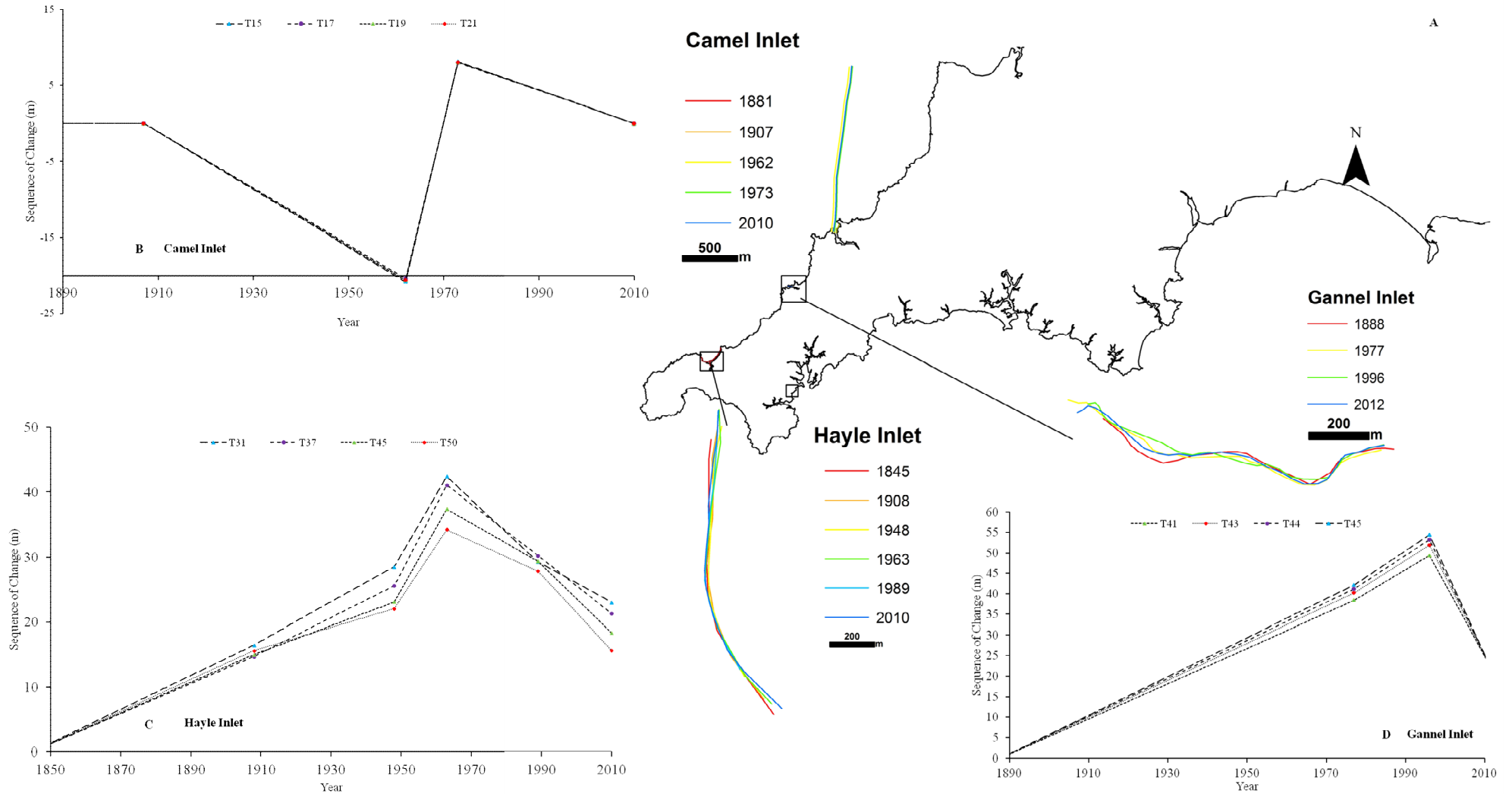


Figure 4.24 Transects positions of the LiDAR cross-sections in Camel Estuary (Inset: transects positions of the cross-sections). Please note different elevation (y-axis) and distance scales (x-axis).



**Figure 4.25** Channel position variability in the estuary inlets (A), and the historical sequence of channel migration as captured in a transect-based average change analysis analysis (B-D). In all transects, the transects extend from the west margin of the inlet, with eastward channel movement shown as positive change and westward channel movement as negative change.

The historical and contemporary evaluation/observation of inlet morphology indicate their positional stability, however, the inlet throat cross - section indicates morphological instability as there are shifts in the inlet channel positions. Headland sheltering is suggested to be mostly probably a factor responsible for positional stability of the inlet in the estuaries (Hume and Herdendorf, 1992). Also, the inlet form is stated to be dependent on the relative strength of tidal and wave energies, and to some extent sediment supply (FitzGerald, 1988; Burningham and French, 2006). The three estuary inlets examined here are localised coastal systems where the physical shape of the bay and estuary environment is a product of bedrock. Tidal flows are constricted between the resistant rock headlands (e.g. Camel and Gannel) or by the unconsolidated sand barriers (for example, Hayle estuary). One might expect therefore that the Hayle inlet would exhibit increased movement, but the sand barrier is underpinned at various points by bedrock, and it is likely that this retains more control that might be expected based on surface characteristics. Rocky features such as Pentire Point East, the Steeper Point and Pentire Point -Widemouth at the mouth of Gannel and Camel estuaries respectively will likely play an important role in protecting the inlet region from the predominantly northerly to westerly wave attack. In St Ives Bay, headlands are not found beyond the inlet (the wider Bay headlands are so distant that their influence would be minimal) and here the ebb-delta of Porth Kidney Sand is large and provides some sheltering.

The time intervals between historical surveys can often mask dynamic inlet behaviour simply due to poor temporal resolution (Burningham, 2005). Further analysis of the inlet regions, using aerial imagery and lidar data, suggests that stability follows over the short-term scale too. The recent physiography of inlet morphology as shown via the GoogleEarth historical imagery is evaluated for Hayle, Gannel and Camel inlets (note: the Google Earth imagery is evaluated without any consideration of tidal cycle variations, and focuses on qualitative assessment of changes in the overall geomorphology). The Hayle inlet displays considerable stability (Figure 4.26). Although the imagery is taken at different stages of the tide, it is clear that the channel has maintained a constant position that favours the westerly bank of the inlet. In the imagery, and the additional time frames provided by the lidar data, it seems that this bias to the west is a consequence of sediment movement into the inlet from beaches to the northeast.

The images and lidar data clearly show small spits extending from the northeast into the inlet region, and it is likely that sustained sediment delivery in this manner would continue to force the channel into a westerly position. This might explain the tendency for the channel to then bend northeastward as it crosses the ebb-delta toward the sea as this meander is forced into position at the apex (within the inlet). There is some evidence that the channel route across the ebb-delta is rather more variable - although broadly maintained a common path, it is clear that smaller-scale meanders and shifts take place in the channel here. This is likely to be the result of the movement of sand bodies such as swash bars across the ebb-delta.



Figure 4.26 The recent Google and Channel Coast Observatory (09/03/2008 and 06/04/2012) aerial photograph of tidal inlet in Hayle Estuary. (Source of the image: Aerial Google Map of southwest England (c) 2013 Infoterra Ltd & Bluesky and Channel Coast Observatory).

#### 4. Shoreline and Estuarine Change Analysis

In the Gannel inlet, the channel hugs the northern margin, and has done historically through to present (Figure 4.27). The meanders here appear to be well-tuned to the valley shape. The channel stays close to the bedrock shoreline through the Crantock beach region, which forms the first meander. It detaches slightly as the bedrock valley narrows and just before the northern shoreline sharply trends to the north, where the valley broadens a little. This might reflect flood tide forcing of the channel position which retains for a while the alignment of the seaward part of the system. The tendency to then return to the northern shoreline, rather than simply cross the valley at this point is related to the large intertidal flat just landward of the inlet. This could be considered the flood-delta and it is a significant depositional zone within the estuary. The general position of the large-scale features change very little over the long- and short-term suggesting that valley shape might exert significant controls on tidal flow and sediment movement here.



**Figure 4.27** The recent Google aerial photograph of tidal inlet in Gannel Estuary. (Source of the image: Aerial Google Map of southwest England (c) 2013 Infoterra Ltd & Bluesky).

Out of the three systems, the Camel inlet shows the least degree of change (Figure 4.28). The channel through this inlet is substantially larger (wider and deeper) than in the Hayle and Gannel, primarily due to the significant difference in estuary area and therefore tidal prism (the intertidal zone of the Camel is 610ha compared to 321ha and 85ha for the Hayle and Gannel respectively).



**Figure 4.28** The recent Google aerial photographs of tidal inlet in Camel Estuary. (Source of the image: Aerial Google Map of southwest England (c) 2013 Infoterra Ltd & Bluesky).

The recent aerial imagery and lidar data show that the inlets and rocky shore in this study are perhaps the most stable part of the coastal systems. Shoreline, intertidal surface and ebb channel change analysis has shown that some significant changes have taken place within these coastal systems over various temporal scales, but that the inlet has remained one of the most consistent features. The ebb tidal delta in all cases comprises large swash-bar type features that migrate across the foreshore, generating complicated patterns of erosion and deposition over the shorter time-scale (see Figures 4.19 – 4.24). This sediment movement can also be linked to changes in the upper foreshore along the inlet-associated margins. Considering this evidence for large-scale sediment movement across the open coast and inlet beaches, it is surprising that the ebb channel has maintained a consistent route. As determined before, it is likely that the bedrock shoreline, both within the inlet regions and beyond, plays a role in maintaining the position of the channel.

Sediment transport directions are variable around the inlet regions, and some anthropogenic activities complicate the sediment supply process further. The Hayle ebb delta for example is skewed to the east, suggesting some west to east longshore sediment transport. Sediment also moves east to west into the inlet via small sand spits and waves that migrate along the eastern margin. Maintenance dredging of the inlet removes much of this sand from the inlet/estuary system (See: [http://www.hayleharbourauthority.com/Public\\_Pages/dredging.aspx](http://www.hayleharbourauthority.com/Public_Pages/dredging.aspx) for details of dredging activities in Hayle Estuary). The Gannel inlet shows small-scale morphological instability as the channel throat slightly widens and/or deepens to varying degrees as tidal processes probably cause fluctuations in sediment movement and supply. The cross-sections which

cover the flood-tidal delta illustrates the role of mobile and migrating sandwaves (wavelength 8 -10m, height 10-30cm) in the re-organisation of sediment over the larger intertidal forms. These are progressively moving into the estuary, so clearly forced by tidal currents - and this in turn drives shifts in channel position. The changes in channel position between the 2008 and 2012 are mostly widening by some ~20 m primarily in response to movement of sediments by tidal forcing.

The complexities of the processes at the inlet have been emphasised in the works of O'Brien (1931), Heath (1975), Walton and Adams (1976), Vincent and Corson (1981), Marino and Mehta (1987), Hume and Herdendorf (1987, 1988a, 1988b), and so on, largely attributed to variance in morphological and hydrological parameters. The inlet exerts significant influence on the morphodynamics of adjacent shorelines (FitzGerald, 1988; Hicks *et al.*, 1999), the interruption of the continuity of longshore sediment transport and exchange of sediments between both landward and seaward sediment systems (Burningham and French, 2006).

#### 4.1.3 Summary of contemporary morphological change

The contemporary behaviour of the shorelines and ebb channels at the systems also reveal spatial and temporary complexity as rock-dominated shorelines, similar to the historical morphodynamics in the system, experienced little or no change over the four years, while the sediment-dominated shorelines exhibit alternation of both minimal advance and retreat. At the yearly scale, intertidal bars and sand waves migrate across the foreshore and into the inlet region. The systems' inlets exhibit the dynamic movements and migration within the short-space of time considered here. Flood dominance in the outer estuary encourages the net landward movement of sediment across inlet-associated beaches and supplies sediment to the macro-tidal estuaries. Temporal behaviour suggests shifts in the flood-ebb balance are occurring on an annual scale, particularly in the Camel estuary where large areas of accretion followed a year or two later by large areas of erosion. Channel migration is an important driver of the erosion and accretion experienced in these estuaries, but these changes are focused on the channel-margins, a distinctly different geomorphic signature to the large-scale accretion and lowering evidenced over the intertidal flats. The analysis presented in this sub-section has shown that some parts of the estuarine systems behave differently, with some being more dynamic than others. Ebb channels showed some mobility, however the spatial constraints imparted by the geology and rock-interface limits the dynamic movements of the channels in the system. Channel migration within each system are shown to be capable of eroding and releasing large volumes of sediment which are then perhaps transported via the ebb tide out of the estuaries to be deposited nearshore to the ebb deltas. It is therefore possible that the net effect over several years is balanced as sediment arriving at the ebb delta might simply be sourced from the release of sediment within the estuary, through channel dynamics.



## 5 METOCEAN ANALYSIS

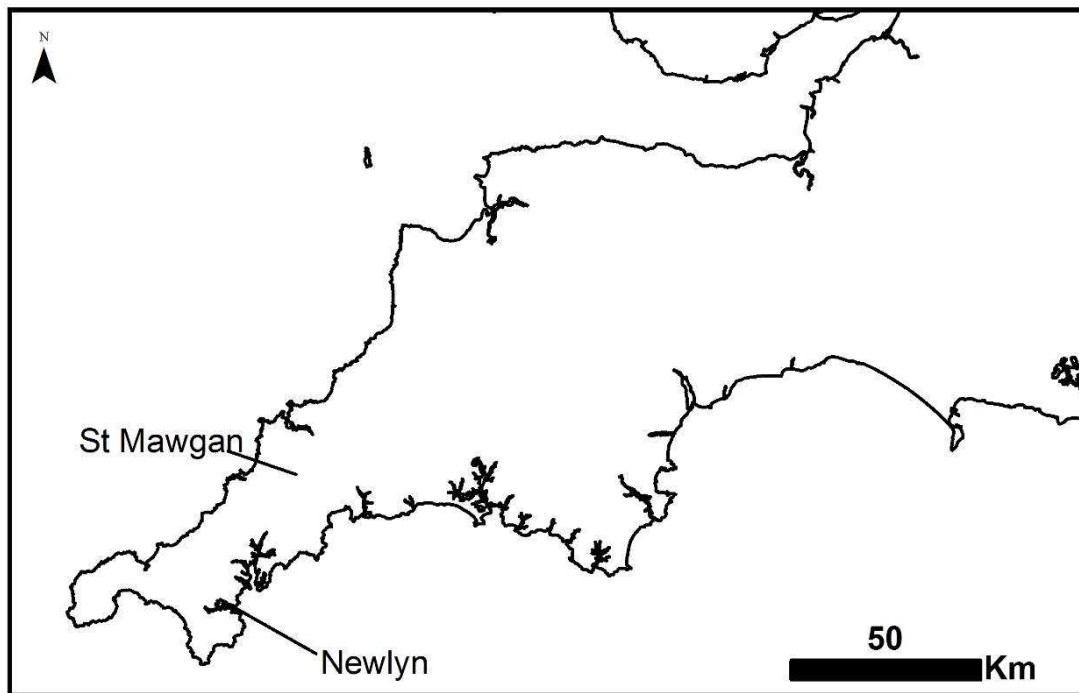
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The previous chapter has focused on the historical and contemporary coastal behaviour and morphodynamics of the study sites. The forcing of coastal change is explored in this chapter and the analysis of key metocean data, focusing on historical and contemporary wind and wave climate as well as tide and sea-level change, are presented here. The objective here is to evaluate the importance of regional forcing as the driver of historical and contemporary coastal change.

### 5.1 Historical coastal forcing

#### 5.1.1 Wind and storm climate

Coastal forces (waves, wind and tide) play major roles in many coastal environmental processes, both at the open ocean and in coastal zones. As waves propagate toward the coast, the interaction between orbital motions and the bottom (Dodet, *et al.*, 2009) drives sediment transport, which has been described as sediment migration (Carter, 1988; Black and Oldman, 1999; Dodet *et al.*, 2009). Wave-driven sediment transport forces much of the morphodynamic behaviour of coastal systems. Therefore, it is essential to understand the historical, spatial and temporal variations of this coastal forcing in evaluating their influence on the morphodynamic evolution of the coast-estuarine environment. This section is focused on reporting the historical coastal parameters for the study area, specifically considering the southwest England wind climate (using data from St Mawgan, which is the only available data for this project) and sea-level record (using data from Newlyn, which provides the tide record for southwest England) (Figure 5.1). The association of wind climate, storminess and the North Atlantic Oscillation (NAO) in influencing geomorphic change within the coastal environment of southwest England over the last 150 years is examined here.

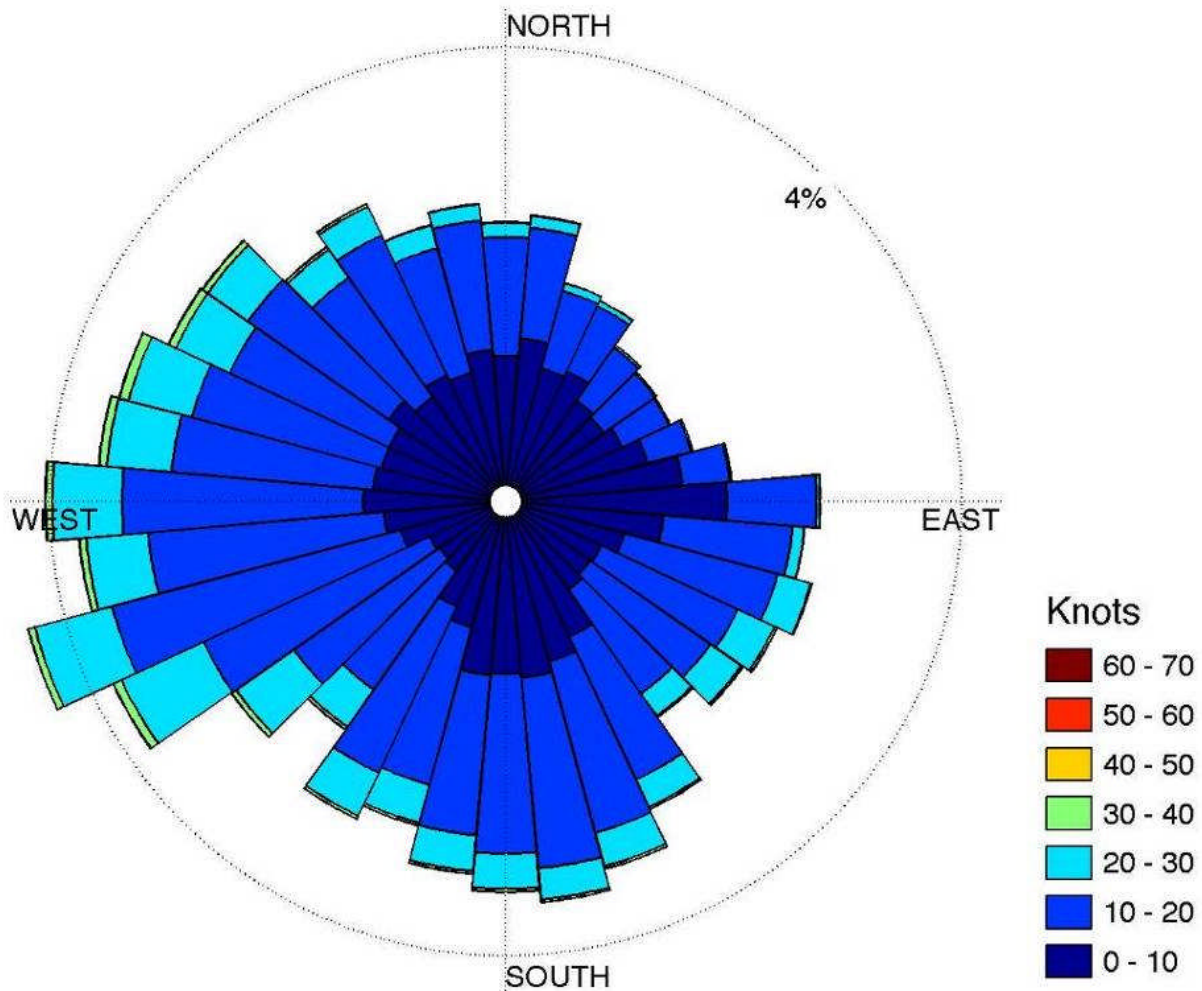


**Figure 5.1 Location of the sites for the historical coastal parameters consider.**

Directional frequency of winds recorded at St Mawgan show that wind direction is predominately westerly (Figure 5.2). Low energy winds (0-10kts) are dominated by southerlies and easterlies whereas higher energy winds (>10kts) are more frequently from the west. High speed easterly winds are rare. Changes in wind speed, wind direction and atmospheric pressure, particularly during storms, enhance the generation of positive surges and large waves (Phillips *et al.*, 2013). These changes can in turn increase coastal erosion risk, affect the shifting of shoreline positions and the general morphology of the coastal environment.

Large-scale atmospheric pressure patterns (e.g. North Atlantic Oscillation) have been linked to changes in wind speeds and directions (Hurrell, 1996; Phillips *et al.*, 2013). The major modes of climatic variability in the Northern Hemisphere are known to exert a strong control on the North Atlantic climate, especially from the central North America to Europe and Northern Area (Bell and Lisbeck, 2009; Phillips *et al.* 2013). The NAO is associated with an oscillation in atmospheric mass between the Arctic and subtropical North Atlantic (Burningham and French, 2012). The station-based NAO index (NAOi) is calculated as a normalised pressure difference between the north (e.g. Iceland) and the south (e.g. Azores), but can also be derived through Empirical Orthogonal Function (EOF) analysis of sea-level pressure anomalies over a wider mid-North Atlantic zone. Positive phases of the NAOi are associated with strengthening of the North Atlantic storm track, resulting in stronger than average wind speeds and increased storminess in mid-latitude, western Europe. Negative phases are linked to drier, calmer conditions in northwest Europe. Wintertime is when the atmosphere is noted to be most active dynamically and the

role of the NAO on storm and wind climate is most pronounced in winter (Hurrell and Deser, 1999; Burningham and French, 2012). The winter NAO index (wNAOi) is calculated as a mean of monthly indices across the winter period: December-March is used here (Figure 5.3) although a range of winter month combinations are more widely used (Burningham and French, 2012).

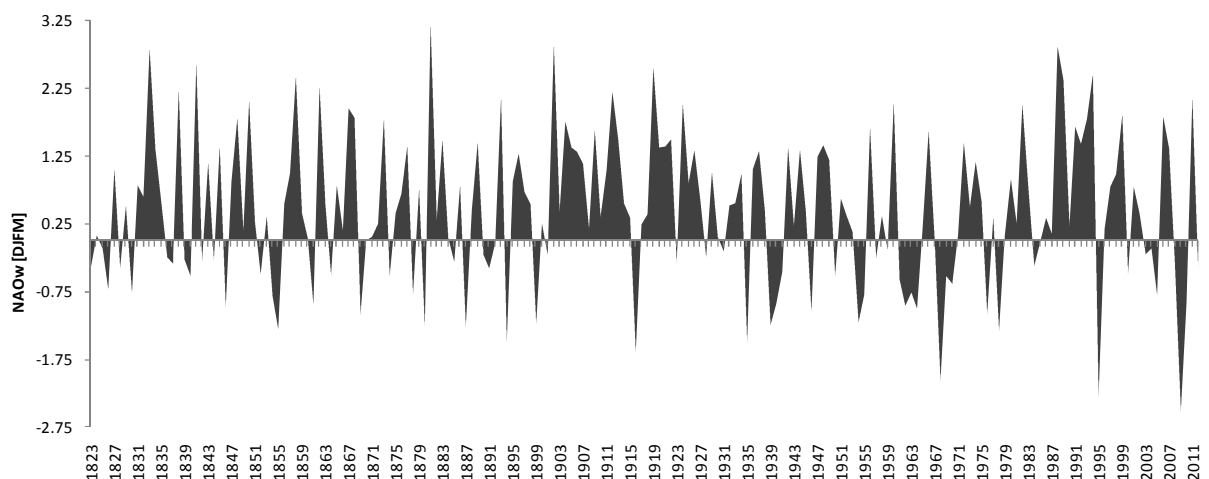


**Figure 5.2** Wind rose (the directional frequency distribution of wind direction) for wind speed and direction for St Mawgan.

The wNAOi is associated with multiple aspects of climate (wind, air temperature, precipitation), which are integrated over space and time (Straile and Stenseth, 2007). The linkages of NAO and some specific climate parameters have been used to predict ecological variability (see Hallet *et al.*, 2004), determination of regional precipitation and dynamic river flow (Trigo *et al.*, 2004; Mares, *et al.*, 2009); wind speed and ocean wave height (Bouws *et al.*, 1996), and more specifically in coastal studies as a proxy for storminess in wave heights (e.g. Esteves *et al.*, 2011), wave directions (Bruneau *et al.*, 2011), wind and wave storms (Qian and Saunders, 2003; Atkinson, 2005; Wolf and Woolf, 2006). The full review of the linkages are provided by Vincente-Serrano and Trigo (2011) and Burningham and French (2012). Of importance in coastal studies is the linkages of the

wNAOi with timing and magnitude of extreme wind events and their role in driving sediment erosion and deposition (e.g. Barthology *et al.*, 2004; Dawson *et al.*, 2004; Burningham, 2005; Clarke and Rendell, 2006; Burningham and French, 2012) and in effecting significant geomorphic change (Davis *et al.*, 2004; Knight and Burningham, 2011; Jiménez *et al.*, 2012).

Persistent positive phases in the wNAOi occurred in the late 1880s and early 1900s, and also from the late-1970s to mid-1990s (Figure 5.3). Extended periods of negative wNAOi are uncommon and relatively short in comparison to the positive phases. The winter months of 1915, 1939, 1955, 1967-1968, and 1975-1976 experienced extreme minima in wNAOi ( $< -1$ ). Most recently, the winters of 1995 and 2009 experienced the most extreme lows. The pattern of change in the wNAOi does not adhere to an overall trend, but rather a cycle of shifts between positive and negative phases. There is some evidence for an increase in the range of variability in more recent years. The implications of positive phases in the NAO for the historical period explored here are increased storminess in the 1980s - early 1990s and followed by a less persistent and more variable climate in recent years.



**Figure 5.3 Time series of winter (DJFM) NAO index.**

The wind direction frequency has been shown to be strongly associated with NAO winter index (Burningham and French, 2012), and this is evidenced in the St Mawgan dataset, which shows a strong positive correlation between the frequency of westerly winds and the wNAOi (Table 5.1). Furthermore, strong positive correlations exist between the strength of westerly winds and the wNAOi. Figures 5.4 and 5.5 present the time series of change in wind direction frequency, median wind speeds associated with these directions, and 99th percentile wind speeds. As highlighted in Table 5.1, there are strong positive correlations between the wNAOi and the frequency of westerly winds ( $R=0.71$ ), and strong negative relationships are observed with the easterlies ( $R=-0.68$ ). Rotation of the direction quadrants by  $45^\circ$  reveals that the significant correlations are associated with northeasterlies ( $-0.68$ )

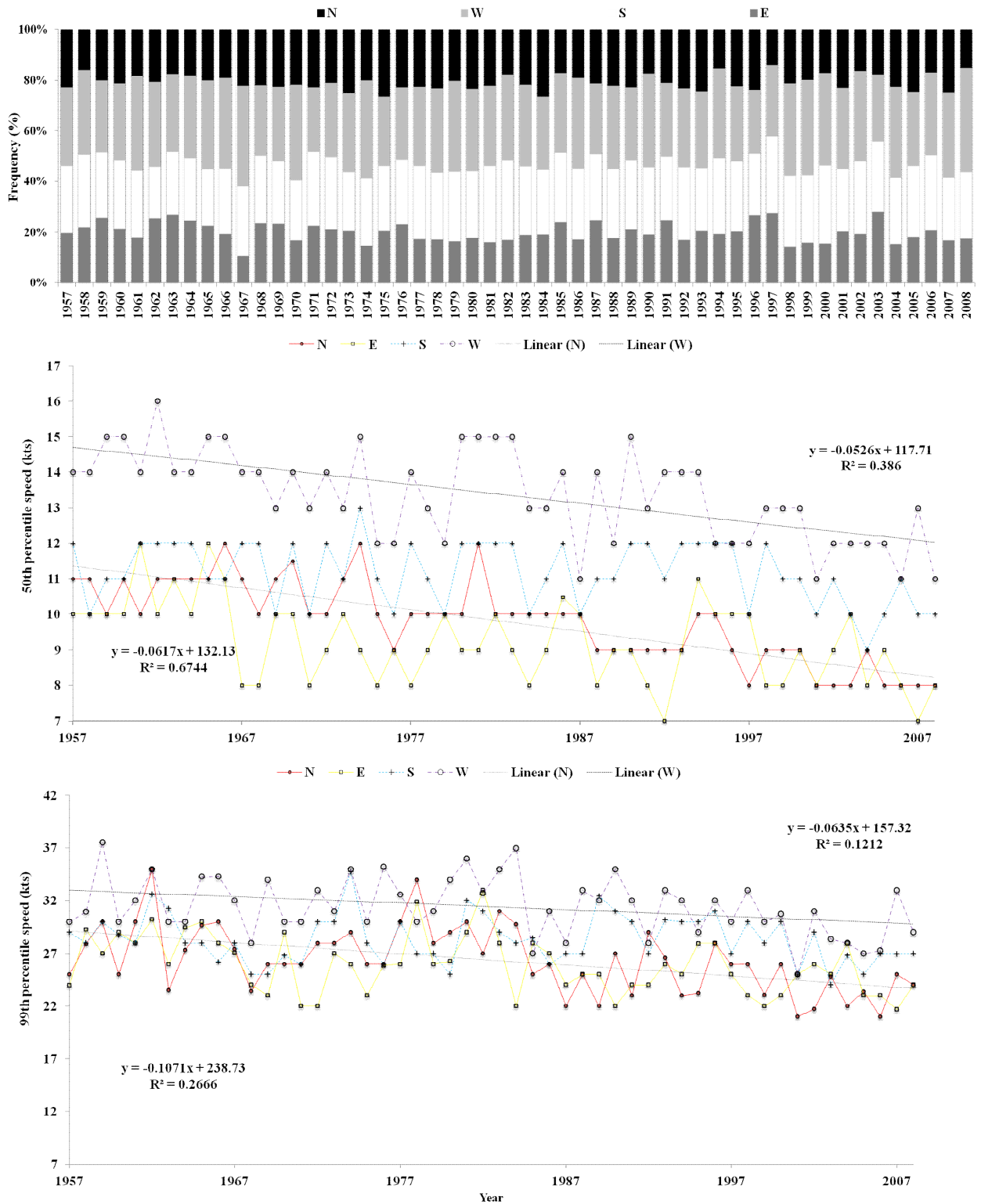
and southwesterlies ( $R=0.76$ ). There was no significant linear relationship between the wNAOi and median or extreme (99th percentile) wind speeds within each of these wind direction quadrants.

**Table 5.1 Correlations for NAO with wind directions for St Mawgan (1957-2008): strong correlations ( $|R|>0.5$  and significant at  $p<0.01$ ) are highlighted in bold/red.**

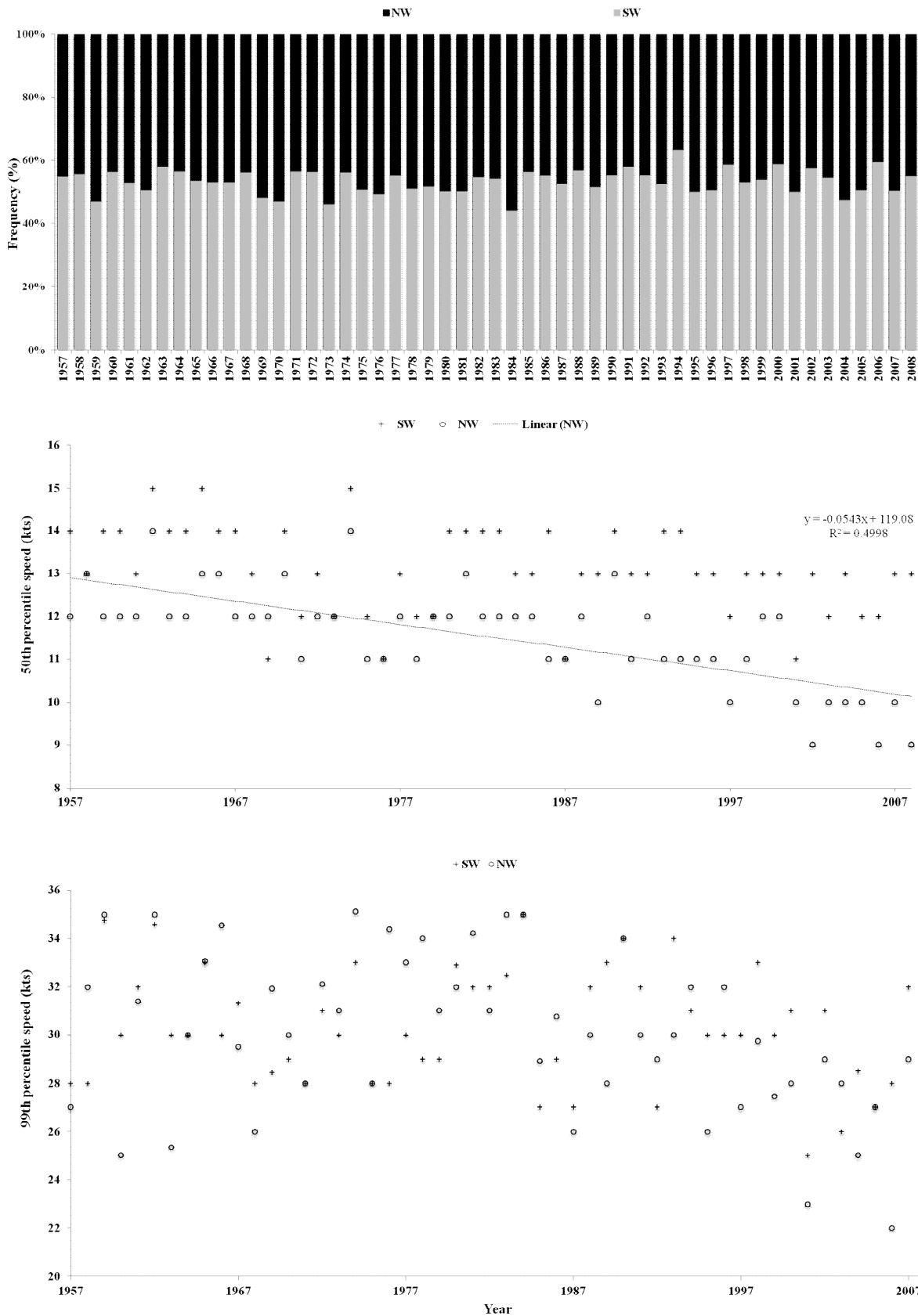
Year (1957-2008)	Wind metric	correlation (R)
Frequency	N (315-45)	-0.36
	E (45-135)	<b>-0.68</b>
	S (135-225)	0.38
	W (225-315)	<b>0.71</b>
50th percentile windspeed (kts)	N	-0.14
	E	-0.43
	S	0.13
	W	0.20
99th percentile windspeed (kts)	N	-0.05
	E	-0.36
	S	0.01
	W	0.04
Frequency	NE (0-90)	<b>-0.68</b>
	SE (90-180)	-0.45
	SW (180-270)	<b>0.76</b>
	NW (270-360)	0.33
50th percentile windspeed (kts)	NE	<b>-0.66</b>
	SE	-0.28
	SW	0.30
	NW	0.23
99th percentile windspeed (kts)	NE	-0.33
	SE	-0.10
	SW	0.20
	NW	0.01
50th percentile speed (kts)	All directions	0.22
99th percentile speed (kts)	All directions	0.18

Correlations between time and these wind measures, which could point to mesoscale (decadal) trends in wind climate, are summarised in Table 5.2. These show quite different patterns of correlations to the analysis with the wNAOi. Whereas it is the proportion of wind recorded from the southwest-west and northeast-east that are strongly associated with the temporally-variable patterns in North Atlantic pressure systems, median wind speeds that show significant temporal trends over the last 50 years. The 50<sup>th</sup> percentile (median) wind speed (from NE direction) is significantly negatively correlated with time ( $R=-0.66$ ) exhibiting a broad decline in speed over the last 50 years. Indeed all correlations between wind speed measures and wNAOi are negative, suggesting that there has been a significant reduction in wind climate energy at St Mawgan over the last 50 years. The correlations with time of median wind speed from the north ( $R=-0.82$ ) and west ( $R=-0.62$ ) shows a significant decrease over the period considered here. This is reiterated when considering the rotated quadrants; median speeds for winds recorded from the northeast, northwest and southeast all show a significant decline over time. These temporal trends are to some degree mirrored in the extreme (99th percentile) wind speeds: but it is only wind recorded from the north that achieves a correlation coefficient of  $|R|>0.5$ . Although all correlation

coefficients associated with the 99th percentiles are negative, the results suggest a rather weaker decreasing trend in the extreme wind speeds. It is particularly notable that the strong positive phase of the wNAOi during the 1980s to mid-1990s is not at all reflected in the median and extreme wind speeds recorded at St Mawgan. The far stronger signal here is the long-term trend of decreasing wind speeds.



**Figure 5.4** Time series of wind climate based on records from St Mawgan, Southwest England, UK: showing 50<sup>th</sup> percentile and 99<sup>th</sup> percentile of wind speed, and direction frequency (collated to cardinal (N, E, S, W) quadrants). Temporal correlations are reported in Table 4.6.



**Figure 5.5 Time series of wind climate based on records from St Mawgan, Southwest England, UK; showing 50<sup>th</sup> percentile and 99<sup>th</sup> percentile of wind speed, and direction frequency (considering only the SW, NW quadrants\*). Temporal correlations are reported in Table 4.6.**

*\*The winter NAOi at NE and SE are found to be insignificant, therefore the presentation of the historical analysis in N,E,S,W, NW and SW (See chapter 2.6.1 for more explanation).*

**Table 5.2 Correlations (temporal) for the wind measures for St Mawgan (1957-2008): strong correlations ( $|R|>0.5$  and significant at  $p<0.01$ ) are highlighted in bold/red.**

Year (1957-2008)	Wind metric	Correlation (R)
Frequency	N (315-45)	-0.07
	E (45-135)	-0.18
	S (135-225)	0.29
	W (225-315)	0.07
50th percentile windspeed (kts)	N	<b>-0.82</b>
	E	-0.47
	S	-0.31
	W	<b>-0.62</b>
99th percentile windspeed (kts)	N	<b>-0.52</b>
	E	-0.40
	S	-0.15
	W	-0.35
Frequency	NE (0-90)	-0.18
	SE (90-180)	-0.06
	SW (180-270)	0.20
	NW (270-360)	0.03
50th percentile windspeed (kts)	NE	<b>-0.69</b>
	SE	<b>-0.63</b>
	SW	-0.34
	NW	<b>-0.71</b>
99th percentile windspeed (kts)	NE	-0.48
	SE	-0.40
	SW	-0.16
	NW	-0.39
50th percentile speed (kts)	All directions	<b>-0.66</b>
99th percentile speed (kts)	All directions	-0.36

The findings/analyses presented in this section confirm that for southwest England, the NAO appears to be responsible for driving year to year changes in the frequency of westerlies and easterlies, but has had little impact on the strength of winds. It is not possible to say that the positive phases of the NAO in the late 1880s and early 1900s and also from around 1978 to 1991 were responsible for increased climatic activity and increased energy, but it is possible that these periods of increased frequency of westerlies might have driven an increase in wave energy, or possibly an increase in west-southwest to east-northeast wind blown sediment transport across beaches in the region. Several studies have linked positive wNAOi in driving coastal geophysical processes through the occurrence of higher than average wind speeds, increased storminess and storm frequency (e.g. Rogers, 1997; Dickson, *et al.*, 2000; Clarke and Rendell, 2009). The dominant positive wNAOi phases at the first half of 20<sup>th</sup> century (also noted by Pye and Neal, 1994) and the frequent stronger southwest wind speed and direction may be accountable for possible storm and stronger climatic parameters which enforced morphological changes of shoreline positions at the study sites. Southwest England is seemingly experiencing a more complex forcing of changing wind climate which can be partly linked to the NAO (in terms of frequency of westerlies) but also comprises a more persistent trend of decreasing energy.

In the northwest Ireland, during the 19<sup>th</sup> and early 20<sup>th</sup> Century, Burningham (2005) showed that the timing of storms impacting the region clustered around the periods of

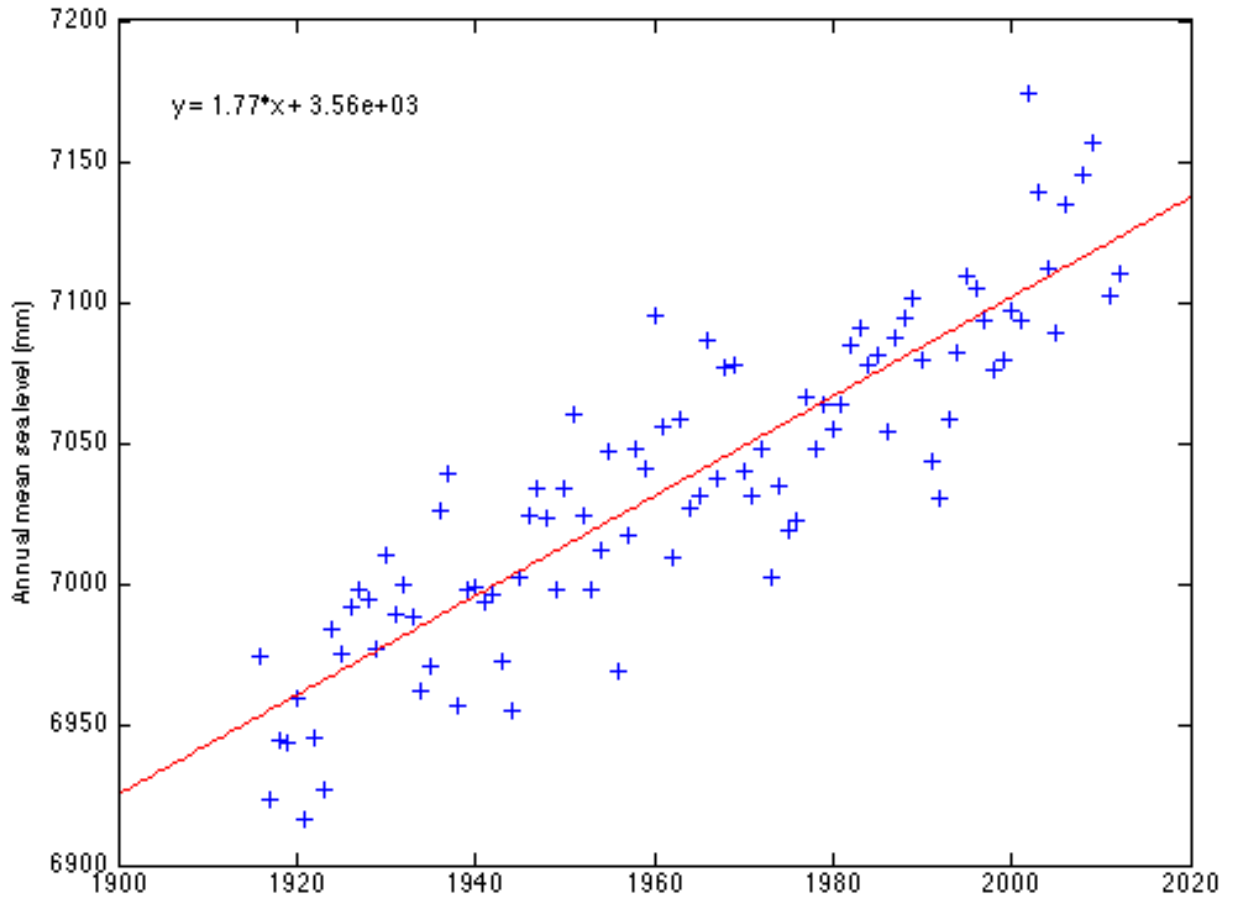


sustained positive NAO winter index. The coastal and maritime climate of the southwest UK has been noted to be largely shaped by the eastward sweep of depressions from the Atlantic coast (Allen and Duffy, 1998; Phillips *et al.*, 2013), and the analyses here show the predominance of west-southwesterlies in the wind climate of this region. The persistent phases of positive NAO do correlate with increased frequency of these west-southwesterlies, and this might drive specific morphological changes associated with direction of forcing, for example shoreline movements. But the 1980s-1990s appear to be one of the least dynamic periods of the history considered in the shoreline change analysis. It is also possible that sustained winds from a specific direction could force estuarine waters to be retained in the valley longer, or conversely the flood tide could be held back by such winds, which would influence tidal transport of sediments within the ebb channel and morphology of the estuary. This is a possibility with the consideration of the orientation of the coastlines of the study sites and the estuaries. Although the land based wind measurements do not reflect coastal oceanic winds (Schwing and Blanton, 1984), winds still remain a critical factor in determining regional weather patterns (Phillips *et al.*, 2013) and changes in dominant patterns do affect shoreline equilibrium and dynamics (Cazenave and Llovel, 2010, Phillips *et al.*, 2013). It cannot be categorically stated that the historical wind measures and the Northern Hemisphere atmospheric pressure as indicated by the North Atlantic Oscillations observed in the century could have enhanced the generation of surge levels which engineered the morphological changes and morphodynamics at the coastlines, the evidence in other studies cited here, however, suggest this is a possibility. Perhaps more important is the role of decreasing wind speeds in coastal dynamics. This would imply a reduction in morphodynamic activity, but there is little evidence of this in the historical morphological change analysis that has shown a broad erosional trend superimposed by decade-scale fluctuations.

### 5.1.2 Sea-level change

Wave and tidal processes are important in the consideration of coastal dynamics, but extended temporal datasets for these parameters are rarely available. The impact or role of these processes on mesoscale coastal dynamics is often controlled by the underlying trends in changing sea-level which influence the vertical position that these processes operate at. Sea-level change is an important aspect of coastal forcing that must be considered when evaluating the behaviour and trends in historical coastal change. Monitoring or understanding sea-level change is important for both socio-economic/environmental reasons (Wöppelmann *et al.*, 2007; Phillips *et al.*, 2013) and the evaluation of its impact on highly vulnerable estuarine and low lying coastal zones (Barbosa and Silva, 2009). Figure 5.6 presents the historical change in mean annual sea-level for Newlyn. There has been a normal increase in Celtic sea-level from 1920, but this has shown some acceleration since the 1960s (Phillips *et al.*, 2013). The published rate of

sea-level rise for southwest England was quoted as c. 5 mm yr<sup>-1</sup> in a 2004 report (Defra/EA, 2004) but is currently recognised as 1.77 mm yr<sup>-1</sup> (PSMSL, 2013).



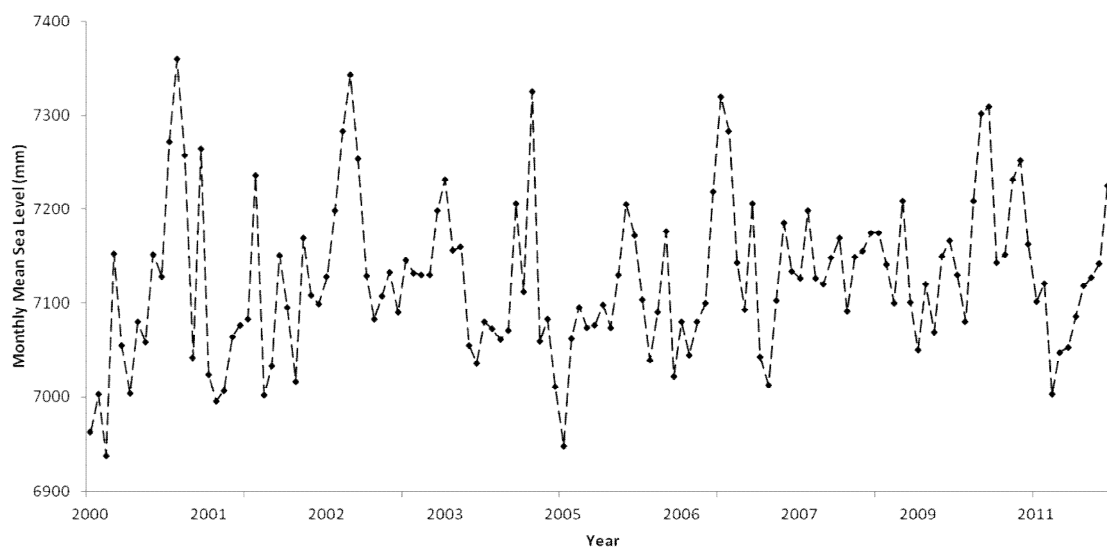
**Figure 5.6 Annual mean sea-level at Newlyn, exhibiting a rise over the 20th century at a rate of c. 1.77 mmyr<sup>-1</sup> ( $R^2 = 0.88$ ,  $p < 0.001$ ).**

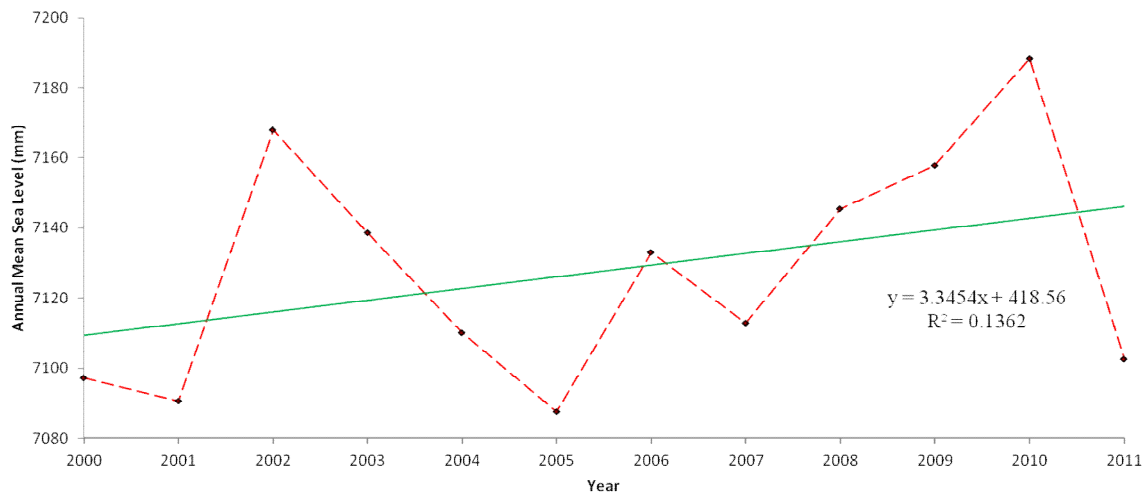
The overall erosion and landward shift in the MLW shoreline positions may be attributed to the rise in sea-level that this region has experienced. Woodworth (2010) described annual mean sea-level as “*the combination of tidal level, surge level, mean sea level, waves and their respective interactions*”. This parameter remains a very important phenomenon as a rise in sea-level increases the elevation at which these coastal processes (tides, surges, waves) operate, and often makes the coastal zone vulnerable to morphologic changes. Furthermore, an increase in sea-level increases the likelihood of inundation in susceptible, low-lying areas and also enables storm surges and waves to penetrate further inland (Gönnert, 2004; Kleinosky *et al.* 2007; Phillips *et al.*, 2013). This is a possible, less specific, threat to the coastal systems considered here, where the ria valleys have little space for low-lying land. But it is certainly likely that sea-level rise has been a key driver of the underlying coastal erosion experienced regionally on the north Cornwall coast as the rise correlates with observed MLW shoreline erosion in the region in the 20<sup>th</sup> century.

## 5.2 Contemporary coastal climate

### 5.2.1 Sea level

It is widely believed that sea-level has risen significantly since the mid-20<sup>th</sup> century, with global rates in mean sea level rise estimated to be  $3.1 \text{ mm yr}^{-1}$  (Cabanés *et al.*, 2001; Holgate and Woodworth, 2004; Leuliette *et al.*, 2004; Church and White, 2006; Woodworth *et al.*, 2009; Teasdale *et al.*, 2011). On a regional scale, the character of sea-level is much more variable (Teasdale *et al.*, 2011) as a result of a more local factors such as tectonic and glacio-isostatic movements (Firth and Stewart, 2000; Teasdale *et al.*, 2011). As discussed earlier, there has been a consistent rise in sea-level in the Celtic Sea since the 1920s. The trend of the rise continues in the 21<sup>st</sup> century, with some fluctuations, at a rate of *c.*  $3.35 \text{ mmyr}^{-1}$  (Figure 5.7). The dataset is too short to place any meaning in this trend, but it does seem clear that annual mean sea-level rise subsided between 2002 and 2005 before increasing again to 2010. The recommended rate for the region remains *c.*  $1.77 \text{ mmyr}^{-1}$  (PSMSL, 2013). With the recent observation and the expected rate, such kind of increase is expected to inevitably affect wave climate, tidal processes and the morphodynamic evolution of the north Cornwall coastlines.





**Figure 5.7** Newlyn monthly mean sea level (top); and annual mean sea level (bottom) with short-term linear trend.

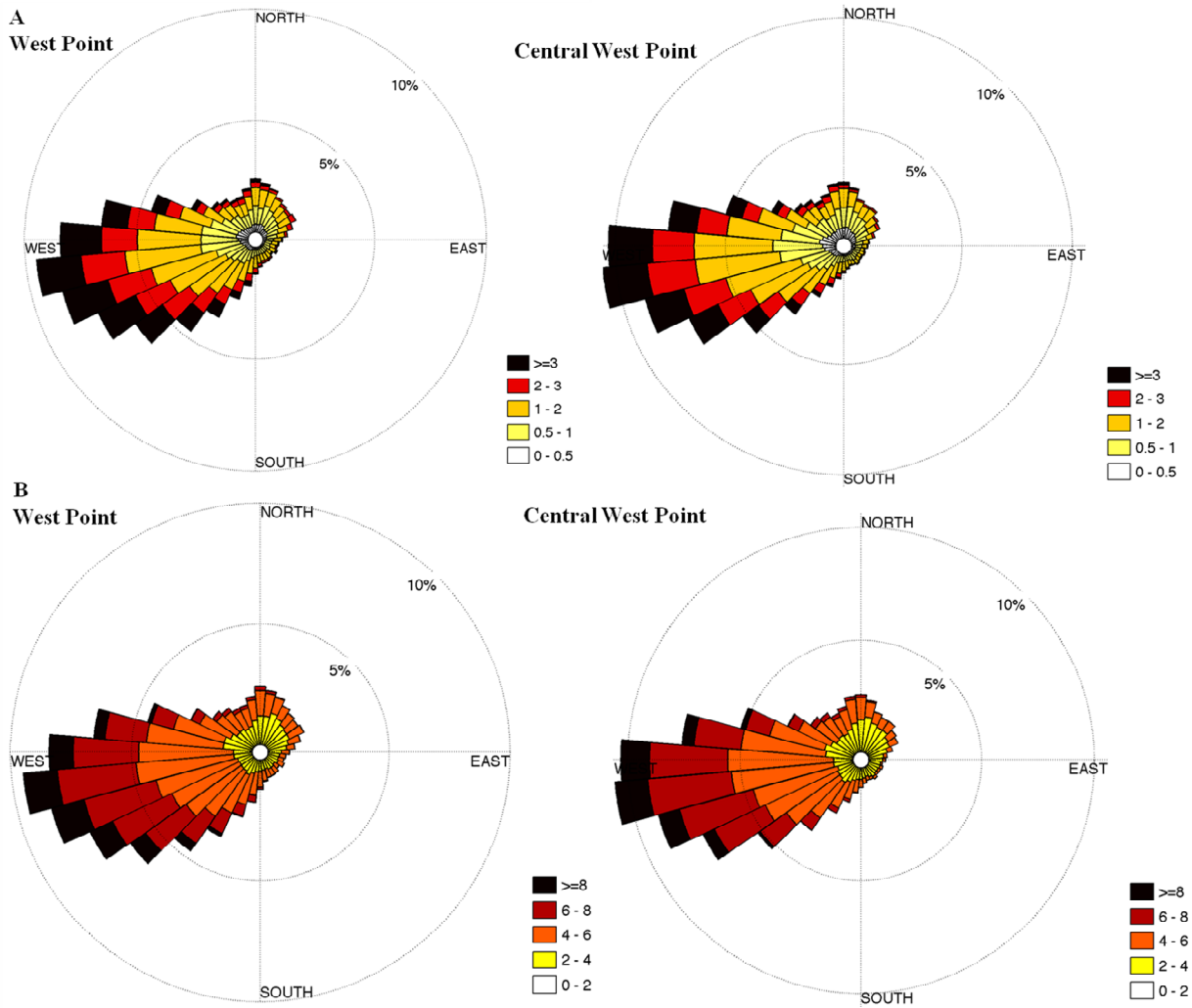
### 5.2.2 Contemporary wave conditions

Waves form when the water surface is disturbed either by wind, earthquakes or planetary gravitational forces (Carter, 1988). ABPmer supplied the 20 year (1999 – 2009) hindcast hourly wave parameters for sites in the southwest Celtic Sea (north of the Cornwall coast). Specifically, West Point (Long. -5.67, Lat. 50.65) and Central West Point (Long. -5.33, Lat. 50.55) data, which are directly associated with the study area, are analysed and presented here. Figure 5.8 presents wave roses for the 1991-2009 data, showing frequency distribution of wave direction, significant wave height and wave period. The largest proportion of waves typically occurs from the westerly with 56.2% and 60.9% at West and Central West points respectively. Waves from the north are far more infrequent, with 17.6% and 19.2% for West and Central West points respectively, and given the reduced fetch, waves from the southeast are very rare.

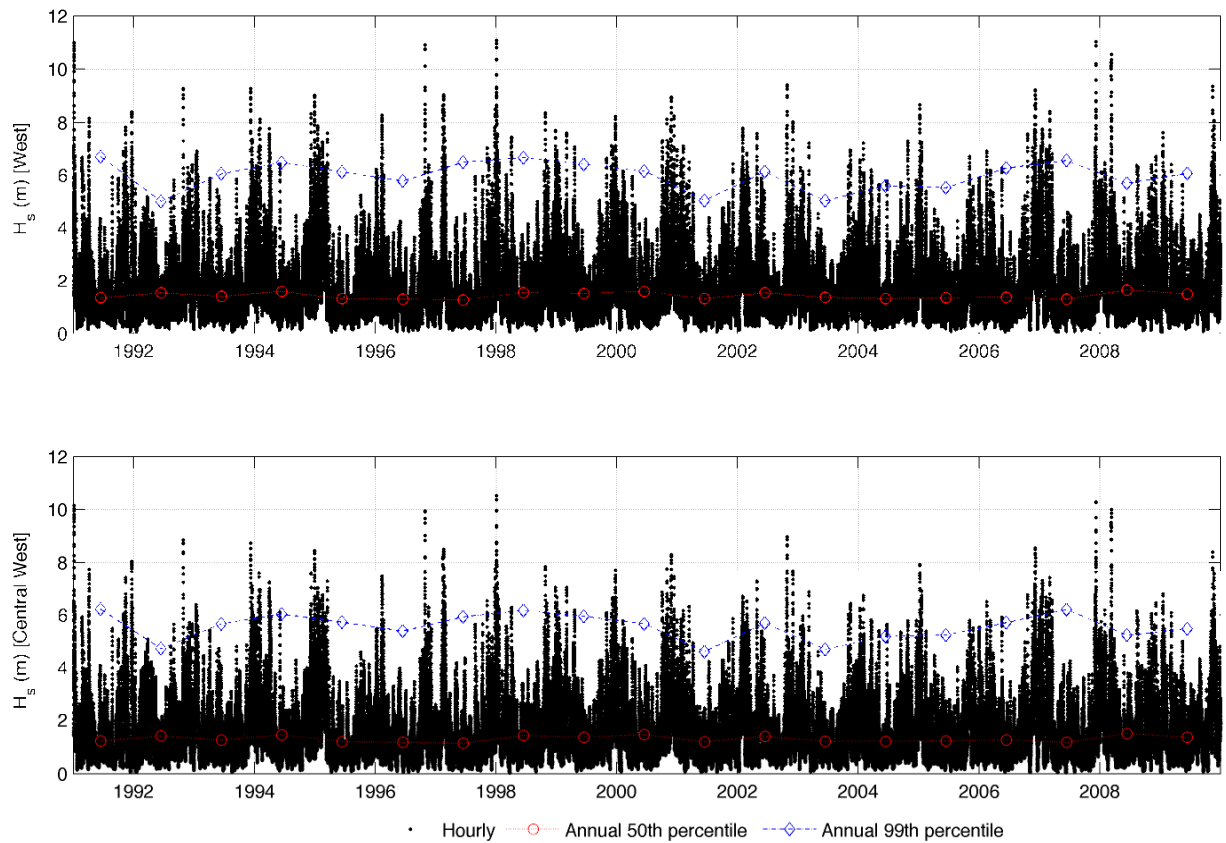
Considering the time-series of change over this period (Figure 5.9), a seasonal signature is evident, whereby summer wave heights are substantially lower than winter wave heights. Lower annual measures (median and 99th percentile wave heights) stand out for the years 1992, 2001 and 2003, and the winters of 1996-7, 1997-8 and 2007-8 show some evidence of higher than normal wave heights. There is no suggestion in these data that wave heights are increasing or decreasing over the 20 year period.

The coastal systems considered in this study all occupy a northwesterly aspect. The offshore wave climate is dominated by westerlies, but in some cases, it might be the more northerly waves that are more aligned to the bays. Basic metrics of the wave climate split on the basis of direction (westerly vs. northerly) are summarised in Table 5.3. The findings show that northerly waves are smaller (in terms of height and period) than westerly waves, but have a slightly wider spread indicating that westerlies are more likely swell-dominated and northerlies comprise an increased wind-wave component. Also, waves reduce in size as they move in from the west: waves at West point are larger than those at Central West

point. Local wave climates will depend quite strongly on location and orientation, and this is explored further in Chapter 7.



**Figure 5.8** Wave roses for 1991-2009 data, showing A) frequency distribution of wave direction and significant wave height and B) frequency distribution of wave direction and wave period.



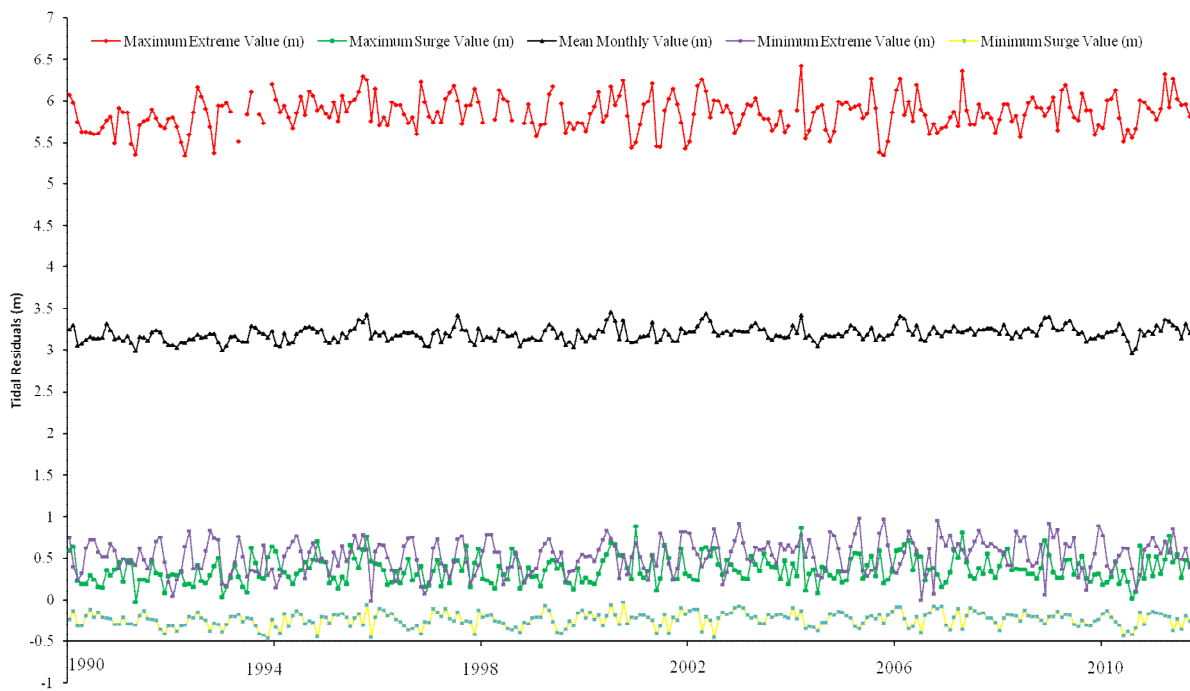
**Figure 5.9** Time series of significant wave height (1991-2009) at the West and Central West points.

**Table 5.3** Wave climate summary (1991-2009) for westerly (225-315°N) and northerly (315-45°N) waves.

	Percentile	Westerly waves		Northerly waves	
		West point	Central West point	West point	Central West point
<b>Proportion (%)</b>		56.2	60.9	17.6	19.2
<b>Vector mean direction</b>	262.58				
<b>Significant wave height (m)</b>	50th	1.67	1.56	0.96	0.89
	90th	3.99	3.69	2.27	2.11
	99th	6.52	6.04	4.39	4.12
<b>Wave period (s)</b>	50th	5.62	5.53	3.90	3.77
	90th	8.12	7.84	5.58	5.43
	99th	10.05	9.77	7.41	7.22
<b>Wave spread (°)</b>	50th	31.00	29.73	34.91	33.73
	90th	41.18	39.57	52.82	50.90
	99th	63.17	60.95	72.22	70.70

### 5.2.3 Tidal conditions

One of the most important coastal factors which influences change on coastlines is the state of the tide. Increased wave energy has greater potential to cause notable hazard on the coastline at high tide. The spring tidal range for the region is around 5-6 m (UKHO, 2003) and the coast can be described as macro-tidal. Tidal currents in the region have been described as generally weak ( $< \sim 0.75\text{ms}^{-1}$ ) except in local areas around the headlands (Halcrow, 2002). Monthly tidal residuals for Newlyn are presented in Figure 5.10. This shows the extent to which abnormally high or low water levels occur. The lowest monthly water levels are around 0-0.5m, with minimum surges of -0.1 - -0.5m. The maximum monthly water levels range 5.5-6.5 m (highest astronomical tide level at Newlyn is 6.13m above chart datum) and monthly mean maximum surges are up to 1 m. The envelope of variability over the 12 year period is relatively consistent, where year to year fluctuations occur on similar scales. The highest monthly mean water level recorded was 6.42m in October 2004 and the lowest was -0.01 in February 1996, but these are not considerably outside the normal range.



**Figure 5.10** Tidal residuals recorded at Newlyn. Levels are relative to Admiralty chart datum.

## 6 SEDIMENTOLOGY AND SEDIMENT PROCESSES

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The study of sediments and sedimentary deposits has been described to be “primarily concerned with the physical classification of sediments, the interpretation of sediment source and provenance, sediment transport processes and the composition and form of depositional features and sedimentary structures” (Friedman and Sanders, 1978). One of the objectives of this study is to examine the sedimentary linkages between the coast and the estuary at the selected study sites. The aim here is to investigate the similarities and differences in sediment texture and geochemistry to understand how closely related the coast and estuary sediment populations are, and gain a better understanding of the controls on sediment supply and transport within and between coast and estuary. The knowledge of temporal and spatial distribution of sedimentation processes of deposition, transport and erosion was noted to be fundamental on a variety of issues in estuaries and transitional basins (Apitz *et al.*, 2007; Molinaroli *et al.*, 2009).

The erosion, transportation, entrainment or deposition of sediment particles by any medium/fluid is partly controlled by the chemical and physical properties of the particles themselves and also that of the driving mechanisms (Blott, 2001). Sediment characteristics may be changed during the transport processes and be sorted according to size, shape, mineralogy and density (Pye, 1994). Grain size is one of the most important of the physical properties of sediments, and can reveal important information about the sediment source, transport history and depositional situation (Folk and Ward, 1957; Friedman, 1979, Bui *et al.*, 1990; Boggs, 2001). The influence of heterogeneous sediment properties on coastal processes was shown by Holland and Elmore (2008) to be commonly underestimated due to difficulties in characterising and quantifying the various types of sediments. The application of extended and multivariate statistical analyses of grain size distributions can be effective at identifying discrete similarities and differences between mixed sediment populations (Lucio *et al.*, 2004; Mante *et al.*, 2007), and this broader consideration of grain size data is followed here. Furthermore, the use of XRF technology (an analytical technique which exposes solid samples to an x-ray source (Billets, 2006)) to ascertain sediment geochemistry through elemental composition is therefore also considered here in the characterisation of sediment composition. Here, laser-sizing analysis of sediment texture is supported by X-ray fluorescence (XRF) analysis of selected samples to estimate the elemental composition and spatial variations of the sediment source and connectivity (between estuary and coast) in the study sites.

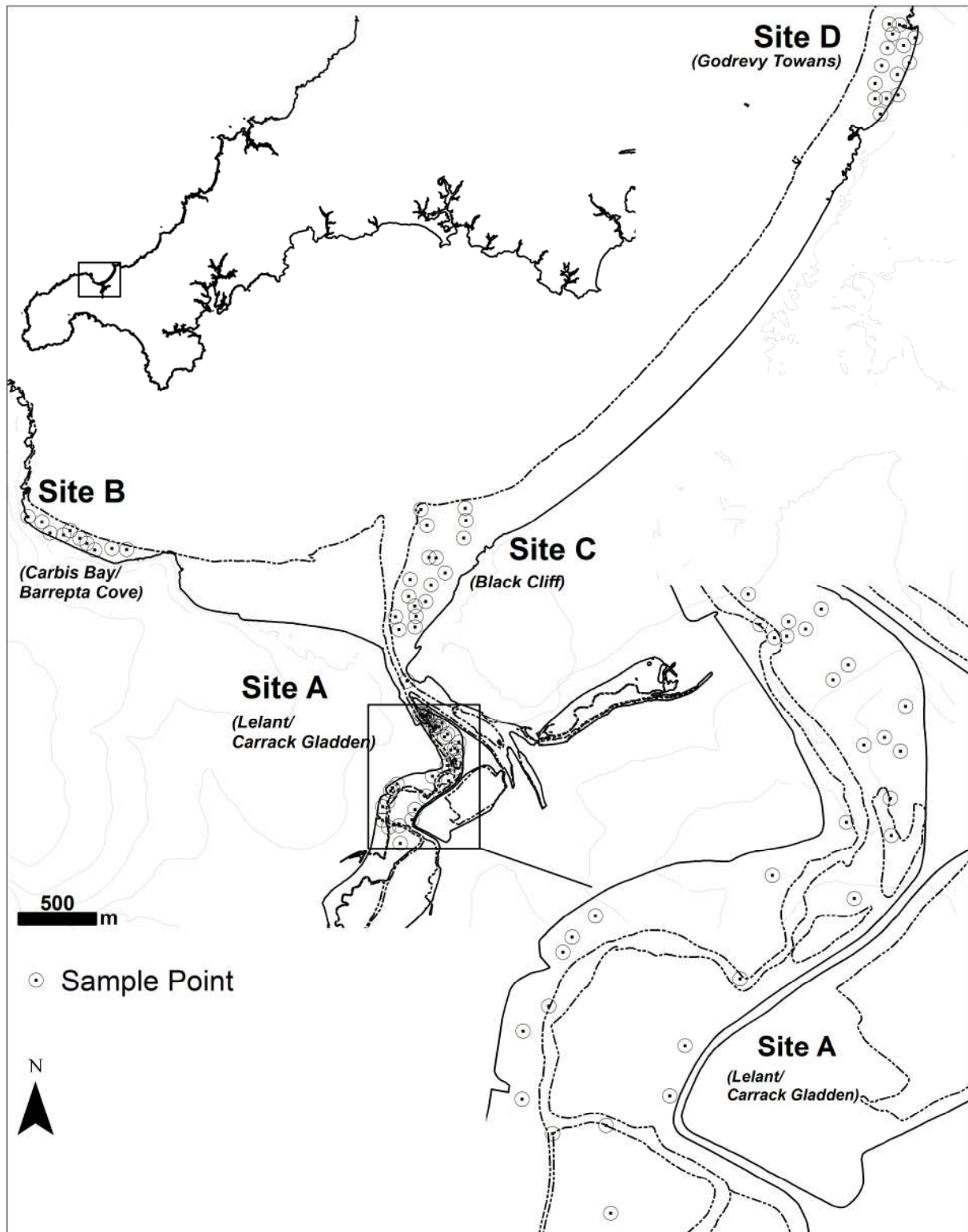


## **6.1 Sedimentology**

The nature of estuary sediments reflects the transport processes operating at local and regional scales as well as the longer-term evolution of estuary morphology (Anthony and Héquette, 2007). Grain-size remains the most important property to inform our understanding of these linkages as it provides fundamental information on sediment transport dynamics and the history and provenance of sediment supply (Blott and Pye, 2001). Grain size statistics calculate from the distribution - median, sorting and skewness - are most commonly used to explore the nature of the sediments investigated, and the broad similarities and differences between sample populations. The following section explores the variability in sediment characteristics within each system with a view to elucidating the nature of the sedimentary linkages that occur between the estuary and adjacent open coast.

### **6.1.1 St Ives Bay and the Hayle estuary**

A total of 80 short cores were collected in October 2011, from four different zones within the Hayle estuary and St Ives Bay intertidal sedimentary environment (Figure 6.1). Site A, in the inner estuary (Lelant Water/Carrack Gladden; Figure 6.2) is a broad intertidal flat, the surface of which is characterised by two forms of bedforms: sandy megaripples (c. 10-20m wavelength ( $\lambda$ )) and irregular small scale (c. 1-2m) hollows (scour features) in muddier unconsolidated sediments. The sandy upper planar foreshore of St Ives Bay beaches (sites B and D; Figure 6.2) merge with a broader and flatter beach at the inlet of the Hayle estuary (site C) where megaripples (c.10-20m wavelength) and transverse wave-current ripples (c.10-25cm wave length) persist.



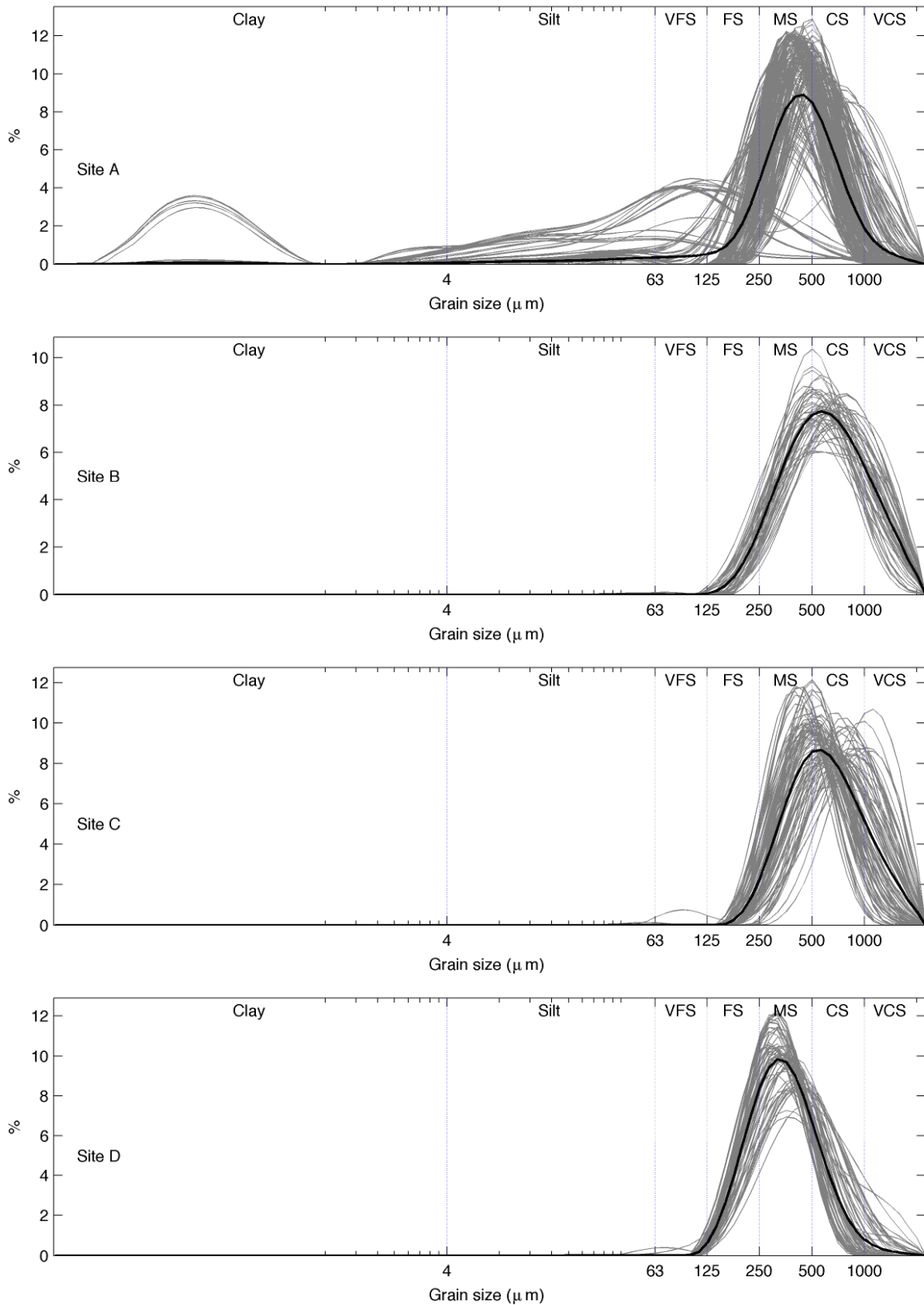
**Figure 6.1** The St Ives Bay - Hayle Estuary sites sampled for sediment analysis, Inset: the location of the site in southwest England.

*{Note: the establishment of larger parts of the system as SSSI constrained the spatial distribution of sediment sampling}*



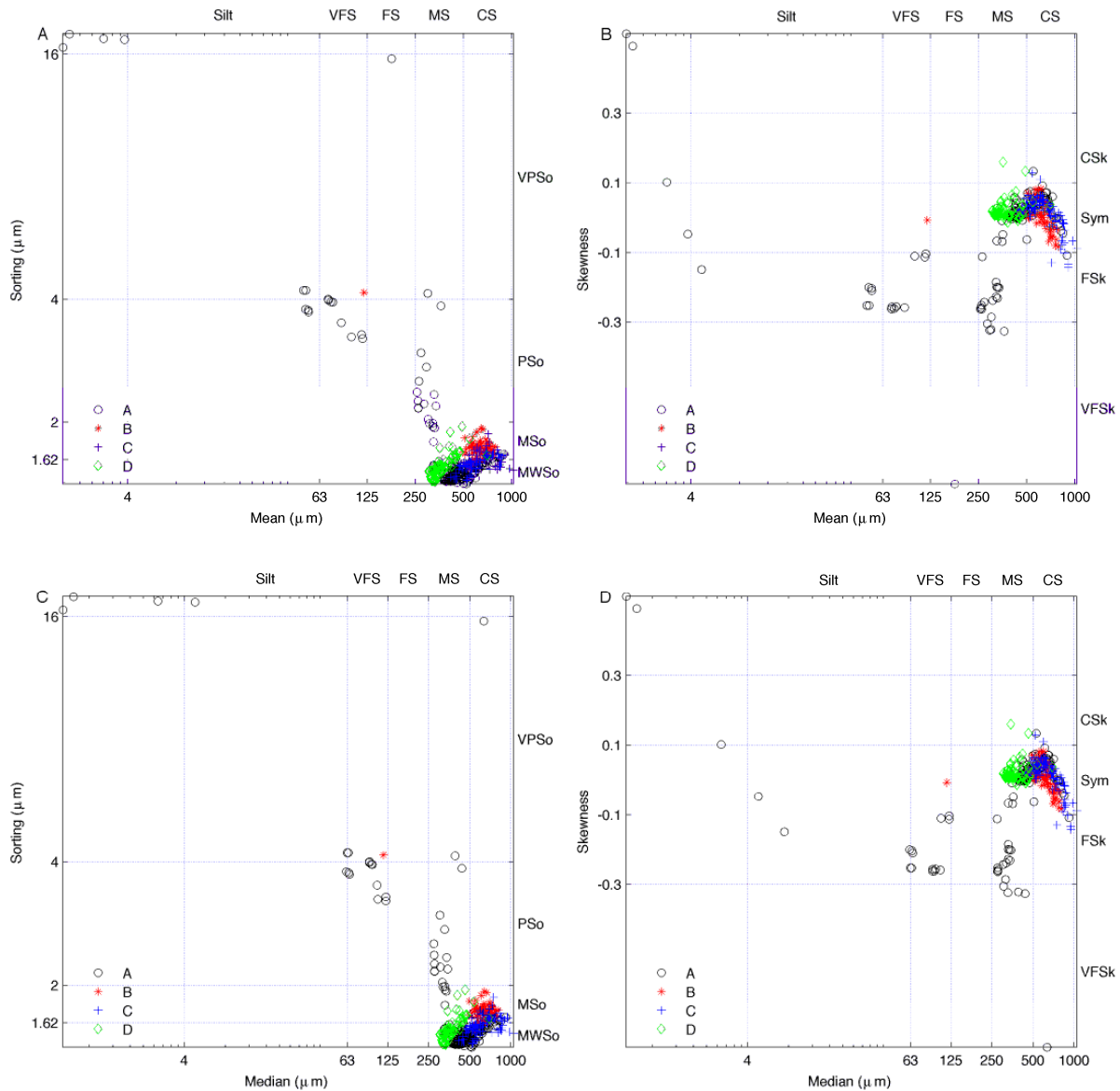
**Figure 6.2 St Ives-Hayle photographs showing surface conditions in the four main sedimentary environments surveyed. Sites are A – Lelant/Carrack Gladden, B – Carbis Bay/Barrepta Cove, C – Black Cliff and D – Godrevy Towans (see Figure 6.1 for location).**

Grain size distributions of sediment sampled from sites A to D are summarised and presented in figures 6.3. Sediment at sites A and D are dominated by particles in the medium sand range (250-500  $\mu\text{m}$ ) while sites B and C comprise, in comparison, a mixture of medium sand and coarser distribution (500-1000  $\mu\text{m}$ ). The grain size distribution here illustrates the clear consistency of sediment sampled in sites B with the modal size lying within the coarser sand (CS) region of the size spectrum (around 600  $\mu\text{m}$ ). The mean distribution at site C is very similar to that at site B, but site C lacks consistency between samples which range between medium coarse and very coarse sand. Site D comprises mostly medium sand (MS) population, again with a broad consistency between samples. Site A in the inner estuary is distinct in the significance presence of finer material, either as a distinct clay population, a silty population or a silty tail to a dominant sandy population. Clay and silt are not present in the surface samples obtained at sites B-D. The beach samples (sites B-D) are a mixture of coarse/very coarse sand. The presence of the fine-medium sand population in all of the sites however suggests that sediment exchange is active between sites, possibly moving for one site to the other.



**Figure 6.3** Surface sediment characteristics in the St Ives Bay - Hayle estuary system. Grain size distributions are shown for all samples obtained within the depth range 0-15cm at locations in the 4 main sedimentary environments examined: sediment at each site is also summarised as a mean distribution (solid black line). Sites are A – Lelant/Carrack Gladden, B – Carbis Bay/Barrepta Cove, C – Black Cliff and D – Godrevy Towans.

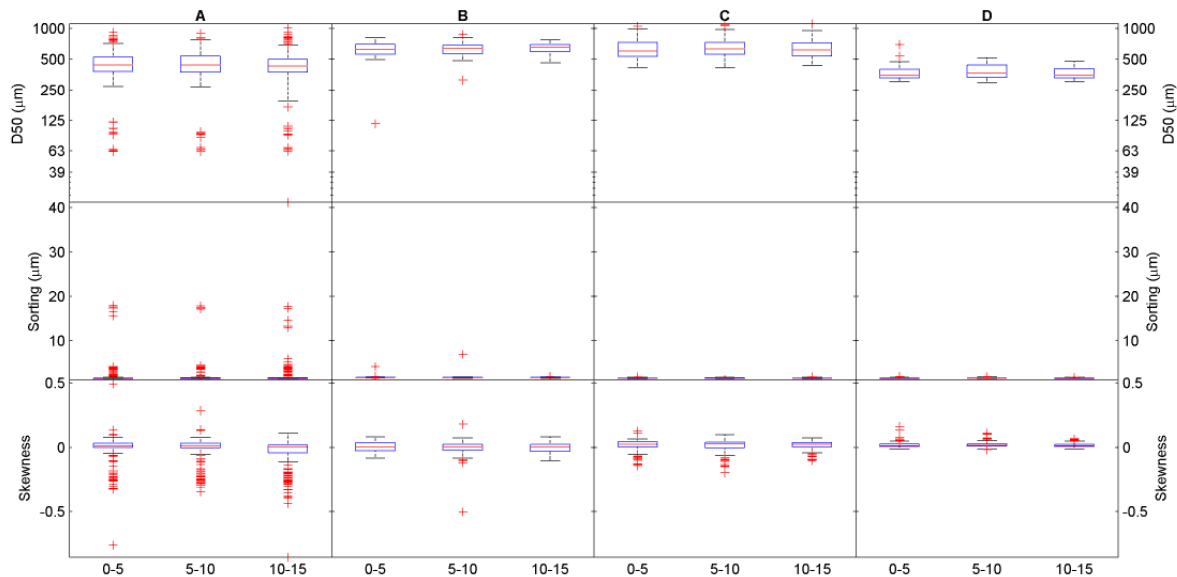
Descriptive sediment statistics (Figure 6.4) show that surface sediments of the open coast and inlet (Carbis Bay, Black Cliff and Godrevy Towans, Sites B, C and D) are generally moderately well (MWS<sub>0</sub>) / moderately sorted (MS<sub>0</sub>) and largely symmetrical. These sites do show some discrete differences. Site B is moderately sorted whilst C and D are moderately well sorted. Sites B and D are generally coarser than site C which is primarily medium sand (MS). The inner estuary samples (Lelant/Carrack Gladden, Site A) are a mix of silts, very fine (VFS), and medium sands (MS) that are poorly (PS<sub>0</sub>) / very poorly sorted (VPS<sub>0</sub>), and are largely negatively (fine) skewed (FSk).



**Figure 6.4 Exploratory sediment analysis – grain-size statistics – (A) Mean vs. Sorting (B) Mean vs. Skewness (C) Median vs. Sorting and (D) Median vs. Skewness. See Table 2.10 for the Folk and Ward classification boundaries of these metrics.**

Figure 6.5 presents a summary of grain size statistics obtained from the sites. Comparison of grain size statistics grouped by site (sedimentary environment) and sample depth (0-5cm, 5-10cm and 10-15cm from the intertidal sediment surface) reveals little systematic variation in Temitope Oyedotun

grain size parameters with depth. However, differences between sub-environments are evident, with the estuarine samples (Site A) being finer, less well sorted, and more strongly negatively skewed. Kruskal Wallis analysis of variance shows that differences between sites are significant (at the 99% level) for the median ( $\mu\text{m}$ ), sorting ( $\mu\text{m}$ ) and skewness statistics (Table 6.3). This is primarily driven by the properties of sediments from site A which is significantly different from all other sites for all metrics except skewness (for site B) and sorting (for site D). There is no significant difference between the median grain sizes at sites B and C, and no significant difference between skewness at sites C and D. Perhaps more interesting is the lack of significant difference in grain size statistics between sample depth (at the 99% level). The results show the consistency in sediment characteristics with depth suggesting that the depositional environments are well mixed to at least 15cm depth. The analysis shows that variability in sediment size characteristics within the St Ives Bay - Hayle intertidal system is the product of sedimentary environment, not sample depth.



**Figure 6.5** Summary of sediment statistics for sedimentary environments at the Hayle Estuary. Data are divided based on Site (A - D, located in Figure 6.1) and depth (using 0-5cm, 5-10cm and 10-15cm stratigraphic units).

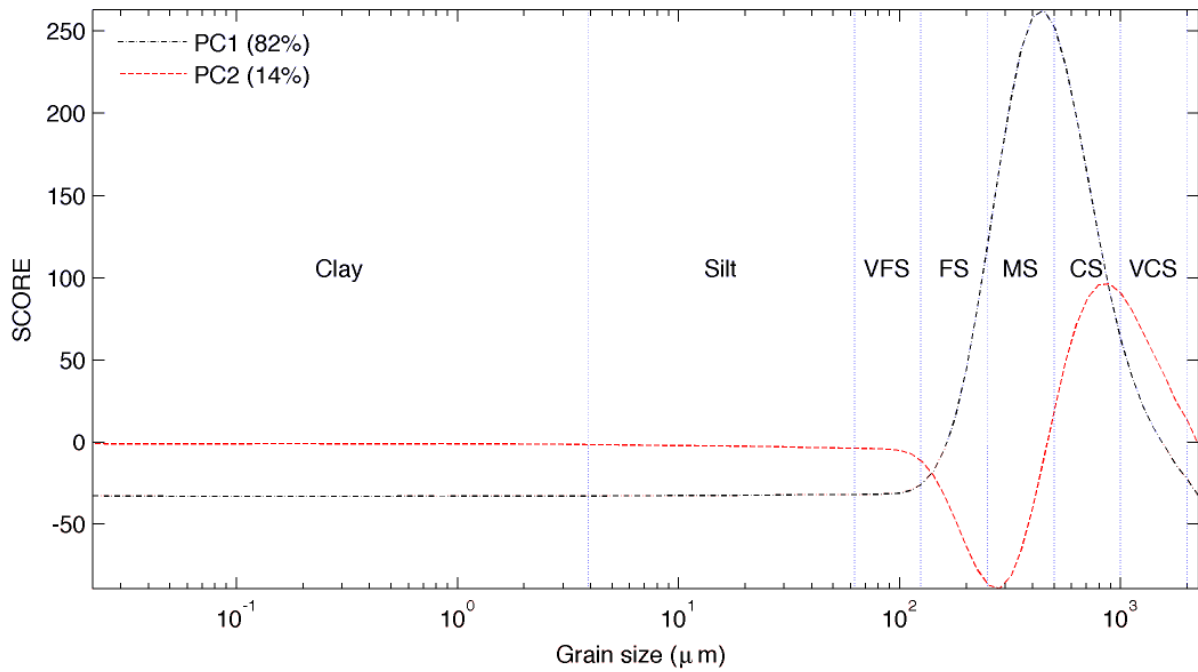
**Table 6.1** Results (p-value) of one-way analysis of variance of selected sediment statistics, considering groupings based on sample site and depth, using the Kruskal Wallis non-parametric method.

Group	D50	Sorting	Skewness
Site	<0.001	<0.001	<0.001
Depth	0.793	0.562	0.076
Site A & Depth	0.685	0.44	0.025
Site B & Depth	0.67	0.817	0.782
Site C & Depth	0.484	0.075	0.841
Site D & Depth	0.186	0.277	0.738
0-5cm & Site	<0.001	<0.001	0.006
5-10cm & Site	<0.001	<0.001	0.007
10-15cm & Site	<0.001	<0.001	<0.001

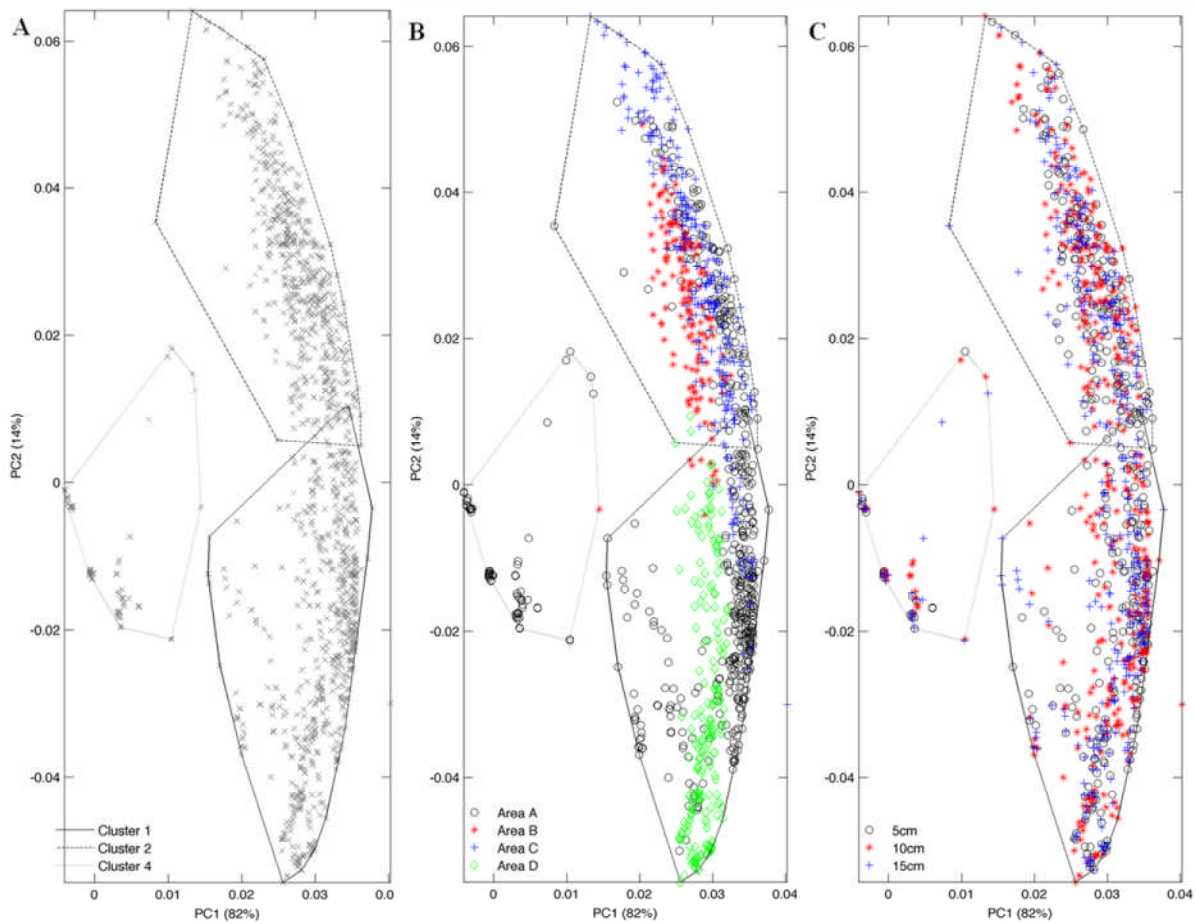
Multivariate analyses were undertaken to explore patterns in the full particle size distribution. A principal component analysis (PCA) reduced the data to two principal components (PCs) which in combination, account for 96% of the total variance (Figure 6.6). PC1 (82% of the variance) reflects the presence of medium sand (MS), to a lesser extent coarse/very coarse sand (CS/VCS), and some fine sand (FS), but a distinct lack of material smaller than this. PC2 (14% of variance) relates to a coarser component (presence of coarse and very coarse sand), and a lack of a fine-medium sand. PC1 is strongly correlated (negatively) with sorting, whereas PC2 is very strongly correlated (positively) with median grain size. Biplots of these PCs (Figure 6.7B) show that samples are distinctly separated on the x axis (PC1) and spread across a large range on the y axis (PC2). Samples from sites B and D (west and east extent of the open coast) are strongly separated on PC2: samples from B are associated with positive PC2 scores (coarser sand) compared to negative scores for D (fine-medium sand), but both are associated with mid-high PC1 scores (relatively well sorted). Only samples from site A (estuary) show any significant distribution along PC1, reflecting a mix of well to poorly sorted sediments at this site, in addition to the presence of very fine material. Samples from site C (inlet) suggest a mix of sediment characteristics from sites B (west bay) and the better sorted sediments from A (estuary). The PCA provides no evidence of association between sediment characteristics and sample depth (Figure 6.7C), but again highlights the strong association with sedimentary environment.

Cluster 1 refers to medium to high values on both PC1 and PC2, indicating a dominance of the coarser grain sizes and small contribution of finer material to these distributions. This cluster generally characterises the beach environments. Cluster 2 refers to high PC1 and low PC2 values, which corresponds to a dominance of fine and medium sand in the grain size distribution. This cluster largely represents estuarine sediments, though several beach samples also exist in this group. Cluster 4 refers specifically to low PC1 and PC2 values, representing those samples containing a mix of fine material (silt and very fine sand) and limited coarser component: cluster 4 comprises entirely estuarine samples (Figure 6.7A).

The clusters identified are closely associated with site (sedimentary environment), which is a significantly more effective discriminator of sediment characteristics (Figure 6.7B) than stratigraphic depth (Figure 6.7C). The results reveal that the open coast environment is predominantly characterised by a mixture of medium-coarse sand while the estuarine intertidal is characterised by a mixture of medium to fine sand and some finer material. Stratigraphically, there appears to be a high degree of consistency in the PC-based sample clustering from surface through to 15 cm deep (Figure 6.7C). These results also suggest that sediment characterisation in this physical context is relatively insensitive to the sampling depth within the near-surface zone. A more detailed analysis of stratigraphic variations is undertaken in Section 6.1.5.



**Figure 6.6** Principal component scores in relation to the grain size distribution for the St Ives Bay - Hayle system (see text for explanation).



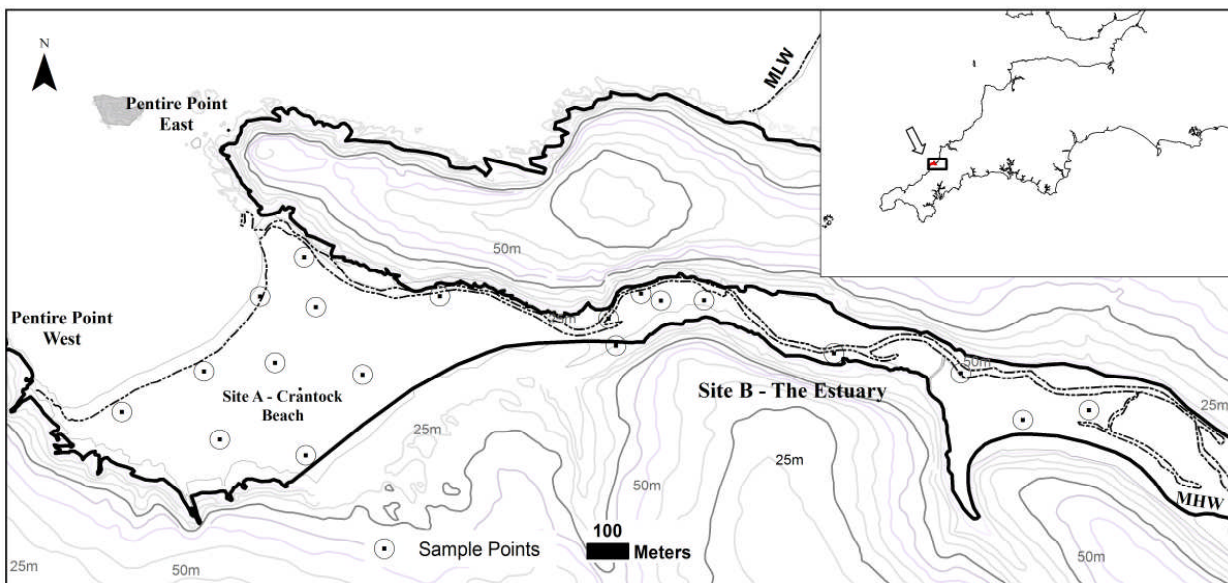
**Figure 6.7** St Ives – Hayle combined plots of PCA and cluster analysis of the grain size distribution (A), comparing the relative sub-environment (B) and relative stratigraphic depth (C).

\*Note: Cluster demarcation - Cluster 1 {Thick line}, Cluster 2 {dashed line}, and Cluster 3 {light dot line}  
 Temitope Oyedotun



### 6.1.2 Crantock beach and the Gannel estuary

In Gannel Estuary, a total of 19 short cores (length < 15 cm) were collected, during October 2011 field sampling, from the Gannel - Crantock intertidal zone (Figure 6.8) using a 65 mm diameter tube. Sample locations were positioned using a hand-held Global Positioning System (GPS), ( $\pm 4$  m). The Gannel is a ria estuarine system comprising sandy intertidal flats (c.70% of the valley is intertidal Davidson, *et al.*, 1991) within a narrow valley merging with a large sandy beach-dune system (Crantock) at the seaward extent, which is characterised by sandy megaripples (c. 10 - 25m wavelength) bedform sediments that merge with a narrow sandy intertidal flats and saltmarshes that infilled the valley at the landward estuarine extent where megaripples (c. 5-10m wavelength) persists (Site B, Figure 6.9B).



**Figure 6.8** The Crantock Beach - Gannel Estuary sites sampled for sediment analysis.



**Figure 6.9** Photographs showing surface conditions in the two main sedimentary environments surveyed. Sites are A – Crantock Beach and B – Gannel Estuary (see Figure 6.8 for location).



Figure 6.9 cont.

Grain size distributions of sediment sampled from the two sites (A and B) are summarised and presented in figures 6.10. Sediments at site A (Crantock Beach) are dominated by particles in a mixture of medium sand (250-500  $\mu\text{m}$ ) and coarser/very coarser sand distribution (500-1000  $\mu\text{m}$ ) while sediments at site B (the inner estuary) in the inner estuary comprises a more broad medium sand (MS, 250-500  $\mu\text{m}$ ), and relative population of fine sand (FS, 125-250  $\mu\text{m}$ ), silt (4-63  $\mu\text{m}$ ) and clay (0-4  $\mu\text{m}$ ). The continued presence of the medium sand population in the two sites suggests that sediment exchange is active between the estuary and the beach.

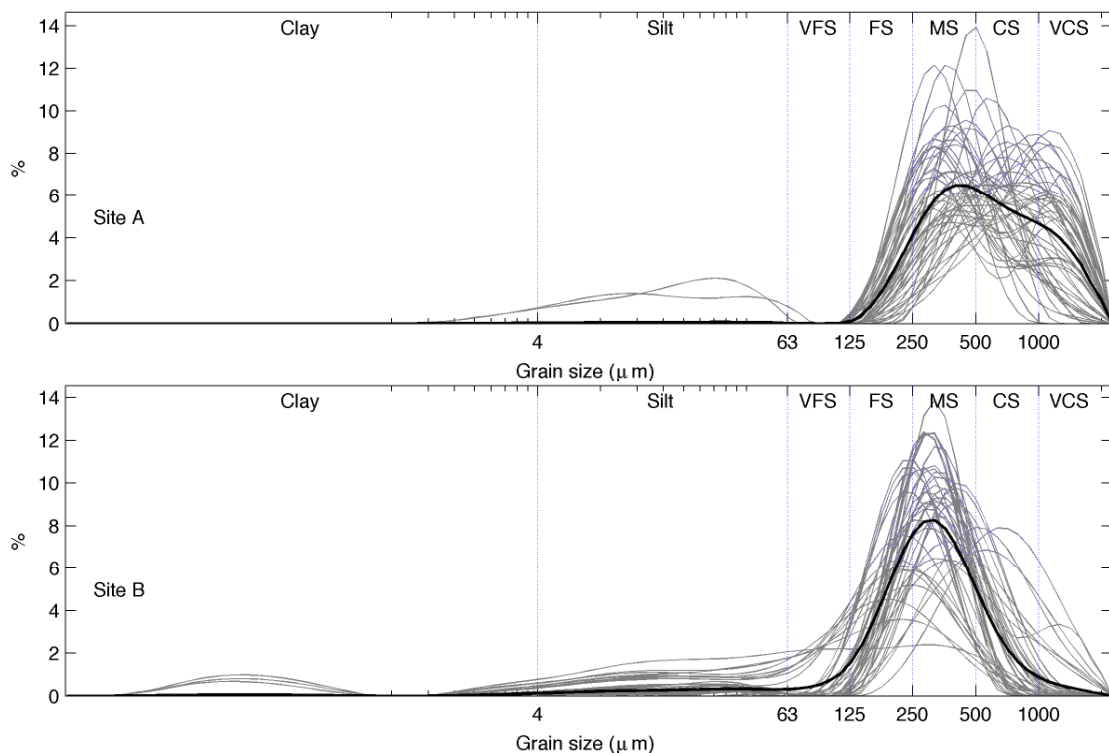
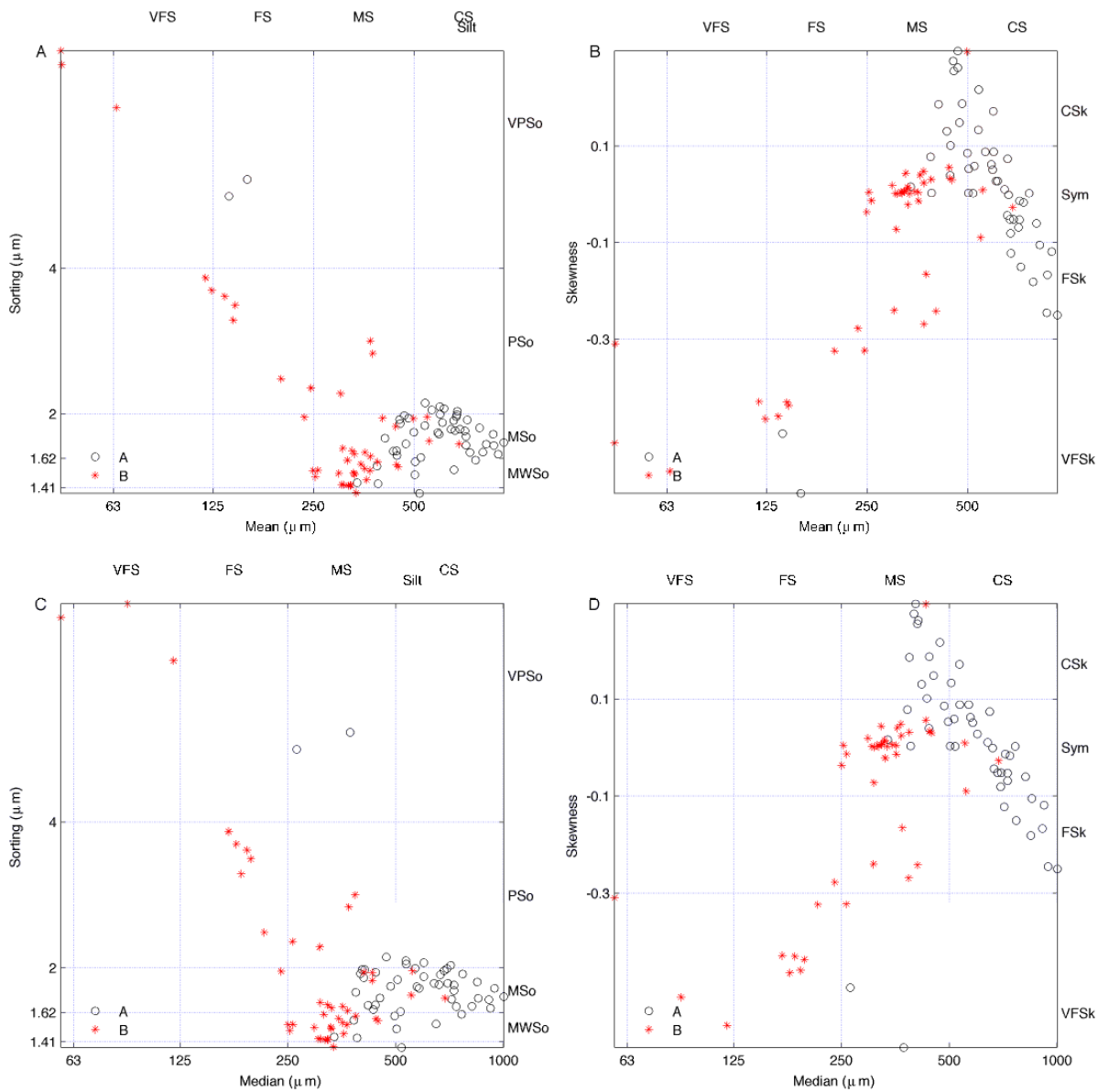


Figure 6.10 Surface sediment characteristics in the Crantock beach - Gannel estuary system, for all samples obtained within the depth range 0-5cm: sediment at each site is also summarised as a mean distribution (solid black line). Sites are A – Crantock Beach, B – Estuary.

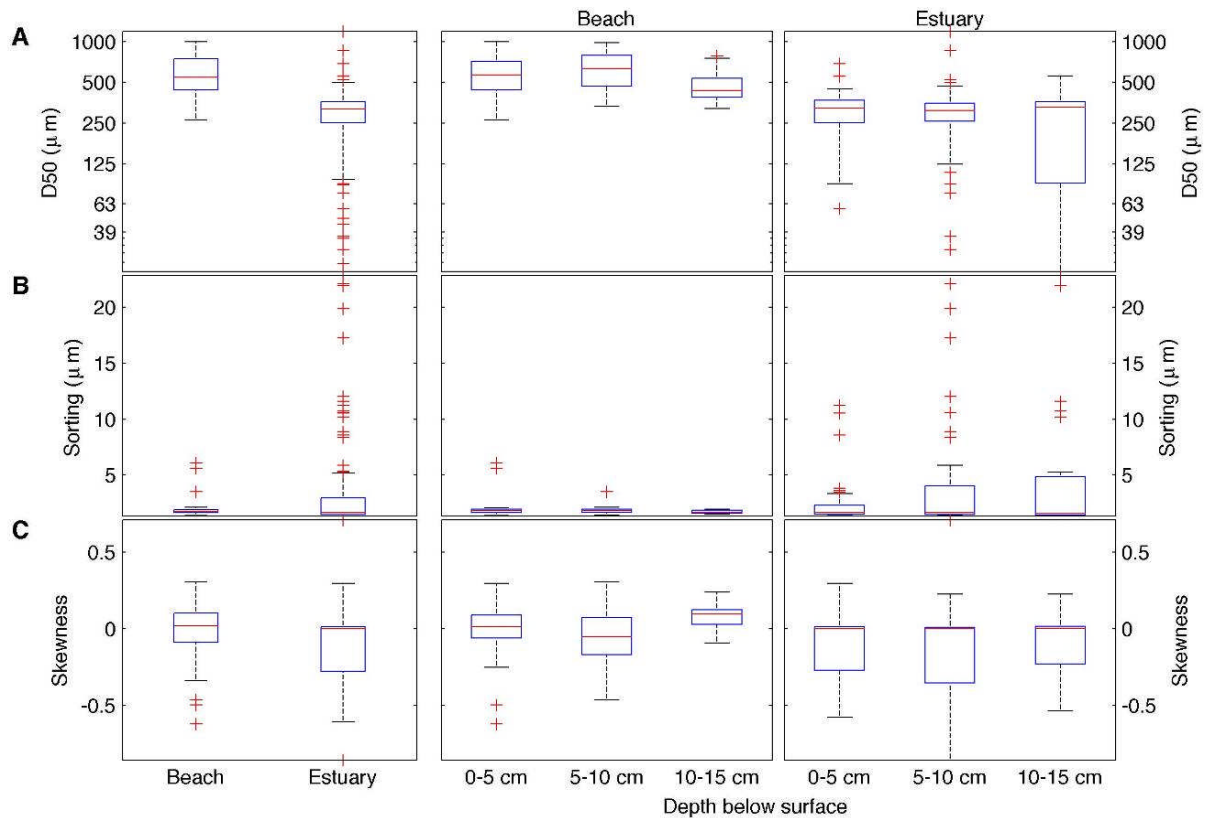


**Figure 6.11 Exploratory sediment analysis – grain-size statistics – (A) Mean vs. Sorting (B) Mean vs. Skewness (C) Median vs. Sorting and, (D) Median vs. Skewness.**

Median ( $\mu\text{m}$ ), sorting ( $\mu\text{m}$ ) and skewness values of sediment samples (sites identified in Figures 6.8 and 6.9) from both estuary and beach environment are summarised in Figure 6.12. Median grain size is consistently variable through the shallow stratigraphies examined here, but sediment recovered from the two sub-environments show marked differences. The bulk of the samples (76%) can be classified as moderately to well sorted sand, while about 24% of samples can be described as poorly to extremely poorly sorted sand or silt. Sediment size sorting improves with an increase in grain size. The more poorly sorted sediments are classified as silt/fine sand and the moderately to well sorted sediments are classified as medium/coarse sand.

Figure 6.12 shows sediment results for the Gannel-Crantock system defined by site (sedimentary environment) and sample depth (0-5cm, 5-10cm and 10-15cm from the intertidal sediment

surface). The boxplot analyses here show little systematic variation in grain size parameters with depth as there are significant difference in depth for median statistical parameters but no significant different for the sorting and skewness. The significant differences for median (with the exception of sorting and skewness) are reported across all the sites with depth and at 10-15 cm for skewness. Differences between estuary and beach environments are significant (at 99% level) for both the median ( $\mu\text{m}$ ) and skewness across the sites but not significant for sorting (standard deviation expressed in  $\mu\text{m}$  units) (Table 6.4). The results clearly show the consistency in the sedimentary processes over the depth of 15cm for the two sites as there is no significant difference based on the sample depth ( $p > 0.05$ ) across all the sites and depth and for all the statistical parameters considered here (Site A & Depth and Site B & Depth, Table 6.4 and Figure 6.12). Here, the sample sites are not associated with significant differences but with sample depth for median, irrespective of the depth (up to 15 cm). There is no significant impact of sorting through the 0 – 15 cm depth, 0 – 10 cm depth for skewness but significant difference for the 10 – 15 cm depth for skewness.



**Figure 6.12** Summary of sediment statistics for sedimentary environments at the Gannel Estuary. Data are divided based on sub-environment (Beach and Estuary, located in Figure 6.5) and depth (using 0 – 5cm, 5- 10cm and 10 – 15cm stratigraphic units)

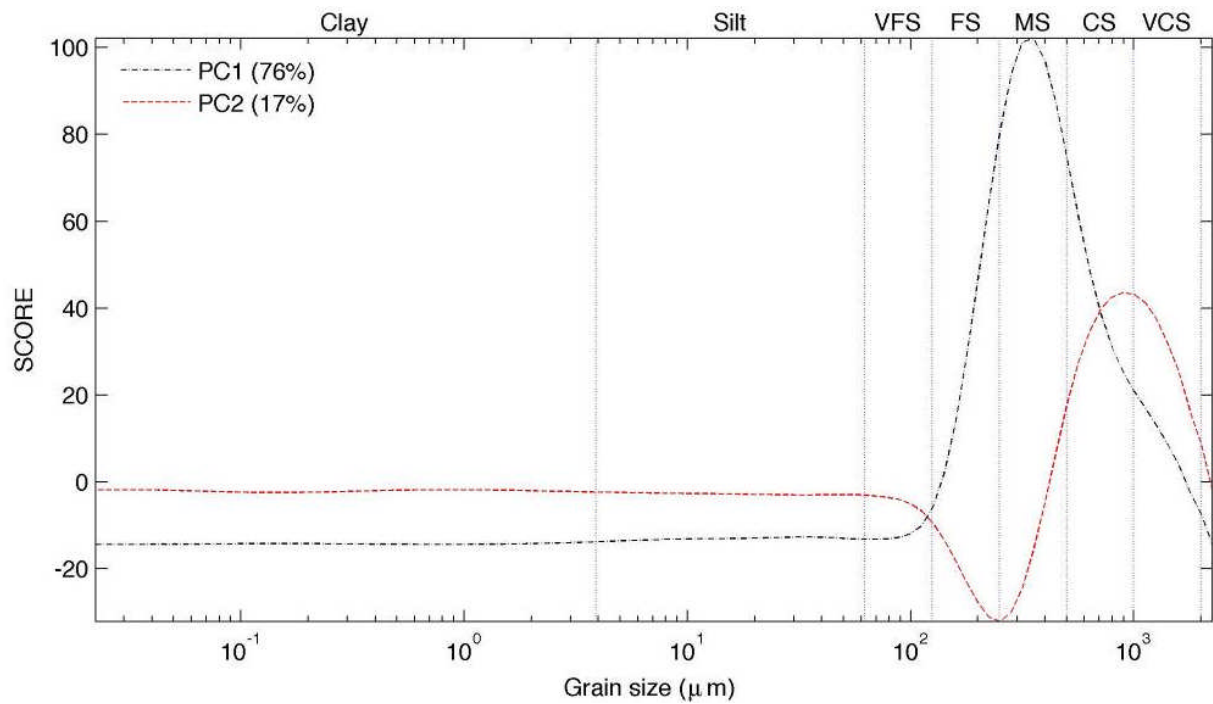
Differences in the sediment population, and evidence for mixed sediment sources (e.g. the likely input of mining waste derived sediment vs. the contribution from the marine environment) may explain the differences in grain size texture, but these summary statistics are often blunt tools with which to compare sediments with complicated grain size distributions. Multiple modes are

particularly difficult to account for in summary statistics, but the full distribution allows recognition of these sub-populations (Figure 6.10). The difficulty with distribution data is that it is not readily comparable (sample to sample), but multivariate statistics can be used to derive a smaller number of variables which to compare the majority of the variance in the data, in addition to exploring differences and associations in the data for the grouping of similar characteristics.

**Table 6.2 Results (p-value) of one-way analysis of variance of selected sediment statistics, considering groupings based on sample site and depth, using the Kruskal Wallis non-parametric method.**

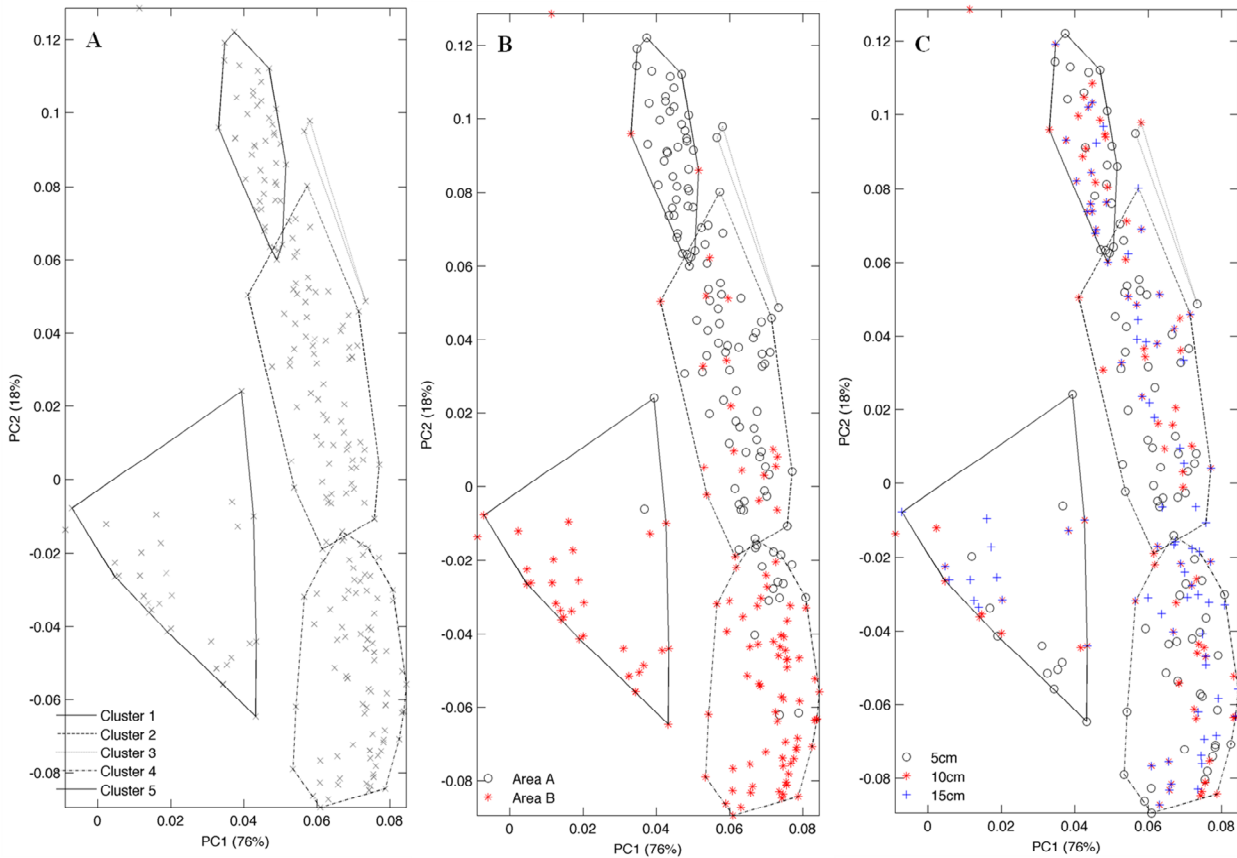
<b>Group</b>	<b>D50</b>	<b>Sorting</b>	<b>Skewness</b>
<b>Site</b>	<0.001	0.605	<0.001
<b>Depth</b>	0.431	0.896	0.409
<b>Site A &amp; Depth</b>	0.11	0.503	0.161
<b>Site B &amp; Depth</b>	0.38	0.733	0.837
<b>0-5cm &amp; Site</b>	<0.001	0.283	0.005
<b>5-10cm &amp; Site</b>	<0.001	0.693	0.087
<b>10-15cm &amp; Site</b>	<0.001	0.61	<0.001

Principal Component Analysis (PCA) was used to reduce the grain size distributions across all samples into a smaller number of key variables. Hierarchical cluster analysis (using Euclidean distance and average linkage, which produced the strongest cophenetic correlation of 0.74) was applied to the grain size distributions to organise samples into groups comprising similar sedimentological characteristics. The principal component analysis of the grain size distribution presented here derived two principal components (PCs) which also together account for approximately 93% of the variance (Figure 6.13). PC1 explains 76% of the variance and is dominated by the medium sand (MS) part of the distribution, and to a lesser extent coarse/very coarse sand (CS/VCS) and some fine sand (FS), but a distinct lack of material smaller than fine sand. PC2, accounting for 17% of the variance, relates to a coarse component, specifically the presence of coarse and very coarse sand (VCS), and the lack of a fine-medium sand (FS/MS) component.



**Figure 6.13** Principal component scores in relation to the grain size distribution (see text for explanation).

The principal component and cluster analyses of the Gannel sediments reveal that the beach environment is predominantly characterised by a mixture of medium-coarse sand while the estuarine intertidal is characterised by a mixture of medium-fine sand and finer material. However, there is some clear overlap in sediment populations from these sub-environments, evidenced in clusters 1 and 2 (Figure 6.14A). This implies that there is at least some sediment exchange (sand) between beach and estuary and that this is contemporary, given that it is evidenced by sediments at, and close to, the surface. Stratigraphically, there appears to be a high degree of consistency in the PC-based sample clustering from surface through to 15 cm deep (Figure 6.14C and Section 6.1.5). This further supports the inference that both the compartmentalisation and partial exchange between beach and estuarine sub-environments can be attributed to the contemporary process regime. These results also suggest that sediment characterisation in this physical context is relatively insensitive to the sampling depth within the near-surface zone.



**Figure 6.14 Crantock beach - Gannell combined plots of PCA and cluster analysis of the grain size distribution (A), comparing the relative sub-environment (beach vs. estuary (B)) and relative stratigraphic depth (C).**

*\*Note: Cluster demarcation - Cluster 1 {Thick line}, Cluster 2 {dashed line}, and Cluster 3 {light dot line}*

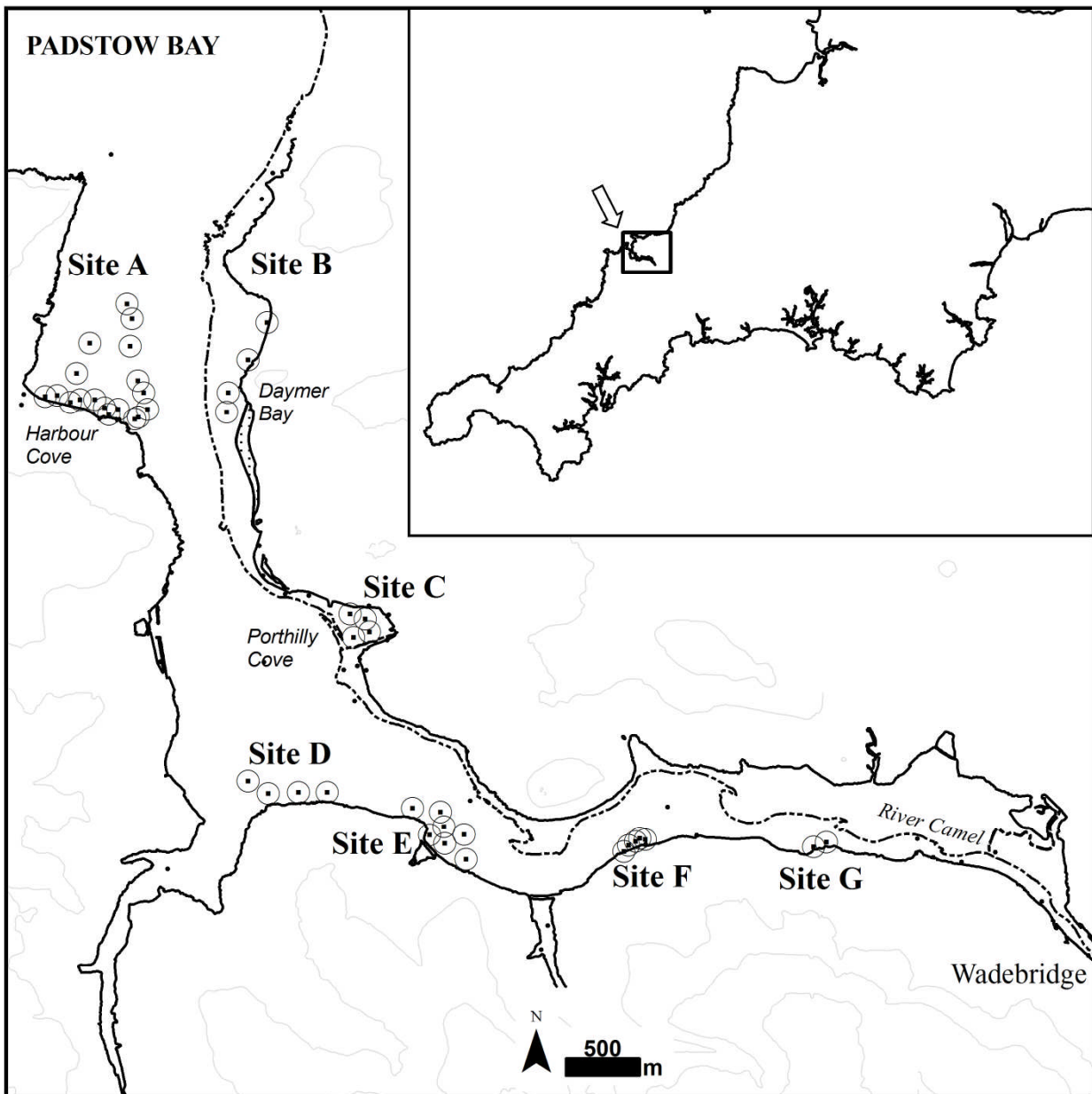
Comparison of these first two principal components in a bivariate plot shows that sub-environment (estuary or beach) is a clear discriminator of sediment characteristics (Figure 6.14B), whilst stratigraphic depth is not (Figure 6.14C). Hierarchical cluster analysis of the grain size distributions facilitates a more formal grouping of samples comprising similar grain size distributions. The separation of samples identified in the PCA is clarified in the clustering of samples into 5 groups; all but 2 samples (both mid-depth, estuarine samples) are within clusters 1, 2 and 4, which can be described as environment-specific groupings (Figure 6.14). Cluster 1 refers to medium to high values on both PC1 and PC2, indicating a dominance of the coarser grain sizes and small contribution of finer material to these distributions. This cluster generally characterises the beach environment. Cluster 2 refers to high PC1 and low PC2 values, which corresponds to a dominance of fine and medium sand in the grain size distribution. This cluster largely represents estuarine sediments, though several beach samples also exist in this group. Cluster 4 refers specifically to low PC1 and PC2 values, representing those samples containing a mix of fine material (silt and very fine sand) and limited coarser component: cluster 4 comprises entirely estuarine samples.

### 6.1.3 Padstow Bay and the Camel estuary

Using a 65-mm-diameter tube, 44 short cores (length < 15 cm) were collected, in October 2011, from the seven separate intertidal sedimentary environments (sites) across the Camel estuary (Figure 6.15). Sample positions were recorded ( $\pm 3$  m rms error) using a hand-held Global Positioning System (GPS). The sedimentary environments of the estuary are characterised by extensive sand flats. In the outer estuary, planar high intertidal beaches merge with low intertidal flats (e.g. site A, Figure 6.16), whilst the middle reaches are characterised by a variety of bedforms (sites C, D and F, Figure 6.16) ranging from megaripples (c. 10-20m wavelength) and to wave-current ripples (c. 10-25 cm wavelength). In the upper reaches of the estuary, extensive sand flats give way to narrow muddier features that merge with relic gravel shoreline deposits.

Consideration of the full grain size distribution across the sites provides an opportunity to characterise sediment populations and explore mixing (Figure 6.17). The grain size distributions illustrate the clear similarity across a large proportion of the sediments sampled, with the modal size generally lying within the medium sand (and upper parts of the fine sand) region of the size spectrum. Sediment in the range 160-500  $\mu\text{m}$  (representing the overall 16th-84th percentiles) constitutes the dominant sediment population in this estuary, and this population is present throughout the system, except at the far inner estuary (site G). Site D (southeast of Padstow) is possibly the only site where this population is not significantly supplemented with sediment across a broader range of sizes. In the outer estuary, the 160-500  $\mu\text{m}$  population merges with a coarser (500-2000  $\mu\text{m}$ ) one, whereas mid-estuary sediment (C, E and F) is mixed with a distinct finer (silt and clay) population presenting a bimodal distribution. The inner estuary site G is also bimodal, but comprises a clay population and a more dominant broad silt/very fine sand population.





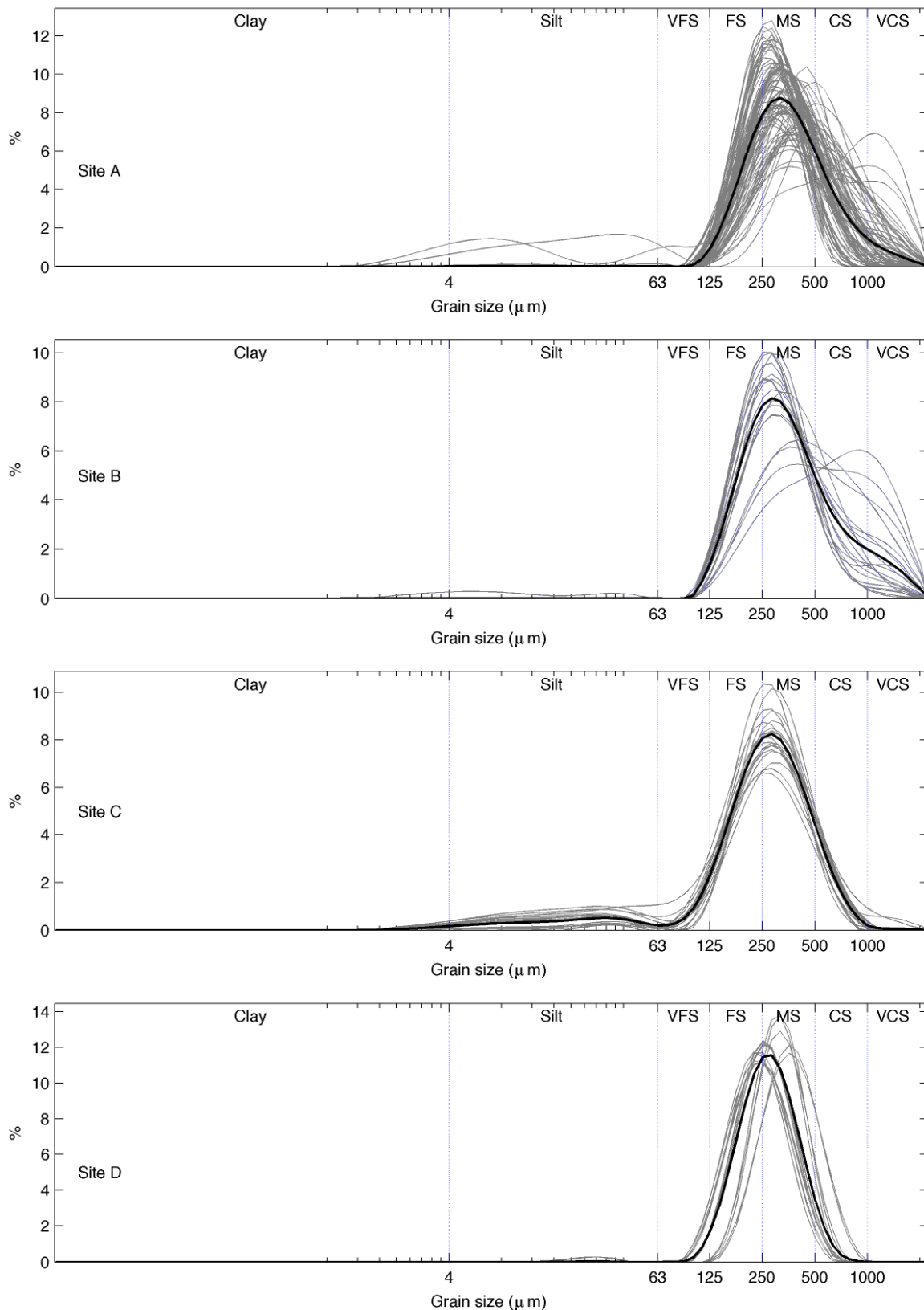
**Figure 6.15** The Padstow Bay - Camel Estuary sites sampled for sediment analysis.

*{Note: the establishment of larger parts of the system as SSSI constrains the spatial distribution of sediment sampling}*

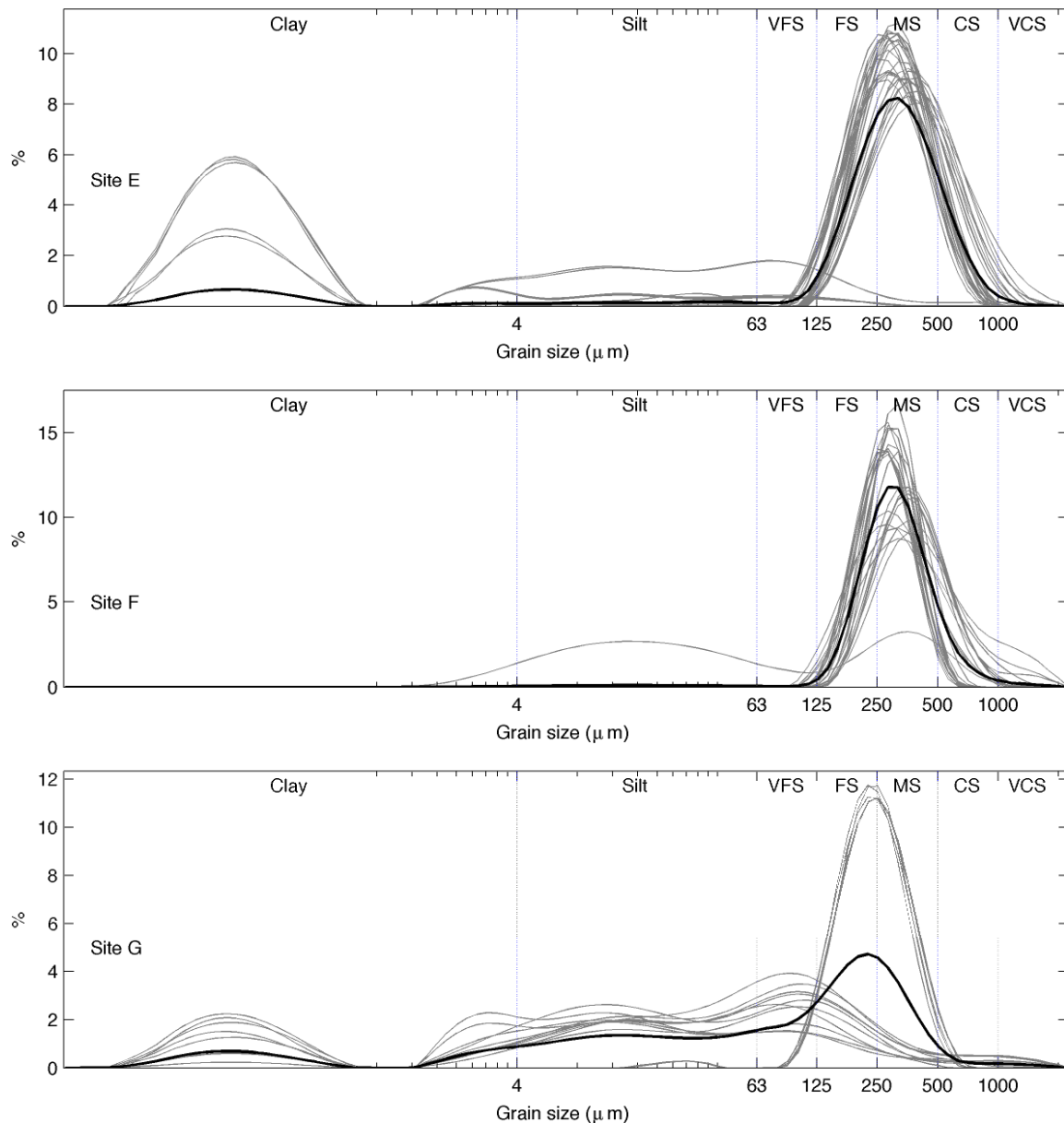
Visual inspection of the outer estuary samples (sites A and B) suggests that the coarse to very coarse sand population that is mixed with the core fine-medium sand population, is composed of shell fragments. This is a common feature of outer-estuary and inlet-associated beaches (Buyneveich and Fitzgerald, 2003), and the lack of this population from the rest of the estuary suggests i) lower energy processes that are unable to break down intact shells, leading to a paucity of shell fragments; ii) lack of transport or attrition during transport of shell fragments from the outer to inner estuary; and possibly iii) a lack of mollusc-habitat.



**Figure 6.16 Padstow – Camel photographs showing surface conditions in the seven main sedimentary environments surveyed. Sites are the outer estuary (A – Harbour Cove/Hawker’s Cove, B – Daymer Bay), mid-estuary (C – Porthilly Cove, D – near Padstow, E, F) and inner estuary (G). See Figure 6.15 for location.**



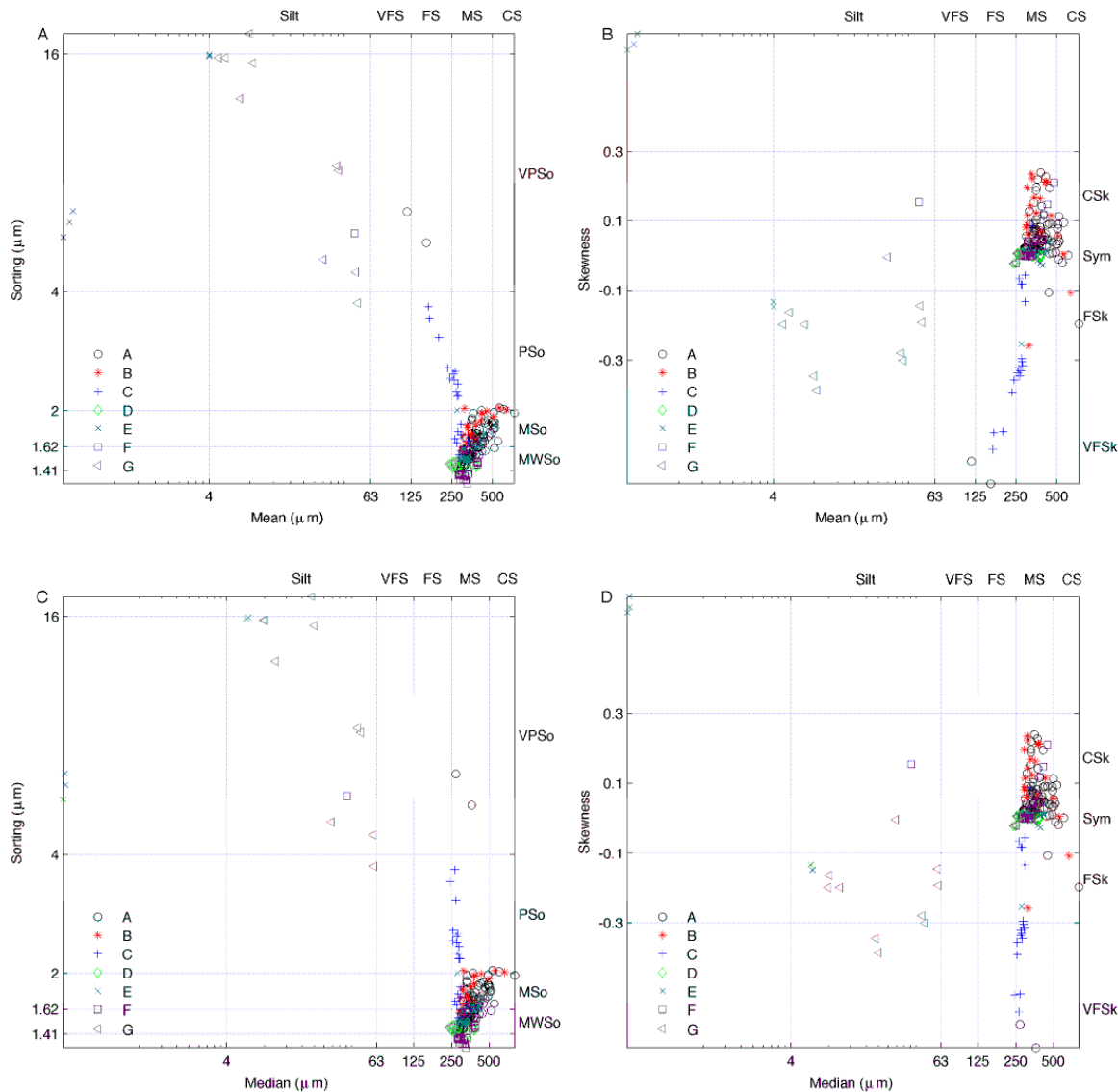
**Figure 6.17** Surface sediment characteristics in the Padstow Bay - Camel estuary system. Grain size distributions are shown for all samples obtained within the depth range 0-15cm at locations in the 7 main sedimentary environments examined: sediment at each site is also summarised as a mean distribution (solid black line). Sites are A – Harbour Cove/Hawker’s Cove, B – Daymer Bay, C – Porthilly Cove, D – near Padstow, E – mid-estuary, F – mid-estuary, and G – inner-estuary.



**Figure 6.17 cont. Surface sediment characteristics in the Padstow Bay - Camel estuary system.**

The exploratory sediment analysis of grain size statistics – mean vs. sorting, mean vs. skewness, median vs. sorting and median vs. skewness are presented in Figure 6.18. The seaward sites A and B comprise 12% and 57% positively skewed and mid-estuary sites D and F are largely symmetrical. Very positively skewed sediments only occur at site E, where symmetrical distributions dominate but negatively skewed sediments are also present. Sites C and G are dominated by negatively and very negatively skewed sediments (73% and 90% respectively). Overall, sediment distributions from the outer estuary have a coarse tail (i.e. an important coarse sand component), and those from sites C (Porthilly Cove) and G (inner estuary) comprise a significant fine tail (of fine sand, silt and clay). This suggests that the headland to the immediate north of Porthilly Cove might have provided important protection to the tidal flat there, allowing the deposition of very fine material. In general, the sediment statistics show that the outer and middle estuarine sediments are moderately well/well sorted, near-symmetrical/positively skewed

medium-coarse sand. Inner estuary samples are finer (sand and silt), less well sorted and negatively skewed. Sites in the mid estuary exhibit characteristics of both the seaward and landward sediments.



**Figure 6.18 Exploratory sediment analysis – grain-size statistics – (A) Mean vs. Skewness (B) Mean vs. Sorting (C) Median vs. Skewness and, (D) Median vs. Sorting**

The median (μm), sorting (μm) and skewness statistics derived from the grain size distributions of sediment sampled from each of the sub-environments are summarised and presented in Figure 6.19. Median grain size remains relatively consistent across sites A to F, broadly classed as medium sand (250 - 500 μm). There is clear consistency (and no significant difference) in sedimentology at each site, irrespective of depth below the surface (Table 6.5). The seaward sites (A and B) also comprise coarser samples (8 - 12% coarse sand) whilst the mid-estuary sites (C and D) comprise finer samples (10 - 18% fine/very fine sand). Farther into the estuary, silts and clays are increasingly present. Sediment at sites E and F retains the medium sand characteristics of the seaward sites, but several samples here are silt or clay (<63 μm). Silt dominates (97%) at

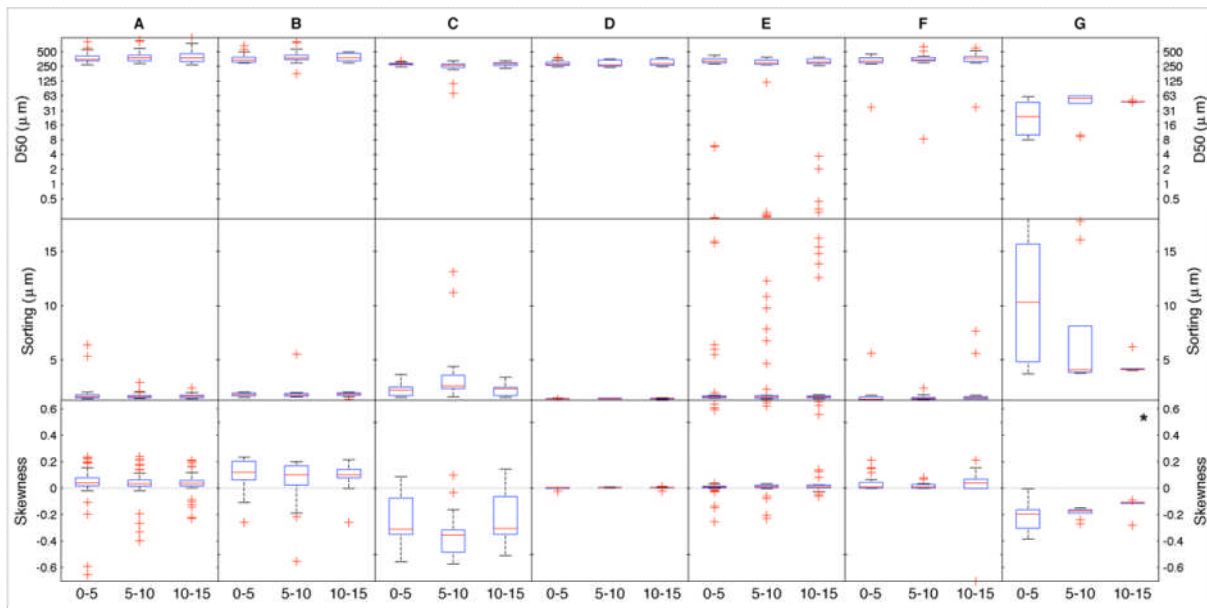
site G where some variation with depth is apparent: fine silt at the surface and very coarse silt at depth.

The vast majority of sediments throughout the estuary are either moderately well sorted (46%) or moderately sorted (33%), but those at site G are very poorly sorted (Figure 6.19). There is also a significant difference in sorting at different depths at site G, where surface sediments are far more poorly sorted than those found at depth. Sediment at sites C and D in the broadest part of the estuary (Porthilly Cove and Padstow respectively) also exhibit significant, but less pronounced differences in sorting with depth. Where sorting varies with depth, there is no consistent trend: at site D, sorting worsens with depth, but at site C the 5 - 10cm unit is more poorly sorted than deeper or surface sediments. Sediment near Padstow (D) is particularly well sorted, as with most sediment from site E where there are also occasional samples across the depths that are extremely poorly sorted. Sediment size distributions are predominately symmetrical (72% of samples).

The results clearly show that the contemporary sedimentary processes are consistent over a depth of 10 to 15 cm. The sedimentological discrimination demonstrated here is present throughout the cm-scale units. This could be the result of contemporary sediment activation (transport mechanisms) occurring throughout the near-surface profile. Alternatively, this may indicate significant consistency in the processes responsible for transport and deposition over the sedimentary timescale associated with the accretion of this profile. It is clear that a consistent sedimentary interpretation is achieved irrespective of where a sediment sample is obtained within 10 to 15 cm of the intertidal surface.

The continued presence of the fine-medium sand population within the near-surface deposits throughout the outer and central the estuary suggests that sediment exchanges remain quite active between these zones. This might reflect the characteristics of the primary sediment source for this sediment, which could be marine, largely derived from glacial shelf sands that contribute a fine-medium sand population to a wide range of coastal sedimentary environments in northwest Europe (Ballantyne, 2002). Large-scale tidal-current forced bedforms extend well into the central region of the estuary, demonstrating the ability of tidal currents to transport large quantities of this fine-medium sand (Figure 6.19). It is this tidal forcing that is clearly most important here in transferring sediments between the sedimentary systems, and enabling the delivery of the core fine-medium sand to most parts of the estuary.

Sedimentologically, the inner estuary presents a significant departure from the other environments examined. The fine-medium sand population has not been transported this far into the estuary: it is likely that channel-margin deposits will comprise some of this core sediment, but the intertidal flats here are largely mud-dominated, reflecting a progressive reduction in energy regime toward the estuary head and estuary margins.

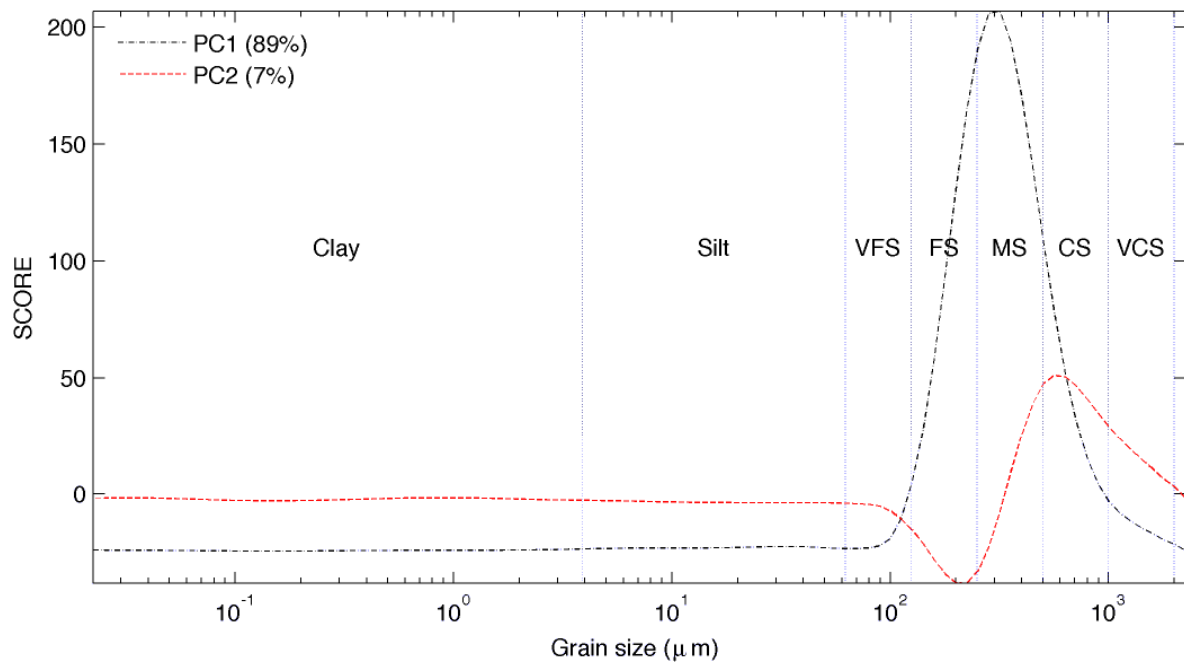


**Figure 6.19 Summary of sediment statistics for sedimentary environments within Padstow Bay/Camel estuary. Data are divided on the basis of site (A to G, located in Figure 10) and depth (using 0-5cm, 5-10cm and 10-15cm stratigraphic units)**

**Table 6.3 Results (p-value) of one-way analysis of variance of selected sediment statistics, considering groupings based on sample site and depth, using the Kruskal Wallis non-parametric method.**

Group	D50	Sorting	Skewness
Site	<0.001	<0.001	<0.001
Depth	0.405	0.681	0.355
Site A & Depth	0.527	0.820	0.82
Site B & Depth	0.257	0.656	0.633
Site C & Depth	0.111	0.019	0.051
Site D & Depth	0.322	0.036	0.708
Site E & Depth	0.188	0.6	0.608
Site F & Depth	0.125	0.088	0.408
Site G & Depth	0.549	0.536	0.254
0-5cm & Site	<0.001	<0.001	<0.001
5-10cm & Site	<0.001	<0.001	<0.001
10-15cm & Site	<0.001	<0.001	<0.001

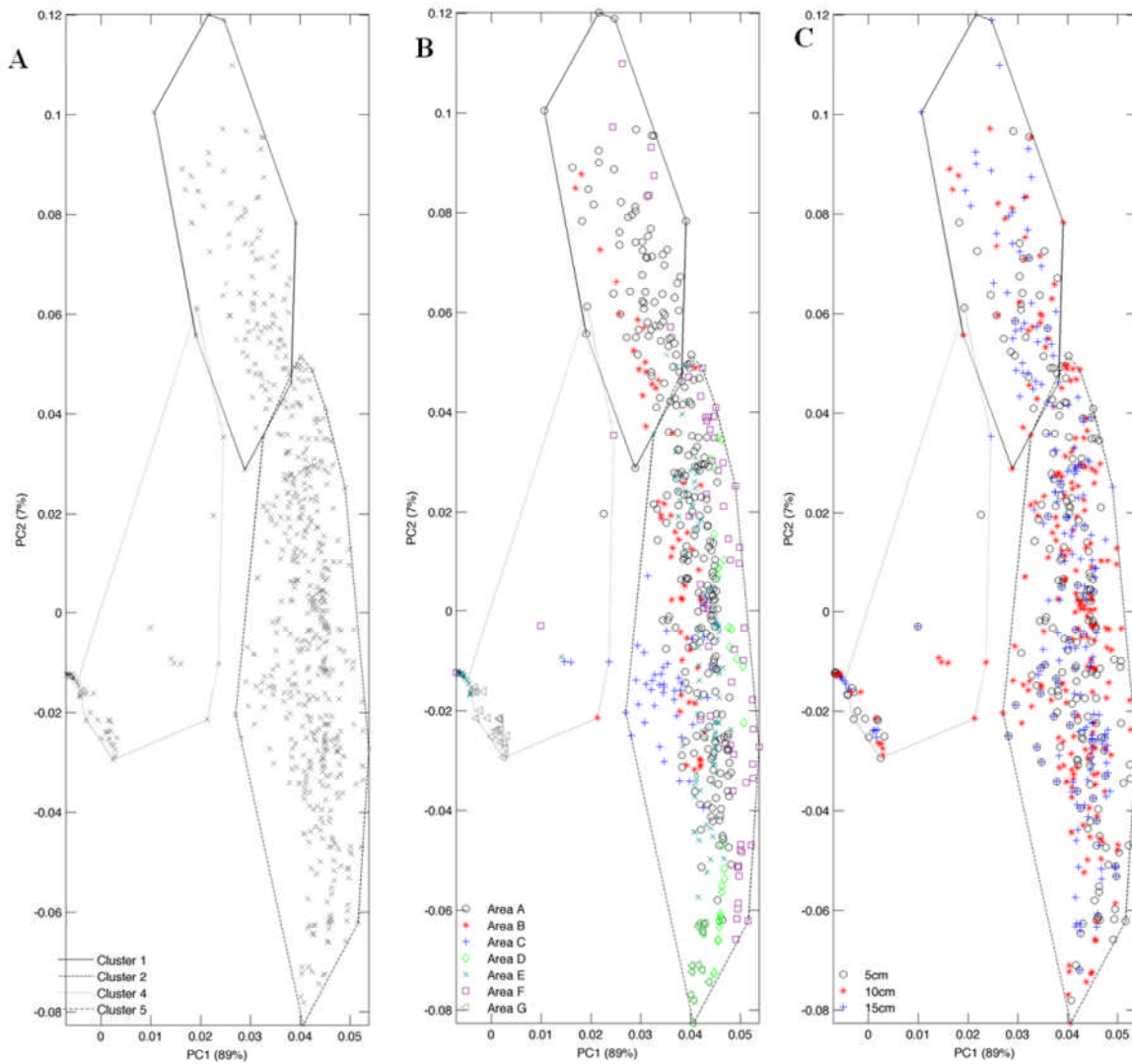
In Camel Estuary, the principal component analysis of the grain size distribution account for approximately 96% of the variance (Figure 6.20). The PC1 indicates 89% of the variance is dominated by the medium sand (MS) part of the distribution, and to a lesser extent coarse/very coarse sand (CS/VCS) and some fine sand (FS), but a distinct lack of material smaller than fine sand. PC2, accounting for 7% of the variance, relates to a coarse component, specifically the presence of coarse and very coarse sand (VCS), and the lack of a fine-medium sand (FS/MS) component.



**Figure 6.20** Principal component scores in relation to the grain size distribution at Camel Estuary (see text for explanation).

Combined plots of PCA and cluster analysis of the grain size distribution presented in Figure 6.21 compare the principal components of the relative sub-environment (B) and relative stratigraphic depth (C). This comparison shows that the main sub-environments (outer-estuary, mid-estuary or the inner-estuary) are the clear discriminator of sediment characteristics (Figures 6.21A and B), whilst stratigraphic depth is not (Figure 6.21C). Separation of samples identified in the PCA is clarified in the clustering of samples into 4 groups; all but 2 samples (both mid-depth, estuarine samples) are within clusters 1, 2 and 4, which can be described as environment-specific groupings (Figure 6.21A). Cluster 1 refers to medium to high values on both PC1 and PC2, indicating a dominance of the coarser grain sizes and small contribution of finer material to these distributions. This cluster generally characterises the outer-estuary and mid-estuary environment. Cluster 2 refers to high PC1 and low PC2 values, which corresponds to a dominance of fine and medium sand in the grain size distribution. This cluster largely represents mid - estuarine sediments. Cluster 4 refers specifically to low PC1 and PC2 values, representing those samples containing a mix of fine material (silt and very fine sand) and limited coarser component: cluster 4 comprises entirely inner estuarine samples.





**Figure 6.21 Padstow – Camel combined plots of PCA and cluster analysis of the grain size distribution (A), comparing the relative sub-environment (B) and relative stratigraphic depth (C).**

*\*Note: Cluster demarcation - Cluster 1 {Thick line}, Cluster 2 {dashed line}, and Cluster 3 {light dot line}*

Sediment populations are relatively coherent throughout the 15cm sampling depth, and more broadly do not present any consistent or well developed trends from surface to depth (Figure 6.21C). Overall, this suggests that compartmentalisation and sediment interchange within the estuary can be attributed to the sedimentary process regime, and that the grain size signature of this is almost completely insensitive to depth. Only in the upper reaches of the estuary are there significant and systematic variations in sedimentology with sediment depth, exhibiting a fining upward and increasingly poorly sorted sequence. This suggests a broadly low energy regime that is possibly impacted infrequently by higher energy processes. Without further analysis of sediment geochemistry, it is not clear the extent to which these are sourced from fluvial inputs, or indeed if they are linked in any way to mining waste. Section 6.2 explores the sedimentary connectivity of the system through the evaluation of geochemical composition of the intertidal sediments.

#### 6.1.4 Regional comparison of surface sedimentology

In general, the sedimentary environments of the systems investigated in North Cornwall are characterised by sand flats. However, the differences in sediment patterns are evident based on the grain size distributions from the different depositional environments. On a regional level, there is evidence that the open coast and beach/dune system of all the three coastal systems are composed of the coarse/very coarse (CS/VCS) and medium sand (MS) grain sizes with small contributions of finer material to the distributions (Figures 6.3, 6.10, 6.17). A closer look at the distribution of the sediment on a regional perspective shows that about 82% (for Hayle), 76% (for Gannel) and 89% (for Camel) of the sediment composition are dominated by medium sand (MS) part of the distribution, and to a lesser extent coarse/very coarse sand (CS/VCS) and some fine sand (FS). The components of the sand at the beaches and open coast of the estuary are predominantly characterised by a mixture of medium – coarse sand while the estuarine sediment population are mainly a mixture of medium - finer sand and finer materials. Although silts and clays are present in the inner environment of the estuaries, they are however absent in the open coast/beaches/outer section of the estuaries. This ubiquitous pattern of arrangement shows that grain size diameter varies spatially in response to the local hydrodynamic forces and conditions. In terms of sorting and skewness, the sediments along the coastlines of the estuaries in the region, are largely moderately well sorted with near symmetrical/positive skewness while those found in the inner estuaries are less well sorted and some, negatively skewed (See Sections 6.1.1 – 6.1.3).

The sediments sampled along the coastlines/outer estuary-seaward indicate the mixture of fine medium and coarse sand population, likely reflects the combination of marine sediment source and higher energy processes. Within the estuaries, the silt and clay population, combined with the fine-medium sand, suggests mixing with fluvially-sourced material. The coarse sediments found in some points within the estuarine environments may have constitute ‘lag’ deposits which may be too heavy to be transported during the flow processes thereby left “*in situ*” as other materials are being sorted and transported.

In summary, from the grain size composition/distribution perspective, the sand population in most of the outer estuary/beaches in all of the three estuaries in the region are composed of similar single particle-size population with minor variation in systematic characteristics. The simple interpretation which can be given to this form of distribution is that the major sand population in the region is derived from a seaward source (possibly from the Celtic sea where the estuaries are opened to) with possible small contributions from the fluvial/river borne sediments. The overlap of marine derived and fluvial-derived sediment population is evidenced in where there is exchange between the estuary and the beach (coast), notably by samples from the estuary mouth and inlet – (for example, sites C in Hayle, site B in Gannel and sites C and D in Camel). This means that to a large extent, there is at least some exchange between the inner estuary and

the beach, evidenced by the sediment at, and close, to the surface. This line of hypothesis is investigated further by examining the elemental composition of the sediment samples at the estuary and along the coast in some of the sites of the investigation in all of the three estuaries - this is discussed in section 6.2.

### **6.1.5 Stratigraphic variations in sediment texture**

The study of any grain size trend should take into the account the sampling depth. Gao and Collins (1992) stated that sampling depth must not be too great so as to avoid mixing “ancient” and “modern” net transport, if the grain-size trend is aimed at identifying the local dynamic forces determining the transport of sediment. This section provides a generalised indication of down core (length <15 cm) changes in sediment textures in the estuaries. The stratigraphic investigation of the texture can provide information or important insights into depositional processes and probably the environmental condition driving the depositional processes.

#### **6.1.5.1 Local site-specific detail**

The principal component and cluster analyses of the sediments in the estuaries have been used to decompose the grain-size distributions into four main clusters of sediments compositions. Figures 6.22, 6.24 and 6.26 for St Ives bay-Hayle, Crantock-Gannel and Padstow-Camel systems respectively present the stratigraphic of sediment distribution from the surface through to 15cm depth. In St Ives-Hayle system, there appears to be a degree of consistency in sediment distribution pattern from surface through the 15cm depth in all of the sample sites, except at Site B where there is a contribution of silt at 6 – 7cm below the surface (Figure 6.22). Similarly in Crantock-Gannel system, the relative consistency of sediments composition and distribution through-out the 15cm sub-surface depths are noticed in the two sites, except at 1 – 2 cm and 3 – 4 cm where there are relative significant contribution of silt in Site A (Crantock Beach) and notable signature of clay sediment from 6 cm down-core to 15 cm at Site B (the Gannel’s inner estuary) (Figure 6.24). For Padstow-Camel system, the variation in depth of sediment composition is pronounced at Site F and G where silt (Site F) and combination of silt and clay sediments (Site G) provide the variation in sediment consistency. The slight variation is also observed at 6 – 7 cm and 4 – 6 cm at Sites B and C (as a result of presence of silt and clay respectively) (Figure 6.26).

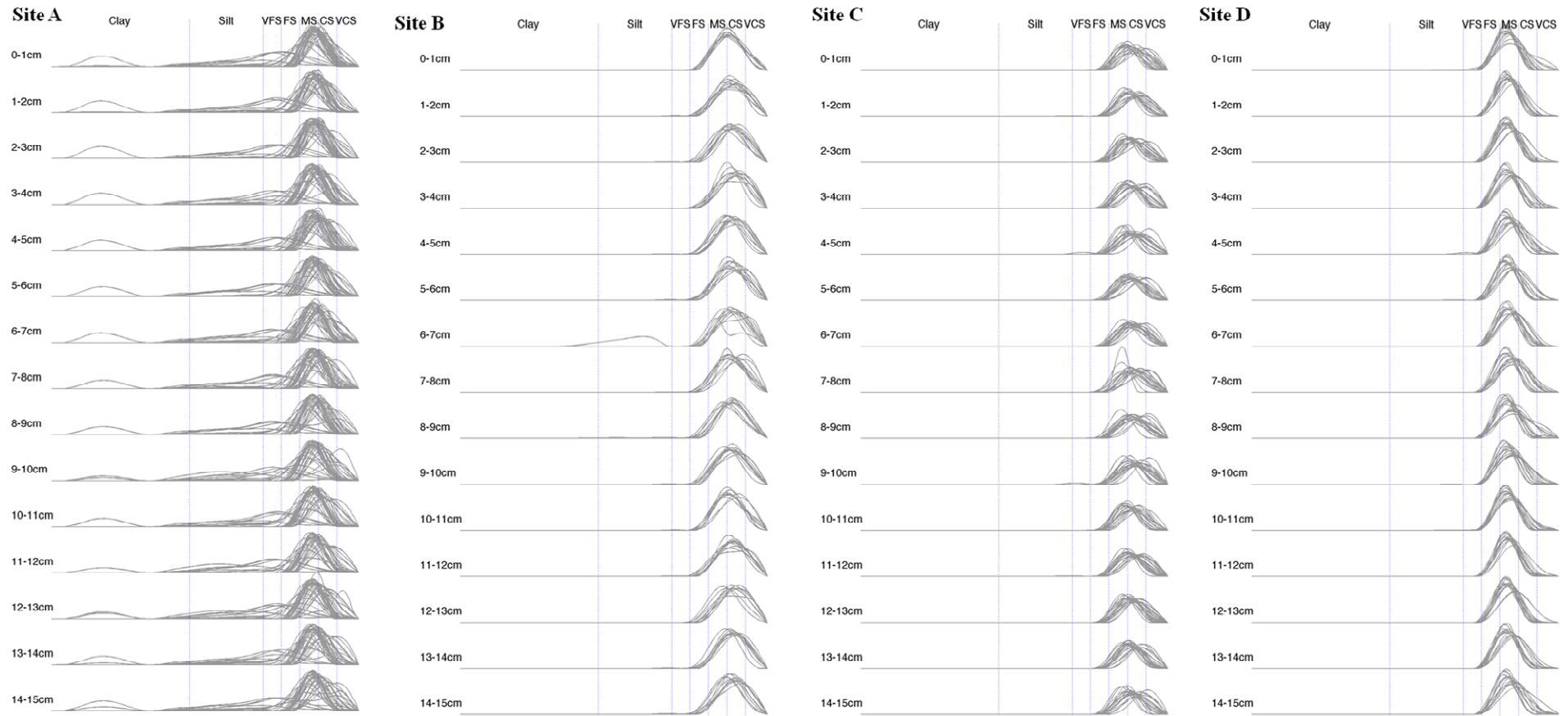
Figures 6.23, 6.25 and 6.27 respectively present the stratigraphical clustering of the surface through the 15cm depth. The sediment samples in the estuaries are classified in the clustering of the samples into distinct environment of specific groups based on Principal Components (PC) discussed in Section 6.1.1 (specifically based on Figures 6.7, 6.14 and 6.21).

Cluster 1 refers to medium to high values of the principal sediment components, indicating a dominance of coarser grain sizes and small contribution of finer materials to the distributions. This cluster type characterises the beach environment of Godrevy Towans of the Hayle Estuary (Figure 6.23), Crantock Beach of Gannel Estuary (Figure 6.25) and the outer-estuary of Camel (Figure 6.27) respectively.

Cluster 2 refers to the high and low values of sediments principal components which correspond to the dominance of fine and medium sand in the grain size distribution. This cluster group largely represents most parts of the Hayle and Camel Estuaries and the beach-estuarine sedimentary environment in Gannel Estuary, respectively.

Clusters 4 and 5 refers specifically to low values of sediment principal components and represent the samples containing a mix of fine material (silt and very fine sand) and limited or no coarser components. The clusters 4 and 5 relates almost entirely to estuarine samples although scattered representation of the group are found in at Crantock Beach of Gannel Estuary indicating a direct sedimentary exchange between the beach and estuary (see Figures 6.23, 6.25 and 6.27).

Stratigraphically, there appears to be a high degree of consistency in the principal component-based sample clustering from surface through the 15cm depth. Despite the lack of overall significance difference, there are minor occurrences of clay-silt peaks sub-surface in several cores. This observation does support the inference that both the compartmentalisation and partial exchange between the beach/coastal sediments and estuarine sub-environments can be attributed to the contemporary processes in the region. These findings also suggest that sediment characterisation in this physical context is relatively insensitive to the sampling depth within the near-surface zone.



**Figure 6.22 Stratigraphical sediment size distribution analysis for the St Ives Bay - Hayle estuary system from the sampling sites. Sites are A – Lelant/Carrack Gladden, B – Carbis Bay/Barrepta Cove, C – Black Cliff and D – Godrevy Towans (see Figure 6.1 for location).**



Figure 6.23 Depth variation in the distribution of sediment sub-populations clusters within the St Ives Bay - Hayle estuary system.

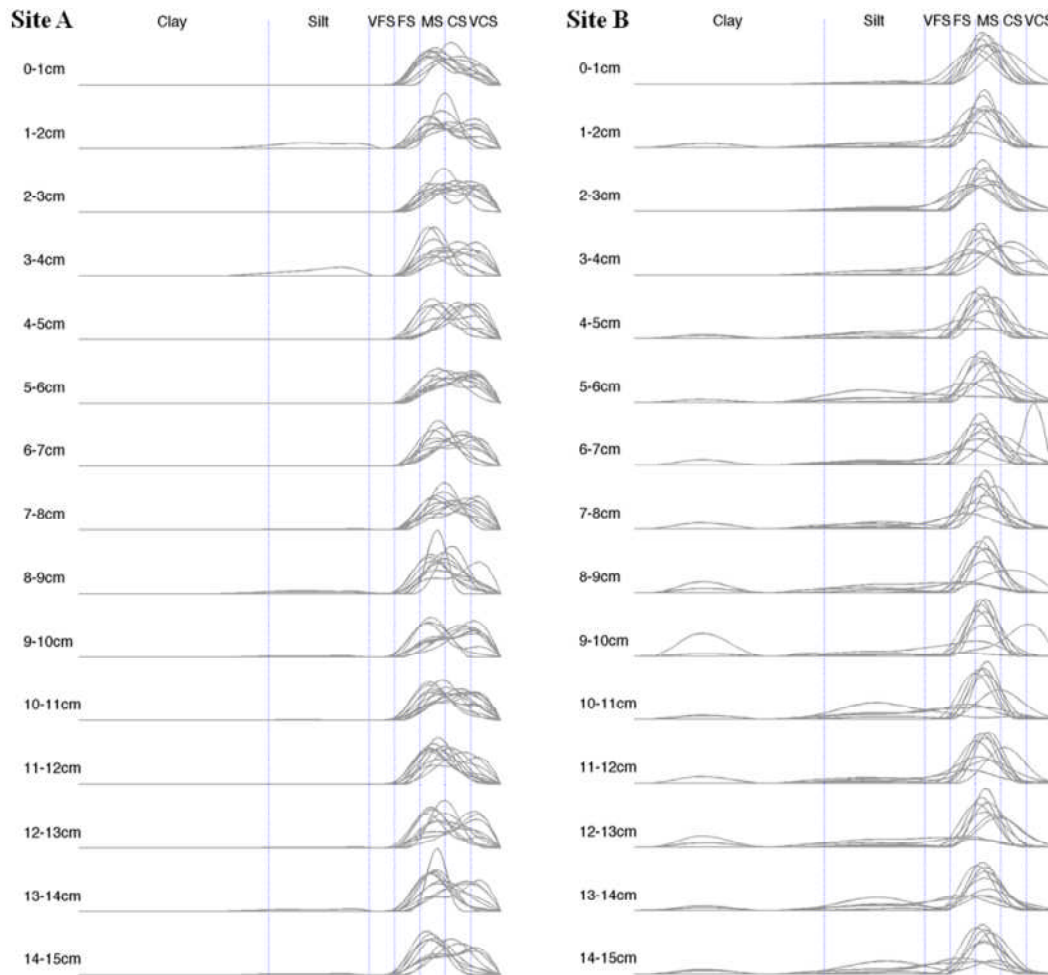


Figure 6.24 Stratigraphical sediment size distribution analysis for the Crantock-Gannel system from the sampling sites. Site A – Crantock beach; Site b – Gannel estuary.

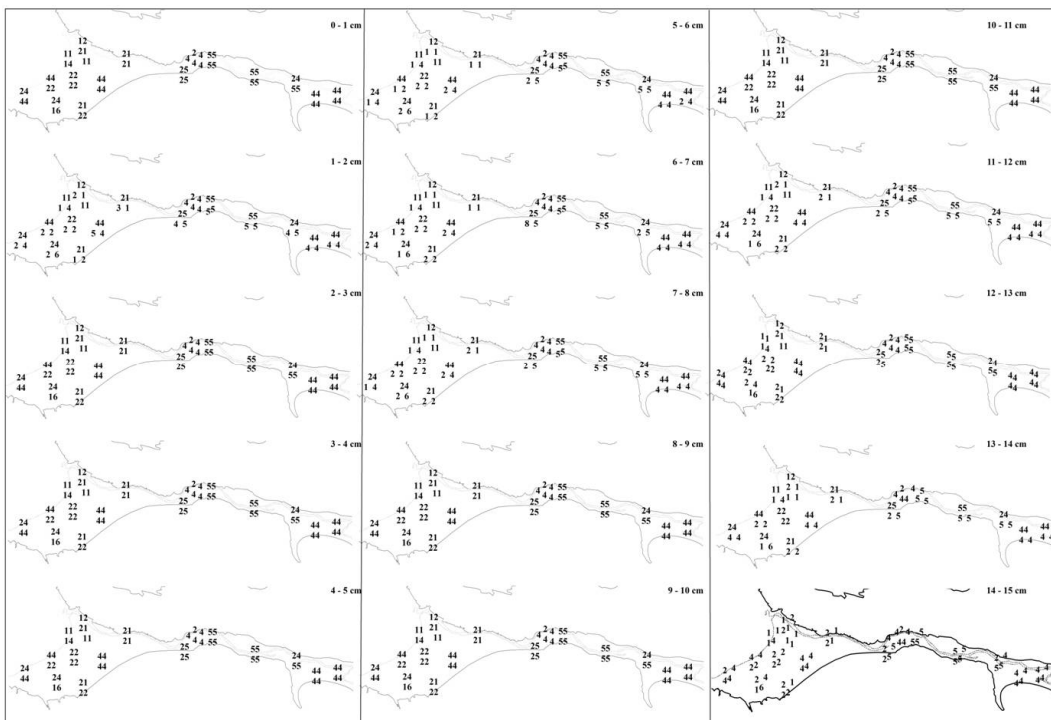
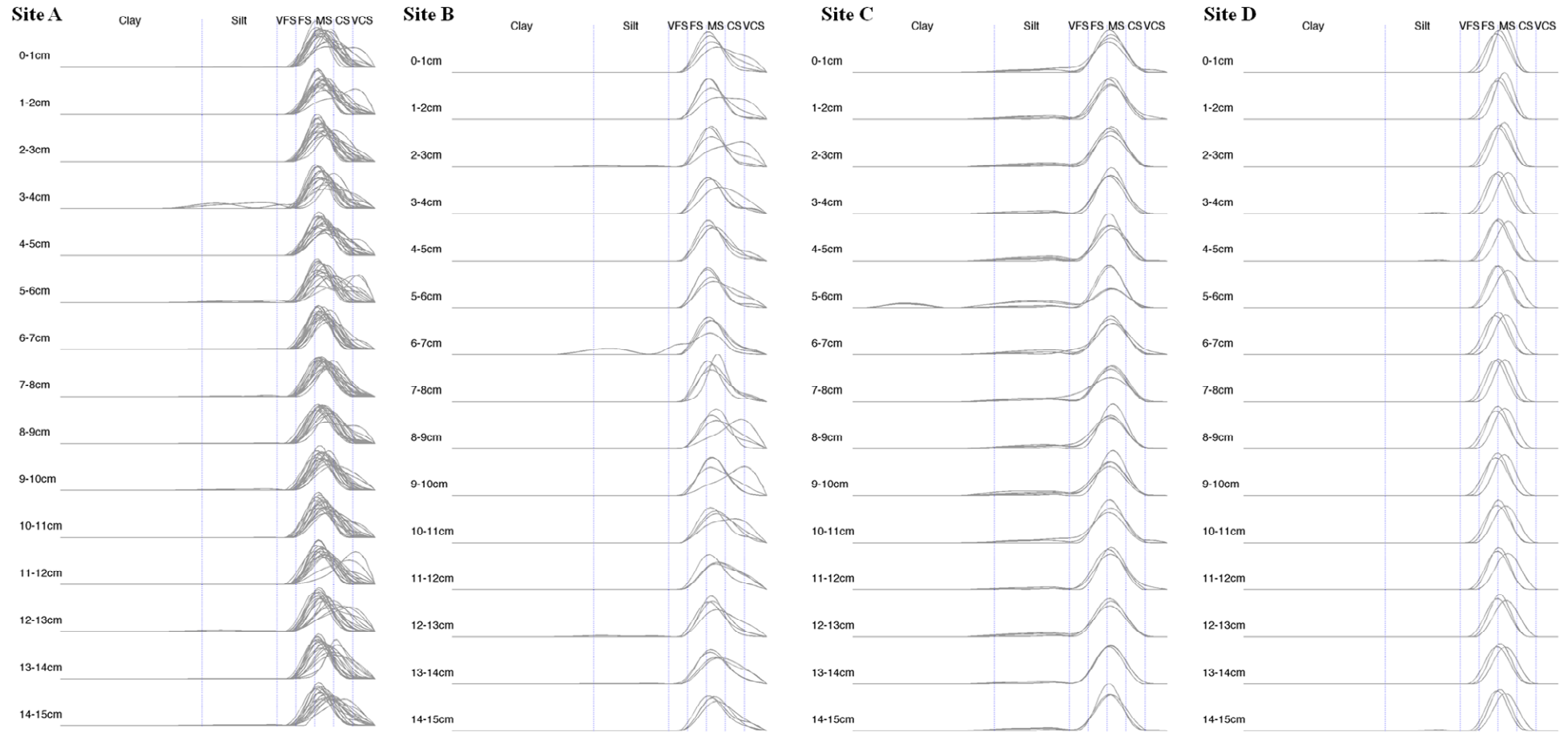


Figure 6.25 Depth variation in the distribution of sediment sub-populations clusters within the Gannel estuary and the beach.



**Figure 6.26** Stratigraphical sediment size distribution analysis for the Padstow/Camel system from the sampling sites. Sites are outer estuary/open coast (A – Harbour Cove/Hawker’s Cove, B – Daymer Bay), mid-estuary (C – Porthilly Cove, D – near Padstow, E, F) and inner estuary (G). See Figure 6.15 for location.



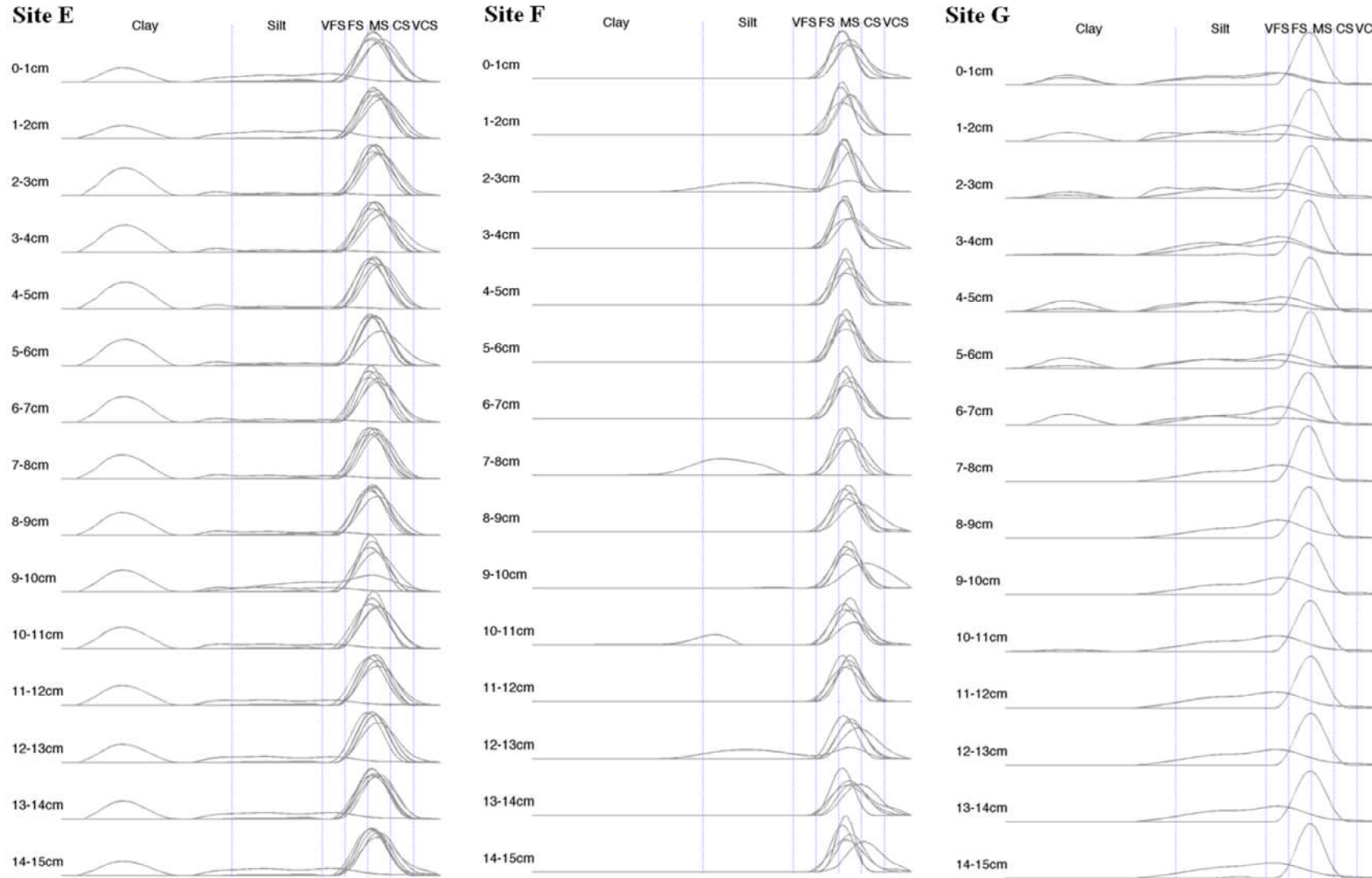
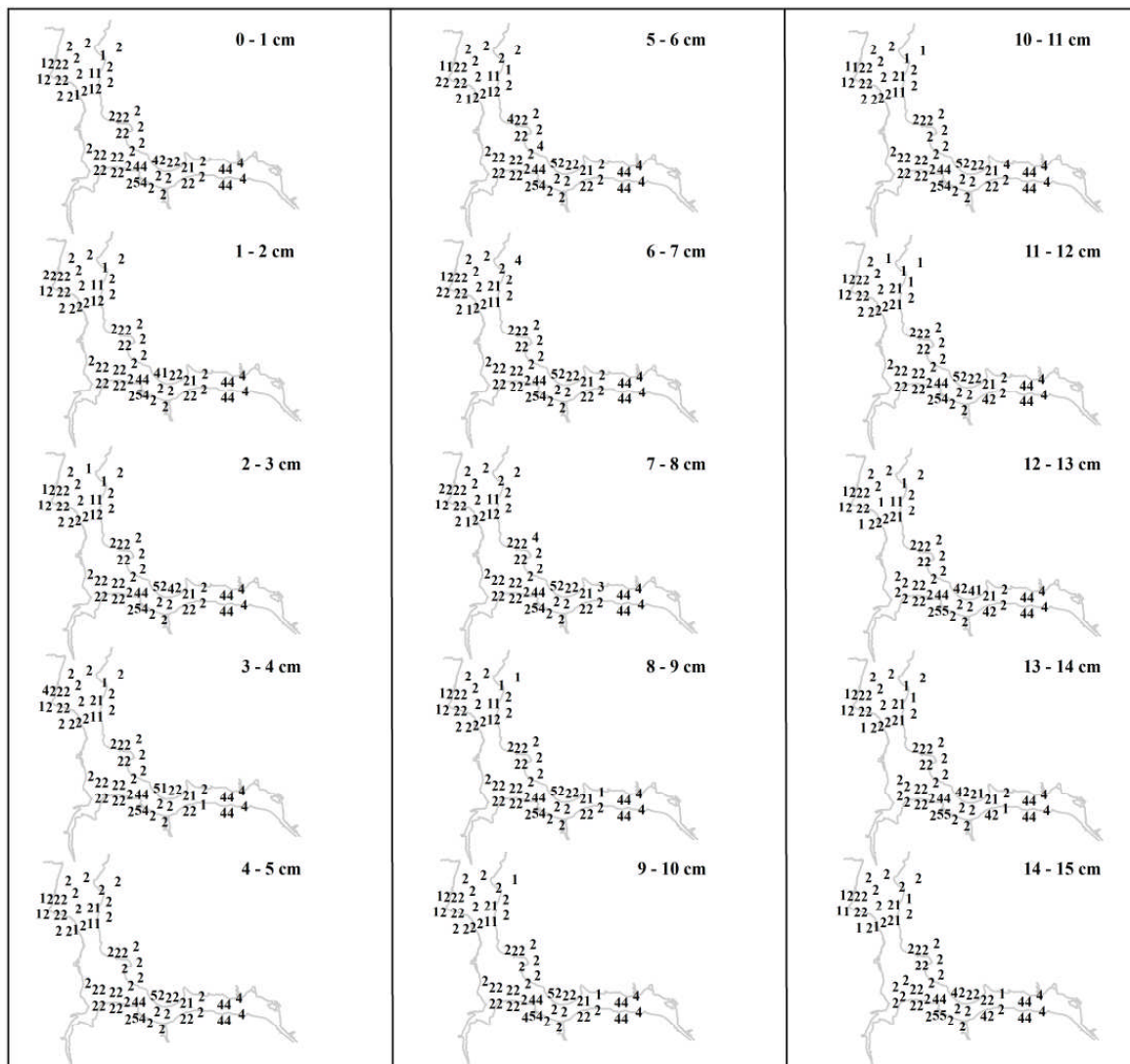


Figure 6.26 cont. Stratigraphical sediment size distribution analysis for the Padstow/Camel system.

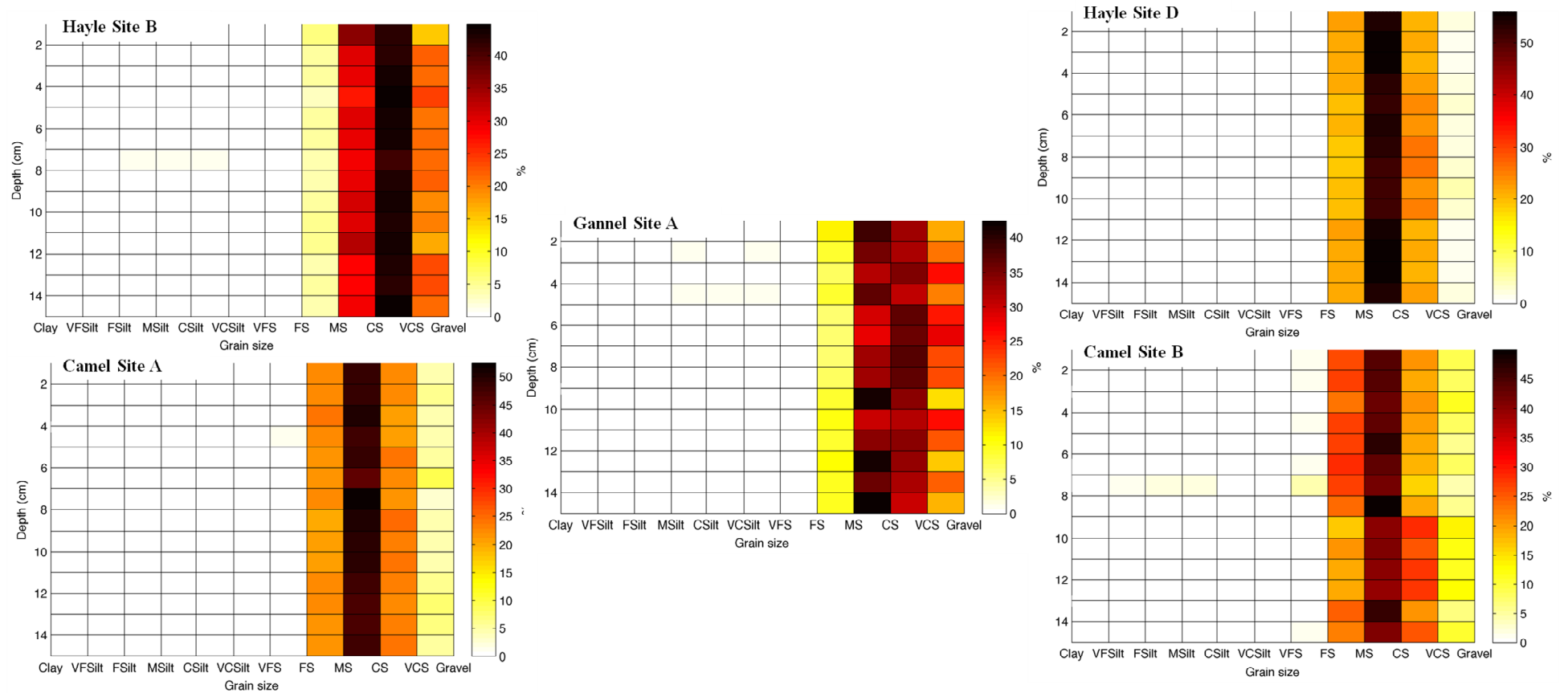


**Figure 6.27** Depth variation in the distribution of sediment sub-populations within the Camel estuary.

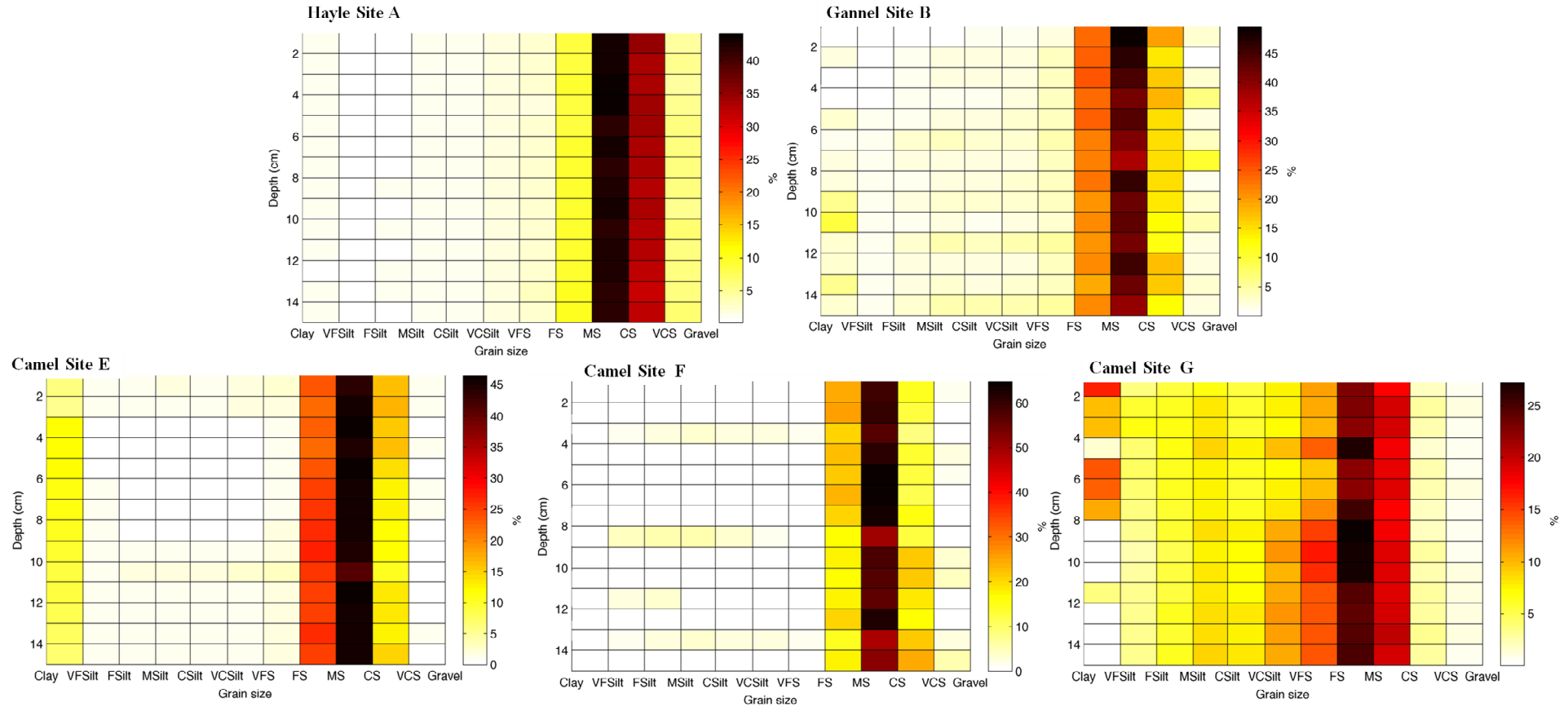
### 6.1.6 Regional comparison of intertidal sedimentary environments

The comparative examination of the down-core grain size distributions across the beach sites studied in the region are presented in Figure 6.28 as ‘heat maps’, which illustrate changes in the percent frequency distribution through variance in colour intensity. An equivalent comparison of estuarine tidal flat sites is presented in Figure 6.29. Across the open-coast sites, the beach and outer-estuary sediments comprise a mix of fine, medium, coarse and very coarse sands, and the distributions are broadly consistent through the stratigraphy (Figure 6.28). The estuarine environment sediment size distributions are also relatively coherent throughout the 15cm sampling depth, with no evidence of specific trends from surface to depth (Figure 6.29). A clay population is notably present within the inner Camel estuary, and to a lesser extent in the Hayle and Gannel. Apart from this, the estuarine sediment size distribution is centred on FS, MS and to a lesser extent, CS.

The spatial sedimentology presented here concurs with many previous studies of sediments in beach and estuary environments. The energy regime within the open-coast - estuary systems considered here shifts from high energy (wave-dominated) within the open-coast, beach environment, to high energy (tide-dominated) within the constricted inlet regions, to low energy within the inner estuarine environment. Here, sediments across the region are generally characterised by medium sands. The sediment of open-coast, beach environments tends to skew the distribution to coarser, with the presence of coarse sand. This reflects the higher energy of these environments. Energy levels decrease within the estuarine environment: although the system is macrotidal, the tidal prism here is limited by the narrow accommodation space, and open coast waves are unable to propagate into the estuary. This leads to a shift in the distribution to finer sediments, with a prevalence of fine sand and the presence of small populations of very fine material.



**Figure 6.28** Grain size distributions, represented as heat maps, for all the beach sites. Colour scale within the heat map represents the percent frequency (%) of the grain size distribution down-core. Note: VFSilt – Very fine silt, FSilt – Fine silt, MSilt – Medium silt, VCSilt – Very coarse silt, VFS – Very fine sand, FS – Fine sand, MS – Medium sand, CS – Coarse sand, VCS – Very coarse sand).



**Figure 6.29** Grain size distributions, represented as heat maps, for all tidal flat sites. Colour scale within the heat map represents the percent frequency (%) of the grain size distribution down-core. Note: VFSilt – Very fine silt, FSilt – Fine silt, MSilt – Medium silt, VCSilt – Very coarse silt, VFS – Very fine sand, FS – Fine sand, MS – Medium sand, CS – Coarse sand, VCS – Very coarse sand).

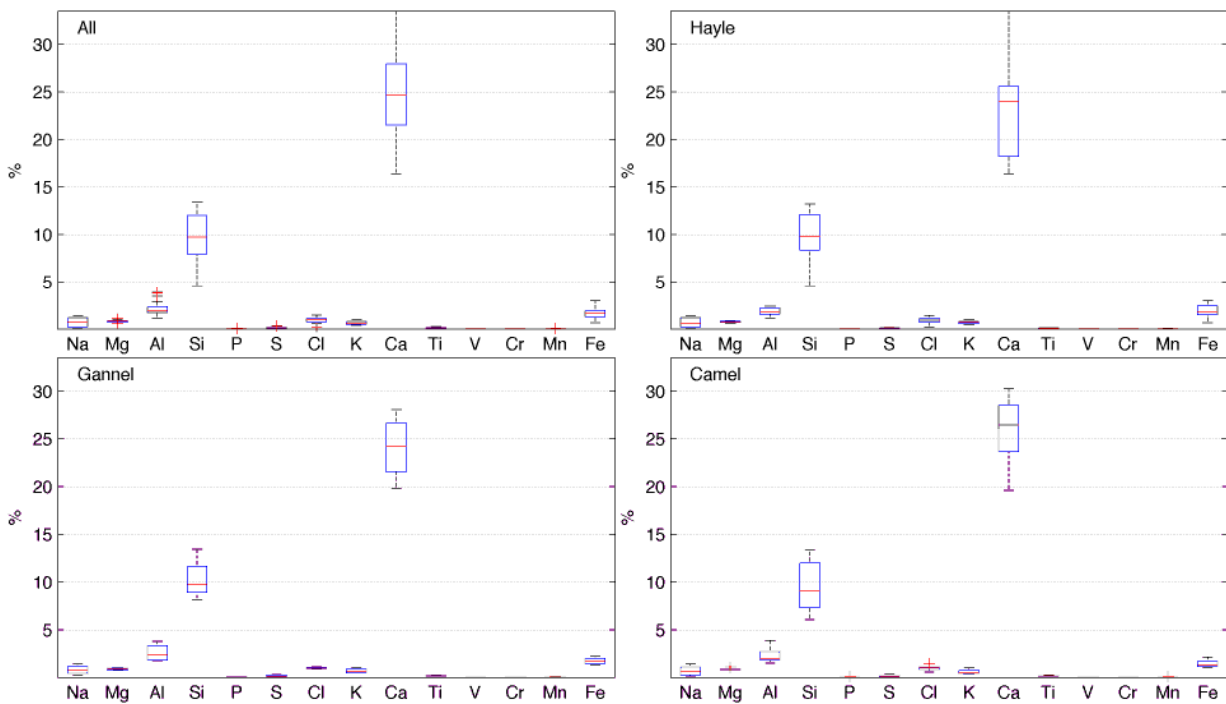
## 6.2 Geochemistry of southwest coastal and estuarine sediments

Previous research on the estuaries in the North Cornwall have primarily focused on the impact of mining on sediments and sedimentation (for example, Reid and Scrivenor, 1906; Bryan *et al.*, 1980., Pirrie *et al.*, 1999; Pirrie *et al.*, 2000a, b; Rollinson *et al.*, 2007; Pirrie *et al.*, 2009, etc). The historical siltation of the estuaries' mouth has been attributed to a combination of sediments released from mine works in the catchments supplemented with marine-derived shell-rich sand (Reid & Scrivenor, 1906), implying that sediments throughout the estuarine mouth comprise a mixed population of sediments from these two sources. Heavy metal contamination research in estuaries in southwest England has confirmed the strong sedimentary link to mining wastes. The present section complements these previous works by exploring the sedimentary connectivity of the system through the evaluation of the geochemical composition of the intertidal sediments within the various sedimentary environments in all of the estuaries.

### 6.2.1 Elemental composition of intertidal sediments

The major and minor/trace elemental analysis of a selection of some few samples from the field samples in each of the three systems is presented in Figures 6.31 – 33 and 6.36 – 6.38 respectively. The major elements are determined as a percentage composition (Norrish and Chappell, 1977) while the minor/trace elements analysis are undertaken to obtain data in concentrations of one to several tons and parts per million (microgram-*mg* or a gram *g*). Sample sediments from Sites A, C, and D of Hayle Estuary (Sample sites in Figure 6.1), Sites A and B of Gannel Estuary (Sample site in Figure 6.8) and Sites A, B, C, E and F of Camel Estuary (Sample sites in Figure 6.15) respectively are analysed for elemental composition and the results of the XRF analysis are presented in this section.

Major geochemical element analysed (XRF) here are: Ca (Calcium), Si (Silicon), Al (Aluminium), Fe (Iron), Cl (Chlorine), Mg (Magnesium), Na (Sodium), K (Potassium), Ti (Titanium), S (Sulphur), P (Phosphorus), Mn (Manganese), V (Vanadium), and Cr (Chromium). The comparison of total base cation content (Si, Mn, P, Cl and Fe) of the Hayle estuaries is high compared to total content analysed for other estuaries while Mg, Al, S, and K of the major elements considered are, however, higher in Camel Estuaries (Figures 6.30). The total base cation content (Na, Mg and K) is low (<5% in total) in all of the sites with the exception of Ca which is much higher (~>= 20%). Patterns in Ca distribution at the systems are broadly similar across the sites. Shell material was clearly present in the sediments sampled, and fragments were noted to contribute to the medium and coarse sand size populations. However, in all of the estuaries, Na, Mg, Si, S, and K have relative lower percentage (0.1 – 6%) of composition in all of the system.



**Figure 6.30** Statistical comparison of major element (XRF) composition (%) of intertidal sediments

The summary comparisons of major elemental composition between the estuarine sediments and the beach/coastal sediments can be observed from the figures 6.31 – 6.33 and the first five samples of the major elements is spatially represented in figure 6.34. The beach sediments in Hayle have higher content of Si, Al and Fe (~13%, ~2% and ~2%) than estuarine (~8%, ~1.5% and ~1.5%) sediments respectively, while there is no significant difference in the elemental compositions of these major elements between the coastal and estuarine sediments in Gannel. In another comparison, the beach sediments in Hayle have lower content of Ca (~20%) than its composition in the estuarine (~34%) sediments. Similarly in Gannel, there is no significant difference in the percentage elemental dimensions of Ca in both estuarine (~20 - ~28%) and beach (~25%) sediments. In Camel estuary, however, the seaward sites (A - B) have lower content of Al, Si and Fe (~2%, ~8% and ~2%) compared to the mid-estuarine samples (Sites C & D, which are ~4%, ~12% and ~2%) and inner-estuarine samples (Site F, which are ~3%, ~13% and ~2%) respectively.

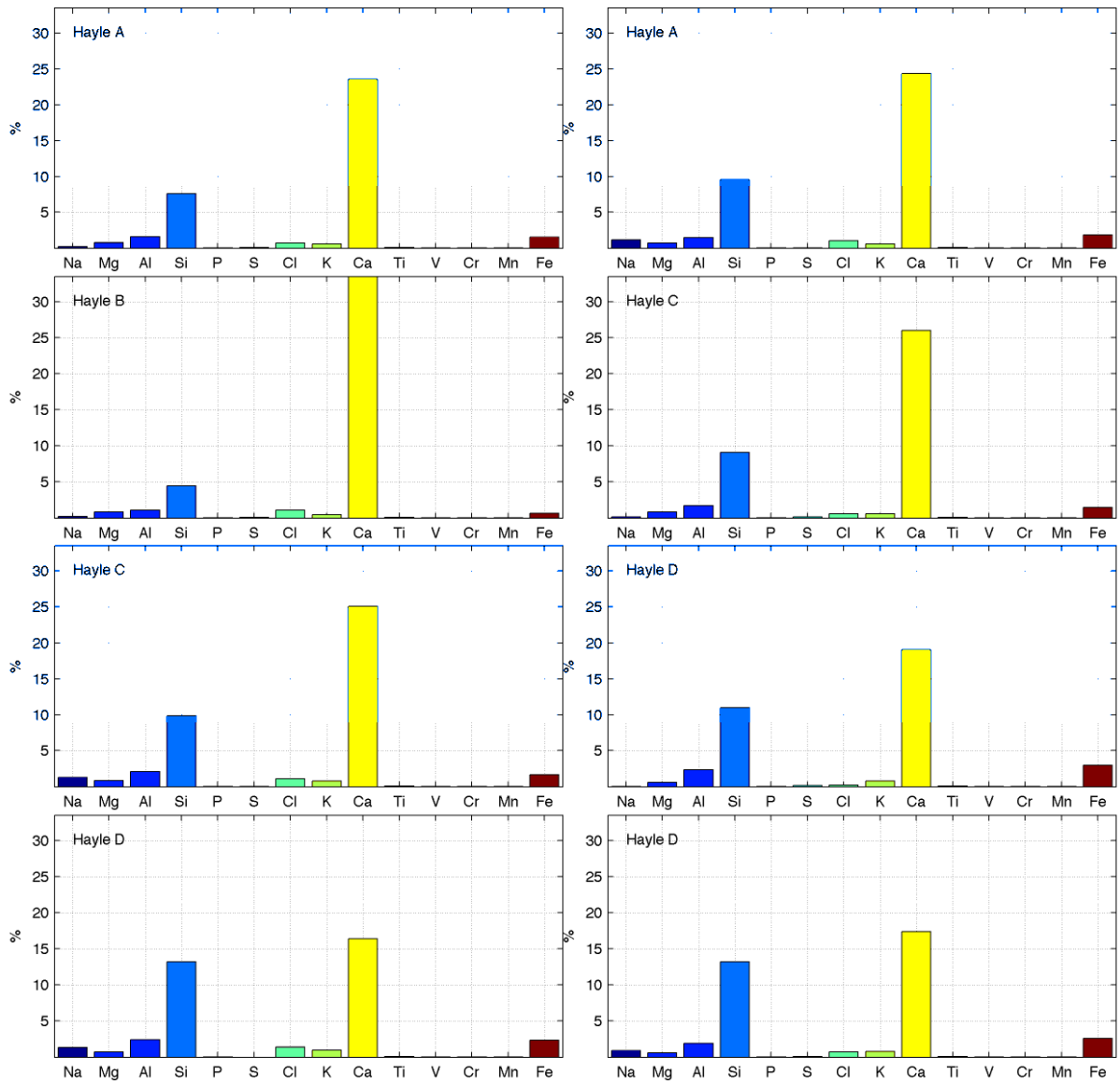


Figure 6.31 Major element (XRF) composition (%) of intertidal sediments at sampling sites in Hayle estuary.

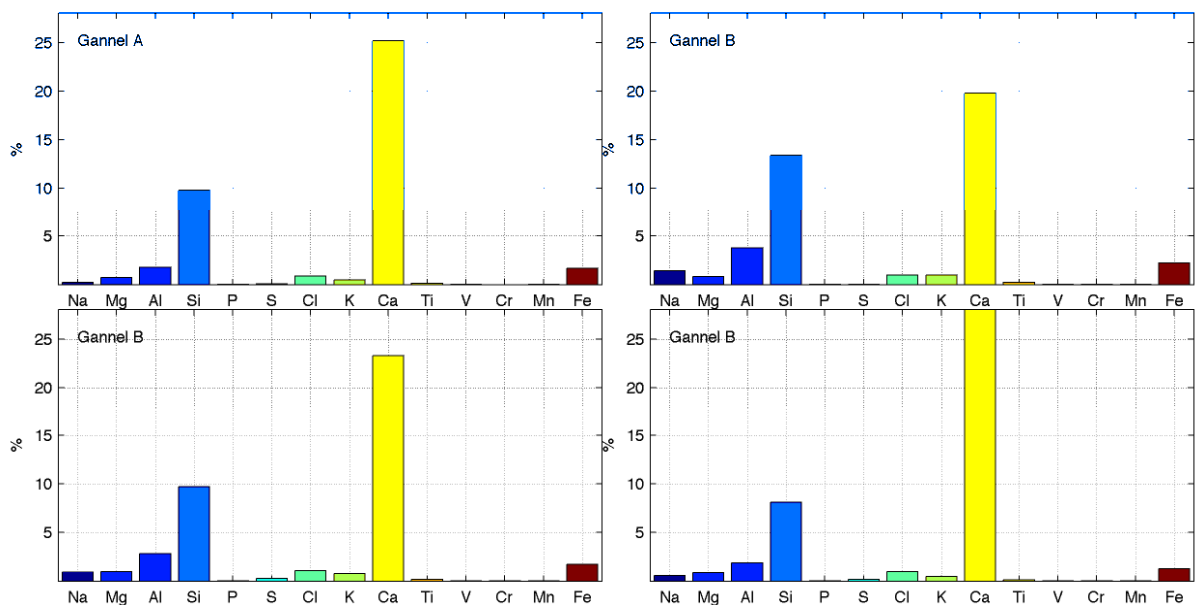
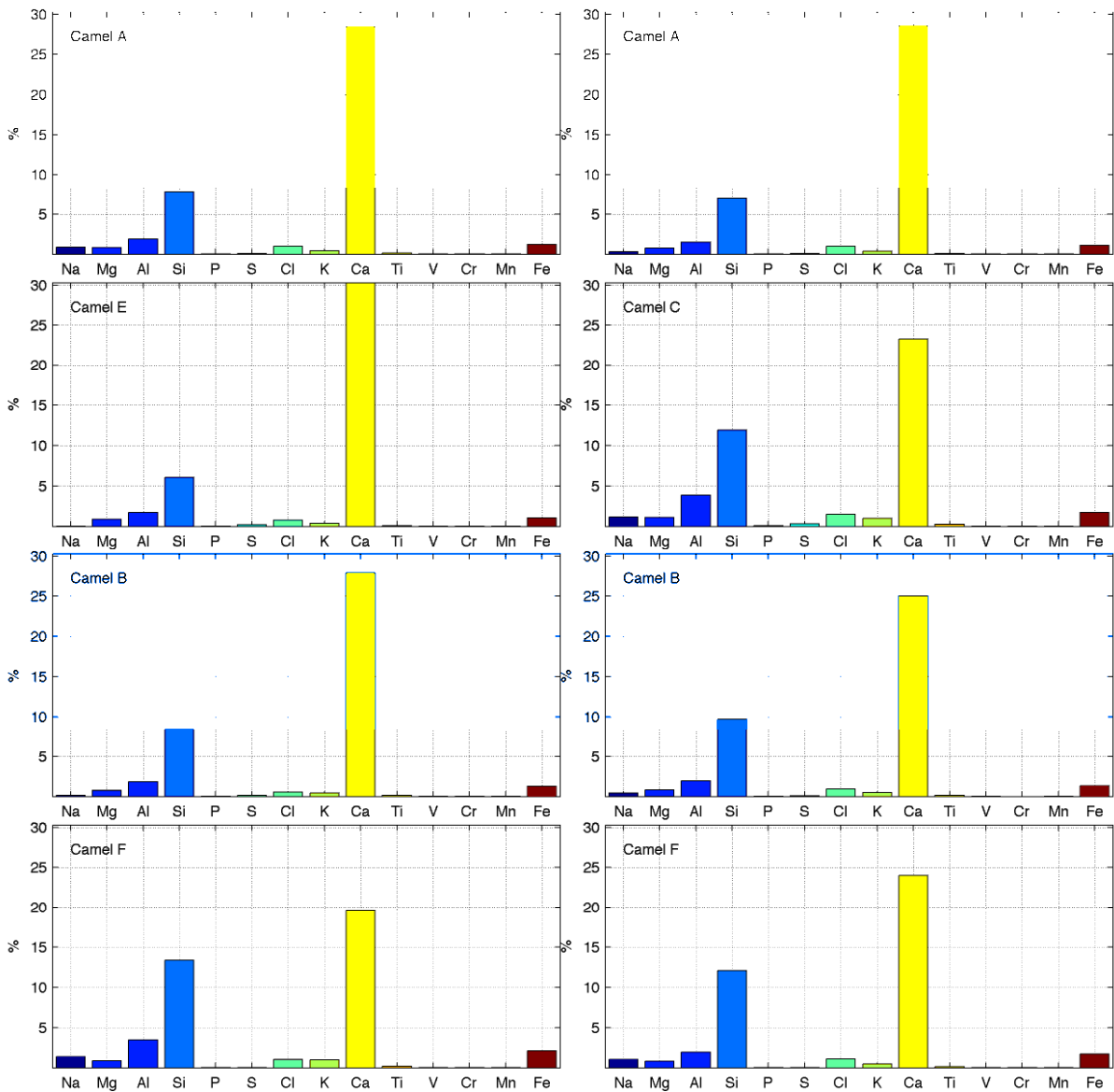


Figure 6.32 Major element (XRF) composition (%) of intertidal sediments at Gannel system.





**Figure 6.33 Major element (XRF) composition (%) of intertidal sediments at the Camel system.**

Comparatively, in Hayle, the estuarine and inlet samples (Site A and C) exhibit a higher content (23 – 33%) of Ca than the open coast/beach sample (Site D) (16 – 19%). In the Gannel, both the estuarine and beach samples exhibit the similar proportions of Ca (19 – 28%). Calcium in the Camel varies spatially: the outer estuary has a high percentage (sites A-C between 25 - 28%), the mid- and far inner estuary slightly less (~20% at sites D & F). Site E in the inner estuary though has the highest concentration of Ca at around 30%. This is the opposite trends observed for Al, Fe and other related major elements. The Al and Fe content across all sites are around 1 - 3% except in Camel sites C, D & F where the Al is around 3.5 - 4% (See figures 6.31 -6.33).

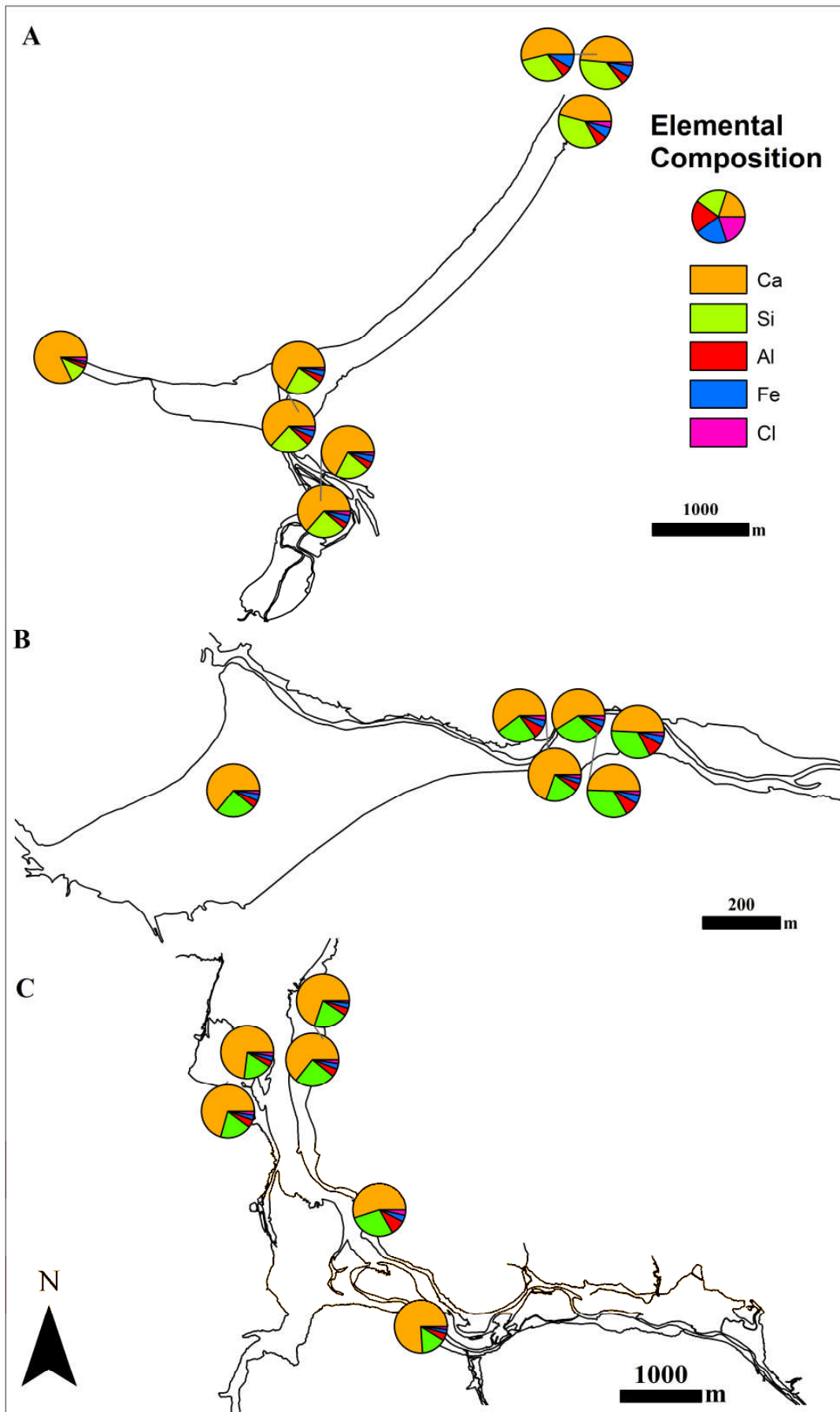


Figure 6.34 Comparative sample of some major elemental composition in the estuaries (A – Hayle; B – Gannel; C – Camel estuaries respectively)

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The geochemical profile of the trace elements sampled for analysis for the estuaries show Ti (Titanium), Cr (Chromium), Co (Cobalt), Sr (Strontium), Se (Selenium), Sb (Antimony), and U (Uranium) are abundantly registered in Camel compared to Hayle and Gannel while V (Vanadium), Zn (Zinc), Br (Bromine), Zr (Zirconium), Ba (Barium), Ce (Cerium), Hg, and Pb (Lead) are higher in Gannel Estuary and Cu (Copper), Ga (Gallium), Ce (Cerium), As (Arsenic), Rb (Rubidium), Y (Yttrium), Mo (Molybdenum), Ag (Silver), Sn (Tin), Te (Tellurium), I (Iodine), Cs (Caesium), La (Lanthanum), Hf (Hafnium), Ta (Tantalum), W (Tungsten), Tl (Thallium), Bi (Bismuth), and Th (Thorium) in Hayle respectively. Trace elemental compositions of the sample sediments from the sampling sites are presented in Figures 6.35 – 6.38 with the comparison of some few selected trace elements spatially compared in Figure 6.39.

Trace elements such as Zn, Rb, Sn, Sr, Zr, Ba, Pb, Ce, La, have high concentrations in all of the samples when compared with other elemental dimensions. There is over 55% concentration of Zn in all of the samples in Hayle and Gannel ( $> 70 \mu\text{g/g}$ ) (Figures 6.35, 6.36 and 6.37), which are higher than the concentrations in the outer-estuarine samples of Camel estuary (Sites A – B,  $\sim 25 - 28 \mu\text{g/g}$ ), Figure 6.38). It is only the mid-inner estuarine samples in Camel (Sites C - F) which exhibit a significant composition of these elements ( $\sim 70 - > 170 \mu\text{g/g}$ ). The coastal/beach sediments of Hayle Estuary have higher composition of Rb ( $> 100 \mu\text{g/g}$ ), than estuarine samples ( $\sim 75 \mu\text{g/g}$ ), while they are of low content in Gannel ( $< 60 \mu\text{g/g}$ ) and Camel ( $< 50 \mu\text{g/g}$ ) estuaries respectively (except at site F, the inner estuary in Camel). The composition at the coastal sediments of site D in Hayle is a bit lower than that of other concentration in the samples. The Zr composition in Gannel and Camel estuaries are higher ( $> 35 \mu\text{g/g}$ ), than sediments' composition of this element in the Hayle Estuary ( $< \sim 35 \mu\text{g/g}$ ), while it is a different scenario for the Sn concentration as there are higher concentration of this element in Hayle ( $> 400 \mu\text{g/g}$ ), than in the Gannel ( $< \sim 107 \mu\text{g/g}$ ) and Camel ( $< 30 \mu\text{g/g}$ ) estuaries. Ba and Pb are also of notable composition ( $> 50$  and  $> 10 \mu\text{g/g}$  respectively) in all of the sites with the significant dimension of concentration recorded in Camel's inner estuarine samples at site F ( $> 106$  and  $84 \mu\text{g/g}$  respectively).

Sr (Strontium) is strongly associated with Ca (Calcium) and it is therefore strongly present where Ca is apparent in all of the three systems. Sr content in sediments are highly controlled by combination of parent rock materials and climate, and therefore its concentration is higher with a range of  $50 - 1000 \text{ mg kg}^{-1}$  (Taylor, 1964). Here, the composition of Sr is higher in all of the sample sites ( $> 1000 \mu\text{g/g}$ ) except at Hayle Beach Site D where it is less than ( $<$ )  $1000 \mu\text{g/g}$ . Although Sr is easily mobilised and derived during weathering processes, notably in oxidising acidic environments, it can also be incorporated in clay materials and fixation of organic materials (Salminen, *et al.*, 2005). The anthropogenic sources from industrial waste, especially from Zn refineries, incineration ash and disposal of coal ash are other possible derivation of Sr in sediments (Reimann and Caritas, 1998). History of mining wastes in the system are thought to

contribute to the high content of Sr observed at the study sites in figures 6.35 and 6.39 (also See section 6.2.2.).

The majority of the samples in all of the sites exhibit a reasonable high percentage of Si dimension with Si being prominent at samples across the seaward/coastal zones, reflecting the importance of the quartz component. The proportions associated with the other major elements, for these samples, are minimal (Figures 6.35 and 40).

The result of the Principal Component Analysis (PCA), using the correlation-type in Paleontological Statistics (PAST) software is presented in Figure 6.41. The first three main eigenvalues (12.09, 8.9, 3.79) of the nineteen values in the analysis correspond to 35.6%, 26.2% and 11.2% of the total variance respectively. Thus the first two principal components (PC), presented as Biplot in Figure 6.41, provides the basic information about the differences in the elemental composition. The x axis presents the PC1 while the y axis indicates the PC2 of the elemental composition. Quite a lot of the minor elements are at/just above detection level and therefore are ignored in the detailed analysis. Here, the difference between the Hayle and the other two estuaries are obvious. Specifically, the Hayle is much higher in metal pollutants than the other estuaries, and much lower marine carbonates (Ca, Sr) (See also Figure 6.40). The inclusion of the grain size statistics did not really change the pattern of results (in the cluster or PCA analyses), but it shows that coarser grain sizes in the Hayle are rather more strongly associated with the metals Cu and Sn, but not associated with the metals Pb and Fe in the PCA result presented here. This is a result of the Hayle system being contaminated by mining in the 19<sup>th</sup> century.

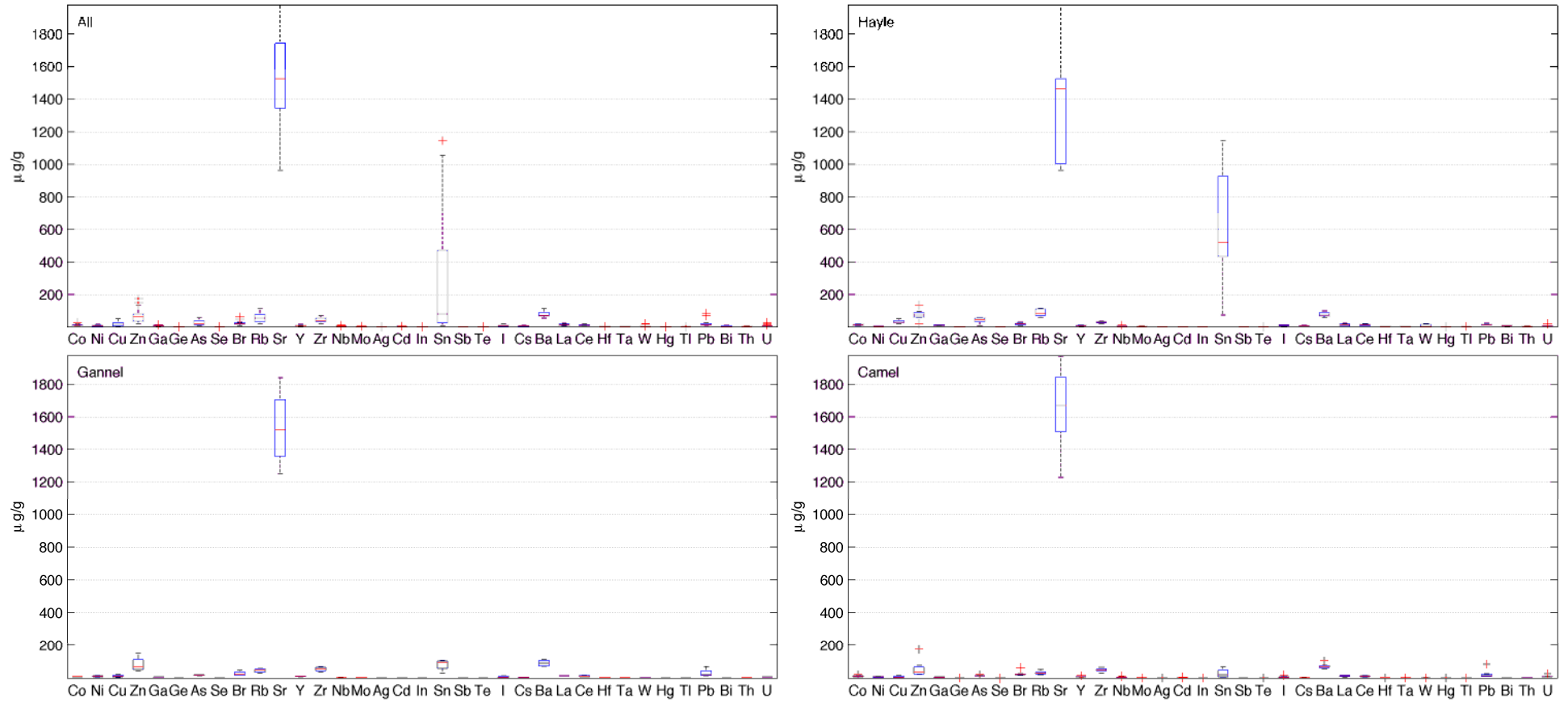


Figure 6.35 Statistical comparison of minor element (XRF) composition (%) of intertidal sediments.

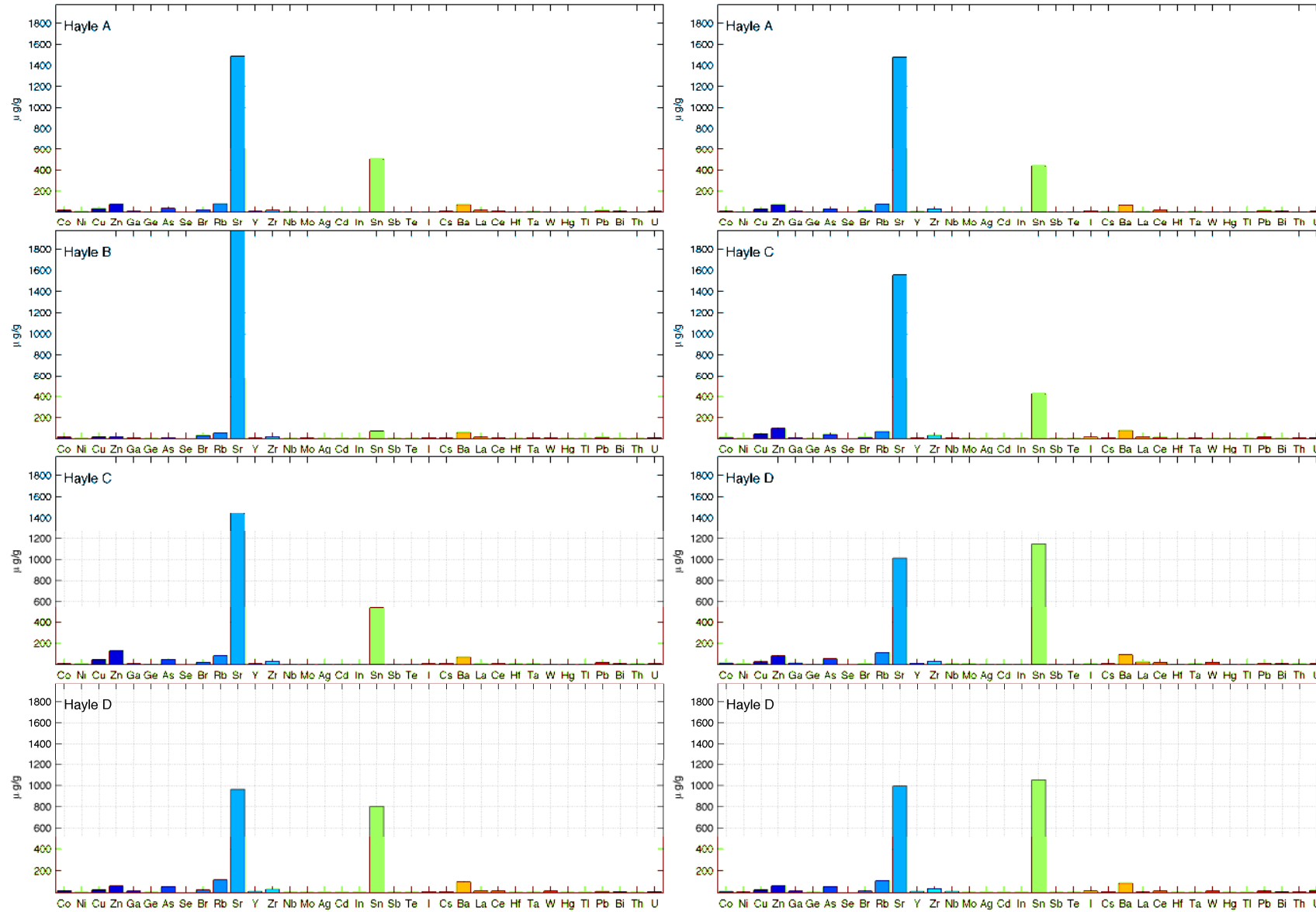


Figure 6.36 Minor/Trace element (XRF) composition (ug/g) of intertidal sediments at sampling sites in St Ives Bay (B – D) and the Hayle Estuary (A).

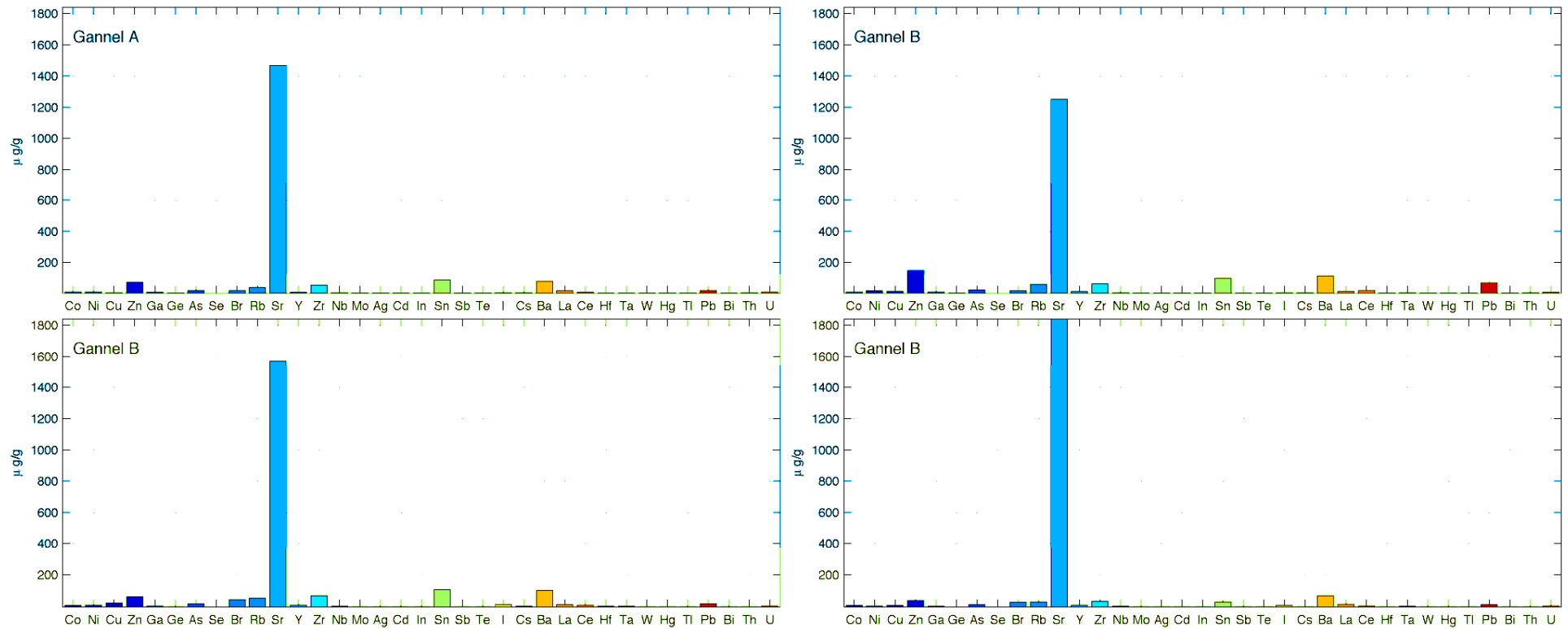


Figure 6.37 Minor/Trace element (XRF) composition (ug/g) of intertidal sediments at sampling sites in Crantock beach (A) and the Gannel Estuary (B).



Figure 6.38 Minor/Trace element (XRF) composition (ug/g) of intertidal sediments at sampling sites in Camel Estuary.



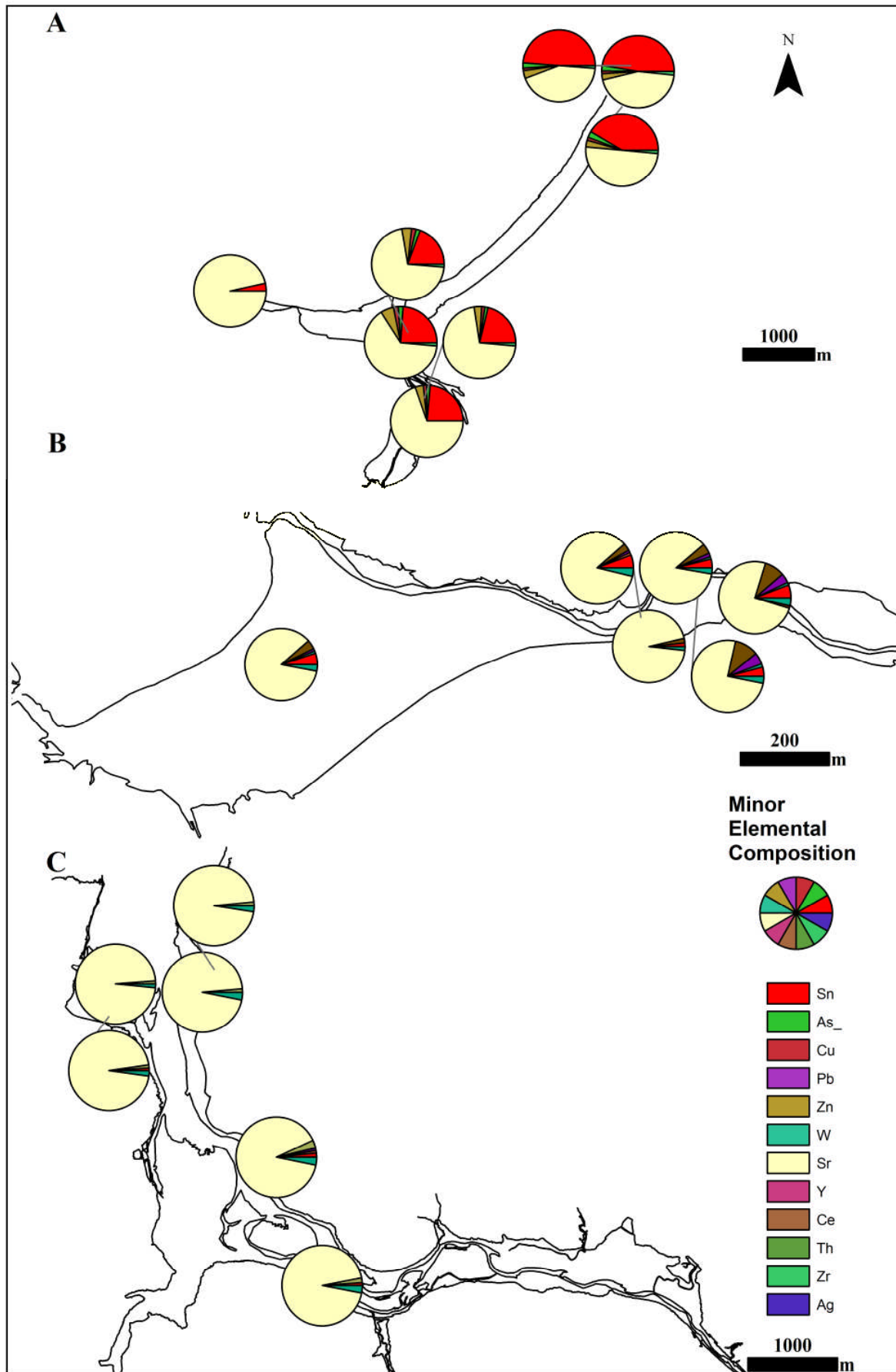
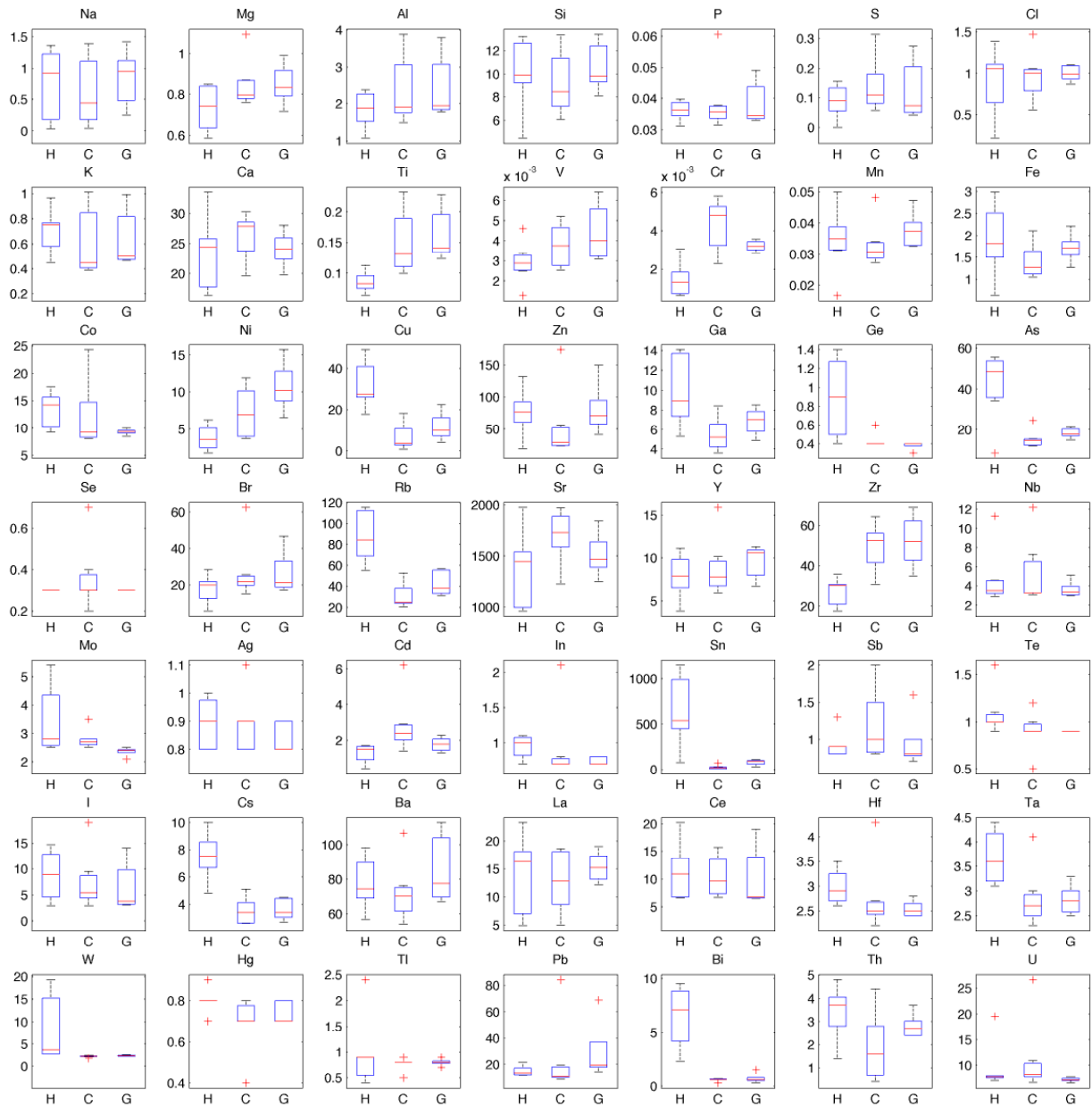


Figure 6.39 Comparative sampling of some minor elemental composition in the systems (A – St Ives-Hayle; B – Crantock-Gannel and C – Padstow-Camel systems respectively).



**Figure 6.40** Comparison of major (Na to Fe) and minor/trace (Co to U) element composition across the three sites (H - Hayle; C - Camel; G - Gannel). Elements Na to Fe are measured in %; elements Co to U are measured in  $\mu\text{g/g}$ .



### 6.2.2 Evidence for sediment sources

The current coastal and estuarine sediment build-up is as a function of either onshore or offshore supply of natural sediments coupled with supplies arising from human activities (Pirrie *et al.*, 2000a). Cornish estuaries have received considerable attention regarding sediment geochemistry - principally as a result of past mining activities in the region. The distribution of Sn and other heavy materials in the superficial portion of the sediments in Hayle Beach and Gwithiam area was attributed to the transportation of mine waste by the River in the documented work of Hosking and Ong (1963-64). Although the River Hayle is very active in the estuary and drains a significant part of the mining area, Pirrie *et al.* (1999) observed that River Hayle alone could not have supplied much of such sediment to Hayle's beach as the estuary acts as an "efficient sediment trap". Other studies have recognised the sizeable depositions of Sn in the Hayle estuary, including the works of Yim (1976), Merefild (1993), Healy (1995), Healy (1996), Pirrie *et al.* (1999), Rollinson *et al.* (2007) and Pirrie *et al.* (2009). Rollinson *et al.* (2007: 328) using Figure 6.42C to highlight over 60 hard-rock mines operations which contribute discharge of large volumes of fine grained tailings into the Hayle Estuary. The major mining operation areas (as black circles in the figure), numerous smelting/mineral processing plants (as open circles in the figure) and tin processing plants (location represented as grey circles) contributed the discharge of large volumes of fine sediments enriched in Sn, Cu, As and Zn. Hayle was important sites for Cu, Sn and large scale tin smelting and iron foundry in the eighteen and nineteen century, the cessation of which contributed to the release of particulate mine waste to the estuary (Firth and Smith, 1999; Buckley, 1999; Rollinson *et al.*, 2007).

Pirrie *et al.* (2000b) suggests the Camel estuary is significantly enriched in Sn, W and Zr, sourced from the release of particulate mine wastes directly from the hard-rock mining activities at Mulberry and Lanivet region. Figure 6.42 (after Jenkin, 1963, 1964 in/from Pirrie *et al.*, 2000: 26) shows that tin mine waste in the Camel was likely sourced from around Mulberry and Lavinet, where large quantities of cassiterite were discharged into the estuary through local streams. The geochemical elemental profile of the estuarine sediments shows the composition of mining related sediment supplied to the estuarine system (Pirrie, *et al.* 2000b). Based on findings by Pirrie, *et al.* (2000b) and as indicated in Figure 6.42B, "the Pb-Zn-Ag mine waste in the Gannel Estuary was derived from the mines in the Newlyn Downs area such as East Wheal Rose" (2000b:26). This is also in line with the findings of Bryan, *et al.* (1980) which also recognised the significant presence of Pb in Gannel Estuarine sediments. The source could be attributed to the "cross-course" mineralisation and mining activities at the estuary.

From the results presented in the previous section and the introduction in this section, it can be stated that the elemental composition of the geochemical of both the estuarine and beach/open coast sediment samples show that the build-up of the inter-tidal sediments in the estuaries are as a result of offshore sources combined with the onshore sediments

transported into the estuaries (which have been impacted as a result of human activities, notably mining). The almost equal concentration of the major biogenic elements in all of the estuaries supports the view that the valleys of the estuaries, with the infilling of sediments of similar geochemical content at almost equal proportion, are derived as a result of flood of the early Holocene. Pirrie *et al.* (2000a) stated that “in Cornwall, the Coastal valleys or ria systems were flooded as a result of sea level rise in the early Holocene to form the modern estuary system” (2000a:21). The almost homogenous concentration of the major geochemical elements in the three estuaries suggest that bulk of the sediments which in-filled the estuaries are derived from offshore as a result of the flooding of the valley during the early Holocene.

Aluminium, potassium, manganese and iron (Al, K, Mn, and Fe) are the dominant signals for the terrestrial/onshore inputs into the sediments in the region. The sedimentary concentrations of these elements follow similar pattern in all of the estuaries. This indicates here that both onshore and offshore contributions (evidenced by the concentration of marine elements such as Mg, Sr, and so on) also interplay in supplying sediments to the estuaries. In addition, one of the most important contributors to the siltation of the estuaries in the 19<sup>th</sup> and 20<sup>th</sup> century is “the release of particulate waste from upstream mining” (Pirrie *et al.*, 2000b). The previous studies/works in the region (examples listed earlier) have clearly indicated the significant role of previous mining industries in the region on sediment supply to the coastal zones as evidenced in the concentration of some elements (e.g, Sn, Sb, Pb, Zn, Ag, Cu and so on) which were the principal elements in the mining industry.

The previous studies on Hayle Estuary (For example, Hosking and Obial, 1966; Yim, 1976; Merefield, 1993; Brown, 1977; Pirrier, *et al.*, 1999b; Rolinson, *et al.*, 2007) show significant signature of metallic mine waste release into the estuary with record high values of Sn, Cu, W, Pb and As in sediments sampled analysed for this study. Also, as stated by Pirrie, *et al.* (2000b), the geochemical data for Camel estuary clearly indicated a pulse of sediments which are significantly rich in Sn, W and Zr which “corresponds mineralogically with abundant cassiterite, wolframite, zircon (Zr), monazite (Ce and La) and xenotime (Y)” (Page 26). This suggests that the sediments is “clearly sourced from the release of particulate mine waste derived from hard-rock mining activity centred around high temperature sn-rich main stage mineralisation” (Pirrie, *et al.*, 2000b:26). Of all the estuaries, the Gannel is recognised to contain the highest Pb contamination of any estuary in the South-West Engalnd (Bryan, *et al.*, 1980; Pirrie, *et al.*, 2000b). The geochemical parameters of the sediments indicate that the sediment might have been “sourced from particulate waste from mining activity centred on cross-course mineralisation” (Pirrie, *et al.*, 2000:27). Previous work in the estuary (Reid and Scrivenor, 1906; Bryan, *et al.*, 1980; Thorne, 1983; Pirrie, *et al.*, 1999b; Pirrie, *et al.*, 2000b) clearly suggest that Gannel Estuary received “significant mine waste from mines working Pb-Ag-Zn lodes” (Pirrie, *et al.*, 2000b: 27).

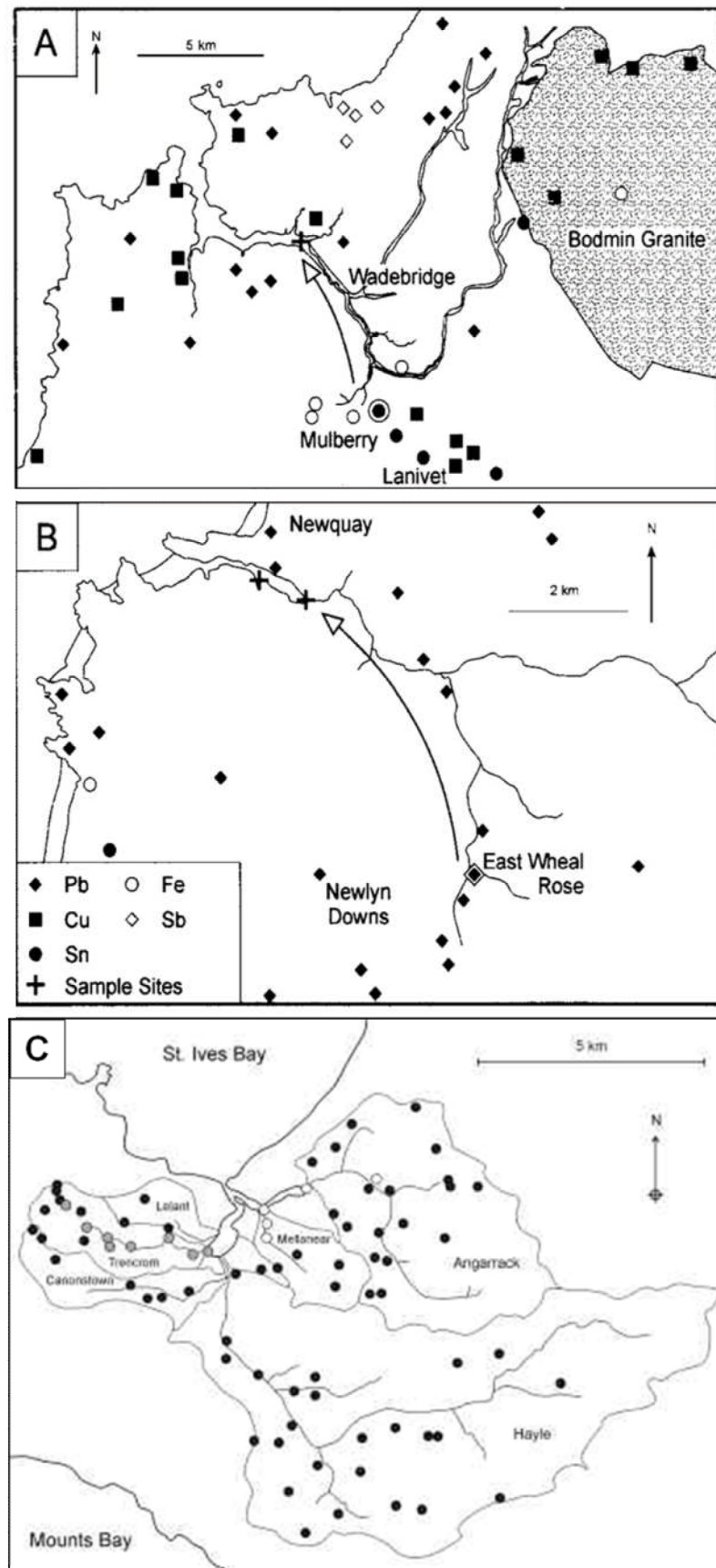


Figure 6.42 Summary diagram showing the main mining operations in the catchments of (A) the Camel Estuary, (B) the Gannel Estuary, and (C) the Hayle Estuary, (A and B after Jenkin, 1963, 1964 and Pirrie, *et al.*, 2000b: 26 and C from Rollinson, *et al.*, 2007:328).

## 7 REGIONAL BATHYMETRIC CHANGE

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The previous chapters have focused on shoreline morphodynamics and sedimentology of the study sites. Of importance, also, to the overall concept of morphological dynamics and adjustments in coastal environment is the seabed behaviour. Nearshore bathymetric changes are widely recognised as a potential force and control on coastal dynamics with wave energy dissipation and modification of propagating waves, thereby resulting in longshore variations of wave energy distribution and sediment transportation (MacDonal and O'Connor, 1996; Maa, *et al.* 2001; Bender and Dean, 2003; Brooks, 2010; Hequette and Aernouts, 2010). This chapter focuses on the morphological history of the seabed adjacent to the St Ives to Padstow Bay coastlines, southwest England. SWAN wave modelling is undertaken to investigate how the bathymetry influences nearshore wave climate, and bathymetric change analysis between 1931 and 2008 is undertaken to assess what impact changes in seabed morphology might have on this wave climate.

### 7.1 Bathymetric change analysis

The seabed off the north coast of Cornwall comprises a steadily deepening shoreface. Unlike other parts of the shoreface around England and Wales, there are no significant offshore sand banks or ridge features (Figure 7.1). Numerous shipwrecks scatter the seabed in this region owing to the presence of rocky outcrops and submerged rocky reefs. Even those features named as shoals or banks (e.g. Bann Shoal and Cape Cornwall Bank) are indeed rocky ridges or outcrops. Bathymetric contours broadly follow the coastline configuration except for around St Ives and Padstow bays. At the former, contours extend some distance offshore and the shoreface to the north and northwest of St Ives Bay is considerably shallower than the neighbouring coastlines. In contrast, seabed contours move landwards at Padstow Bay, where the immediate shoreface is considerably deeper than elsewhere on this coastline. Within 10km of Padstow Bay however, lie multiple rocky outcrops. Based on annotations on the most recent Admiralty chart for the region, the seabed comprises sand, broken shell and bare rock outcrops. It is clear from the bathymetry that the mobile sediments are not organised into large-scale deposits, but instead form discrete patches across a bedrock surface.

The analysis of historical change of the seabed in the region of interest between 1931 and 2008 is presented in Figure 7.2. Sea-level change has not been adjusted for in these analyses, but as the comparison of bathymetric surfaces, derived from digitised depth soundings shows some degree of stability through the 77 year period. Scales of change are relatively small, but with only discrete locations showing larger scale changes. The overall picture of change however is one of shallowing -broad areas of the seabed unit show a positive signature of change, indicating that

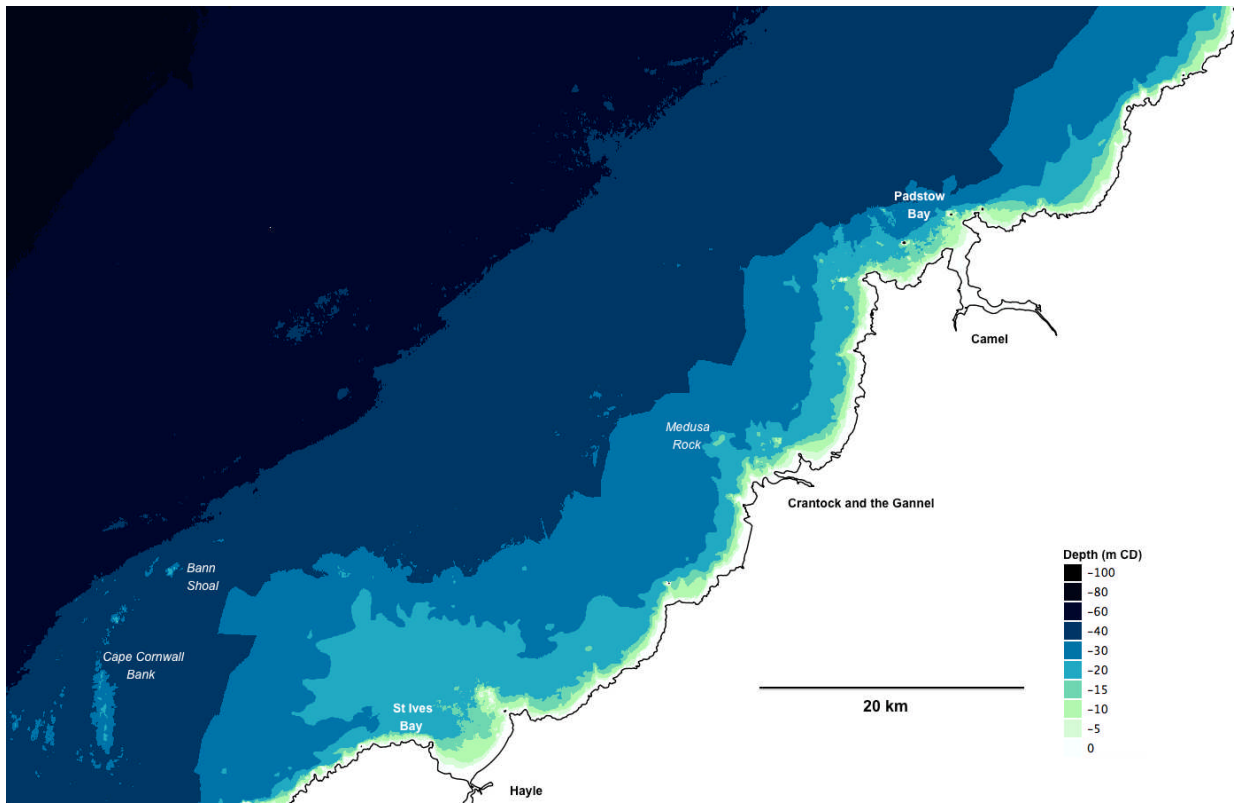


Figure 7.1 Current bathymetry of the north Cornwall shoreface.

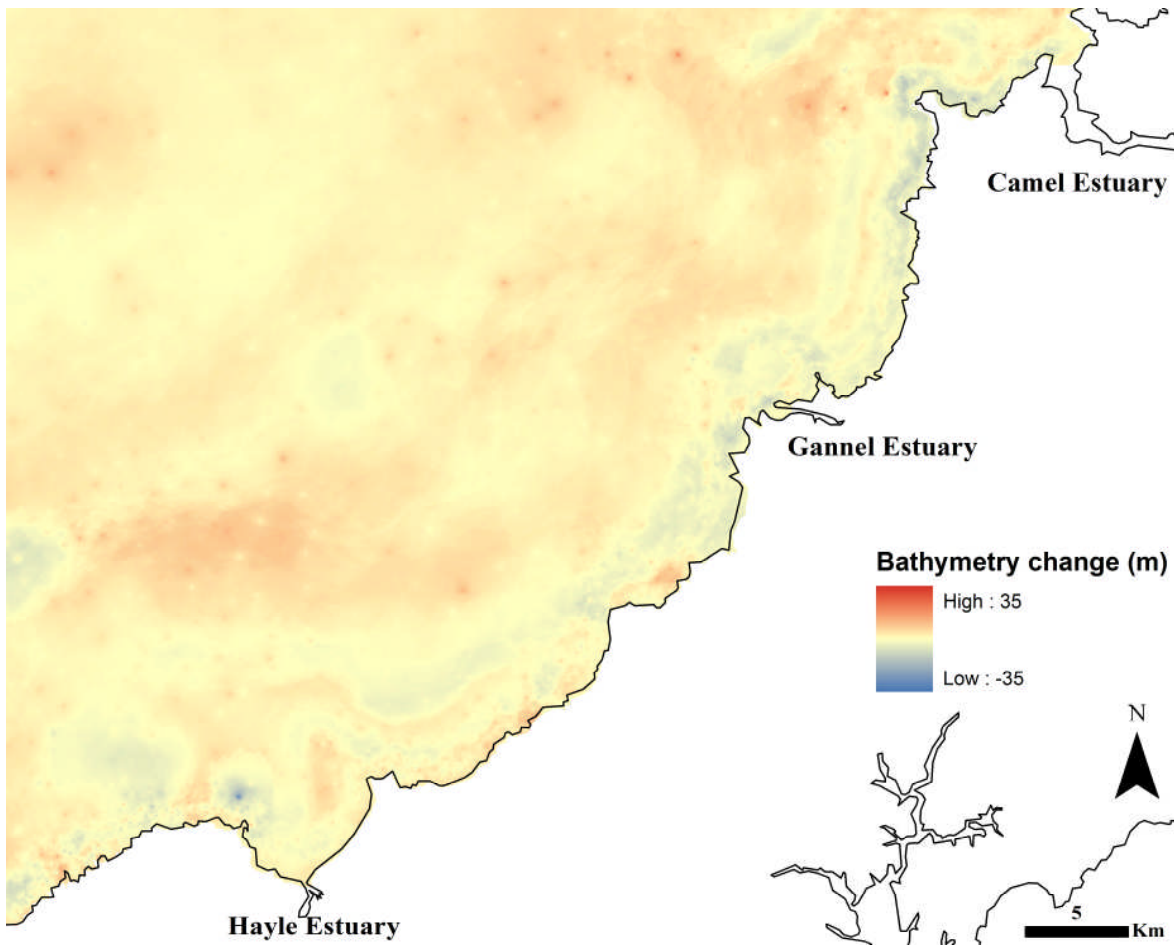


Figure 7.2 The pattern of change in the seabed at Southwest England (1931 to 2008).



the shoreface surfaced as accreted. Negative change (downwearing) is found in narrow patches primarily closer to, and associated with, the rocky shorelines. The most significant region of accretion is c. 15km to the north of St Ives Bay. The seabed here is covered in medium sand and broken shell suggesting that it might be quite dynamic.

An estimate of the volume associated with this historical change was computed based on the volume across the region of interest (kept constant) in 1931 and 2008 (Table 7.1). Based on this analysis, the volume of seabed sediment increased by c.  $8.3 \times 10^8 \text{ m}^3$ , equating to an average vertical change of +3.6 m between 1931 and 2008 across the entire shoreface analysed. As a constant rate of change between 1931 and 2008, this is equivalent to  $0.05 \text{ myr}^{-1}$ . Errors associated with bathymetric surveying, datum conversions and interpolation procedures are usually of the order  $0.5 \pm \text{ m}$ . van der Wal and Pye (2003) reported a confidence interval of  $\pm 0.58 \text{ m}$ , so this suggests that the changes observed here are well beyond the error margin.

**Table 7.1 Area and volumetric seabed change in the region between 1931 and 2008.**

Year	Volume above OD datum ( $\text{m}^3$ )	2D Area covered $\text{m}^2$	Volumetric Change ( $\text{m}^3$ )	Average vertical change (m)
1931	67,695,288,575	2,306,017,499	8,313,542,205	3.61
2008	76,008,830,780	2,306,017,499		

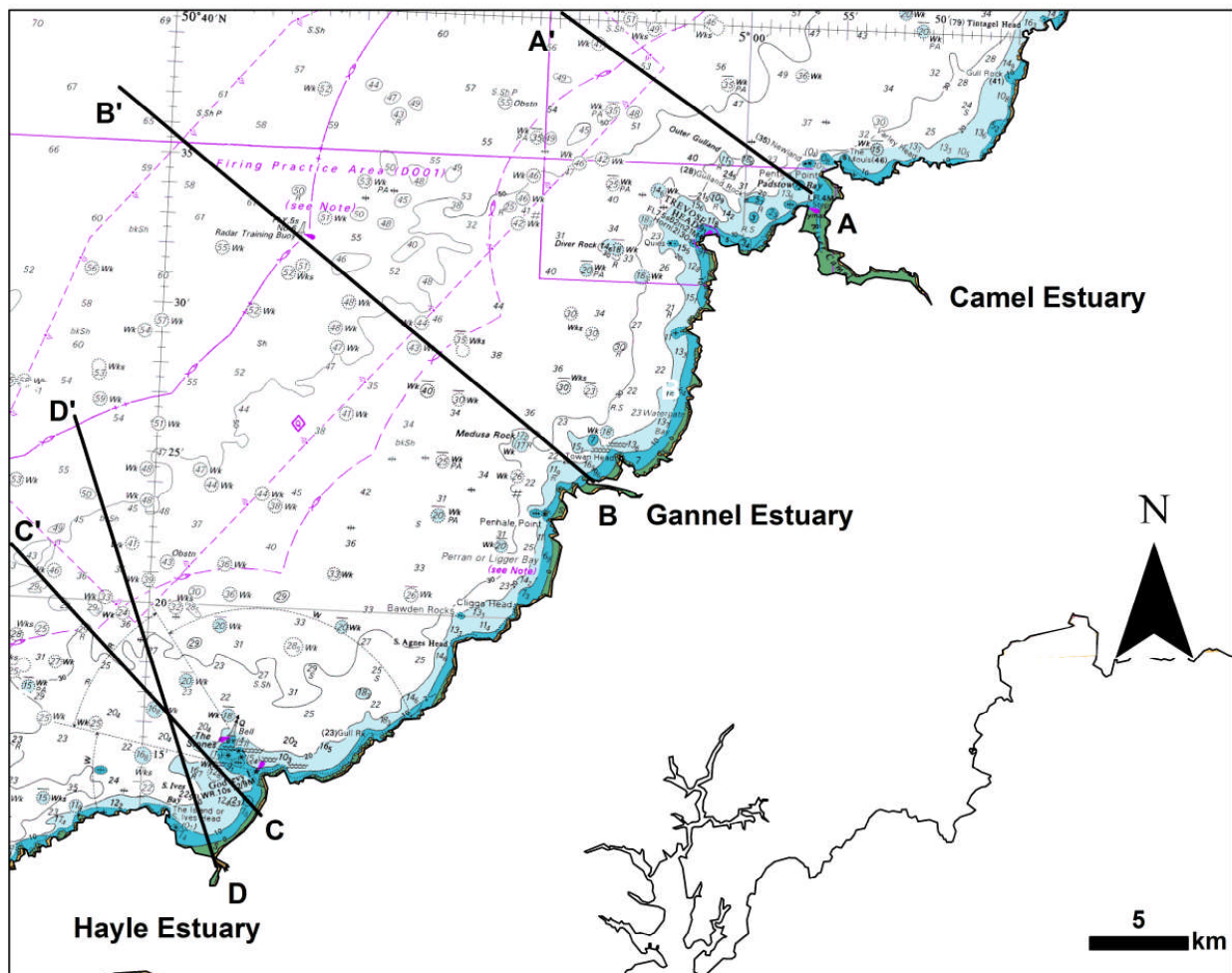
The depth of closure is an empirically-based measure that represents the seaward extent of significant cross-shore sand transport by waves. Based on the work of Hallermeier (1981), it can be calculated from wave metrics using the equation:

$$d = 2.28H - 68.5(H^2/gT^2)$$

where  $d$  = depth of closure;  $H$  = significant wave height, and  $T$  = wave period. Using this equation, and the median wave height/period (1.67 m, 5.62 s) for westerly waves in this region gives a depth of closure of 3.19 m. This implies that under normal conditions, one might expect the morphological change and sediment movement across the seabed to a depth of c. 3 m (i.e. the nearshore zone). Sediment movement in water depths beyond this would be attributed to storm waves or tidal currents. Using the equation again, but based on the 90th percentile wave statistics (which might represent higher energy, perhaps storm conditions) gives a depth of 7.4 m. Given that seabed changes appear to cover the entire shoreface, morphological changes are taking place beyond the depth of closure (even for high energy waves), and therefore a combination of sediment transport processes must be taking place.

Shore-normal transects extending from the study sites for this research in north Cornwall coast (Figure 7.3) reveal more about the changes shown (Figure 7.4). The transects are quite similar in large-scale structure, with a more steeply dipping upper shoreface (around  $0.36^\circ$ ) and a more

gradual sloping lower foreshore (around  $0.035^\circ$ ). Transect A extends from Padstow Bay to 12 km offshore, and it is around 10-12 km where the slope angle decreases. Gains and losses are present along the full profile. Close to the shore, a nearshore feature present in the 1931 bathymetry has been removed, or possibly moved offshore as the same region in 2008 shows accretion seaward of this 1931 feature. Accretion is evident along most of the profile to a distance of about 10-12km, where erosion takes place. Sand and gravel cover much of the seabed offshore from Padstow Bay, so the dynamics shown here are entirely possible.



**Figure 7.3** The recent Admiralty chart for north Cornwall (no. 1178), and shore-normal transects used in the bathymetric change analysis.

The transect offshore from Crantock is similar in structure to that from Padstow, and here the upper to lower shoreface profile slope changes around 10 km. Relatively smaller changes are found in the upper shoreface, erosion in the nearshore zone suggests steepening has occurred. Offshore from 5 km, accretion dominates the change in profile, with 1-4 m deposition across the seabed. The modern bathymetric chart shows that the upper shoreface comprises patches of bedrock and sand, while an almost continuous coverage of sand and gravel is present across the rest of the transect.

### 7. Regional Bathymetry Change

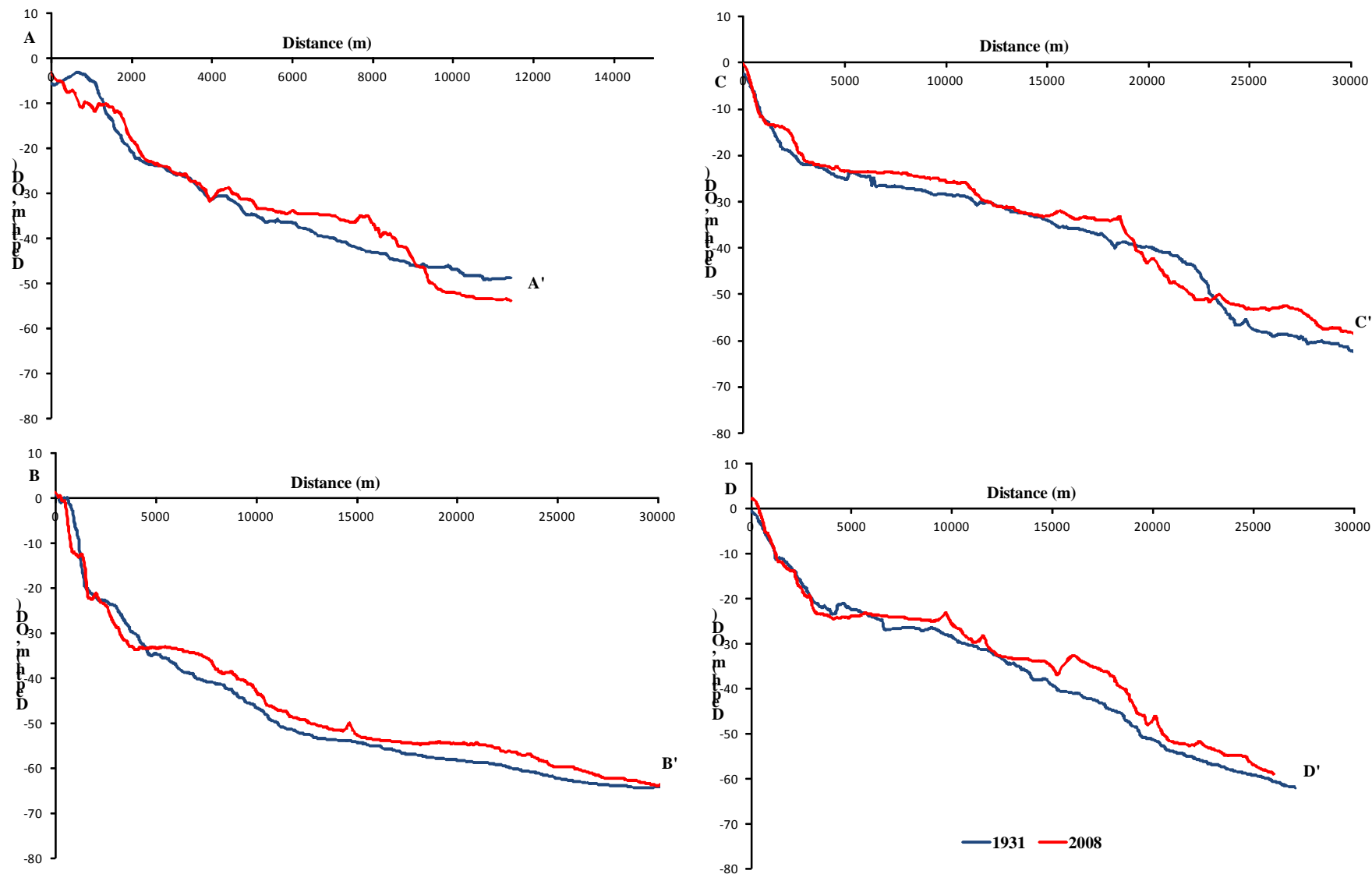


Figure 7.4 Cross-estuary seabed profile (shore-normal transects) to the estuaries near Southwest England from 1931 to 2008 extracted from the bathymetric gridded surfaces (A - Padstow Bay; B - Crantock Beach, C - St Ives Bay - from Gwithiam Towans; and D - St Ives Bay- from Hayle Bar).

St Ives Bay contains two transects, the first extending northeastward from Gwithian Towans and the second northward from the Hayle inlet. Behaviour of the immediate nearshore is comparable across both transects where almost no change has taken place down to around 12m water depth. Beyond this, the upper shoreface seaward of Gwithian Towans shows accretion, while the seabed north of the Hayle inlet continues to exhibit no significant change, out to a depth of around 20m (3.5km offshore). It is around this point that the profile slope decreases significantly. From here to seaward, both profiles display evidence of erosion and accretion. Accretion dominates rather more in the Hayle transect, and in places up to 10m of material has been moved, but in both transects there are patches where no significant change has taken place. St Ives Bay is predominantly sandy, but offshore from here, the seabed is a mix of bedrock and sandy/shelly deposits. In places the bedrock can be quite continuous which might explain the presence of significantly stable areas amongst more changeable areas.

The results of this analysis have shown that the seabed topography in the region is not static, with patterns of erosion and accretion, and hence net sediment movement (1931-2008), varying spatially across the seabed.

## 7.2 Regional wave modelling

Nearshore wave climate reflects the nature of the nearshore and offshore seabed, in addition to both the regional and distant wind climate. As waves propagate toward the shore, they start to interact with the seabed when the water depth is less than half the wavelength. Long waves (swell waves, generated in the open ocean) will first interact with the seabed at deeper depths than short waves (sea waves, generated locally). Interaction with the seabed causes slowing of the wave (due to friction), and where the seabed shallows variably, waves will refract in response to variable slowing. Changes in seabed bathymetry are therefore expected to influence nearshore and coastal wave climates through modifications to patterns of wave refraction. The SWAN spectral wave model is used here to assess wave propagation in the region of study and to evaluate the role of bathymetry controls on the nearshore wave climate.

### 7.2.1 Climate controls on nearshore wave climate

The wind and wave climate of southwest England is driven primarily by the northeast Atlantic Ocean. Three-month averages for significant wave height ( $H_s$ ) and wind speed show a strong seasonality (Figures 7.5). Nearshore wave heights ( $H_s$ ) on the north coast of Cornwall are c. 1 - 1.4 m during the summer, but reach 1.8 - 2.2 m during winter months. Wind speed drops significantly at the shoreline, and is similarly reduced during summer months. The maritime climate of the British Isles is largely influenced by the eastward sweep of depressions from the Atlantic Ocean (Thomas, 1960; Palutikof *et al.*, 1985; Cook and Prior, 1987; Allen and Duffy,

7.Regional Bathymetry Change

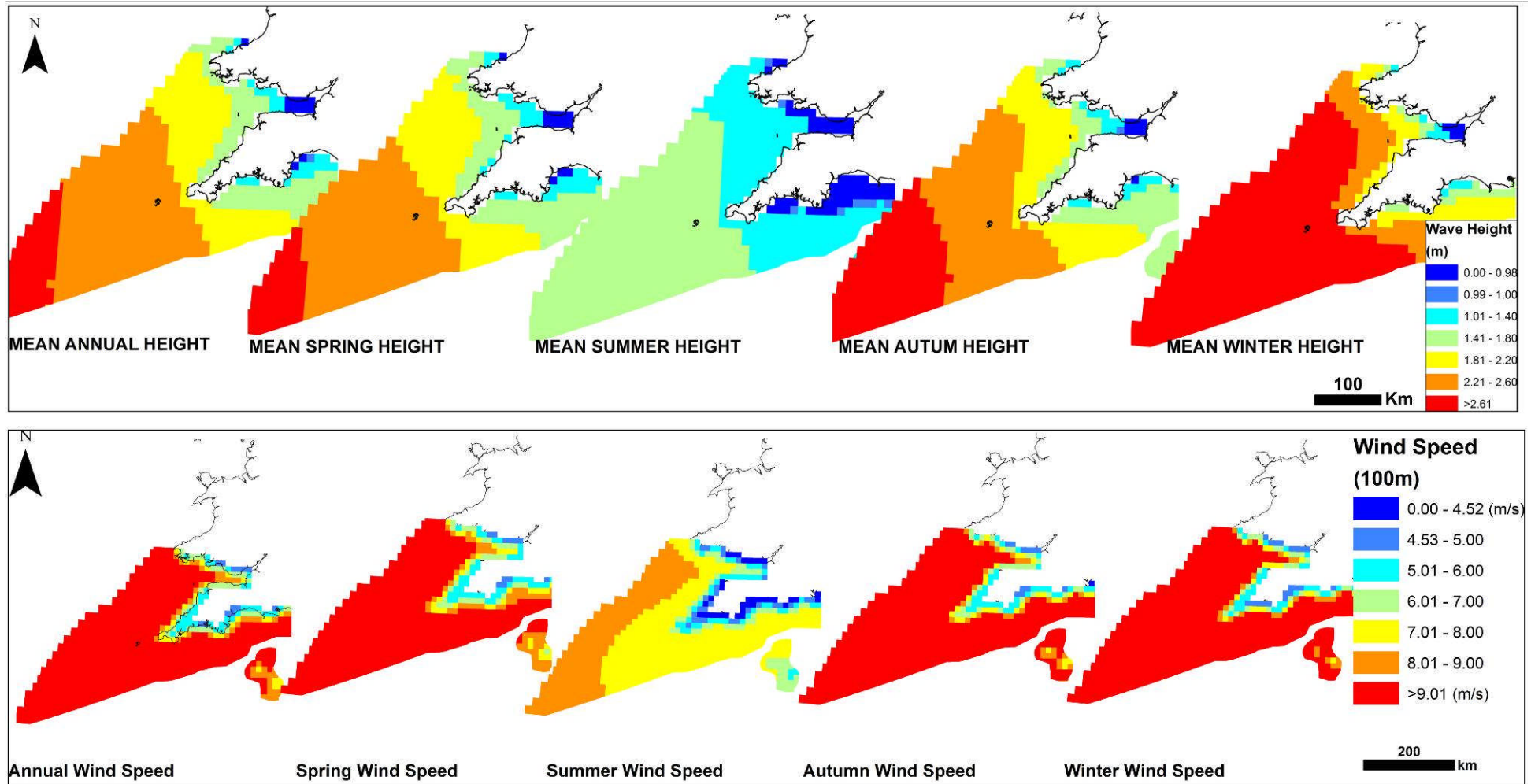


Figure 7.5 The average seasonal wave (top) and wind speed (bottom) pattern in Southwest England (Data source from ABPmer).

1998). It is thought that the local wind - wave climate strongly influences the morphodynamics of the north Cornwall coast (Allen and Duffy, 1998). In the study area, the wind speeds are generally and comparatively high with frequent western gales (according to Hardman *et al.*, 1973; Cook and Prior, 1987; Allen and Duffy, 1998). Apart from the seasonal variation in the wind speed in the region, the wind speed also varies locally on a seasonal (Smith, 1983), diurnal (Shellard, 1976), annual - decade (Hulme and Jones, 1991) and longer trend (Palutikof *et al.*, 1987) scales.

### 7.2.2 Bathymetric controls on nearshore and offshore wave climate

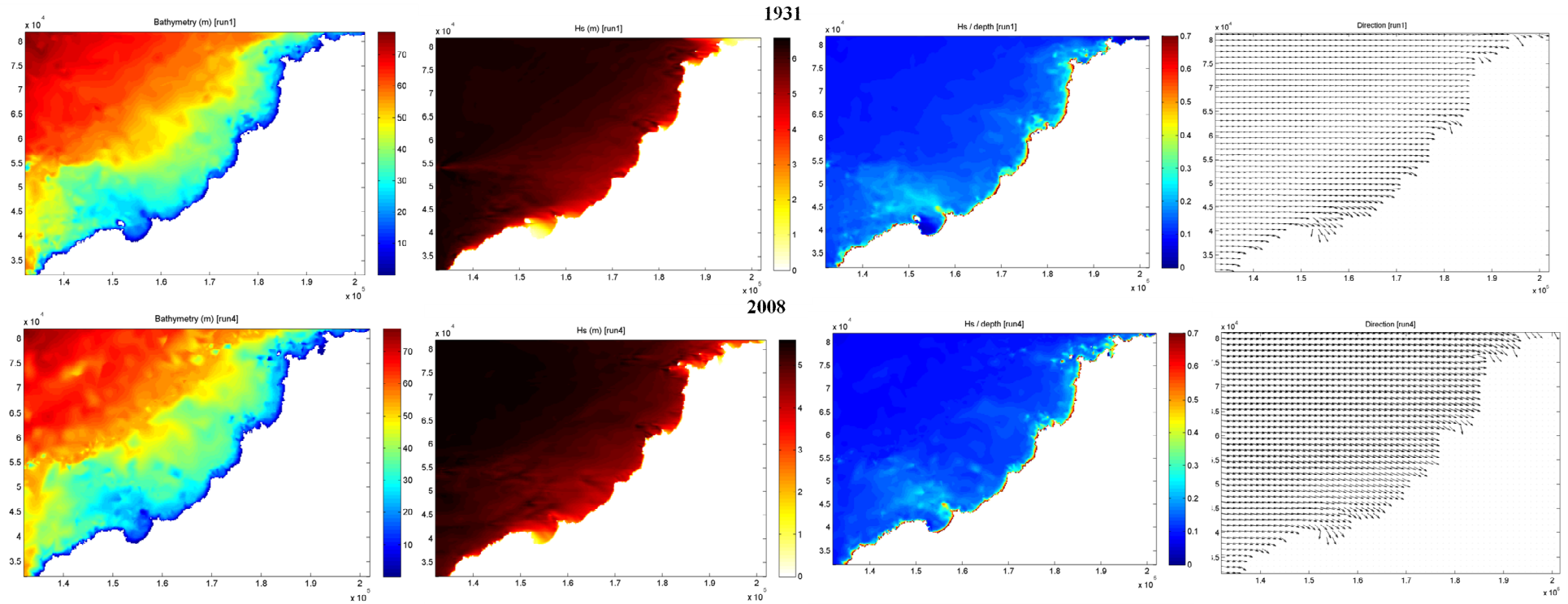
SWAN was used to model wave climate response to changes in bathymetry. Simulations were undertaken twice, using first the 1931 bathymetry and second the 2008 bathymetry; input wave climate scenarios were consistent between the 1931 and 2008 runs. Two representative offshore wave climates were used in the simulation of influence of bathymetric controls on the nearshore and offshore wave climate. The first simulations make use of the significant wave energy offshore (the West point) of the ABPmer hindcast model with  $H_s$  6.52m; wave period of 9.3s (Table 7.2). The results of this simulation is presented in Figure 7.6. The second scenario is based on the wave parameters recorded at a the wave buoy off the southwest coast (Wave bouy data from 26 February, 2013 at Sevenstones Lightship, downloaded from National Data Buoy Centre- [www.ndbc.noaa.gov](http://www.ndbc.noaa.gov), accessed on 26/02/2013). The significant wave height of 4.5m having a period of 10.0s is simulated on the two bathymetries (1931 and 2008) and the results of the wave climate (direction, wave height, wave height average by wave depth and wave height average by direction) is presented in Figure 7.7.

**Table 7.2 Wave climate scenarios for use in SWAN wave modelling.**

Run	Bathymetry	Scenario	Direction (°N)	Hs (m)	T0 (s)	Spread (°)
1	1931	<b>Extreme conditions: 99th percentile of the westerly wave climate (ABPmer hindcast)</b>	270	6.52	9.3	28.5
4	2008					
2	1931	<b>Winter conditions: Sevenstones Lightship - 26-Feb-13</b>	270	4.5	10	28.5
3	2008					

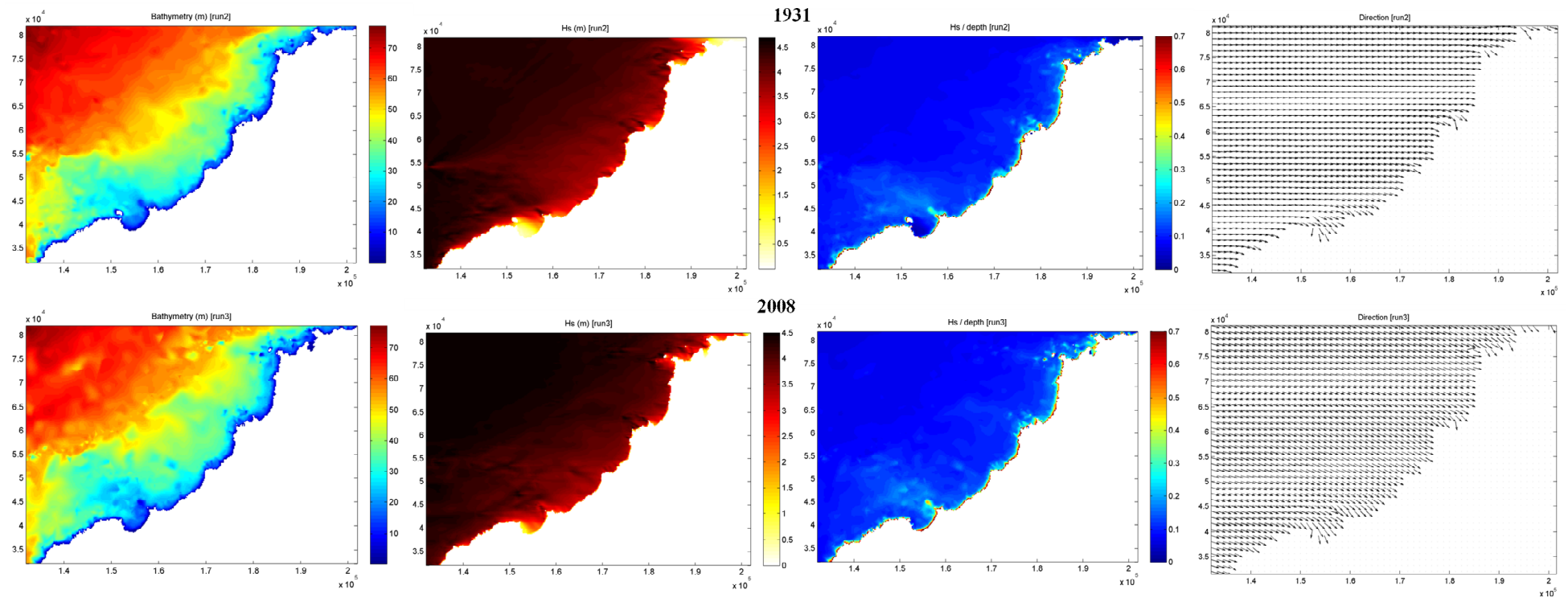
SWAN modelling of wave propagation across the 1931 and 2008 bathymetries reveals no significant change (between the bathymetries) in wave direction, and only minimal changes/variations in the spatial pattern of wave heights. The bathymetric influence on significant wave heights using the first wave climate scenario (extreme conditions) is around 1 m (Figure 7.6), where the range of wave heights modelled on the modern bathymetry are less than for the 1931 bathymetry. This reduction in maximum wave heights across the region of interest is most likely a consequence of shallowing across most of the lower shoreface. Although the water is relatively deep (>50 m) here, swell waves propagating in from the North Atlantic

## 7.Regional Bathymetry Change



**Figure 7.6 Simulation of changes in significant wave height for westerly waves propagating over 1931 and 2008 bathymetries using SWAN model. The diagrams show results (input bathymetry, output wave height ( $H_s$ ), the ratio between wave height and depth, and wave direction) obtained for waves with  $H_s$  of 6.52, period of 9.3s. The upper diagram is for 1931 while the lower diagram is for 2008 bathymetries.**

## 7.Regional Bathymetry Change



**Figure 7.7** Simulation of changes in significant wave height for westerly waves propagating over 1931 and 2008 bathymetries using SWAN model. The diagrams shows results (input bathymetry, output wave height ( $H_s$ ), the ratio between wave height and depth, and wave direction) obtained for waves with  $H_s$  of 4.5, period of 10.0s. The upper diagram is for 1931 while the lower diagram is for 2008 bathymetries.



typically have wavelengths greater than 100m, meaning that wave base for these waves would be further offshore from the region of interest. In this case then, any significant change in bathymetry will have a consequence for wave heights and energy in the region. Wave heights decrease quite rapidly across the upper shoreface, and there is clear evidence of refraction around, and wave-shadowing in the lee of some headlands. The nearshore is characterised by local differences in wave height, and these are much more pronounced at St Ives Bay, where the offshore platform promotes significant attenuation. Spatial patterns are not significantly different when comparing results from the second scenario (winter conditions), but again broad wave heights are lower on the 2008 bathymetry than the 1931 bathymetry (Figure 7.7).

In depth-limited conditions (i.e the nearshore), the ratio between height and depth ( $H/d$ ) is frequently used to determine the depth of wave breaking. Many authors continue to use the threshold of 0.78 to define wave breaking (as determined by McCowan (1894)), but in reality local seabed slope and the wave steepness can influence this, and the threshold is often considered to lie between 0.72 and 1.18. Wave breaking here is limited to the shoreline, and over offshore rocky outcrops and submerged reefs, but it is clear that the subtidal platform that extends north of St Ives Bay significantly attenuates wave energy.

Wave conditions related to the second scenario (February conditions) for the 2008 bathymetry show a broadly similar pattern to the first scenario, but with a reduction in wave heights and  $H/d$  ratios. This is as expected given the change from an extreme to a normal winter wave climate. There appear to be minimal differences in patterns of wave refraction though.

The shore-normal transects highlight the transformation in wave climate from offshore to the nearshore zone. Figures 7.8-7.11 present the wave climate results along each transect, comparing bathymetries (1931 and 2008) and wave climate scenarios (extremes, and winter (2013)). In St Ives Bay, the north-extending, central transect shows how significant the wave attenuation is relatively close to the shoreline (Figure 7.8). Offshore wave heights are significantly different between the two bathymetries due to seabed accretion in the lower shoreface (captured in a coarser resolution coastal area model run). But the nature of wave height and period reduction in the nearshore zone is similar between bathymetries. A similar pattern is exhibited in the easterly transect in St Ives Bay (Figure 7.9), though here, the role of the offshore platform to the northwest of St Ives Bay is more apparent. Here, wave heights are reduced in the immediate interaction with the platform, but as the platform is relatively level, continued attenuation does not take place and wave heights stay relatively similar until the nearshore zone.

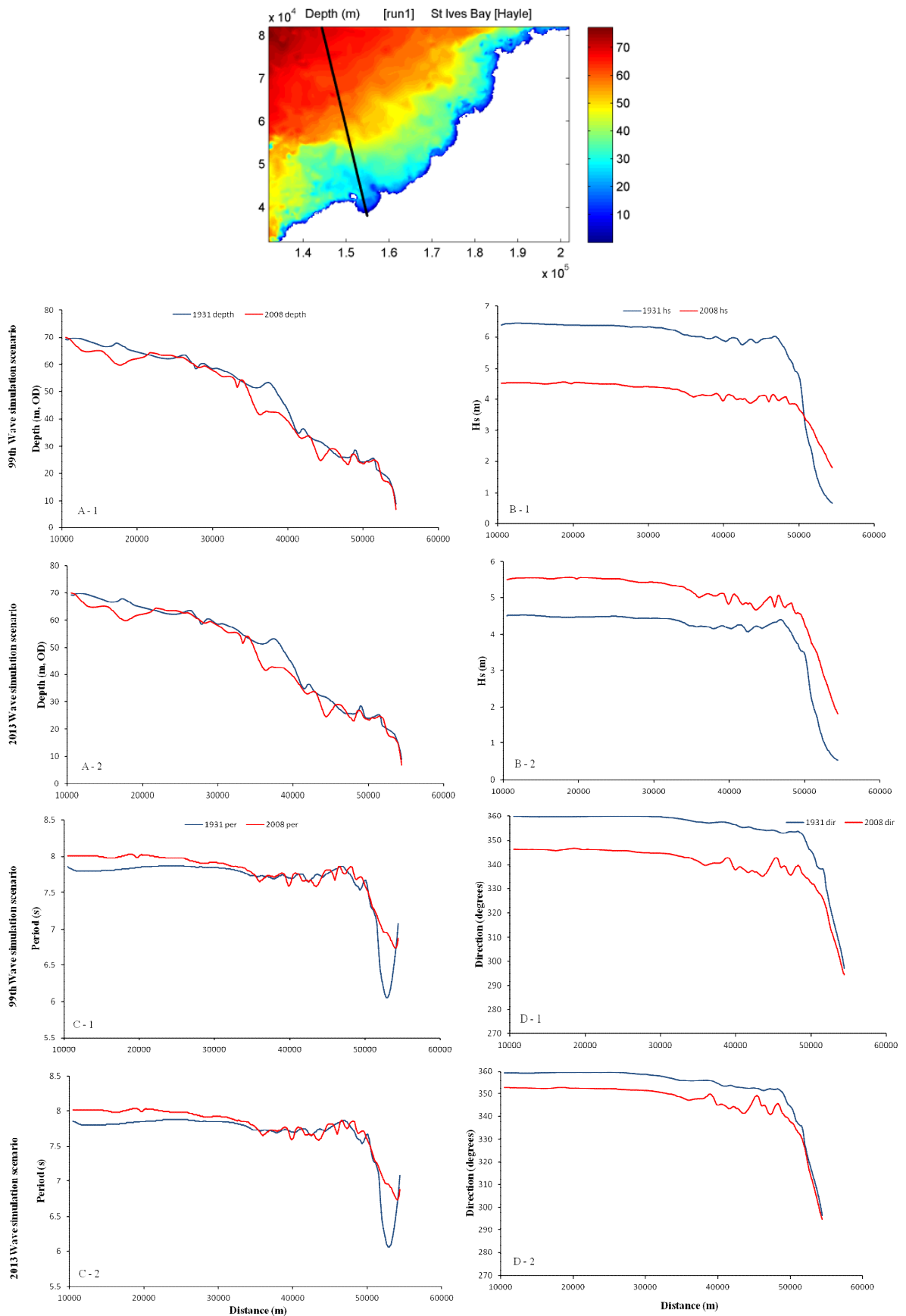


Figure 7.8 Shore-normal transects of the SWAN simulation at Hayle Bar of St Ives Bay extracted from the SWAN simulation results (A - Depth; B - Hs, C – Wave Period; and D - Direction).

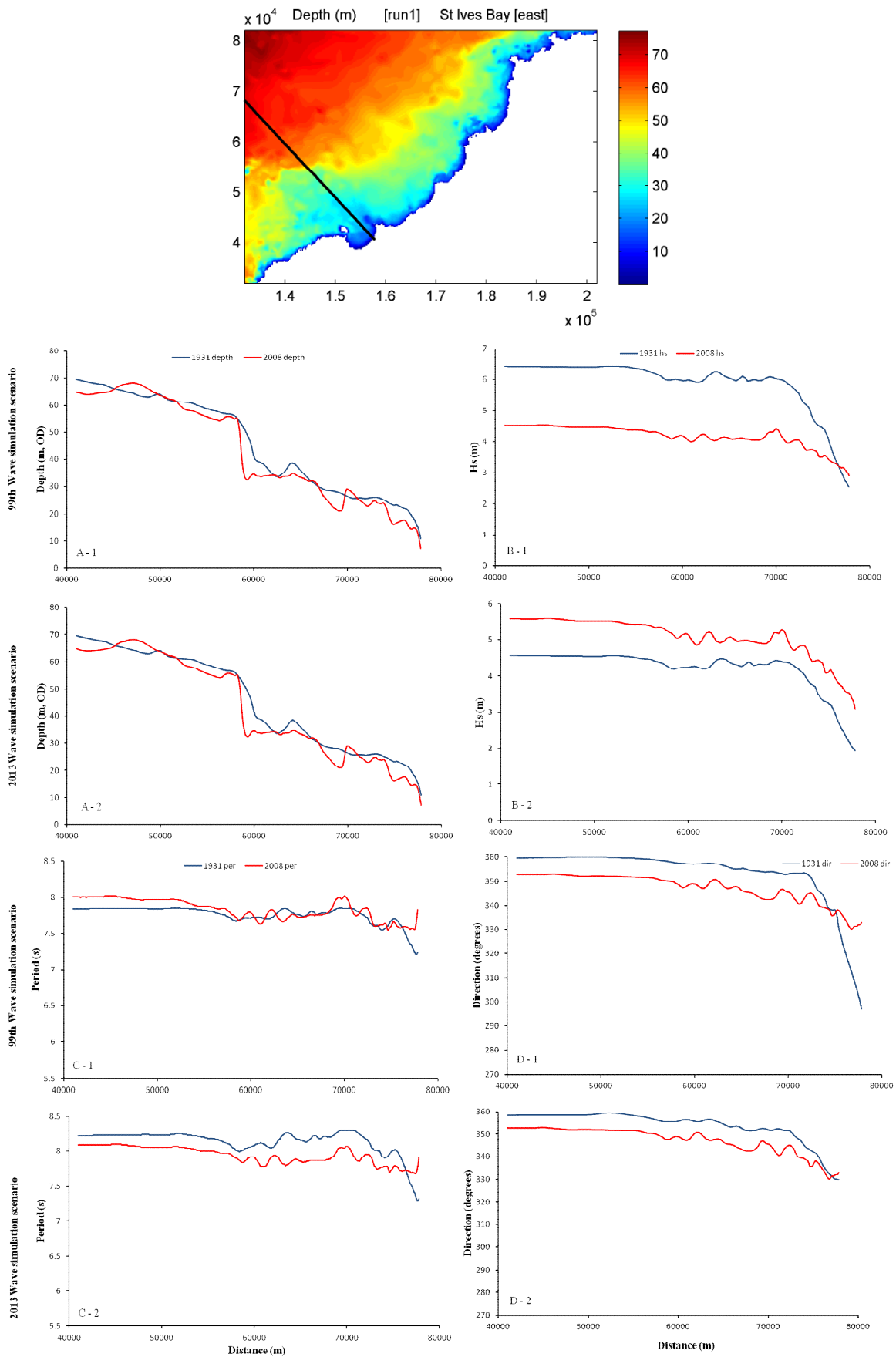


Figure 7.9 Shore-normal transects of the SWAN simulation at East of St Ives Bay extracted from the SWAN simulation results (A - Depth; B - Hs, C – Wave Period; and D - Direction).

Further north, the transects from Crantock (Figure 7.10) show that in areas where the upper shoreface is steeper, wave attenuation is less pronounced. Here, wave heights are maintained closer to the coastline than in St Ives Bay, but then also go through the same decrease as observed elsewhere. At Padstow Bay (Figure 7.11) the short transects reveal little about offshore to nearshore transformation, but alongwith Crantock, these transects do suggest that these bays can experience wave heights of 4m in the context of high energy conditions. This is important as, under the same conditions, St Ives Bay does not experience waves of this order.

The results from this wave modelling analysis has shown that offshore waves are significantly attenuated as they approach the north Cornwall coastline, but that the degree of attenuation is dependent on the rate of shallowing. The broad offshore ledge to the north of St Ives Bay is responsible for enhanced attenuation here in comparison to what is observable at the Crantock and Padstow Bay sites. Furthermore, the lower shoreface accretion evident in the comparison between 1931 and 2008 bathymetries is responsible for a broad-scale reduction in wave heights across the region of interest.

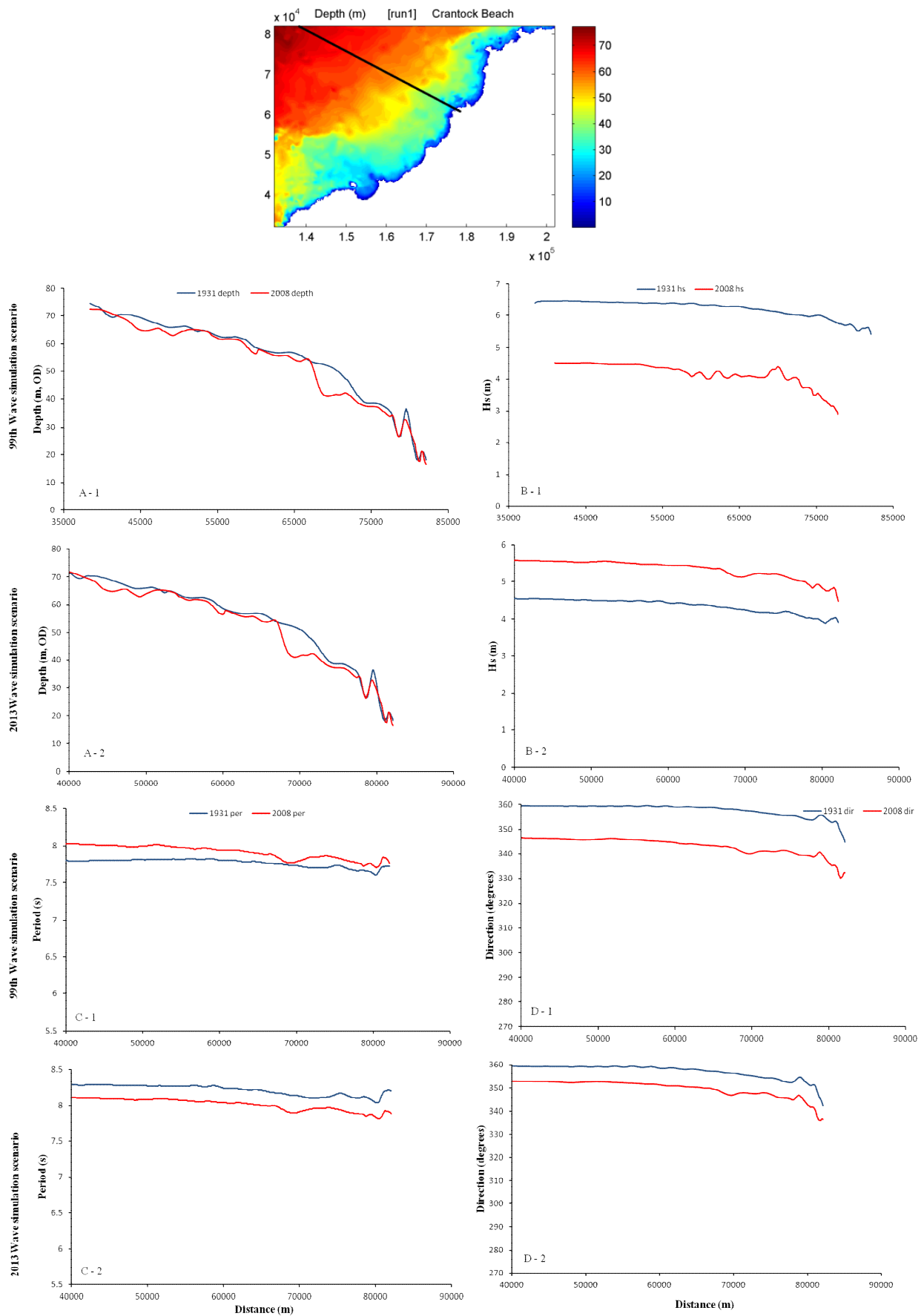


Figure 7.10 Shore-normal transects of the SWAN simulation at Crantock Beach extracted from the SWAN simulation results (A - Depth; B - Hs, C – Wave Period; and D - Direction).

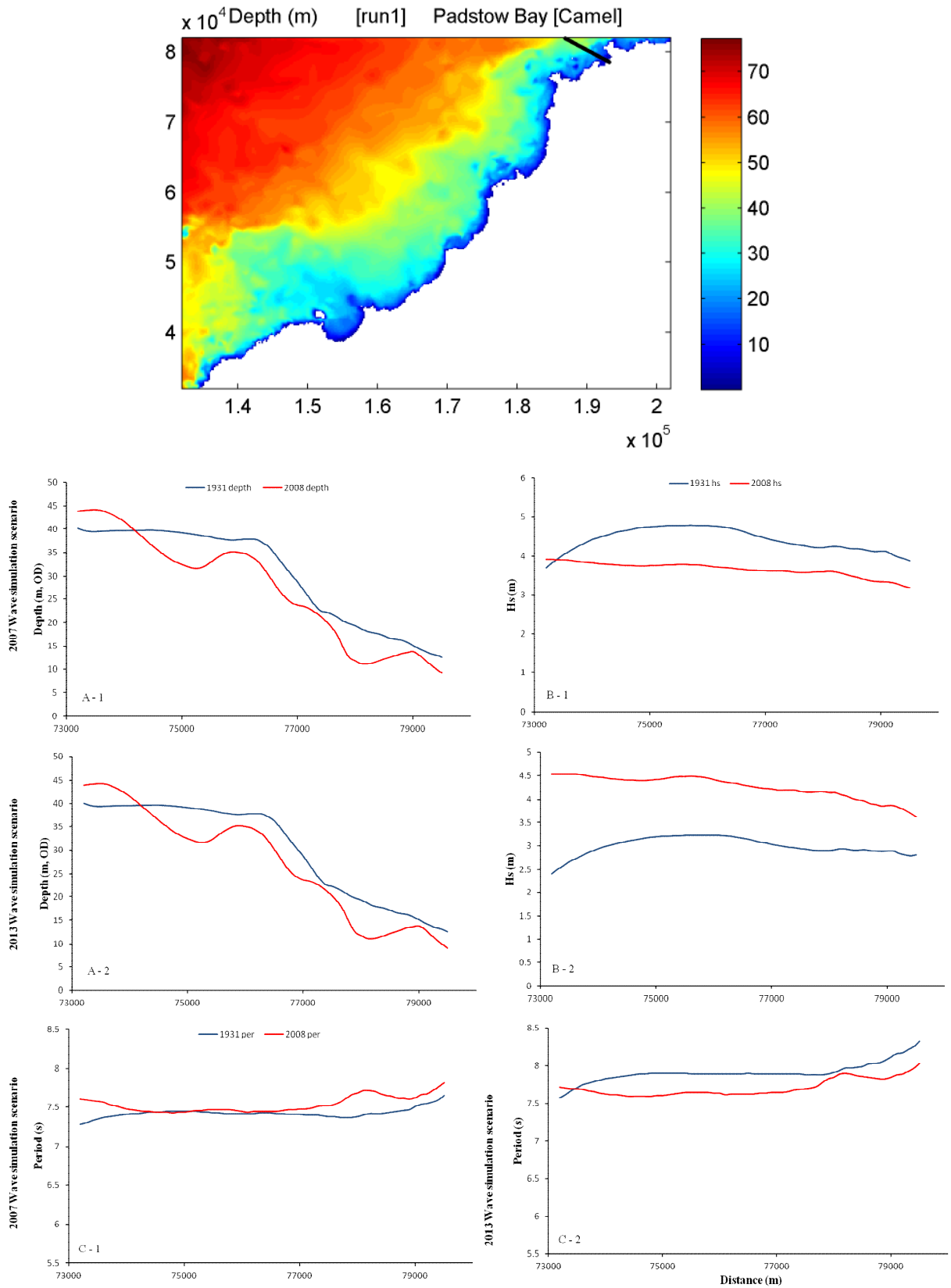


Figure 7.11 Shore-normal transects of the SWAN simulation at East of St Ives Bay extracted from the SWAN simulation results (A - Depth; B - Hs, C – Wave Period).

## 9 REFERENCES

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- Abel, N., Gorddard, R., Harman, B., Leitch, A., Langridge, J., Ryan, A., Heyenga, S.,  
2011. Sea level rise, coastal development and planned retreat: analytical framework,  
governance principles and an Australian case study. *Environmental Science and Policy*  
14 (3), 279 -288.
- ABP MER, University of Plymouth, University College London, Discovery  
Software, HR Wallingford, & Delft Hydraulics 2008, *Development and Demonstration  
of Systems-Based Estuary Simulators. R & D Technical Report FD 2117/TR*, Joint  
DEFRA/EA Flood and Coastal Erosion Risk Management R & D Programme,  
FD2117/TR.
- Adam, P., 2002. Saltmarshes in a time of change. *Environ. Conserv.* 29, 39–61.
- Adamo, F., Capua, C. D., Filianoti, P., Lanzolla, A. M. L. and Morello, R. 2014. A coastal  
erosion model to predict shoreline changes. *Measurement* 47, 734 – 740
- Ado, K. A., Walkden, M and Mills, J. P. 2008. Detection, measurement and prediction of  
shoreline recession in Accra, Ghana. *ISPRS Journal of Photogrammetry and Remote  
Sensing* 63, 543 - 558
- Agunmya, A. & Hunter, G.J. 1997. Determining fitness for use in geographic  
information. *ITC Journal*, 2, 109-113
- Ahnert, F. 1994. Equilibrium, scale and inheritance in geomorphology. *Geomorphology*  
11, 125 – 140.
- Al Bakri, D. 1996. A geomorphological approach to sustainable planning and management  
of the coastal zone of Kuwait. *Geomorphology*, 17, 323-337.  
[http://dx.doi.org/10.1016/0169-555X\(96\)00009-8](http://dx.doi.org/10.1016/0169-555X(96)00009-8)
- Albert, P. & Jorge, G. 1998. Coastal changes in the Ebro delta: natural and human f  
actors. *Journal of Coastal Conservation*, 4, 17-26
- Alexander, L.V., Tett, S.F.B., Jonsson, T., 2005. Recent observed changes in severe  
storms over the United Kingdom and Iceland. *Geophysical Research Letters* 32,  
L13704.
- Allen, G. P., Salomon, J. C., Bassoullet, P., Du Penhoat, Y., & de Grandpré, C. 1980. Effects  
of tides on mixing and suspended sediment transport in macrotidal estuaries. *Sedimentary  
Geology*, 26(1-3), 69-90

- Allen, J.R.L. 2004. Annual textural bending in Holocene estuarine silts, Severn Estuary Levels (SW Britain): patterns, cause and implications. *The Holocene*, 14 (4), 536-552.
- Allen, J.R.L. and Duffy, M.J. 1998. Temporal and spatial depositional patterns in the Severn Estuary, southwestern Britain; intertidal studies at spring-neap and seasonal scales, 1991-1993. *Marine Geology*, 146, 147-171.
- Anders, F.J. & Byrnes, M.R. 1991. Accuracy of shoreline change rates as determined from maps and aerial photographs. *Shore and Beach*, 59, 17-26
- Anfuso, G., Pranzini, E., Vitale, G., 2011. An integrated approach to coastal erosion problems in northern Tuscany (Italy): littoral morphological evolution and cell distribution. *Geomorphology* 129, 204 -214.
- Anthony, E. J. & Héquette, A. 2007. The grain-size characterisation of coastal sand from the Somme estuary to Belgium: Sediment sorting processes and mixing in a tide- and storm- dominated setting. *Sedimentary Geology*, 202, 369 – 382.
- Apitz, S.E., Barbanti, A., Bernstein, A.G., Bocci, M., Delaney, E., Montobbio, L., 2007. The assessment of sediment screening risk in Venice lagoon and other coastal areas using international sediment quality guidelines. *J. Soil Sed.* 7, 326–341.
- Araújo, I.B., and Pugh, D.T., 2008. Sea Levels at Newlyn 1915-2005: Analysis of trends for future flooding risks, *Journal of Coastal Research*. Vol. 24, No. 4C pp. 203-212
- Arthurton, R.S., 1998. Marine-related physical natural hazards affecting coastal megacities of the Asia-Pacific region-awareness and mitigation. *Ocean and Coastal Management* 40, 65 - 85.
- Atkinson, N., Harman, K., Lynn, M., Schwarz, A., Tindal, A., 2006. Long-term wind speed trends in north-western Europe. Garrad Hassan, Bristol, p. 4.
- Aubrey, G.G., McSherry, T.R., Eliet, P.P., 1993. Effects of multiple inlet morphology on tidal exchange: Waquoit bay, Massachusetts. In: Aubrey, G.G., Giese, G.S. (Eds.), *Formation and Evolution of Multiple Tidal Inlets. Coastal and Estuarine Studies*, 44. American Geophysical Union, Washington, pp. 213–225.
- Babtie Group Limited 2002, *Hayle Harbour Hydrodynamic Modelling*
- Bagnold, R.A., Barndorff-Nielsen, O., 1980. The pattern of natural distributions. *Sedimentology* 27, 199–207.
- Ballantyne, C.K. 2002. Paraglacial geomorphology. *Quaternary Science Reviews*, 21, 1935-2017
- Ballinger, R. C. 1999. The evolving organisational framework for Integrated Coastal Management in England and Wales. *Marine Policy*, 23:501–23.
- Ballinger, R. C. 2005. Coastal management in the UK: evolution and devolution. In: Temitope Oyedotun



- Smith H, Potts JS, (ed.) *Managing Britain's Marine and Coastal Environment: Towards a Sustainable Future*. Abingdon: Routledge and National Maritime Museum., p. 186–216.
- BaMasoud, A. and Bryne, M-L. 2012. The impact of low ice cover on shoreline recession: A case study from Western Point Pelee, Canada. *Geomorphology*, 173-174, 141 – 148.
- Bao, J.-W., Wilczak, J.M., Choi, J.-K., Kantha, L.H., 2000. Numerical simulations of air–sea interaction under high wind conditions using a coupled model: a study of hurricane development. *Mon. Weather Rev.* 128, 2190–2210.
- Barbier, E.B., Koch, E.W., Silliman, B.R., Hacker, S.D., Wolanski, E., Primavera, J., Granek, E.F., Polasky, S., Aswani, S., Cramer, L.A., Stoms, D.M., Kennedy, C.J., Bael, D., Kappel, C.V., Perillo, G.M.E., Reed, D.J., 2008. Coastal ecosystem-based management with nonlinear ecological functions and values. *Science* 319, 321–323.
- Barbosa, S.M. & Silva, M.E. 2009. Low frequency sea-level change in Chesapeake Bay: Changing seasonality and long-term trends. *Estuarine, Coastal and Shelf Science*, 83, 30-38
- Bartholody J, Christiansen C, Kunzendorf H. 2004. Long term variations in backbarrier saltmarsh deposition on the Skallingen peninsula – the Danish Wadden Sea. *Marine Geology* **203**: 1–21, DOI: 10.1016/S0025-3227 (03) 00337-2.
- Basu, A. 2003. A perspective on quantitative provenance analysis. in: R. Valloni, A. Basu (Eds.), *Quantitative Provenance Studies in Italy*, Memorie Descrittive della Carta Geologica dell'Italia, Vol. 64 (2003), pp. 11–22
- Beardall, C. H., Dryden, R. C. and Holzer, T. J. 1991. *The Suffolk Estuaries*, Suffolk Wild Life Trust, Segment Publications.
- Beetham, E. P. and Kench, P. S. 2013. Wave energy gradients and shoreline change on Vabbinfaru platform, Maldives. *Geomorphology*, <http://dx.doi.org/10.1016/j.geomorph.2013.11.029>
- Bell, I. & Visbeck, M. North Atlantic Oscillation. 2009. 28-5-2013.  
[Available at: [www.ideo.columbia.edu/res/pi/NAO](http://www.ideo.columbia.edu/res/pi/NAO). Accessed on 28th May, 2013]
- Bender, C.J. & Dean, R.G. 2003. Wave field modification by bathymetric anomalies and resulting shoreline changes: a review with recent results. *Coastal Engineering*, 49, 125-153
- Bere, R. 1982. *The Nature of Cornwall*. Buckingham, Bauracude Books Limited.
- Bertin, X., Chaumillon, E., Weber, N., Tesson, M., 2004. Morphological evolution and

- time-varying bedrock control of main channel at a mixed energy tidal inlet: Maumusson Inlet, France. *Marine Geology* 204, 187 - 202.,
- Bertin, X., Chaumillon, E., Sottolichio, A., Pedreros, R., 2005. Tidal inlet response to sediment infilling of the associated bay and possible implications of human activities: the Marennes-Oléron Bay and the Maumusson Inlet, France. *Cont. Shelf Res.* 25, 1115–1131.,
- Billets, S. 2006, *Innovative Technology verification report: Niton XLt 700 Series XRF Analyser. National Exposure Research Laboratory.*, US Environmental Protection Agency.
- Bird, E. 1998. *The coasts of Cornwall.* Cornwall, Alexander Associates, Fowey.
- Bird, E.C.F. 1985. *Coastline changes: A Global Review* Chichester, John Wiley.
- Bird, E.C.F. 1996. *Beach Management* Chichester, Wiley.
- Bitner-Gregersen, E. M., Ewans, K. C., and Johnson, M. C. 2014. Some uncertainties associated with wind and wave description and their importance for engineering applications. *Ocean Engineering*, (Article in Press).  
<http://dx.doi.org/10.1016/j.oceaneng.2014.05.002i>
- Black, K.P. & Oldman, J.W. 1999. Wave mechanisms responsible for grain sorting and non-uniform ripple distribution across two moderate-energy, sandy continental shelves. *Marine Geology*, 162, 121-132
- Bloemsma, M. R., Zabel, M., Stuut, J. B. W., Tjallingii, R., Collins, J. A., Weltje, G. J. 2012. Modelling the joint variability of grain size and chemical composition in sediment. *Sedimentary Geology*, 284 - 285, 135 – 148. doi:10.1016/j.sedgeo.2012.04.009
- Blott, S.J. 2001. *Morphological and Sedimentological Changes on Artificially Nourished Beaches, Lincolnshire, UK.* PhD Thesis submitted to Department of Geology, University College London.
- Blott, S.J. & Pye, K. 2001. GRADISTAT: A grain size distribution and statistics package for the analysis of unconsolidated sediments. *Earth Surface Processes and Landforms*, 26, 1237-1248
- Blott, S.J., Pye, K., van der Wal, D., & Neal, A. 2006. Long-term morphological change and its causes in the Mersey Estuary, NW England. *Geomorphology*, 81, 185-206
- Boggs, S.Jr. 2001. *Principles of Sedimentology and Stratigraphy* New Jersey, Prentice Hall.
- Booji, N., Ris, R.C., Holthuijsen, L.H., 1999. A third generation wave model for coastal  
Temitope Oyedotun

- regions 1. Model description and validation. *Journal of Geophysical Research*, 104, 7649-7666.
- Boothroyd, J. C. 1985. Tidal inlets and tidal deltas. In: Davis Jr., R. A. (Ed), *Coastal Sedimentary Environments*. Springer-Verlag, New York, pp. 445 – 532.
- Bowen, D. Q. 1994. Late Cenozoic Wales and South-West England, *In Annual Conference of the Ussher Society*, pp. 209-213.
- Borsje, B.W., van Wesenbeeck, B.K., Dekker, F., Paalvast, P., Bouma, T.J., van Katwijk, M.M., de Vries, M.B., 2011. How ecological engineering can serve in coastal protection. *Ecol. Eng.* 37, 113 - 122.
- Bos, A.R., Bouma, T.J., de Kort, G.L.J., van Katwijk, M.M., 2007. Ecosystem engineering by annual intertidal seagrass beds: sediment accretion and modification. *Estuar. Coast.Shelf Sci.* 74, 344–348.
- Bouma, T. J., van Belzen, J., Balke, T., Zhu, Z., Airoidi, L., Blight, A. J., Davies, A. J., Galvan, C., Hawkins, S. J., Hoggart, S. P. G., Lara, J. L., Losada, J. L., Maza, M., Ondiviela, B., Skov, M. W., Strain, M. E., Thompson, R. C., Yang, S., Zanuttigh, B., Zhang, L., Herman, P. M. J. 2013. Identifying knowledge gaps hampering application of intertidal habitats in coastal protection: Opportunities & steps to take, *Coastal Engineering*, <http://dx.doi.org/10.1016/j.coastaleng.2013.11.014>
- Bouws, E., Jannink, D. and Komen, G. 1997. ‘The increasing wave height in the North Atlantic Ocean’, *Bull. Am. Meteorol. Soc.*, **77**(10), 2275–2277.
- Bracken, L. J. and Wainwright, J. 2006. Geomorphological equilibrium: myth and metaphor? *Trans Inst Br Geogr* NS 31, 167 – 178.
- Brew, D.S. & Gibberd, B.B. 2009. Geomorphological change and its impact on habitats in the Camel Estuary, Cornwall, UK. *Geoscience in South-West England*, 12, 95-100
- British Broadcasting Corporation, BBC, 2011. Fears for the future of Hayle Beach. [<http://www.bbc.co.uk/news/uk-england-cornwall-14415539>. Accessed on 11th August, 2011]
- Brew DS, Holt T, Pye K, Newsham R. 2000. Holocene stratigraphy, sediments and palaeocoastlines of the Fenland embayment, eastern England. In *Holocene Land–Ocean Interaction and Environmental change around the North Sea*, Geological Society Special Publication 166, Geological Society Publishing House: Bath; 253–273.
- British Atmospheric Data Centre BADC (URL) for wind data from Meteorological Office Integrated Data Archive System (MIDAS) Land and Marine Surface Stations Data ([http://badc.nerc.ac.uk/view/badc.nerc.ac.uk\\_ATOM\\_dataent\\_ukmo-midas](http://badc.nerc.ac.uk/view/badc.nerc.ac.uk_ATOM_dataent_ukmo-midas)).

- Brooks, S. M. and Spencer, T. 2010. Temporal and spatial variation in recession rates and sediment release from soft rock cliffs, Suffolk coast, UK. *Geomorphology*, 124, 26 – 41
- Brooks SM, Spencer T, Boreham S. 2012. Deriving mechanisms and thresholds for cliff retreat in soft-rock cliffs under changing climates: Rapidly retreating cliffs of the Suffolk coast, UK. *Geomorphology*, 153/154, 48-60. DOI: 10.1016/j.geomorph.2012.02.007.
- Brown, E.I., 1928. Inlets on sandy coasts. In: Proceedings of the American Society of Civil engineers, New York: ASCE, 54, 505-553.
- Brown, B.E. 1977. Effects of mine drainage on the River Hayle, Cornwall, A) factors affecting concentrations of copper, zinc and iron in water, sediments and dominant invertebrate fauna. *Hydrobiologia*, **52**, 221-233.
- Bruneau N., Fortunato, A. B., Dodet, G., Freire, P., Oliveira, A., and Bertin, X. 2011. Future evolution of a tidal inlet due to changes in wave climate, sea level and lagoon morphology (O' bidos lagoon, Portugal). *Continental Shelf Research* **31**: 1915–1930.
- Bruun, P., 1986. Morphological and navigational aspects of tidal inlets on littoral drift shores. *J. Coastal Res.* 2 (2), 123–145.
- Bruun, P., Gerritsen, F., 1959. Natural by-passing of sand at coastal inlets. *J. Waterways Harbours Div.* 85 (4), 75–107.
- Bruun, P., Gerritsen, P., 1960. Stability of Coastal Inlets. North Holland, Amsterdam.
- Bruun, P., Metha, A.J., Johnson, I.G., 1978. Stability of Tidal Inlets. Elsevier Scientific Publishing Company, Amsterdam, p. 510.
- Bryan, G.W., Langston, W.J., & Hummerstone, L.G. 1980. The use of biological indicators of heavy-metal contamination in estuaries. *Marine Biological Association, Occasional Publications*, 1, p. 73.
- Buck, A.L. 1993. *An Inventory of UK Estuaries. Volume 2 South-west Britain*. Peterborough, Joint Nature Conservation Committee.
- Buckley, A. 1999. Historical evidence of alluvial tin streaming in the river valleys of Camborne, Illogan and Redruth. *Journal of Trevithick Society*, **26**, 89-99.
- Bui, E.N., Mazullo, J., & Wilding, L.P. 1990. Using the quartz grain size and shape analysis to distinguish between eolian and fluvial deposits in Dallol Bosso of Niger (West Africa). *Earth Surface Processes and Landforms*, 14, 157-166
- Burgess, K., Jay, H., Hosking, A., 2004. Futurecoast: predicting the future coastal evolution of England and Wales. *Journal of Coastal Conservation* 10, 65–71.
- Burningham H. 2005. Morphodynamic Behaviour of a High-Energy Coastal Inlet: Loughros Beg, Donegal, Ireland. In *High Resolution Morphodynamics and Sedimentary Evolution of Estuaries*, Fitzgerald DM, Knight J (eds). Springer: Dordrecht, 215–242.

- Burningham, H. 2008. Contrasting geomorphic response to structural control: The Loughros Estuaries, Northwest Ireland. *Geomorphology*, 97, 300-320
- Burningham, H. & French, J. 2006. Morphodynamic behaviour of a mixed sand-gravel ebb-tidal delta: Deben estuary, Suffolk, UK. *Marine Geology*, 225, 23-44
- Burningham, H. & French, J. 2008. *Historical changes in the seabed of the Greater Thames estuary*, Marine Estate Research Report. The Crown Estate.
- Burningham, H. and French, J. 2011. Seabed dynamics in a large coastal embayment: 180 years of morphological change in the outer Thames estuary. *Hydrobiologia*, 672, 105-119
- Burningham, H. and French, J. 2012. Is the NAO winter index a reliable proxy for wind climate and storminess in northwest Europe? *International Journal of Climatology*, DOI: 10.1002/joc.3571
- Burrough, P.A. 1986. *Principle of Geographical Information Systems for Land Resources Assessment* Oxford, Clarendon Press.
- Bury, N.R. & Durrant, C. 2009. The effects of metal pollution on the population genetic traits of brown trout (*Salmo trutta L.*) living in the river Hayle, Cornwall, UK. *Comparative biochemistry and Physiology*, 153, (Part A) S90-S113
- Buscomb, D.D. & Scott, T.M. 2008. *The Coastal Geomorphology of North Cornwall: St Ives Head to Trevoise Head. Wave hub Impact on Seabed and Shoreline Processes (WHISSP)*. University of Plymouth.
- Buynevich, I.V. and FitzGerald, D.M. 2003. Textural and compositional characterisation of recent sediments along a paraglacial estuarine coastline, Maine, USA. *Estuarine, Coastal and Shelf Science*, 56 (1), 139-153.
- Cabanes, C.A., Cazenave, A., & Le Provost 2001. Sea-level rise during the past 40 years determined from satellite and in-situ observations. *Science*, 294, 840-842.
- Cai, F., Su, X., Liu, J., Li, B. And Lei, G. (2009) Coastal erosion in China under the condition of global climate change and measures for its prevention. *Progress in Natural Science*, 19, 415 – 426
- Campbell, S. 1998, "Godrevy," *In The Quaternary of Southwest England.*, S. Campbell et al., eds., London: Chapman.
- Carrasco, A. R., Ferreira, Ó., Matias , A., and Freire, P. 2012. Natural and human-induced coastal dynamics at a back-barrier beach. *Geomorpholog*, 159 – 160, 30 – 36.
- Carretero, J.C., Gomez, M., Lozano, I., de Elvira, A.R., Serrano, O., Iden, K., Reistad, M.,

- Reichardt, H., Kharin, V., Stolley, M., von Storch, H., Gunther, H., Pfizenmayer, A., Rosenthal, W., Stawarz, M., Schmith, T., Kaas, E., Li, T., Alexandersson, H., Beersma, J., Bouws, E., Komen, G., Rider, K., Flather, R., Smith, J., Bijl, W., de Ronde, J., Mietus, M., Bauer, E., Schmidt, H., Langenberg, H., 1998. Changing waves and storms in the northeast Atlantic? *Bulletin of the American Meteorological Society* 79, 741–760.
- Carter, R.W.G. 1988. *Coastal Environment: An Introduction to the Physical, Ecological and Cultural Systems of Coastlines*. London, Academic Press.
- Cashin, J.A. 1949. Engineering works for the improvement of the Mersey. *Journal of the Institute of Civil Engineers*, Number 7, 296-367
- Castaing, P. and Allen, P. 1981. Mechanisms controlling seaward escape of suspended sediment from the Gironde: A macrotidal estuary in France. *Marine Geology*, 40, 1-2, 101 – 118.
- Castaing, P. & Guilcher, A. 1995, "Geomorphology and sedimentology of Rias.," *In Geomorphology and Sedimentology of Estuaries and Developments in Sedimentology*, No. 53 ed. G. M. E. Perillo, ed., Amsterdam: Elsevier Science, pp. 69-111.
- Castelle, B., Bourget, J., Molnar, N., Strauss, D., Deschamps, S., Tomlinson, R., 2007. Dynamics of a wave-dominated tidal inlet and influence on adjacent beaches, Currumbin Creek, Gold Coast, Australia. *Coastal Eng.* 54, 77–90.
- Castelle, B., Lazarow, N., Marty, G., Tomlinson, R.B., 2006. Impact of beach nourishment on Coolangatta Bay morphology over the period 1995–2005. In: *Proceedings of the 15th NSW Coastal Conference (Coffs Harbour, New South Wales, Australia)*. 12p.
- Cazenave, A., and Llovel, W., 2010. Contemporary sea level rise. *Annual Review of Marine Science* 2, 145–173.
- Cazenave, A., Nerem, R.S., 2004. Present-day sea level change: Observations and causes. *Reviews of Geophysics* 42, RG3001.
- Chakraborty, P., Babu, P.V.R., Sarma, V.V., 2012. A study of lead and cadmium speciation in some estuarine and coastal sediments. *Chem. Geol.* 294–295, 217–225.
- Chandramohan, P., Nayak, B.U., 1994. A study for the improvement of the Chilka Lake tidal inlet, east coast of India. *J. Coastal Res.* 10 (4), 909–918.

- Chapman, S., 1923. A note on the fluctuation of water level in a tidal power reservoir. *Philos. Mag. J. Sci., XLVI, Sixth series*, Dec., 101–108.
- Chini, N., Stansby, P., Leake, J., Wolf, J., Roberts-Jones, J., Lowe, J., 2010. The impact of sea level rise and climate change on inshore wave climate: a case study for East Anglia (UK). *Coastal Engineering* 57, 973–984.
- Chapman, S., 1923. A note on the fluctuation of water level in a tidal power reservoir. *Philos. Mag. J. Sci., XLVI, Sixth series*, Dec., 101–108.
- Church, J.A. & White, A. 2006. A 20th Century acceleration in global sea-level rise. *Geophysical Research Letters*, 33, L01602
- Clark, J.R., 1996. *Coastal Zone Management Handbook*. Lewis Publishers, USA
- Clarke ML, Rendell HM. 2006. Effects of storminess, sand supply and the North Atlantic Oscillation on sand invasion and coastal dune accretion in Western Portugal. *The Holocene* 16(3): 341–355, DOI: 10.1191/0959683606hl932rp.
- Clarke ML, Rendell HM. 2009. The impact of North Atlantic storminess on western European coasts: a review. *Quaternary International* 95(1–2): 31–41, DOI: 10.1016/j.quaint.2008.02.007.
- Clayton, K. & Shamon, N. 1998. A new approach to the relief of Great Britain 1. The machine readable database. *Geomorphology*, 25, 31-42
- Clayton, K. M. 1995, "Predicting sea level rise and managing the consequences.," *In Environmental Science for Environmental Management*, T. O'Riordan, ed., Harlow: Longman.
- Cook, N.J. & Prior, M.J. 1987. Extreme wind climate of the United Kingdom. *Journal of Wind Eng. Wind Aerodyn.*, 26, 371-389
- Cooper, J.A.G., McKenna, J., Jackson, D.W.T., & O'Connor, M. 2007. Mesoscale coastal behaviour related to morphological self-adjustment. *Geology*, 35, 187-190
- Cooper, N.J. & Pontee, N.I. 2006. Appraisal and evolution of the littoral 'sediment cell' concept in applied coastal management: Experiences from England and Wales. *Ocean & Coastal Management*, 49, 498-510
- Cooper, N.J., Hooke, J.M., Bray, M.J., 2001. Predicting coastal evolution using a sediment budget approach: a case study from southern England. *Ocean and Coastal Management* 44, 711 – 728
- Costanza, R., Pérez-Maqueo, O., Martinez, M.L., Sutton, P., Anderson, S.J., Mulder, K., 2008. The value of coastal wetlands for hurricane protection. *Ambio* 37 (4), 241–248.
- Coulombier, T., Florence, T. and Brenon, I. 2013. Seasonal monitoring of sediment

- dynamics in a highly turbid estuary (Charente Estuary, France): Source and sink of the turbidity maximum. *Coastal Dynamics*, 387 - 396
- Cowell, P.J., and Thom, B.G., 1994. Morphodynamics of coastal evolution. In: Carter, R.W.G., Woodroffe, C.D. (Eds.), *Coastal Evolution*. Cambridge University Press, Cambridge, pp. 33–86.
- Crowel, M., Leatherman, S.P., & Buckley, M.K. 1991. Historical shoreline change-error analysis and mapping accuracy. *Journal of Coastal Research*, 7, 839-852
- Cundy, A. B., Croudace, I. W., Cearreta, A. & Irabien, M. J. 2003. Reconstructing historical trends in metal input in heavily-disturbed, contaminated estuaries: studies from Bilbao, Southampton Water and Sicily. *Applied Geochemistry*, 18, 311 – 325.
- Dallas, K. L. and Barnard, P. L. 2011. Anthropogenic influences on shoreline and nearshore evolution in the San Francisco Bay coastal system. *Estuarine, Coastal and Shelf Science*, 92, 195 – 204.
- Dalrymple, R.W., Zaitlin, B.A., & Boyd, R. 1992. Estuarine facies models: conceptual basis and stratigraphic implications. *J.Sediment.Petrol.*, 62, 1130-1146,
- Das, S. and Vincent, J.R. 2009. Mangroves protected villages and reduced death toll during Indian super cyclone. *Proc. Natl. Acad. Sci. U.S.A.* 106 (18), 7357–7360.
- Davidson, N. C. & Buck, A. L. 1997, *An Inventory of UK Estuaries.*, Joint Nature Conservation Committee (JNCC).
- Davidson, N. C., Laffoley, D. D., Way, L. S., Key, R., Drake, C. M., Pienkowski, M. W., Mitchell, R., & Duff, K. L. 1991, *Nature conservation and estuaries in Great Britain*, Nature Conservancy Council, Peterborough, UK.
- Davis, R. A. 1978, "Beach and Near-Shore Zone.," *In Coastal Sedimentary Environments*, R. Davis, ed., New York: Springer-Verlag.
- Davis Jr., R.A., Fox, W.T., 1981. Interaction between wave- and tide-generated processes at the mouth of a microtidal estuary: Matanzas River, Florida (U.S.A.). *Marine Geology* 40, 49 - 68.
- Dawson A., Elliott, L., Noone, S., Hickey, K., Holt, T., Wadhams, P., and Foster, I. 2004. Historical storminess and climate ‘see-saws’ in the North Atlantic region. *Marine Geology* **210**: 247–259, DOI:10.1016/j.margeo.2004.05.011.
- Dawson, R.J., Dickson, M.E., Nicholls, R.J., Hall, J.W., Walkden, M.J.A., Stansby, P., Mokrech, M., Richards, J., Zhou, J., Milligan, J., Jordan, A., Pearson, S., Rees, J., Bates, P., Koukoulas, S., Watkinson, A., 2009. Integrated analysis of risks of coastal flooding and cliff erosion under scenarios of long term change. *Clim. Chang.* 95 (1–2), 249–288.



- de Vriend, H. J. 1991. Mathematical modelling and large-scale coastal behaviour. *Journal of Hydraulic Research*, 29 (6), 727 - 753
- de Vriend, H. J., Capobianco, M., Chesher, T., de Swart, H. E., Latteux, B. And Stive, M. J. F. 1993. Approaches to long-term modelling of coastal morphology: A review. *Coastal Engineering*, 21, (1-3), 225 – 269.
- Dean, R.G. & Dalrymple, R.A. 2002. *Coastal Processes- with Engineering Applications*. Cambridge, Cambridge University Press.
- Dean, R.G., 1988. Sediment interaction at modified coastal inlets: processes and policies. In: Aubrey, D., Weishar, L. (Eds.), *Hydrodynamics and Sediment Dynamics of Tidal Inlets*, Lecture Notes on Coastal and Estuarine Studies vol. 29. Springer, New York, pp. 412–439.
- Defra 2002, *Futurecoast*, Defra.
- Defra 2006, *Flood and Coastal Defence Appraisal Guidance FC DAG3 Economic Appraisal*, Supplementary Note to Operating Authorities - Climate Change Impacts, October, 2006.
- DEFRA/EA 2004, *Integrated Research Results on Hydrobiosedimentary Processes in Estuaries*, DEFRA/Environment Agency Flood and Coastal Defence R & D Programme.
- Dhar, O. N. and Nandargi, S. 2003. Hydro meteorological aspects of floods in India. *Natural Hazards*, 28, 1- 33
- Di Lorenzo, J.L., 1988. The overtide and filtering response of small inlet-bay systems. In: Aubrey, D.G., Weishar, L. (Eds.), *Hydrodynamics and Sediment Dynamics of Tidal Inlets*. Springer-Verlag, pp. 24-54.
- Dickson RR, Osborn TJ, Hurrell JW, Meincke J, Blindheim J, Adlandsvik B, Vinje T, Alekseev G, Maslowski W. 2000. The Arctic Ocean response to the North Atlantic Oscillation. *Journal of Climate* 13: 2671–2696, DOI: 10.1175/1520-0442(2000)013<2671:TAORTT>2.0.CO;2.
- Dickson, M., Walkden, M. J. A. & Hall, J. W. 2007. Systematic impacts of climate change on an eroding coastal region over the twenty-first century. *Climate Change*, 84, 141-166.
- Dissanayake, D.M.P.K., Roelvink, J.A., Van der Wegen, M., 2009. Modelled channel patterns in a schematized tidal inlet. *Coastal Eng.* 56 , 1069–1083.
- Dobson, J. E. 1992. Global challenges demand more precision, better generalization. *GIS World*, 68-69.
- Dodet, G., Bertin, X., & Taborda, R. 2010. Wave climate variability in the North-East Atlantic ocean over the last six decades. *Ocean Modelling*, 31, 120-131

- Donat, M.G., Renggli, D., Wild, S., Alexander, L.V., Leckebusch, G.C., et al., 2011. Reanalysis suggests long-term upward trends in European storminess since 1871. *Geophys. Res. Lett.* 38, E1–E6.
- Donnelly, J.P., Cleary, P., Newby, P., Ettinger, R., 2004. Coupling instrumental and Geological records of sea-level change: evidence from southern New England of an increase in the rate of sea-level rise in the late 19th century. *Geophysical Research Letter* 31, L05203.
- Dorst, L.L. (2009) *Estimating Sea Floor Dynamics in the Southern North Sea to Improve Bathymetric Survey Planning*. Hydrographic Service of the Royal Netherlands Navy.
- Douglas, B. C. & Crowell, M. 2000. Long-term shoreline position prediction and error propagation. *Journal of Coastal Research* 16, 145 – 152.
- Draper, L. 1991, *Wave climate atlas of the British Isles*. London.
- Draut, A. E., Logan, J. B. And Mastin, M. C. 2011. Channel evolution on the dammed Elwha river, Washington, USA. *Gemorphology*, 127, 71 – 87.
- DTI, 2004. *Atlas of UK Marine Renewable Energy Resources*
- Durning, B. 1989. A new model for the development of the Variscan facing confrontation at Padstow, north Cornwall. *Proceedings of the Ussher Society*, 7, 141-145.
- Dyer, K.R. 1986. *Coastal and Estuarine Sediment Transport* Chichester, Wiley-Interscience.
- Dyer, K. R. 2002, "FutureCoast Estuary Assessment," *In Futurecoast CD-ROM prepared for Defra.*, Halcrow, ed.
- Edwards, R. J. 2006. Mid- to late-Holocene relative sea-level change in southwest Britain and the influence of sediment compaction. *The Holocene*, 16,4, 557 – 587.
- Elias, E.P.L., Cleveringa, J., Buijsman, M.C., Roelvink, J.A., Stive, M.J.F., 2006. Field and model data analysis of sand transport patterns in Texel tidal inlet (The Netherlands). *Coastal Eng.* 53, 505–529.
- Elias, E.P.L., van der Spek, A.J.F., 2006. Long-term morphodynamic evolution of Texel Inlet and its ebb-tidal delta (The Netherlands). *Mar. Geol.* 225, 5–21.
- EMPHASYS Consortium 2000, *Modelling Estuary Morphology and Process*, produced by the EMPHASYS consortium for MAFF project FD1401.
- Environment Agency, 1999. *The State of the Environment in England and Wales: Coasts*. TSO, London.
- Escoffier, F.F., 1940. The stability of tidal inlets. *Shore Beach* 8 (4), 114–115.
- Eshel G., Levy G.J., Mingelgrin, U. and Singer M.J. 2004. Critical evaluation of the use of

- laser diffraction for particle-size distribution analysis. *Soil Science Society of America Journal*, **68**, 736-743.
- Esteves, L. S., William, J. J. and Brown, J. M. 2011. Looking for evidence of climate change impacts in the eastern Irish Sea. *Natural Hazards and Earth System Sciences*, **11**, 1641 – 1656.
- Esteves, L.S., William, J.J., Nock, A., & Lyubery, G. 2009. Quantifying shoreline changes along the Sefton coast (UK) and the implications for research-informed coastal management. *Journal of Coastal Research*, **S156**, 602-606.
- European Commission, 2004. Living with Coastal Erosion in Europe e Sediment and Space for Sustainability. Part I - Major Findings and Policy Recommendations of the EUROSION Project. Office for Official Publications of the European Communities, Luxembourg, 40 pp.
- EUROSION, 2004. Living with coastal erosion in Europe: sediment and space for sustainability. Report to Directorate General Environment, European Commission.
- Evans, E., Ashley, R., Hall, J., Penning-Rowell, E., Saul, A., Sayers, P., Thorne, C., Watkinson, A., 2004a. Foresight. Future Flooding. Executive Summary. Office of Science and Technology, London.
- Evans, E., Ashley, R., Hall, J., Penning-Rowell, E., Saul, A., Sayers, P., Thorne, C., Watkinson, A., 2004b. Foresight. Future Flooding. Scientific Summary: Volume I Future Risks and their Drivers. Office of Science and Technology, London.
- Everard, C.E., 1962. Mining and shore-line evolution near St. Austell, Cornwall. *Trans. R. Geol. Soc. Corn.* **19**, 199 – 219.
- Everard, M., Jones, L., Watts, B., 2010. Have we neglected the societal importance of sand dunes? An ecosystem services perspective. *Aquat. Conserv. Mar. Freshw. Ecosyst.* **20** (4), 476–487.
- Faiz, S. & Boursier, P. 1996. Geographic data quality: From assessment to exploitation. *Cartographica*, **33**, (1) 33-40
- Fenster, M.S., Dolan, R., & Elder, J.F. 1993. A new method for predicting shoreline positions from historical data. *Journal of Coastal Research*, **9**, (1) 147-171
- Firth, A. and Smith, R.S. 1999. Hayle Estuary historic audit: *Wessex Archaeology Report Reference 43091.2 for the Environment Agency*.
- Firth, C.R. & Stewart, I.S. 2000. Post glacial tectonics of the Scottish glacio-isostaic

- uplift centre. *Quaternary Science Reviews*, 19, 1-22
- FitzGerald, D.M., 1982. Sediment bypassing at mixed energy tidal inlets. Proc. of 18th International Conference on Coastal Engineering. ASCE, Cape Town, pp. 1094–1118.
- FitzGerald, D.M. 1984. Interactions between the ebb tidal delta and landward shoreline: Price Inlet, South Carolina. *Journal of Sedimentary Petrology*, 54, 1303-1318.
- FitzGerald, D. M. 1988, "Shoreline erosional-depositional processes associated with tidal inlets.," *In Hydrodynamics and Sediment Dynamics of Tidal Inlets.*, D. G. Aubrey & L. Weishar, eds., New York: Springer-Verlag, Inc., pp. 186-225.
- FitzGerald, D.M., 1996. Geomorphic variability and morphologic and sedimentologic controls on tidal inlets. *J. Coast. Res.* 23, 47– 71.
- FitzGerald, D.M., Buynevich, I.V., Fenster, M.S., & McKinlay, P.A. 2000a. Sand dynamics at the mouth of a rock bound, tide-dominated estuary. *Sediment.Geol.*, 131, 25-49
- FitzGerald, D.M., Buynevich, I.V., Davis\_Jr, R.A., & Fenster, M.S. 2002. New England tidal inlets with special reference to riverine-associated inlet systems. *Geomorphology*, 48, 179-208
- FitzGerald, D.M., Fico, C., and Hayes, M.O. 1979. Effects of the Charleston Harbor, South Carolina, jetty construction on local accretion and erosion. Proceedings of the Speciality Conference on Coastal Structures, 79 (ASCE, Alexandria, Virginia), pp. 641-644.
- FitzGerald, D.M., Kraus, N.C., Hands, E.B., 2000b. *Natural Mechanisms of Sediment Bypassing at Tidal Inlets*. US Army Engineer Research and Development Center, Vicksburg, MS. CHETN-IV-30.
- FitzGerald, D.M. and Hayes, M.O. 1980. Tidal inlet effects on barrier island development. Proceedings of Coastal Zone '80 (ASCE, Hollywood, Florida), pp. 2355-2379.
- FitzGerald, D.M., Buynevich, I.V., Davis Jr., R.A., Fenster, M.S., 2002. New England tidal inlets with special reference to riverine associated inlet systems. *Geomorphology* 48, 179–208.
- Flemming, B. W. 1988. Process and pattern of sediment mixing in a microtidal coastal lagoon along the west coast of South Africa. In: De Boer, P. L., van gelder, A., Nio, S. D. (Eds). *Tide-Influenced Sedimentary Environments and Facies*. D. Reidel Publ. Co., Dordrecht, 275 – 288.
- Flemming, B.W. 2007. The influence of grain-size analysis methods and sediments mixing on curve shapes and textural patterns: implications for sediment trend analysis. *Sedimentary Geology*, 202, (425) 435

- Flemming, N. C. 1982. Multiple regression analysis of earth movements and eustatic sea-level change in the United Kingdom in the past 9000 years. *Proc. Geol. Soc.*, **93** (1), 113-125.
- Fletcher, C.H.; Rooney, J.J.B.; Barbee, M.; Lim, S.-C., and Richmond, B.M., 2003. Mapping shoreline change using digital orthophotogrammetry on Maui, Hawaii. *Journal of Coastal Research*, Special Issue No. 38, pp. 106–124.
- Fletcher, S., Jefferspn, R., Glegg, G., Rodwell, L. and Dodds, W. 2014. England's evolving marine and coastal governance framework. *Marine Policy*, *45*, 261 – 268.
- Folk, R.L. & Ward, W.C. 1957. Brazos river bar: a study in the significance of grain size parameters. *Journal of Sedimentary Petrology*, *27*, 3-26
- Fontolan, G., Pillon, S., Delli Quadri, F. and Bezzi, A. 2007. Sediment storage at tidal inlets in northern Adriatic lagoons: Ebb-tidal delta morphodynamics, conservation and sand use strategies. *Estuarine, Coastal and Shelf Science*, *75*, 261 – 277.
- French, P.W. 1997. *Coastal and Estuarine Management* London, Routledge.
- Friedman, G.M. & Sanders, J.E. 1978. *Principles of Sedimentology* New York, John Wiley & Sons.
- Friedman, G.M. 1979. Differences in size distributions of populations of particle among the sands of various origins. *Sedimentology*, *26*, 3-32
- Friend, P. L., Velegrakis, A. F., Weatherston, P. D. & Collins, M. B. 2006. Sediment transport pathways in a dredged ria system, southwest England. *Estuarine, Coastal and Shelf Science* *67*, 491 – 502.
- Fuller, R. M. and Randall, R. E. 1988. The Orford Shingles, Suffolk, Uk – Classic conflicts in coastline management. *Biological Conservation*, *46*, 95 – 114.
- Gallay, M. 2013. Direct Acquisition of Data: Airborne laser scanning. In Clarke, L. E. and Nield, J. (Ed) *Geomorphological Techniques (Online Edition)*. British Society for Geomorphology, London, UK. ISSN 2047 – 0371. Chapter 2, Section 1.4.
- Gallien, T. W., Sanders, B. F. and Flick, R. E. 2014. Urban coastal flood prediction: Integrating wave overtopping, flood defences and drainage. *Coastal Engineering*, *91*, 18 – 28.
- Galloway, J. A. 2009. Storm flooding, coastal defence and land use around the Thames Estuary and tidal river c.1250 – 1450. *Journal of Medieval History*, *35*, 171 – 188
- Gao, S. & Collins, M. 1992. Net sediment transport patterns inferred from grain-size trends, based upon definition of "transport vectors". *Sedimentary Geology*, *81*(1), (1) 47-60
- Gao, S. & Collins, M. 1994. Analysis of grain size trends , for defining sediment

- transport pathways in marine environments. *Journal of Coastal Research*, 10(1), (1) 70-78
- Gao, S. and Collins, M. B. 2014. Holocene sedimentary systems on continental shelves. *Marine Geology*, 352, 268 - 294
- Gao, S., Collins, M., Lanckneus, J., de Moor, G., & van Lancker, V. 1994. Grain size trends associated with net sediment transport patterns: an example from Belgian continental shelf. *Marine Geology*, 121, ((1/2)) 171-185
- Gaudio, D.J., Kana, T.W., 2001. Shoal bypassing in mixed energy inlets: geomorphic variables and empirical predictions for nine South Carolina inlets. *Journal of Coastal Research* 17, (2), 280–291
- Gauss, A. G. and House, M. R. 1972. The Devonian successions in the Padstow area, North Cornwall. *Journal of the Geological Society*, 128, 151 – 172.
- Gedan, K.B., Kirwan, M.L., Wolanski, E., Barbier, E.B., Silliman, B.R., 2011. The present and future role of coastal wetland vegetation in protecting shorelines: answering recent challenges to the paradigm. *Climate Chang.* 106, 7–29.
- Gibbs, A.E., 1999. Gelfenbaum, Bathymetric Change off the Washington-Oregon Coast. *Coastal Sediments*. ASCE, 1627–1641.
- Gilbert, G. K. 1877. *Report on the geology of the Henry Mountains*. United States Geographical and Geological Survey of the Rocky Mountains Region US Government Printing Office, Washington.
- Godwin H, Godwin ME. 1940. Submerged peat at Southampton: data for the study of post-glacial history. *V. New Phytologist* **39**: 303–307.
- Goldberg, E.D. 1994. *Coastal zone space- Prelude to Conflict?* Paris, UNESCO.
- Gönnert, G. 2004. Maximum storm surge curve due to global warming for the European North Sea region during the 20th - 21st Century. *Natural Hazards*, 32, (211) 218
- Gonzalez-Santamaria R., Zou Q.-P. and Pan S. 2011. Two-way coupled wave and tide modelling of a wave farm, *Journal of Coastal Research*, SI 64, 1038–1042, ISSN 0749-0208.
- González-Santamaria, R., Zou, Q. and Pan, S. 2012. Modelling of the impact of a wave farm on nearshore sediment transport. *Coastal Engineering 2012*. 1-9
- González-Villanueva, R., Costas, S., Pérez-Arlucea, M., Jerez, S., Trigo, R. M. 2013; Impact of atmospheric circulation patterns on coastal dune dynamics, NW Spain. *Geomorphology*, 185 (2013) 96–109

- Gordon, A.D., 1990. Coastal lagoon entrance dynamics. In: Proceedings of 22<sup>nd</sup> International Coastal Engineering Conference, Delft. ASCE, pp. 2880–2893.
- Graf, W.L. 2000. Locational probability approach for a damned urbanizing stream: Salt River, Arizona, USA. *Environmental Management*, 25, 321-335
- Granek, E.F., Ruttenberg, B.I., 2007. Protective capacity of mangroves during tropical storms: a case study from Wilma and Gamma in Belize. *Mar. Ecol. Prog. Ser.* 343, 101–105.
- Greenwood, B. 1969. Sediment parameters and environment discrimination: an application of multi-variate statistics. *Canadian Journal of Earth Sciences*, 6, 1347-1357
- Gulev, S.K., Grigorieva, V., 2004. Last century changes in ocean wind wave height from global visual wave data. *Geophysical Research Letters* 31.
- Gulev, S.K., Hasse, L., 1999. Changes of wind waves in the North Atlantic over the last 30 years. *International Journal of Climatology* 19, 1091–1117.
- Hackney, C., Darby, S. E., Leyland, J. . 2013. Modelling the response of soft cliffs to climate change: A statistical, process-response model using accumulated excess energy. *Geomorphology*, 187, 108 – 121.
- Hadley, D. 2009. Land use and the coastal zone. *Land Use Policy*, 26S, S198 – S203.
- Haigh, I., Nicholls, R. J. & Wells, N. Rising sea levels in the English Channel 1900 to 2100 ICE-*Maritime Engineering*, 2011. 81-92
- Haines, P., Tomlinson, R., Thom, B., 2006. Morphodynamic assessment of intermittently open/closed coastal lagoons in New South Wales, Australia. *Estuarine, Coast Shelf Sci.* 67, 321–332.
- Halcrow, 2002. *Futurecoast*. London, Halcrow Ltd.
- Halcrow Group Ltd., HR Wallingford, John Chatterton Associates, 2001. *National appraisal of assets at risk of flooding and coastal erosion in England and Wales*. Final Report for the Department of Environment, Food and Rural Affairs, London.
- Halcrow, 2006. Wave Hub Development and Design Phase Coastal Processes Study Report. South West of England Regional Development Agency
- Hallermeier, R.J., 1981. A profile zonation for seasonal sand beaches from wave climate, *Coastal Engineering*, 4, 253-277.
- Hallet, T. B., Coulson, T., Pilkington, J. G., Clutton-Brock, T. H., Pemberton, J. M.,

- Grenfell, B. T. 2004. Why large-scale climate indices seem to predict ecological processes better than local weather. *Nature* **430**: 71–75, DOI:10.1038/nature02708.
- Hammer, Ø., Harper, D.A.T., Ryan, P.D. 2001. PAST: Paleontological statistics software package for education and data analysis. *Palaeontologia Electronica* 4(1): 9pp. [http://palaeo-electronica.org/2001\\_1/past/issue1\\_01.htm](http://palaeo-electronica.org/2001_1/past/issue1_01.htm)
- Hansom, J.D. 2001. Coastal sensitivity to environmental change: a view from the beach. *Catena*, 42. 291 – 305
- Hanson, H., Jonsson, L., & Broms, B. 1984, *Beach Erosion in Liberia: Causes and Remedial Measures*, Department of Water Resource Engineering, University of Lund, Sweden Sweden, Report 3090.
- Hapke, C.J.; Reid, D.; Richmond, B.M.; Ruggiero, P., and List, J., 2006. National Assessment of Shoreline Change: Part 3: Historical Shoreline Change and Associated Coastal Land Loss along Sandy Shorelines of the California Coast. U.S. Geological Survey Open File Report 2005-1401. <http://pubs.usgs.gov/of/2006/1219/> (accessed November, 12, 2013).
- Hapke, C. J., Kratzmann, M. G. And Himmelstoss, E. A. 2013. Geomorphic and human influence on large-scale coastal change. *Geomorphology*. 199, 160 – 170.
- Hardman, C.E., Helliwell, N.C., & Hopkins, J.S. 1973. Extreme wind speeds over the United Kingdom for periods ending in 1971. *Meteorol. Office. Climatol. Mem.*, 50A, 1-31
- Harris, P. T., Pattiaratchi, C. B., Keene, J. B., & Cole, A. 1990, *Modelling the evolution of a linear sandbank field, Moreton Bay, Queensland.*, Ocean Sciences Institute, University of Sydney.
- Hartmann, D. & Christiansen, C. 1992. The hyperbolic shape triangle as a tool for discriminating populations of sediment samples of closely connected origin. *Sedimentology*, 39, 697-708
- Hashim, R., Kamali, B., Tamin, N.M., Zakaria, R., 2010. An integrated approach to coastal rehabilitation: mangrove restoration in Sungai Haji Dorani, Malaysia. *Estuarine, Coastal and Shelf Science* 86, 118 -124.
- Hayes, M.O., 1975. Morphology of sand accumulation in estuaries: an introduction to the symposium. In: Cronin, L.E. (Ed.), *Estuarine Research*. Academic Press, New York, pp. 3– 22.
- Hayes, M.O., 1979. Barrier island morphology as a function of tidal wave and regime. In: Leatherman, S.P. (Ed.), *Barrier Islands: From the Gulf of St. Lawrence to the Gulf*



- of *Messico*. Academic Press, New York, pp. 1-28.
- Hayes, M.O., 1980. General morphology and sediment patterns in tidal inlets. *Sedimentary Geology* 26, 139-156.
- Hayes, M.O. and Kana, T.W. 1976. Terrigenous clastic depositional environments. Technical report No. 11, CRD, Department of Ge-ology, University of South Carolina, Columbia, South Carolina, 364p.
- Healy, M.G. 1995. Mine waste sedimentation on the Cornish Coast. *Final report for the commision of the European communities environment programme (DGXII)*
- Healy, M. G. 1996, "Holocene coastal evolution at Marazion marsh and Hayle Copperhouse, West Cornwall.," *In Late Quaternary Coastal Change in West Cornwall, UK Field Guide.*, M. G. Healy, ed., Research Publication 3 of the Environmental Research Centre, Department of Geography, University of Durham., pp. 46-59.
- Heap, A.D. & Nichol, S.L. 1997. The influence of limited accommodation space on the stratigraphy of an incised-valley succession: Weiti River estuary, New Zealand. *Marine Geology*, 144, 229-252
- Heath, R.A. 1975. *N.Z. J.Mar.Fresh.Res.*, 9, 449-457
- Héquette, A. & Aernouts, D. 2010. The influence of nearshore sand bank dynamics on shoreline evolution in a macrotidal coastal environment, Calais, northern France. *Continental Shelf Research*, 30, 1349-1361
- Hibma, A., Stive, M.J.F., Wang, Z.B., 2004. Estuarine morphodynamics. *Coastal Engineering* 51, 765 - 778.
- Hicks, D.M. and Hume, T.M., 1996. Morphology and size of ebb tidal deltas at natural inlets on open-sea and pocket-bay coasts, North Island, *New Zealand. J. Coast. Res.* 12 (1), 47–63.
- Hicks, D.M., Hume, T.M., Swales, A., Green, M.O., 1999. Magnitudes, spatial extent, time scales and causes of shoreline change adjacent to an ebb tidal delta, Katikati Inlet, *New Zealand. J. Coast. Res.* 15 (1), 220–240.
- Hill, A.E., 1994. Fortnightly tides in a lagoon with variable choking. *Estuar. Coast. Shelf Sci.* 38, 423e434.
- Hill, H.W., Kelley, J.T., Belknap, D.F., Dickson, S.M., 2004. The effects of storms and stormgenerated currents on sand beaches in Southern Maine, USA. *Marine Geology* 210 (1–4), 149–168.
- Hodson F, West IM. 1972. Holocene deposits of Fawley, Hampshire, and the development of Southampton Water. *Proceedings of the Geologists' Association* **83**: 421–441.

- Hodgkin, E.P., Clark, R., 1988. Wilson, Irwin and Parry Inlets: The Estuaries of the Denmark Shire. Report No. 3, Environmental Protection Authority, Western Australia.
- Holgate, S.J. & Woodworth, P.L. 2004. Evidence for enhanced coastal sea-level rise during the 1990s. *Geophysical Research Letters*, 31, (L07305)
- Holland, K.T. & Elmore, P.A. 2008. A review of heterogenous sediments in coastal environments. *Earth Science Review*, 89, 116-134
- Hollick, L.M., Shail, R.K. and Leveridge, B.E. 2006. Devonian rift-related sedimentation and Variscan tectonics - new data on the Looe and Gramscatho basins from the resurvey of the Newquay District. *Geoscience in south-west England*, 11, 191-198.
- Holloway, P. E. 1996, "A field investigation of water exchange between a small coastal embayment and an adjacent shelf," *In Coastal and Estuarine Studies: Mixing in Estuaries and Coastal Seas.*, C. Pattiaratchi, ed., Washington, D.C.: American Geophysical Union, Washinton, D.C..
- Holthuijsen, L.H., and Tolman, H.L., 1991. Effects of the Gulf Stream in ocean waves. *J. Geophys. Res. C* 96, 12755–12771.
- Hosking, K. F. G. & Obial, R. 1996. A preliminary study of the distribution of certain Metals of economic interest in the sediments and waters of Carrick Roads (West Cornwall) and of its 'feeder' rivers. *Camborne School of Mines Magazine*, 17 – 37
- Hosking, K. F. G. & Ong, P. M., 1963 – 1964. The distribution of tin and certain other heavy metals in the superficial portions of the Gwithian/Hayle beach of West Cornwall. [19], 351-390. *Transactions of the Royal Geological Society of Cornwall*.
- Houser, C and Mathew, S. 2011. Alongshore variation in foredune height in response to transport potential and sediment supply: South Padre Island, Texas. *Geomorphology*, 125, 62 - 72
- Houser, C., Hapke, C. And Hamilton, S. 2008. Controls on coastal dune morphology, shoreline erosion and barrier island response to extreme storms. *Geomorphology*, 100, 223 – 240.
- HR Wallingford 2001, Harwich harbour strategic studies analysis for the *Bathymetric surveys of the Stour and Orwell estuaries* Report EX4424.
- HR Wallingford, ABPmer, & Pethick, J. 2006, *Review and formalisation of*

- geomorphological concepts and approaches for estuaries.*, R & D Technical Report FD2116/TR2. Joint DEFRA EA Flood and Coastal Erosion Risk Management R&D Programme.
- Hulme, M. & Jones, P.D. 1991. Temperatures and windiness over the United Kingdom during the winters of 1989=90 compared with previous years. *Weather*, 46, 126-136
- Hume, T. M. & Herdendorf, C. E. 1987. *Tidal inlet stability.*, Wellington: National Water and Soil Conservation Authority, Wellington.
- Hume, T.M. & Herdendorf, C.E. 1988a. The "Fukert-Heath" relationship for tidal inlet stability reviewed. *New Zealand Journal of Marine and Freshwater Research.*, 22, 129-134
- Hume, T.M. & Herdendorf, C.E. 1988b. A geomorphic classification of estuaries and its application to coastal resource management- A New Zealand example. *Ocean Shoreline Management*, 11, 249-274
- Hume, T.M. & Herdendorf, C.E. 1992. Factors controlling inlet characteristics on low drift coasts. *Journal of Coastal Research*, 8, (2) 355-375
- Hurrell, J.W. 1996. Influence of variations in extra-tropical wintertime teleconnections on Northern Hemisphere temperature. *Geophysical Research Letters*, 23, (6) 665-668
- Hurrell, J. W., Kushnir, Y., Visbeck, M., & Ottersen, G., . 2003. An overview of the North Atlantic Oscillation. Hurrell, J. W., Kushnir, Y., Ottersen, G., and Visbeck, M. [134], 1-35. Geophysical Monograph Series. The North Atlantic Oscillation: Climate Significance and Environmental Impact.
- Hurrell, J. W., and Deser, C. 2010. North Atlantic climate variability: the role of the North Atlantic Oscillation. *Journal of Marine Systems* 79(3-4): 231–244.
- Hughes, S.H., 2000. The geochemical and mineralogical record of the impact of historical mining within estuarine sediments; Fal estuary, Cornwall, UK. Unpublished PhD thesis, University of Exeter.
- Ijmker, J., Stauch, G., Dietze, E., Hartmann, K., Diekmann, B., Locket, G., Opitz, S., Wünnemann, B., and Lehmkuhl, F. 2012. Characterisation of transport processes and sedimentary deposits by statistical end-member mixing analysis of terrestrial sediments in the Donggi Cona Lake catchment, NE Tibetan Plateau. *Sedimentary Geology*, 281, 166 – 179.
- Intergovernmental Panel on Climate Change (IPCC) 2007. *Climate Change 2007:*

- The Physical Science Basis*, Intergovernmental Panel on Climate Change, Cambridge and New York.
- Intergovernmental Panel on Climate Change (IPCC), 2013. *Climate change 2013: The Physical science basis*. Contribution of working group 1 to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) on climate change.
- Jabaloy-Sánchez, A., Lobo, F. J., Azor, A., Martín-Rosales, W., Pérez-Peña, J. V., Bárcenas, P., Macías, J.M. Fernández-Salas, L. M. and Vázquez-Vílchez, M. 2013. Six thousand years of coastline evolution in the Guadalfeo deltaic system (southern Iberian Peninsula). *Geomorphology*, <http://dx.doi.org/10.1016/j.geomorph.2013.08.037>.
- Janssen, P.A.E.M., 1989. Wave induced stress and the drag of air flow over sea waves. *J. Phys. Oceanogr.* 19, 745–754.
- Janssen, P.A.E.M., 1991. Quasi-linear theory of wind-wave generation applied to wave forecasting. *J. Phys. Oceanogr.* 21, 1631–1642.
- Janssen, P.A.E.M., 1992. Experimental evidence of the effect of surface waves on the airflow. *J. Phys. Oceanogr.* 22, 1600–1604.
- Jarrett, J.T., 1976. Tidal Prisms Inlet Area Relationships. GITI Report 3. US Army Coastal Engineering Research Center, Waterways Experiment Station, Vicksburg, Mississippi, 32 pp.
- Jay, D. A. & Musiak, J. D. 1996, "Internal Tidal Asymmetry in channel flows: Origins and Consequences.," *In Coastal and Estuarine Studies: Mixing in Estuaries and Coastal Seas*, C. Pattiaratchi, ed., Washinton, D.C.: American Geophysical Union.
- Jeftic, L., Sheavly, S., & Adler, E. 2009. *A Marine Litter: A Global Challenge* United Nations Environment Programme.
- Jenkin, A.K. 1963. *Mines and miners of Cornwall: VII Perranporth and Newquay*. Worden Ltd, Cornwall.
- Jenkin, A.K. 1964. *Mines and miners of Cornwall: IX Padstow, St Coulomb and Bodmin*. Worden Ltd, Cornwall.
- Jenkins, R.; Gould, R. W.; Gedcke, D. 1995. *Quantitative X-Ray Spectrometry*, Second Edition, , Marcel Dekker, Inc. QD96.X2 J46 ISBN 0-8247-9554-7.
- Jimenez, J.A., Sancho-García, A., Bosom, E., Valdemoro, H.I. and Guillén, J., 2012.

- Storm-induced damages along the Catalan coast (NW Mediterranean) during the period 1958–2008. *Geomorphology*, 143– 144, 24–33.
- Jing, K., Zhiguo, G., Yunzhong, J., Wanghao, A., 2012. Current study on estuarine coastal ecological environment and its development. *Procedia Engineering* 28, 171 - 177.
- JNCC (URL) *River Camel*. Joint Nature Conservation Committee.  
<http://jncc.defra.gov.uk/protectedsites/sacselection/sac.asp?EUCode=UK0030056>.  
 (Accessed 28-06-2013)
- Johnson, D.W. 1919. *Shore processes and shoreline development* New York, Wiley.
- Johnsson, M. J. 1993. The system controlling the composition of clastic sediments. In: M.J. Johnsson, A. Basu (Eds.), *Processes Controlling the Composition of Clastic Sediments*, Geological Society of America Special Paper, 284 (1993), pp. 1–19
- Jones, C. 1997. *Geographical Information Systems and Computer Cartography* Essex, Addison Wesley Longman Limited.
- Jones, P.D., Jónsson, T., & Wheeler, D. 1997. Extension to the North Atlantic Oscillation using early instrumental pressure observations from Gibraltar and South-West Iceland. *Int.J.of Climato.*, 17, 1433-1450
- Kantha and Clayson, 2004;
- Karunarathna, H., Reeve, D. and Spivack, M. 2008. Long-term morphodynamic evolution of estuaries: An inverse problem. *Estuaries, Coastal and Shelf Science* 77, 385 – 395.
- Katz, O. and Mushkin, A. 2013. Characteristics of sea-cliff erosion induced by a strong winter storm in the eastern Mediterranean. *Quaternary Research*, 80, 20 – 32.
- Kelsey, J. 1972. Geodetic aspects concerning possible subsidence in South-Eastern England. *Philosophical Transactions of the Royal Society of London*, A 272, 141-149.
- Keulegan, G.H., 1967. Tidal flow in estuaries, water level fluctuations of basins in communication with seas. Comm. *Tidal Hydraul.*, Army Corps Eng. Vicksbg. Miss., Tech. Bull. 4, 89.
- Kidson, C. and Heyworth, A. 1978. Holocene eustatic sea level change . *Nature, Lond.* , 273, 748- 50.
- Kjerfve, B., 1986. Comparative oceanography of coastal lagoons. In: Wolfe, D.A. (Ed.), *Estuarine Variability*. Academic, San Diego, California, pp. 63e81.
- Kjerfve, B., Knoppers, B.A., 1991. Tidal-choking in a coastal lagoon. In: Parker, B. (Ed.), *Tidal Hydrodynamics*. John Wiley, N.Y, pp. 169e181.
- Kleinosky, L.R., Yarnal, B., & Fisher, A. 2007. Vulnerability of Hampton Roads, Virginia to storm-surge flooding and sea level rise. *Natural Hazards*, 40, (43) 70

- Knight, J. and Burningham H. 2011. Boulder dynamics on an Atlantic facing rock coastline, northwest Ireland. *Marine Geology* **283**(1–4): 56–65, DOI:10.1016/j.margeo.2010.07.008.
- Knight, J. and Harrison, S 2013. ‘A land history of men’: The intersection of geomorphology, culture and heritage in Cornwall, southwest England. *Applied Geography*, *42*, pp 186 – 194.
- Koerth, J., Jones, N., Vafeidis, A. T., Dimitrakopoulos, P. G., Melliou, A., Chatzidimitriou, E. and Koukoulas, S. 2013. Household adaptation and intention to adapt coastal flooding in the Axios – Loudias – Aliakmonas National Park, Greece. *Ocean and Coastal Management*, *82*, 43 – 50
- Komar, P.D. 1976. *Beach Processes and Sedimentation*. Englewood, Cliffs, N.J., Prentice Hall.
- Komar, P.D. 2010. Shoreline evolution and management of Hawke's Bay, New Zealand: tectonics, coastal processes and human impacts. *Journal of Coastal Research*, *26*, (1) 143-156
- Komen, G.J., Cavaleri, L., Donelan, M., Hasselmann, K., Hasselmann, S., Janssen, P.A.E.M., 1994. *Dynamics and Modelling of Ocean Waves*. Cambridge University Press, Cambridge. 532 pp.
- Krumbein, W.C. 1934. Size frequency distribution of sediments. *Journal of Sedimentary Petrology*, *4*, 65-77
- Krumbein, W.C. 1938. Size-frequency distribution of sediments and the normal phi curve. *Journal of Sedimentary Petrology*, *8*, 84-90
- Kushnir, Y., Cardone, V.J., Greenwood, J.G., & Cane, M.A. 1997. The recent increase in North Atlantic wave height. *J.Climate*, *10*, 2107-2113
- Lambeck K. 1995. Late Devensian and Holocene shorelines of the British Isles and North Sea from models of glacio-hydro-isostatic rebound. *Journal of the Geological Society*, London *152*: 437–448.
- Larson, M., and Kraus, N.C., 1994. Temporal and spatial scales of beach profile change, Duck, North Carolina. *Marine Geology* *117* (1–4), 75–94.
- Lawler, D. M. 2005. The importance of high-resolution monitoring in erosion and deposition dynamics studies: examples from estuarine and fluvial systems. *Geomorphology*, *64*(1-2), 1-23.
- Leeder, M. R. 1988. Recent developments in Carboniferous geology: a critical review with implications for the British Isles and N.W. Europe. *Proc. Geol. Ass.* *99*(2) , 73-100
- Le Roux, J.P. & Rojas, E.M. 2007. Sediment transport patterns determined from grain size

- parameters: Overview and state of the art. *Sedimentary Geology*, 202, 473-488
- Lee, G.-h, Nicholls, R.J., Birkemeier, W.A., 1998. Storm-driven variability of the beachnearshore profile at Duck, North Carolina, USA, 1981–1991. *Marine Geology* 148 (3–4), 163–177.
- Leopold, L.B., Wolman, M.G., Miller, J.P., 1964. *Fluvial Processes in Geomorphology*. W.H. Freeman and Co, San Francisco. 522p.
- Leopold, L.B., Collins, J.N., Collins, L.M., 1993. Hydrology of some tidal channels in estuarine marshland near San Francisco. *Catena* 20, 469–493.
- Leuliette, E.W., Nerem, R.S., & Mitchum, G. 2004. Calibration of TOPEX/Poseidon and Jason altimeter data to construct a continuous record of mean sea level change. *Marine Geodesy*, 27, 79-94
- Leyland, J. and Darby, S. E. 2008. An empirical-conceptual gully evolution model for channelled sea cliffs. *Geomorphology*, 102, 419 – 434.
- Lieske, D. J., Wade, T. and Roness, L. A. 2013. Climate change awareness and strategies for communicating the risk of coastal flooding: A Canadian Maritime case example. *Estuarine, Coastal and Shelf Science*. 1 – 2  
<http://dx.doi.org/10.1016/j.ecss.2013.04.017>
- Lillesand, T. M. and Keifer, R. W. 2000. *Remote Sensing and image interpretation* (4<sup>th</sup> ed.). New York, NY: Willey (724 pp).
- Lin, J., 1996. Coastal modification due to human influence in south-western Taiwan. *Quaternary Science Reviews* 15, 895 – 900
- Liquete, C., Zulian, G., Delgado, I., Stips, A. and Maes, J. 2013. Assessment of coastal protection as an ecosystem service in Europe. *Ecological Indicators*, 30, 205 – 217.
- Longuet-Higgins, M.S., Stewart, R.W., 1960. Changes in the form of short gravity waves on long waves and tidal currents. *J. Fluid Mech.* 8, 565–583.
- Loos, E.A. & Niemann, K.O. 2002. Shoreline feature extraction from remotely sensed imagery. *IEEE Int.*, 6, (24-28) 3417-3419
- López-Ruiz, Alejandro, 2014. A note on alongshore sediment transport on weakly curvilinear coasts and its implications. *Coast. Eng.* 88, 143.
- Lucio, P.S.; Dupont, H.S., and Bodevan, E.C., 2004. Sediment transport paths in the Westerschelde: one-di-mensional alternative to determine sediment trend. *Journal of Coastal Research*, 20(3), 771-775.
- Maa, J.P.-Y., Hobbs III, C.H., Hardaway Jr., C.S., 2001. A criterion for determining the

- impact on shorelines caused by altering wave transformation. *J. Coast. Res.* 17, 107–113.
- MacDonald, N.J., O'Connor, B.A., 1996. Changes in wave impact on the Flemish coast due to increased mean sea level. *J. Mar. Syst.* 7, 133–144.
- MacMahan, J., van de Kreeke, J., Reniers, A., Elgar, S., Raubenheimer, B., Thornton, E., Weltmer, M., Rynne, P., and Brown, J. 2014. Fortnightly tides and subtidal motions in a choked inlet. *Estuarine, Coastal and Shelf Science*, pp1-7. <http://dx.doi.org/10.1016/j.ecss.2014.03.025>
- Maiti, S. & Bhattacharya, A.K. 2009. Shoreline change analysis and its application to prediction: a remote sensing and statistics based approach. *Marine Geology*, 257, 11-23
- Malvern 1999. *Operators Guide*. Malvern Instruments Ltd., Worcestershire, UK.
- Manning, A. J., Langston, W. J., & Jonas, P. J. C. (2010). A review of sediment dynamics in the Severn Estuary: influence of flocculation. *Marine pollution bulletin*, 61(1-3), 37-51
- Mante, C., Yao, A-F., Degiovanni, C. 2007. Principal component analysis of measures, with special emphasis on grain-size curves. *Computational Statistics and Data Analysis*, 51, 4969 – 4983.
- Marani, M., Seminara, G., Lanzoni, S., Rinaldo, A., 2002. Tidal meanders. *Water Resour. Res.* 38 (11), 1225–1239.
- Marchand, M., Sanchez-Arcilla, A., Ferreira, M., Gault, J., Jiménez, A. J., Markovic, M., Mulder, J., van Rijn, L., Stănică, A., Sulisz, W., Sutherland, J. 2011. Concepts and science for coastal erosion management - An introduction to the CONSCIENCE framework. *Ocean and Coastal Management*, 54, 859 – 866.
- Mares, C., Mares, I., and Stanciu, A. 2009. Extreme value analysis in the Danube lower basin discharge time series in the 20th century. *Theoretical and Applied Climatology* 95(3–4): 223–233, DOI: 10.1007/s00704-008-0001-0.
- Marino, J. N., & Mehta, A. J. 1987. Inlet ebb tide shoals related to coastal parameters. *Coastal Sediments '77*, ASCE, pp. 1608 – 1622.
- Masalu, D.C.P., 2000. Coastal and marine resource use conflicts and sustainable development in Tanzania. *Ocean and Coastal Management* 43, 475 - 494.
- Mason, S.J., Hansom, J.D., 1988. Cliff erosion and its contribution to a sediment budget for part of the Holderness coast, England. *Shore and Beach* 56 (4), 30–38.
- Mason, D.C., Scott, T.R. & Wang, H.-J. 2006. Extraction of tidal channel networks from airborne scanning laser altimetry. *ISPRS Journal of Photogrammetry and Remote Sensing*, 61(2): 67–83.
- Masselink, G. 1992. Longshore variation of grain size distribution along the coast of the Rhone Delta, South France: A test of the McLaren model. *Journal of Coastal Research*, 8(2), (2) 286-291



- Massey, A. C., Gehrels, R. W., Charman, D. J., Milne, G. A., Peltier, W. R., Lamberck, K. and Selby, K. A. 2008. Relative sea-level change and postglacial isostatic adjustment along the coast of south Devon, United Kingdom. *Journal of Quaternary Science*, 23 (5), 415 – 433.
- Mastenbroek, C., Burgers, G., Janssen, P.A.E.M., 1993. The Dynamical coupling of a wave model and a storm surge model through the atmospheric boundary layer. *J. Phys. Oceanogr.* 23, 1856–1866.
- McCave, I.N. 1978. Grain size trends and transport along beaches: an example from eastern England. *Marine Geology*, 26, M43-M51
- McCowan, J. 1894. On the Highest Wave of Permanent Type, *Philosophical Magazine*, 38, 351-358.
- McLaren, P. 1981. An interpretation of trends in grain size measurements. *Journal of Sedimentary Petrology*, 55(4), (4) 0457-0470
- McLaren, P. 1983. Coastal sediments of the Strait of Juan de Fuca: Implications for oil spills. *Current Research*, Pt A, 241-244
- McLaren, P. 1984. The Whytecliff oil spill, British Columbia: Sediment trends and oil movement on a beach. *Current Research*, Pt B, 81-85
- McLaren, P. & Bowles, D. 1985. The effects of sediment transport on grain size distributions. *Journal of Sedimentary Petrology*, 55, (4) 457-470
- McLaren, P. & Powys, R. I. L. 1989. The use of sediment trends to assess the fate of dredged material., *In Proceedings of WODCON XII World Dredging Congress* , pp. 223-233.
- McLaren, P., Collins, M., Gao, S., & Powys, R.I.L. 1993. Sediment dynamics in the Severn Estuary and Bristol Channel. *Journal of Geological Society (London)*, 150(6), (6) 589-603
- McLaren, P., Hill, S.H., & Bowles, D. 2007. Deriving transport pathways in a sediment trend analysis (STA). *Sedimentary Geology*, 202, 489-498
- McLaren, P. & Singer, J. 2008. Sediment transport and contaminant behaviour in the Buffalo River, New York: implications for river management. *Journal of Coastal Research*, 24(4), (4) 954-968
- McLaren et al., 1981;
- McMullen & Associates and Herrington Geoscience. 1989. *Technical Study of the Camel Estuary and Padstow Harbour Approach*. Report to Padstow Harbour Commissioners. Project No. HM.1809.

- McNinch, J.E., 2004. Geologic control in the nearshore: shore-oblique sandbars and shoreline erosional hotspots, Mid-Atlantic Bight, USA. *Marine Geology* 211, 121–141.
- Mellor, G.L., Blumberg, A., 2004. Wave breaking and ocean surface thermal response. *J. Phys. Oceanogr.* 34, 693–698.
- Merefield, J. R. 1982. Modern carbonate marine-sands in estuaries of southwest England. *Geological Magazine*, **119**, 567 – 580
- Merefield, J.R., 1993. *The use of heavy metals in stream sediments for assessing the environmental impact of mining*. Unpublished PhD Thesis, University of Exeter
- Met Office (URL). South West England: Climate. 2012  
[www.metoffice.gov.uk/climate/uk/sw/](http://www.metoffice.gov.uk/climate/uk/sw/) .Accessed on 21-2-2012]
- Metcalf, G., Chambers, F., Charlesworth, A., Forrest, V., Hunt, J., McEwen L., Russell, K., and Schofield, S. (Eds), *Warming to the Idea, Technical Report*, South West Region Climate Change Impacts Scoping Study, 2003, Cheltenham, UK
- Middleton, G.V. 1976. Hydraulic interpretation of sand size distributions. *Journal of Geology*, 84, 405-426
- Millar D.L., Smith H.C.M., Reeve D.E. 2007. Modelling analysis of the sensitive of shoreline change to a wave farm, *Ocean Engineering*, 34, 884-901.
- Milligan, D. A., K.P. O'Brien, C. Wilcox, C. S. Hardaway, JR, 2010a. Shoreline Evolution: City of Newport News, Virginia James River and Hampton Roads Shorelines. Virginia Institute of Marine Science. College of William & Mary, Gloucester Point, VA.  
[http://web.vims.edu/physical/research/shoreline/docs/dune\\_evolution/NewportNews/1NewportNews\\_Shore\\_Evolve.pdf](http://web.vims.edu/physical/research/shoreline/docs/dune_evolution/NewportNews/1NewportNews_Shore_Evolve.pdf)
- Milligan, D. A., K.P. O'Brien, C. Wilcox, C. S. Hardaway, JR, 2010b. Shoreline Evolution: City of Poquoson, Virginia, Poquoson River, Chesapeake Bay, and Back River Shorelines. Virginia Institute of Marine Science. College of William & Mary, Gloucester Point, VA.  
[http://web.vims.edu/physical/research/shoreline/docs/dune\\_evolution/Poquoson/1Poquoson\\_Shore\\_Evolve.pdf](http://web.vims.edu/physical/research/shoreline/docs/dune_evolution/Poquoson/1Poquoson_Shore_Evolve.pdf)
- Milligan, D. A., K.P. O'Brien, C. Wilcox, C. S. Hardaway, JR, 2010c. Gloucester County, Virginia York River, Mobjack Bay, and Piankatank River Shorelines. Virginia Institute of Marine Science. College of William & Mary, Gloucester Point, VA.  
[http://web.vims.edu/physical/research/shoreline/docs/dune\\_evolution/Gloucester/1Gloucester\\_Shore\\_Evolve.pdf](http://web.vims.edu/physical/research/shoreline/docs/dune_evolution/Gloucester/1Gloucester_Shore_Evolve.pdf)
- Milligan, D. A., K.P. O'Brien, C. Wilcox, C. S. Hardaway, JR, 2010d. Shoreline Evolution:

- York County, Virginia York River, Chesapeake Bay and Poquoson River Shorelines. Virginia Institute of Marine Science. College of William & Mary, Gloucester Point, VA. [http://web.vims.edu/physical/research/shoreline/docs/dune\\_evolution/York/1York\\_Shore\\_Evolve.pdf](http://web.vims.edu/physical/research/shoreline/docs/dune_evolution/York/1York_Shore_Evolve.pdf)
- Milne, G.A., 2008. How the climate drives sea-level changes. *Astronomy and Geophysics* 49, 2.24–2.28.
- Mitchell, S., Couperthwaite, J., West, J., & Lawler, D. 2003. Measuring sediment exchange rates on an intertidal bank at Blacktoft, Humber Estuary, UK. *The Science of The Total Environment*, 314-316, 535-549.
- Moiola, R.J. & Weiser, D. 1968. Textural parameters: an evaluation. *Journal of Sedimentary Petrology*, 38, 45-53
- Molinaroli, E., Guerzoni, S., Sarretta, A., Masiol, M., & Pistolato, M. 2009. Thirty-year changes (1970 to 2000) in bathymetry and sediment texture recorded in the Lagoon of Venice sub-basins, Italy. *Marine Geology*, 258, 115-125
- Monbaliu, J., Chen, Z., Felts, D., Ge, J., Hissel, F., Kappenberg, J., Narayan, S., Nicholls, R. J., Ohle, N., Schuster, D., Sothmann, J., Willems, P. 2014. Risk assessment of estuaries under climate change: Lessons from Western Europe. *Coastal Engineering*, (in press) <http://dx.doi.org/10.1016/j.coastaleng.2014.01.001>
- Montreuil, A-L., and Bullard, J. E. 2012. A 150-year record of coastline dynamics within a sediment cell: Eastern England. *Geomorphology* 179, 168 – 185.
- Moon, I-J. 2005. Impact of a coupled ocean wave-tide-circulation system on coastal modelling. *Ocean Modelling*, 8, 203 – 236.
- Moon, I.-J., Oh, I.S., 2003. A study of the effect of waves and tides on storm surge using a coupled ocean wave– circulation model. *J. Korean Meteorol. Soc.* 39 (5), 563–574.
- Moon, I.-J., Oh, I.S., Murty, T., Youn, Y.-H., 2003b. Causes of unusual coastal flooding generated by Typhoon Winnie on the west coast of Korea. *Nat. Hazards* 29, 485–500.
- Moore, L.J. 2000. Shoreline mapping techniques. *Journal of Coastal Research*, 16, 111-124
- Moore, L.J., Ruggiero, P., & List, J.H. 2006. Comparing mean high water and high water line shorelines: should proxy-datum offsets be incorporated in shoreline change analysis? *Journal of Coastal Research*, 22, (4) 894-905
- Moore, R. D., Wolf, J., Souza, A. J. and Flint, S. S. 2009. Morphological evolution of the Dee Estuary, Eastern Irish Sea, UK: A tidal asymmetry approach. *Geomorphology*, 103, 588 – 596.

- Morey, C. R. 1983. Barrier stability. *Quaternary Newsletter* 40: 23–27.
- Mörner, N-A. 1971. Eustatic changes during the last 20,000 years and a method of separating the isostatic and eustatic factors in a uplifted area. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 19, 63 – 65.
- Morris, B.D., Turner, I.L., 2010. Morphodynamics of intermittently open-closed coastal lagoon entrances: new insights and a conceptual model. *Mar. Geol.* 271, 55–66.
- Morris, B.D., Davidson, M.A., Huntley, D.A., 2001. Measurements of the response of a coastal inlet using video monitoring techniques. *Mar. Geol.* 175, 251-272.
- Morris, B.D., Davidson, M.A., Huntley, D.A., 2004. Estimates of the seasonal morphological evolution of the Barra Nova inlet using video techniques. *Cont. Shelf. Res.* 24, 263-278.
- Morton, R. A., & Sallenger Jr., A. H. 2003. Morphological impacts of extreme storms on sandy beaches and barriers. *Journal of Coastal Research* 19, 560 – 573.
- Mothersill, J. 1969. A grain size analysis of longshore bars and troughs, Lake Superior, Ontario. *Journal of Sedimentary Petrology*, 39, 1317-1324
- Motyka, J. M. & Bevern, S. M. 1986, *A Macro-Review of the Coastline of England and Wales. Volume 2: The East Coast - The Tees to the Wash*, Ministry of Agriculture, Fisheries and Food, Hydraulics Research Ltd, Wallingford Report SR 107.
- Motyka, J. M. & Brampton, A. H. 1993, *Coastal Management: Mapping of Littoral Cells*, Ministry of Agriculture, Fisheries and Food, Hydraulics Research Ltd, Report SR 328
- Munji, C.A., Bele, M. Y., Nkwatoh, A. F., Idinoba, M. E., Somorin, O. A. and Sonwa, D. J. 2013. Vulnerability to coastal flooding and response strategies: The case of settlements in Cameroon mangrove forests. *Environmental Development*, 5, 54 – 72.
- Murray, J. 1984. *Betjeman's Cornwall* London, John Murray.
- Natesan, U., Rajalakshmi, P. R., Ferrer, V. A. 2014. Shoreline dynamics and littoral transport around the tidal inlet at Pulicat, southeast coast of India. *Continental Shelf Research*, 80, 49 – 56.
- National Data Buoy Centre (NDBC) - [www.ndbc.noaa.gov](http://www.ndbc.noaa.gov), (accessed on 26/02/2013) Natural England, N. E. 2010, *Conservation objectives: Hayle Estuary and Carrack Gladden SSSI Draft v2 March 2010 Format Version 2.1*, Natural England..
- Nebel, S.H. Trembanis, A.C., and Barber, D.C., 2012. Shoreline analysis and barrier island dynamics: Decadal scale patterns from Cedar Island, Virginia. *Journal of Coastal Research*, 28 (2), 332-341.

- Neill, S. P., Scourse, J. D., Bigg, G. R. and Uehara, K. 2009. Changes in wave climate over the northwest European shelf seas during the last 12,000 years, *Journal of Geophysical Research*, 114, C06015, doi:10.1029/2009JC005288.
- NERC 1998, *United Kingdom Digital Marine Atlas*, BODC UK Natural Environment Research Council, Birkenhead, Merseyside.
- New South Wales Government, 1990. *Coastline Management Manual* (Australia).
- Newman, D. E. 1976, *The Port Hayle. Aspects to be considered in relation to future requirements.*, Hydraulics Research Station.
- Newton, A., Mudge, S.M., 2005. Lagoon-sea exchanges, nutrient dynamics and water quality management of the Ria Formosa. Estuarine, Coastal Shelf Sci. 62, 405–414.
- Nicolls, R. J., Dredge, A., & Wilson, T. 2000, "Shoreline change and fine-grained sediment input: Isle of Sheppey Coast, Thames Estuary, UK," *In Coastal and Estuarine Environments: Sedimentology, Geomorphology, and Geoarchaeology*, K. Pye & J. R. L. Allen, eds., London: Geological Society Special Publications, pp. 305-315.
- Nicholls, R. J., Townsend, I. H., Bradbury, A. P., Ramsbotton, D., and Day, S.A. 2013. Planning for long-term coastal change: Experiences from England and Wales. *Ocean Engineering*, 71, 3 – 16.
- Noall, C. 1984. *The Book of Hayle* Buckingham, England, Barracuda Books Ltd.
- Nordstrom, K.F. 1981. Differences in grain size distribution with shoreline position in a spit environment. *Northeastern Geology*, 3, 252-258
- Nordstrom, K.F. 1989. Downtide coarsening of beach foreshore sediments at tidal inlets: an example from the coast of New Jersey. *Earth Surface Processes and Landforms*, 14, 691-701
- Nordstrom, K. F. & Roman, C. T. 1996 *Estuarine Shores: Evolution, Environments and Human Alterations*. Chichester, England, Wiley.
- Norrish, K. & Chappell, B. W. 1977, "X-ray Fluorescence Spectrometry," *In Physical Methods in Determinative Mineralogy*, 2nd Edition ed. J. Zussman, ed., Academic Press, pp. 201-272.
- O'Brien, M.P., 1931. Estuary tidal prisms related to entrance areas. *Civil Engineering*, 1. ASCE, New York, pp. 738–739.
- O'Brien, M.P., 1969. Equilibrium flow areas of inlets on sandy coasts. *J. Waterways Harbour, Coast, Eng.*, ASCE, 95; , pp. 43–55.
- O'Connor, M.C., Andrew, J., Cooper, G., Jackson, D.W.T., 2011. Decadal behavior of tidal inlet-associated beach systems, northwest Ireland, in relation to climate forcing.

- Journal of Sedimentary Research* 81, 38–51.
- Oertel, G.F., 1972. Sediment transport on estuary entrance shoals and the formation of swash platforms. *J. Sediment. Petrol* 42, 858e868.
- OSPAR 2000. *Quality Status Report 2000, Region III – Celtic Seas*. OSPAR Commission, London.
- Othman, M.A., 1994. Value of mangroves in coastal protection. *Hydrobiologia* 285, 277 - 282.
- Owens, J.S. & Case, G.O. 1908. *Coast erosion and foreshore protection*. London, St Bride's Press.
- Oyedotun, T. D. T. (2014) Section 3.2.2. Shoreline geometry: DSAS as a tool for Historical Trend Analysis. In: Clarke, L. and Nield, J. M. (Eds) *Geomorphological Techniques (Online Edition)*. British Society for Geomorphology; London: UK. ISSN: 2047 – 0371  
([http://geomorphology.org.uk/assets/publications/subsections/pdfs/OnsitePublicationSubsection/42/3.2.2\\_shorelinegeometry.pdf](http://geomorphology.org.uk/assets/publications/subsections/pdfs/OnsitePublicationSubsection/42/3.2.2_shorelinegeometry.pdf))
- Oyedotun, T. D. T., Burningham, H. and French, J. R. (2013) Sediment sorting and mixing in the Camel Estuary, UK. In: Conley, D. C., Masserlink, G., Russell, P. E. and O'Hare, T. J. (Eds), *Proceedings 12<sup>th</sup> International Coastal Symposium* (Plymouth, England), *Journal of Coastal Research*, Special Issue No 65, pp. 1563 – 1568, ISSN 0749-0208. DOI: 10.2112/S165-264.1 ([http://ics2013.org/papers/Paper4455\\_rev.pdf](http://ics2013.org/papers/Paper4455_rev.pdf))
- Oyedotun, T. D. T., Burningham, H. and French, J. R. (2012) Characterisation of estuary and adjacent beach sediments in the Gannel Estuary, south-west England. *Geoscience in south-west England*, 13, 70 – 76.
- Oyegun, C.U., 1993. Land degradation and the coastal environment of Nigeria. *CATENA* 20, 215 - 225.
- Palutikof, J. P., Davies, T. D., & Kelly, P. M. 1985, "An analysis of the spatial and temporal variation of the wind field over the British Isles.," *In European Wind Energy Conference 1984*, W. Palz, ed., pp. 65-70.
- Palutikof, J.P., Kelly, P.M., Davies, T.D., & Halliday, J.A. 1987. Impacts of spatial and temporal windspeed variability on wind energy output. *J.Climate Appl.Meteorol.*, 26, 1124-1133
- Panda, U.S., Mohanty, P.K., Samal, R.N., 2013. Impact of tidal inlet and its geomorphological changes on lagoon environment: a numerical model study. *Estuarine, Coastal Shelf Sci.* 116, 29–40.
- Pascoe, H. 2005. *The Book of Hayle: Portrait of a Cornish coastal town*. Devon, UK., Temitope Oyedotun

- Halsgrove.
- Pascoe, G.A., McLaren, P., & Soldate, M. 2002. Impact of offsite sediment transport and toxicity on remediation of a contaminated estuarine bay. *Marine Pollution Bulletin*, 44, 1184-1193
- Pattiaratchi, C. 1996. *Coastal and Estuarine Studies: Mixing in Estuaries and Coastal Seas*. American Geophysical Union, Washington, D. C.
- Perillo, G.M.E. 1995. Geomorphology and Sedimentology of Estuaries. Definitions and Geomorphologic Classifications of Estuaries, Development in *Sedimentology* 53.
- Pethick, J. 1984. *An Introduction to Coastal Geomorphology*. , Fifth Impression ed. London, Edward Arnold.
- Pettijohn, F.G. & Ridge, J.D. 1932. A textural variation series of beach sands from Cedar Point, Ohio. *Journal of Sedimentary Petrology*, 2, 76-88
- Pettijohn, F. J. Potter, P.E., Siever, R. 1987. *Sand and Sandstone* (Second Edition)Springer, New York (1987)
- Phillips, M.R., Rees, E.F., & Thomas, T. 2013. Winds, sea levels and North Atlantic Oscillation (NAO) influences: An evaluation. *Global and Planetary Change*, 100, 145-152
- Pickering, M. D., Wells, N. C., Horsburgh, K. J., Green, J. A. M. 2012. The impact of future sea-level rise on the European Shelf tides. *Continental Shelf Research* 35, 1 – 15.
- Pickering, H.E., Green, J. A. M., and Ward, S. L. 2013. Modelling tides and sea-level rise: To flood or not to flood. *Ocean Modelling* 63, 21 – 29.
- Pingree, R. & Griffiths, D. 1979. Sand transport paths around the British Isles resulting From M2 and M4 tidal interactions. *Journal of Marine Biological Association, UK*, 59, 197-513
- Pirazzoli PA, Tomasin A, Ullmann A. 2010. Recent changes in measured wind in the NE Atlantic and variability of correlation with NAO. *Annales Geophysicae* 28: 1923–1934, DOI:10.5194/angeo-28-1923-2010.
- Pirazzoli, P. Les variations du niveau marin depuis 2000 ans. *Memoire de Laboratoire de Geomorphologie de l'Ecole Pratiques des Hautes Etudes*, no. 30. pp. 1-421. Dinard.
- Pirrie, D., Hughes, S. H., & Camm, G. S. 1999a, "Late Holocene sedimentation due to mine waste discharge, Fai Estuary.," *In The Quaternary of West Cornwall*, J. D. Scourse & M. F. A. Furze, eds., London: Field Guide, Quarternary Research Association., pp. 113-121.

- Pirrie, D., Beer, A.J., & Camm, G.S. 1999b. Early diagenetic sulphide minerals in the Hayle Estuary, Cornwall. *Geoscience in South-West England*, 9, 325-332
- Pirrie, D., Camm, G.S., 1999c. The impact of mining on sedimentation in the coastal zone of Cornwall. In: Scourse, J.D., Furze, M.F.A. (Eds.), *The Quaternary of West Cornwall. Field Guide, Quaternary Research Association*, London, pp. 62 – 73.
- Pirrie, D., Power, M.R., Wheeler, P.D., & Ball, A.S. 2000a. A new occurrence of diagenetic simonkolleite from the Gannel Estuary, Cornwall. *Geoscience in South-West England*, 10, 018-020
- Pirrie, D., Power, M.R., Payne, G.S., & Wheeler, P.D. 2000b. Impact of mining on sedimentation: The Camel and Gannel estuaries, Cornwall. *Geoscience in South-West England*, 10, 021-028
- Pirrie, D., Power, M. R., Wheeler, P. D., Cundy, A., Bridges, C., & Davey, G. 2002. Geochemical signature of historical mining: Fowey Estuary, Cornwall, UK. *Journal of Geochemical Exploration* 76, 31 – 43.
- Pirrie, D., Rollinson, G.K., & Power, M.R. 2009. Role of automated mineral analysis in the characterisation of mining-related contaminated land. *Geoscience in South-West England*, 12, 162-170
- Pitman, W. C. 1978. Relationship between eustacy and stratigraphic sequences of passive margins. *Geol. Soc. Amer. Bull.* 89, 1389-403.
- Plomaritis, T.A., Paphitis, D., & Collins, M. 2008. The use of grain size trend analysis in macrotidal areas with breakwaters: implications of settling velocity and spatial sampling density. *Marine Geology*, 253, 132-148
- Plumley, W.J. 1948. Black Hills terrace gravels: a study in sediment transport. *Journal of Geology*, 56, 526-577
- Poate, T., Masselink, G., Russel, P., and Austin, M. 2014. Morphodynamic variability of high-energy macrotidal beaches, Cornwall, UK. *Marine Geology*, 350, 97 - 111
- Poizot, E., Mear, Y., Thomas, M., & Garnaud, S. 2006. The application of geostatistics in defining the characteristics distance for grain size trend analysis. *Computers and Geosciences*, 32, 360-370
- Poulos, S.E. & Ballay, A. 2010. Grain-size trend analysis for determination of non-biogenic sediment transport pathways on the Kwinte Bank (southern North Sea) in relation to sand dredging. *Journal of Coastal Research*, S151, 95-100
- Prandle, D., Wolf, J., 1978. The interaction of surge and tide in the North Sea and River Thames. *Geophys. J. R. Astron. Soc.* 55, 203–216.
- Price, W. A. & Kendrick, M. P. 1963. Field and model investigation into the reasons for



- siltation in the Mersey Estuary, *In Proceedings of the Institution of Civil Engineers*, Vol. 7, pp. 473-517.
- Pritchard, D. W. 1967. What is an estuary? Physical viewpoint. In '*Estuaries*'. (Ed. GH Lauff) pp. 3-5. (American Association for the Advancement of Science)
- Prosser, C.D., 2008. The history of geoconservation in England: legislative and policy milestones. In: Burek, C.V., Prosser, C.D. (Eds.), *The History of Geoconservation*. The Geological Society, vol. 300. Special Publications, London, pp. 113–122.
- Prosser, C. D., Bridgland, D. R., Brown, E. J. and Larwood, J. G. 2011. Geoconservation for science and society: challenges and opportunities. *Proceedings of the Geologists' Association*, 122., 337 – 342.
- PSMSL, 2013. Newlyn tide gauge data.  
[<http://www.psmsl.org/data/obtaining/stations/202.php>]
- Pugh, D.T. 1987. *Tides, surges and mean sea-level: a handbook for engineers and scientists* Chichester, Wiley.
- Pye, K. 1994, "Properties of sediment particles.," *In Sediment Transport and Depositional Processes*, K. Pye, ed., Oxford: Blackwell., pp. 1-24.
- Pye, K. 1996, "Evolution of the shoreline of the Dee Estuary, United Kingdom," *In Estuarine Shores: Evolution, Environments and Human Alterations*. , K. F. Nordstrom & C. T. Roman, eds., Chichester, England: Wiley.
- Pye, K. 1997, "UK Geology and Coastal Geomorphology," *In Coastal Processes and Engineering*, Wallingford: English Nature, Wallingford.
- Pye, K. & French, P. W. 1993, *Targets for Coastal Habitat Recreation*. , English Nature, Peterborough.
- Pye K, Neal A. 1994. Coastal dune erosion at Formby Point, North Merseyside, England – causes and mechanisms. *Marine Geology* **119**: 39–56, DOI: 10.1016/0025-3227 (94) 90139-2.
- Pye, K. & van der Wal, D. 2000, *Historical Trend Analysis as a tool for long-term morphological prediction in estuaries*. , MAFF, Report TR 111.
- Qian B, Saunders M. 2003. Seasonal predictability of wintertime storminess over the North Atlantic. *Geophysical Research Letters* **30**(13): 1698, DOI: 10.1029/2003GL017401.
- Quélenec, R.E. 1987. Coastal erosion in West and Central Africa: an outlook on natural and man-made causes and consequences for protection and management of coastal areas. *Nature and Resources*, 23,
- Quinn, J.D., Philip, L.K., Murphy, W., 2009. Understanding the recession of the

- Holderness Coast, east Yorkshire, UK: a new presentation of temporal and spatial patterns. *Quarterly Journal of Engineering Geology & Hydrogeology* 42, 165–178.
- Rabalais, N.N., Turner, R.E., Justic', D., Dortsch, Q. W. J., Wiseman, J. R., Sen-Gupta, B., 1996. Nutrient changes in the Mississippi River and system responses on the adjacent continental shelf. *Estuaries* 19, 386–407.
- Rabouille, C., Conley, D. J., Dai, M. H., Cai, W.-J., Chen, C. T. A., Lansard, B., Green, R., Yin, K., Harrison, P. J., Dagg, M., McKee, B., 2008. Comparison of hypoxia among four river dominated ocean margins: the Changjiang (Yangtze), Mississippi, Pearl, and Rhône rivers. *Continental Shelf Research* 28, 1527 – 1537.
- Reclus, E. 1873. *The Oceans, Atmosphere and Life* New York, Harper and Brothers
- Rees, J.G., Ridgway, J., Ellis, S., Knox, R.W.O., Newsham, R. and Parkes, A., 2000, Holocene Storage in the Humber Estuary, In: I. Shennan, J.E. Andrews (eds.), *Holocene land-ocean interaction and environmental change around the North Sea, Special Publication* 166, London: Geological Society, pp119-143.
- Reid, C. & Scrivenor, J.B. 1906. The geology of the country near Newquay. *Memoir of the Geological Survey, England and Wales, explanation of sheet 346*.
- Reimann, C. and De Caritat, P., 1998: Chemical Elements in the Environment, Factsheets for the Geochemist and Environmental Scientist, Springer-Verlag, 398
- Restrepo A, J. D. 2012. Assessing the effect of sea-level and human activities on a major delta on the Pacific coast of northern South America: The Patía River. *Geomorphology*, 151 – 152, 207 – 223.
- Ritchie, W. and Whittington, G. (1994) Non-synchronous aeolian sand movements in the Uists: the evidence of the intertidal organic and sand deposits at Cladach Mór, North Uist. *Scottish Geographical Magazine*, 110 (1), 40–6.
- Rio, L. D. and Gracia, J. F. 2009. Erosion risk assessment of active coastal cliffs in temperate environments. *Geomorphology*, 112, 82 – 95.
- Río, L. D., Gracia, J. F., Benavente, J. 2013. Shoreline change patterns in sandy coasts. A case study in SW Spain. *Geomorphology*, 196, 252 – 266.
- Rios, F., Ulloa, R. and Cerrea, I. C. S. (2003). Determination of net sediment transport patterns in Lirquen Harbor, Chile through grain-size analysis: a test of methods. *Pesquisas em Geociencias* 30, pp. 65–81.
- Ris, R.C., Booij N. and Holthuijsen, L.H. 1999 A third-generation wave model for

- coastal regions, Part II, Verification. *J. Geophys. Res.* 104, C4, 7667-7681
- Rogers, K. & Woodroffe, C. D. 2012. Incorporating estuaries as a source or sink of sediment within assessments of coastline risk and adaptation to climate change. *21st NSW Coastal Conference Papers* (pp. 1-16). Australia: ACS.
- Rogers JC. 1997. North Atlantic storm track variability and its association to the North Atlantic Oscillation and climate variability of Northern Europe. *Journal of Climate* **10**(7): 1635–1647, DOI: 10.1175/1520-0442(1997)010<1635:NASTVA>2.0.CO;2.
- Rollinson, G. K., Pirrie, D., Power, M. R., Cundy, A., & Camm, G. S. 2007. Geochemical and mineralogical record of historical mining, Hayle Estuary, Cornwall, UK, *In Geoscience in South-West England*, pp. 326-337.
- Romine, B.M.; Fletcher, C.H.; Frazer, L.N.; Genz, A.S.; Barbee, M.M., and Lim, S.-C.; 2009. Historical shoreline change, southeast Oahu, Hawaii; applying polynomial models to calculate shoreline change rates. *Journal of Coastal Research*, 25(6), 1236–1253. West Palm Beach (Florida), ISSN 0749-0208.
- Roos, P.C., Velema, P.C.R., Hulscher, S.J.M.H., Stolk, A., 2011. An idealized model of tidal dynamics in the North Sea: resonance properties and response to large scale changes. *Ocean Dyn.* 61, 2019–2035.
- Rossiter, J. R. 1972. Sealevel observations and their secular variation, *Philosophical Transactions of the Royal Society of London*, A272, 131 – 139.
- Roy, P.S., Williams, R.J., Jones, A.R., Yassini, I., Gibbs, P.J., Coates, B., West, R.J., Scanes, P.R., Hudson, J.P., & Nicholl, S. 2001. Structure and function of South-east Australian estuaries. *Estuar. Coast. Shelf Sci.*, 53, 351-384
- Royal Haskoning 2011, *Cornwall and Isles of Scilly SMP2*, Royal Haskoning
- Royo, C.L., Silvestri, C., Pergent, G., & Casazza, G. 2009. Assessing human-induced pressures on coastal areas with publicly available data. *Journal of Environmental Management*, 90, 1494-1501
- Ruhl, C. A., Schoellhamer, D. H., Stumpf, R. P., & Lindsay, C. L. 2001. Combined Use of Remote Sensing and Continuous Monitoring to Analyse the Variability of Suspended-Sediment Concentrations in San Francisco Bay, California. *Estuarine, Coastal and Shelf Science*, 53(6), 801-812.
- Russell, R. D. 1939, "Effects of transportation of sedimentary particles.," *In Recent Marine Sediments*, P. D. Trask, ed., Tulsa, OK.: Society of Economic Paleontologists and Mineralogists., pp. 32-47.

- Ryu, J.-H., Won, J.-S., & Min, K.D. 2002. Waterline extraction from Landsat TM data in a tidal flat: a case study in Gosmo Bay, Korea. *Remote Sens. Environ.*, 83, 442-456
- Salminen R. , Batista M.J., Bidovec M., Demetriades A., De Vivo B., De Vos W., Duris M., Gilucis A., Gregorauskiene V., Halamic J., Heitzmann P., Lima A., Jordan G., Klaver G., Klein P., Lis J., Locutura J., Marsina K., Mazreku A., O'Connor P.J., Olsson S.Å., Ottesen R.-T., Petersell V., Plant J.A., Reeder S., Salpeteur I., Sandström H., Siewers U., Steenfelt A., Tarvainen T.1 2005. *Geochemical Atlas of Europe. Part 1 – Background Information, Methodology and Maps*. Geological Survey of Finland
- Sherman, D.J. & Bauer, B.O. 1993. Coastal geomorphology through the looking glass. *Geomorphology*, 7, 225-249
- Saengsupavanich, C. 2013. Erosion protection options of a muddy coastline in Thailand: Stakeholders' shared responsibilities. *Ocean and Coastal Management*, 83, 81 – 90.
- Sanò, M., Jiménez, J.A., Medina, R., Stanica, A., Sanchez-Arcilla, A., Trumbic, I., 2011. The role of coastal setbacks in the context of coastal erosion and climate change. *Ocean and Coastal Management* 54 (12), 943 - 950.
- Saye, S.E., van der Wal, D., Pye, K., & Blott, S.J. 2005. Beach-dune morphological relationships and erosion/accretion: An investigation at five sites in England and Wales using LIDAR data. *Geomorphology*, 72, 128-155
- Schiller, A., 2004. Effect of explicit tidal forcing in an OGCM on the water-mass structure and circulation in the Indonesian through flow region. *Ocean Modell.* 6, 31–49.
- Schmith, T., Kaas, E., & Li, T.-S. 1998. Northeast Atlantic winter storminess 1875 – 1995 re-analysed. *Clim.Dyn.*, 14, (529) 536
- Schroede, W. W., Pennock, J. R., & Wiseman, J. W. J. 1996, "A Note on the Influence of a Deep Ship Channel on Estuarine-Shelf Exchange in a Broad, Shallow estuary.," *In Coastal and Estuarine Studies: Mixing in Estuaries and Coastal Seas.* , C. Pattiaratchi, ed., Washington, D.C.: American Geophysical Union.
- Schuttelaars, H. M., de Jonge, V. N. and Chernetsky, A. 2013. Improving the predictive power when modelling physical effects of human interventions in estuarine systems. *Ocean and Coastal Management*, 79, 70 – 82.
- Schumm, S. A. 1975. Episodic erosion: a modification of the geomorphic cycle in Melhorn W. N. and Flemal, R. C. (eds) *Theories of Landform Development*. SUNY Publications in Geomorphology, Binghamton, 69 – 85.
- Schwing, F.B. and Blanton, J.O., 1984. The use of land and sea based wind data in a simple circulation model. *Journal of Physical Oceanography* 14, 193–197.

- Scott, T., Russell, P., Masselink, G., Wooler, A., and Short, A., 2007. Beach rescue statistics and their relation to nearshore morphology and hazards: a case study for southwest England. *Journal of Coastal Research*, SI 50 (Proceedings of the 9th International Coastal Symposium), 1 – 6. Gold Coast, Australia, ISSN 0749.0208
- Scott, D. B. 2005, "*Rapid Coastal changes*," The Netherlands: Springer, pp. 253-255.
- Scourse, J. & Furze, M. 1999. *The Quaternary of West Cornwall: field guide*. London, Quaternary Research Association. Chapman.
- Sea Sediments 1983, *An investigation of sediment dynamics in the Hayle Estuary Cornwall, Sea Sediments*.
- Seitzinger, S.P., Bouwman, A.F., Kroeze, C., 2010. Preface to special section on past and future trends in nutrient export from global watersheds and impacts on water quality and eutrophication. *Global Biogeochemical Cycles* 24, GB0A01, <http://dx.doi.org/10.1029/2010GB003851>.
- Self, R.P. 1977. Longshore variation in beach sands, Nautla area, Veracruz, Mexico. *Journal of Sedimentary Petrology*, 47, 1437-1443
- Sellers D. 2010. Mobilising the Marine Act. Implementing marine spatial planning in the UK: lessons learned from international case studies. WWF-UK in conjunction with the Marine Conservation Society. RSPB and The Wildlife Trusts;
- Selwood, E.B., Thomas, J.M., Williams, B.J., Clayton, R.E., Durning, B., Smith, O., & Warr, L.N. 1998. Geology of the country around Trevoze Head and Camelford. *Memoir of the British Geological Survey Sheets 335 and 336*
- Sennes, G., Castelle, B., Bertin, X., Mirfenderesk, H., Tomlinson, R.B., 2007. Modelling of the Gold Coast Seaway tidal inlet, Australia. *J. Coastal Res.* SI 50 (In: Proceedings of the Ninth International Coastal Symposium), 1086–1091, ISSN 0749.0208.
- Shellard, H. C. 1976, "The wind as a vector.," *In The Climate of British Isles.*, T. J. Chandler & S. Gregory, eds., London: Longman, pp. 39-73.
- Shennan, I., and Horton, B. 2002. Holocene land – and sea – level changes in Great Britain. *Journal of Quaternary Science* 17, 511 – 526.
- Shennan I. 1983. Flandrian and Late Devensian sea-level changes and crustal movements in England and Wales. In *Shorelines and Isostasy*, Smith DE, Dawson AG (eds). Institute of British Geographers Special Publication No.16. Academic Press: London; 255–283.
- Shennan I. 1989. Holocene crustal movements and sea-level changes in Great Britain. *Journal of Quaternary Science* 4: 77–89.
- Shennan, I., Peltier, W.R., Drummond, R., Horton, B.P., 2002. Global to local scale

- parameters determining relative sea-level changes and the post-glacial isostatic adjustment of Great Britain. *Quaternary Science Reviews* 21, 397–408.
- Shepard, C.C., Crain, C.M., Beck, M.W., 2011. The protective role of coastal marshes: a systematic review and meta-analysis. *PLoS One* 6, e27374.  
<http://dx.doi.org/10.1371/journal.pone.0027374>.
- Sherman, D.J. & Bauer, B.O. 1993. Coastal geomorphology through the looking glass. *Geomorphology*, 7, 225-249
- Shuttleworth, B., Woïdt, A., Paparella, T., Herbig, S., Walker, D., 2005. The dynamic behaviour of a river-dominated tidal inlet, River Murray, Australia. *Estuarine Coastal Shelf Sci.* 64 (4), 645–657.
- Siegle, E., Huntley, D. A. and Davidson, M. A. 2007. Coupling video imaging and numerical modelling for the study of inlet morphodynamics. *Marine Geology*, 236, 143 – 163.
- Simmons, H.L., Jayne, S.R., St Laurent, L.C., Weaver, A.J., 2004. Tidally driven mixing in a numerical model of the ocean general circulation. *Ocean Modell.* 6 (3–4), 245–263.
- Sir Alexander Gibb & Partners 1989, *Water Level Control in Hayle Harbour*.
- Smith, S.G. 1983. The seasonal variation of wind speed in the United Kingdom. *Weather*, 38, 98-103
- Smith, H. D. 1999. The historical geography of the seas around the British Isles. *Marine Policy*, 23, 275–287.
- Smith, H. D., Ball, I., Ballinger, R. C., & Stojanovic, T. 2008. Strategy for marine environment conservation and development: United Kingdom. In B. Cicin-Sain, D. VanderZwaag, & M. Baglos (Eds.), *Integrated National and Regional Ocean Policies: comparative practices and future prospects*. Tokyo: United Nations Press.
- Smith, S.D., Anderson, R.J., Oost, W.A., Kraan, C., Maat, N., DeCosmo, J., Katsaros, K.B., Davidson, K.L., Bumke, K., Hasse, L., Chadwick, H.M., 1992. Sea surface wind stress and drag coefficients: the HEXOS results. *Bound. Layer Meteor.* 60, 109–142.
- Stamp, D.L. 1939. Recent coastal changes in South-eastern England V: Some economic aspects of coastal loss and gain. *Geographical Journal*, 93, 496-503
- Stapor, F.W. & Tanner, W.F. 1975. Hydrodynamic implications of beach, beach ridge and dune grain size studies. *Journal of Sedimentary Petrology*, 45, 926-931
- Steers, J.A. 1946. *The coastline of England and Wales*. Cambridge, Cambridge University Press.
- Stive, M.J.F., Wang, Z.B., 2003. Morphodynamic modelling of tidal basins and coastal

- inlets. In: Lakhan, C. (Ed.), *Advances in Coastal Modelling* vol. 13. pp. 367–392.
- Stive, M.J.F., Nicholls, R.J. and De Vriend, H.J., 1991. Sea-level rise and shore nourishment: a discussion. *Coastal Eng.*, 16 ( 1 ): 147-163.
- Stive, M.J.F., M., C., Wang, Z.B., Ruol, P., Buijsman, M.C., 1998. Morphodynamics of a tidal lagoon and adjacent coast. 8th International Biennial Conference on Physics of Estuaries and Coastal Seas, The Hague. pp. 397– 407.
- Stockdon, H. F., Sallenger Jr., A. H., Holman, R. A., & Howd, P. A. 2007. A simple model for the spatially-variable coastal response to hurricanes. *Marine Geology* 238, 1 – 20.
- Stojanovic, T. A. and Ballinger, R. C. 2009. Integrated coastal management: A comparative analysis of four UK initiatives. *Applied Geography*, 29, 49 – 62.
- Stokes, C., Beaumont, E., Russell, P., Greaves, D., 2014. Coastal Impacts of Marine Renewables: Perception of Breaker Characteristics by Beach Water Users. In: Green, A.N. and Cooper, J.A.G. (eds.), Proceedings 13<sup>th</sup> International Coastal Symposium (Durban, South Africa), Journal of Coastal Research, Special Issue No. 70, pp. 389-394, ISSN 0749-0208.
- Straile, D. and Stenseth, N. C. 2007. The North Atlantic Oscillation and ecology: links between historical time-series, and lessons regarding future climate warming. *Climate Research* 34: 259–262, DOI: 10.3354/cr00702.
- Stride, A. 1963. Current-swept sea floors near the southern half of Great Britain. *Quarterly Journal of Geological Society of London*, 119, 175-199
- Stupples, P. 2002. Tidal cycles preserved in late Holocene tidal rhythmites, the Wainway Channel, Romney Marsh, southeast England. *Marine Geology*, 182, 231-246.
- Swift, D. J. P., Ludwick, J. C., & Boehmer, W. R. 1972, "Shelf sediment transport: a probability model.," *In Shelf Sediment Transport - Process and Pattern.*, D. J. P. Swift, D. B. Duane, & O. H. Pilkey, eds., Stroudsburg, PA, Dowden, Hutchinson and Ross, pp. 195-223.
- SWRDA, 2004, Seapower SW Review, Resources, Constraints and Development Scenarios for Wave and Tidal Stream Power in the South West of England
- SWRDA - South West of England Development Agency, 2006. Wave Hub development and design phase, SWRDA Group Limited, coastal processes study report. <http://www.wavehub.co.uk/>.
- Symons, R., 1874. Alluvium in the Par Valley. *J. Roy. Inst. Corn.* 5, 382 – 384.
- Tamin, N.M., Zakaria, R., Hashim, R., Yin, Y., 2011. Establishment of *Avicennia marina* mangroves on accreting coastline at Sungai Haji Dorani, Selangor, Malaysia. *Estuarine, Coastal and Shelf Science* 94 (4), 334 -342.

- Tang, Y.M., Grimshaw, R., Sanderson, B., Holland, G., 1996. A numerical study of storm surges and tide, with application to the north Queensland coast. *J. Phys. Oceanogr.* 26, 2700–2711.
- Taylor, S. R. 1964. Abundance of chemical elements in the continental crust: a new table. *Geochim. Cosmochim. Acta* 28, 1273- 1285.
- Taylor, J.A., Murdock, A.P., & Pontee, N.I. 2004. A macroscale analysis of coastal steepening around the coast of England and Wales. *The Geographical Journal*, 170, (3) 179-188
- Teasdale, P.A., Collins, P.E.F., Firth, C.R., & Cundy, B.A. 2011. Recent estuarine sedimentation rates from shallow inter-tidal environments in western Scotland: implications for future sea-level trends and coastal wetland development. *Quaternary Science Reviews*, 30, 109-129
- Teferle, F. N., Bingley, R. M., Williams, S. D. P., Baker, T. F. and Dodson, A. H. 2006. Using continuous GPS and absolute gravity to separate vertical land movements and changes in sea-level at tide-gauges in the UK. *Philosophical Transactions of the Royal Society: Mathematical, Physical and Engineering Sciences (Series A)* 364: 917–930.
- Temmerman, S., Meire, P., Bouma, T.J., Herman, P.M.J., Ysebaert, T., De Vriend, H.J., 2013. Ecosystem-based coastal defence in the face of global change. *Nature* 493, 45–49. <http://dx.doi.org/10.1038/nature12859>.
- Thampanya, U., Vermaat, J.E., Sinsakul, S., Panapitukkul, N., 2006. Coastal erosion and mangrove progradation of Southern Thailand. *Estuarine, Coastal and Shelf Science* 68 (1), 75 - 85.
- Thébaudeau B, Trenhaile AS, Edwards RJ. 2013. Modelling the development of rocky shoreline profiles along the northern coast of Ireland. *Geomorphology*, 203, 66-78. DOI: 10.1016/j.geomorph.2013.03.027.
- Thieler, E. R. and Danforth, W. W. 1994a. Historical shoreline mapping (1) Improving techniques and reducing positioning errors. *Journal of Coastal Research*, 10, 549-563.
- Thieler, E. R. and Danforth, W. W. 1994b. Historical shoreline mapping (II) Application of the Digital Shoreline Mapping and Analysis Systems (DSMS/DSAS) to shoreline change mapping in Puerto Rico. *Journal of Coastal Research*, 10(3), 600-620.
- Thieler, E. R., Himmelstoss, E. A., Zichichi, J. L., and Ergul, A. 2009. The Digital Shoreline Analysis System (DSAS) Version 4.0 - An ArcGIS Extension for Calculating Shoreline Change. Open-File Report. US Geological Survey Report No. 2008- 1278: <http://woodshole.er.usgs.gov/projectpages/dsas/version4/>
- Thiruventakasamy, K. and Girija, D. K. B. 2014. Shoreline evolution due to construction of Temitope Oyedotun



- rubble mound jetties at Munambam inlet in Ernakulam-Trichur district of the state of Kerala in the Indian peninsula. *Ocean & Coastal Management* 102, 234 - 247
- Thomas, B.A., Cleal, C.J., 2005. Geological conservation in the United Kingdom. *Law, Science and Policy* 2, 269–284.
- Thomas, C. 2000, *ID Modelling of the hydrodynamic response to morphological change in the Mersey Estuary*.
- Thomas, C. 2002. *The application of historical data and computational method for investigating causes of long-term morphological change in estuaries: A case study of the Mersey estuary, UK*. PhD for Oxford Brookes University.
- Thomas, T.M. 1960. Some observations on the tracks of depressions over the eastern half of the North Atlantic. *Weather*, 15, 325-336
- Thorne, M. H. 1983. Studies of Fal Estuary sediment I. Early diagenetic sulphide mineralisation. *Proceeding of the Ussher Socieity*, 5, 445 – 447
- Tooley, M. J. 1978. *Sea Level Changes*. Oxford University Press
- Tolman, H.L., 1991. A third generation model for wind waves on slowly varying, unsteady, and inhomogeneous depth and currents. *J. Phys. Oceanogr.* 21, 782–797.
- Townend, I.H. 2005. An examination of empirical stability relationships for UK estuaries. *Journal of Coastal Research*, 21, (5) 1042-1053
- Townend, I. and Whitehead, P., 2003, A preliminary net sediment budget for the Humber Estuary, *The Science of the Environment*, 314-316, 755-767.
- Trigo, R.M., Pozo-Vázquez, D., Osborn, T.J., Castro-Díez, Y., Gámiz-Fortis, S., Esteban-Parra, M.J., 2004. North Atlantic oscillation influence on precipitation, river flow and water resources in the Iberian Peninsula. *International Journal of Climatology* 24, 925–944.
- Udden, J.A. 1914. Mechanical composition of clastic sediments. *Bulleting of Geological Society of America*, 25, 655-744
- UK Hydrographic Office (UKHO). 2003. Admiralty Tide Tables: Volume 1, United Kingdom and Ireland (including European channel ports). United Kingdom Hydrographic Office, London.
- Uluocha, N.O. 2007. *Elements of Geographic Information Systems* Lagos, Sam Iroanusi Publications.
- Uncles, R.J., Stephens, J. A., & Harris, C. 2006. Runoff and tidal influences on the estuarine turbidity maximum of a highly turbid system: The upper Humber and

- Ouse Estuary, UK. *Marine Geology*, 235(1-4), 213-228.
- USGS, 2013. DSASweb. [<http://marine.usgs.gov/dsasweb>].
- Van Nieuwkoop, J. C. C., Smith, H. C. M., Smith, G. H. and Johanning. 2013. Wave resource assessment along the Cornish coast (UK) from a 23-year hindcast dataset validated against buoy measurements. *Renewable Energy*, 58, 1 – 14.
- Valentin, H. 1954. Land loss at Holderness. Reprinted in 1971. In: Steers JA (ed) *Applied coastal geomorphology*. Macmillan, London, pp 116–137
- Valiela, I., Bowen, J.L., York, J.K., 2001. Mangrove forests: one of the world's threatened major tropical environments. *Bioscience* 51, 807–815.
- van der Wal, D., Pye, K., & Neal, A. 2002. Long-term morphological change in the Ribble Estuary, Northwest England. *Marine Geology*, 189, 249-266
- van der Wal, D. & Pye, K. 2003. The use of bathymetric charts to assess morphological and sediment budget change in estuaries. *Geographical Journal* 169 (1), 21 – 31.
- van der Wal, D. & Pye, K. 2004. Patterns, rates and possible causes of saltmarsh erosion in the Greater Thames area (UK). *Geomorphology*, 61(3 - 4), (3-4) 373-391
- Viguri, J., Verde, J., Irabien, A., 2002. Environmental assessment of polycyclic aromatic hydrocarbons (PAHs) in surface sediments of the Santander Bay, Northern Spain. *Chemosphere* 48, 157–165.
- Viles, H.A. & Spencer, T. 1995. *Coastal Problems: Geomorphology, Ecology and Society at the Coast*. London, Edward Arnold.
- Vincent, C. L., & Corson, W. D. 1981. Geometry of tidal inlets: Empirical equations. *Proceedings ASCE Journal, Waterway Port and Coastal Engineering Division*, 107, (WW1), 1 – 9.
- Vincente-Serrano, S. M. and Trigo, R. M.. (eds). 2011. Hydrological, socioeconomic and ecological impacts of the North Atlantic Oscillation in the Mediterranean region. *Advances in Global Change Research* 46. Springer: Dordrecht, 236pp.
- Visher, G.S. 1969. Grain size distributions and depositional processes. *Journal of Sedimentary Petrology*, 39, 1074-1106
- Wainwright, J. and Mulligan, M. 2003. Modelling human decision making in Wainwright J and Mulligan M (eds) *Environmental Modelling: finding simplicity in complexity*. John Wiley and Sons, Chichester, 225 – 244.
- Waller M. P. and Long A.J. 2003. Holocene coastal evolution and sea-level change on the southern coast of England: a review. *Journal of Quaternary Science* 18: 351–359.
- Walton, T. L., & Adams, W. D. 1976. Capacity of inlet outer bars to store sand.

- Proceedings of 15<sup>th</sup> Coastal Engineering Conferences*, pp. 1919 – 1937.
- Wang, Z.B., Hoekstra, P., Burchard, H., Ridderinkhof, H., De Swart, H.E., Stive, M.J.F., 2012. Morphodynamics of the Wadden Sea and its barrier island system. *Ocean and Coastal Management* 68, 39 - 57.
- Ward, S., Green, J.A.M., Pelling, H.E., 2012. Tides, sea-level rise and tidal power extraction on the European shelf. *Ocean Dyn.* <http://dx.doi.org/10.1007/s10236-012-0552-6>.
- Wasklewicz, T.A., Anderson, S., & Liu, P.-S. 2004. Geomorphic context of channel locational probabilities along the Lower Mississippi River, USA. *Geomorphology*, 63, 145-158
- Watt, D.A., 1905. Notes on the Improvement of River and Harbour Outlets in the United States. *Transactions of American Society of Civil Engineers*, LV, pp. 208–305.
- Waycott, M., Duarte, C.M., Carruthers, T.J.B., Orth, R.J., Dennison, W.C., Olyarnik, S., Calladine, A., Fourqurean, J.W., Heck, K.L., Hughes, A.R., Kendrick, G.A., Kenworthy, W.J., Short, F.T., Williams, S.L., 2009. Accelerating loss of seagrasses across the globe threatens coastal ecosystems. *Proc. Natl. Acad. Sci.* 106, 12377–12381.
- Webster, P.J., Holland, G.J., Curry, J.A., Chang, H.-R., 2005. Changes in tropical cyclone number, duration and intensity in a warming environment. *Science* 309, 1844–1846.
- Welsh, D.J.S., Bedford, K.W., Wang, R., Sadayappan, P., 2000. A parallel-processing coupled wave/current/sediment transport model. Technical Report ERDC MSRC/PET TR/00-20, US Army Engineer Research and Development Center, Vicksburg, MS.
- Weltje, G. J. and von Eynatten, H. 2004. Quantitative provenance analysis of sediments review and outlook. *Sedimentary Geology*, 171, pp. 1–11
- Wentworth, C.K. 1922. A scale of grade and class terms for clastic sediments. *Journal of Geology*, 30, 377-392
- Wetz, M. S. and Yoskowitz, D. W. 2013. An ‘extreme’ future for estuaries? Effects of extreme climatic events on estuarine water quality and ecology. *Marine Pollution Bulletin*, 69, 7 – 18.
- Wheeler, W.H. 1902. *The Sea-Coast* London, Longman, Green and Co.
- Whitley, H.M., 1881. The silting up of the creeks of Falmouth Haven. *J. R. Inst. Corn.* VII, 12 – 17.
- Wolf, J. and Wolf, D.K. 2006. Waves and climate change in the northeast Atlantic. *Geophysical Research Letters*, 33, L06604
- Wolf, J., Hargreaves, J. C. And Flather, R. A. 2000. Application of the SWAN shallow

- water wave model to some UK Coastal Sites. Proudman Oceanographic Laboratory (POL) Report No. 57.
- Woodworth, P.L., 2010. Sea Level[online] Available at: <http://nora.nerc.ac.uk/10531/1/SeaLvlNORA.pdf> [Accessed: 28th July, 2012].
- Woodworth P. L., 1987. Trends in U.K. mean sea level, *Mar. Geod.*, 11, 57–87.
- Woodworth, P.L., White, N.J., Jevrejeva, S., Holgate, S., Church, J.A., & Gehrels, W.R. 2009. Evidence for the accelerations of sea-level on multi-decade and century timescales. *International Journal of Climatology*, 29, (6) 777-789
- Woodworth, P. L., Tsimphs, M. N., Flather, R. A., Shennan, I. 1999. A review of the trends observed in British Isles mean sea level data measured by tide gauges. *Geophy. J. Int.* 136, 651 – 670.
- Wöppelmann, G., Miguez, B.M., Bouin, M.N., Altamimi, Z., 2007. Geocentric sea-level trend estimates from GPS analyses at relevant tide gauges world-wide. *Global and Planetary Change* 57, 396–406.
- Wright, L.D. and Thom, B.G. (1977). Coastal depositional landforms: a morphodynamic approach. *Prog. Phys. Geogr.* 1(3): 412-459 In: *Progress in Physical Geography*. Sage: London. ISSN 0309-1333
- Wroe, D. 2008. *An Illustrated History of the North Cornwall Railway; the Southern Railway Route between Okehampton, Launceston, Wadebridge and Padstow (2nd edition)*. Irwell Press.
- Wyrwoll, K.H. and Smith, G.K. 1985. On using the log-hyperbolic distribution to describe the textural characteristics of eolian sediments. *Journal of Sedimentary Petrology*, 55, 471-478
- Wyrwoll, K.H. & Smith, G.K. 1988. On using the log-hyperbolic distribution to describe the textural characteristics of eolian sediments: reply. *Journal of Sedimentary Petrology*, 58, 161-162
- Yang, Z., Wang, H., Saito, Y., Milliman, J.D., Xu, K., Qiao, S., Shi, G., 2006. Dam impacts on the Changjiang (Yangtze) River sediment discharge to the sea: the past 55 years and after the Three Gorges Dam. *Water Resour. Res.* 42, W4407.
- Yeakel, L.S. 1962. Tuscarora, Juanita and Bald Eagle paleocurrents and paleogeography in the Central Appalachians. *Geological Society of America Bulletin*, 73, 1515-1540
- Yim, W.W.S. 1976. Heavy metal accumulation in estuarine sediments in a historical mining of Cornwall. *Marine Pollution Bulletin*, 7, 147-150
- Young, I.R., Zieger, S., Babanin, A.V., 2011. Global trends in wind speed and wave height. *Science* 332, 451–454.

- Young, A. P., Flick, R. E., O'Reilly, W. C., Chadwicj, D. B., Crampton, W. C. and Helly, J. J. 2014. Estimating cliff retreat in southern California considering sea level rise using a sand balance approach. *Marine Geology*, 348, 15 – 26.
- Zhang, M.Y., Li, Y.S., 1996. The synchronous coupling of a third-generation wave model and a two-dimensional storm surge model. *Ocean Eng.* 6, 533–543.
- Zhang, M.Y., Li, Y.S., 1997. The dynamic coupling of a 3rd-generation wave model and a 3d hydrodynamic model through boundary-layers. *Cont. Shelf Res.* 17, 1141–1170.
- Zuzek, P.J., Nairn, R.B., & Thieme, S.J. 2003. Spatial and temporal consideration for calculating shoreline change rates in the Great Lakes Basin. *Journal of Coastal Research*, 38, 125-146

## 10 APPENDICES

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*The copies of publications and outputs from this thesis that are included are listed here*

- Oyedotun, T. D. T.** (2014) Section 3.2.2. Shoreline geometry: DSAS as a tool for Historical Trend Analysis. In: Clarke, L. and Nield, J. M. (Eds) *Geomorphological Techniques (Online Edition)*. British Society for Geomorphology; London: UK. ISSN: 2047 – 0371 ([http://geomorphology.org.uk/assets/publications/subsections/pdfs/OnsitePublicationSubsection/42/3.2.2\\_shorelinegeometry.pdf](http://geomorphology.org.uk/assets/publications/subsections/pdfs/OnsitePublicationSubsection/42/3.2.2_shorelinegeometry.pdf))
- Oyedotun, T. D. T.**, Burningham, H. and French, J. R. (2013) Sediment sorting and mixing in the Camel Estuary, UK. In: Conley, D. C., Masserlink, G., Russell, P. E. and O’Hare, T. J. (Eds), *Proceedings 12<sup>th</sup> International Coastal Symposium* (Plymouth, England), *Journal of Coastal Research*, Special Issue No 65, pp. 1563 – 1568, ISSN 0749-0208. DOI: 10.2112/S165-264.1 ([http://ics2013.org/papers/Paper4455\\_rev.pdf](http://ics2013.org/papers/Paper4455_rev.pdf))
- Oyedotun, T. D. T.**, Burningham, H. and French, J. R. (2012) Characterisation of estuary and adjacent beach sediments in the Gannel Estuary, south-west England. *Geoscience in south-west England*, **13**, 70 – 76.

### CONFERENCE POSTERS

- 2014 British Society for Geomorphology Annual General Meeting held at University of Manchester from 01<sup>st</sup> – 03<sup>rd</sup> September, 2014. Poster presentation: “*Sediment characterisation in the Hayle Estuary, southwest England*”.
- 2013 British Society for Geomorphology Annual General Meeting held at Royal Holloway University of London from 09<sup>th</sup> – 11<sup>th</sup> September, 2013. Poster presentation: “*Historical coastal morphological change in St Ives Bay, southwest England*”.
- 51<sup>st</sup> Annual Conference of Ussher Society at Tregenna Castle, St Ives, Cornwall, UK 2<sup>nd</sup> – 05<sup>th</sup>, January, 2013. Poster and oral presentation: “*Morphodynamics of Gannel Estuary, southwest England*”