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SHORT COMMUNICATION

Historical Shoreline Changes as Indication of Geomorphic Phases in St Ives and Padstow Bays of Southwest England

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Abstract This study aims to examine the temporal pattern of shoreline changes as indication of geomorphic phases. Selected individual transects from the compartmentalised sections of the St Ives and Padstow systems were shortlisted for examination. Here, four phases of geomorphic response were specifically identified in the St Ives/Hayle system and three phases in the Padstow/Camel system. Despite the exposure of the systems to the same regional climatic and environmental conditions, they responded differently over the historical time-scale. The only constant response in all the estuaries is landward recession of the low water shoreline. The lack of temporal conformity to changes across all the coastal systems, where rates and directions of change occur at different periods throughout the history considered, confirmed that other factors beyond climate change or climate forcing are responsible for site-specific response, adjustment and behaviour. These other factors are structural, such as the shape and orientation of the bedrock valley and embayment, or anthropogenic, such as the construction of training walls and establishment of some sections of the systems as Sites of Specific Scientific Interests (SSSIs).

Keywords St Ives-Hayle · Padstow-Camel · Equilibrium · Disequilibrium · Geomorphic system

1 Introduction

The understanding of the evolution of coastal landscape (e.g., shoreline position) is an important medium by which disturbances in processes or geomorphic phases of coastal-estuarine environment can be well understood. The geomorphic differences between the depositional and erosional features of coastal shorelines at St Ives-Hayle and Padstow-Camel systems examined in their relationship with metocean data

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behaviour by Oyedotun (2016) are followed-up in this presentation. This paper discusses the examination of temporal shoreline positions as indications of geomorphic phases at the study sites. Examination of single or individual transects is utilised here in order to evaluate more fully the shoreline change statistics associated with shoreline change analysis (for example, as discussed in Fletcher et al. 2003; Hapke et al. 2006 and Romine et al. 2009).

2 Method

Historical maps used in this study were sourced from the United Kingdom's Ordnance Survey, and these covered the period 1845, 1908, 1936, 1948, 1963, 1989 and 2010 for St Ives-Hayle bay and the 1881, 1907/8, 1962, 1973, 1979 and 2010 for Padstow-Camel Bay, respectively (See Table 1 of Oyedotun (2016) for the details of the data used in this analysis). Historical Trend Analysis (HTA) in Digital Shoreline Analysis System (DSAS) is the geospatial technique platform utilised as analysis tools in ArcGIS for this study (see Thieler and Danforth 1994a, 1994b; Thieler et al. 2009; Oyedotun 2014). The HTA geospatial technique was adopted specifically for shoreline delineation and examination of shoreline dynamics in this study, as detailed in the previous paper (Oyedotun 2016). The focus here was to quantitatively measure the amount of temporal shoreline shift along some of the transects presented in the previous study. The previous study examined the patterns of historic configurations, investigation of shoreline geometry through three statistical measures in DSAS tool, specifically the Shoreline Change Envelope (SCE), Net Shoreline Movement (NSM) and End Point Rate (EPR) (see Oyedotun 2016 for full details and description of the methodology). Here, the oldest shoreline position was chosen as the baseline to which all other shorelines were referred for the points and along transect measurement. 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 change of two transects in each of the four distinct locations along the coastline of each of the systems were selected for evaluation (Figs. 1 and 2). The transects with SCE of >80.1 m and >40.1 m for St Ives and Padstow Bays, respectively, were shortlisted for the transect-wise examination, so as to minimise noise and also focus on the transects that experience high and relatively high envelope of change during the periods of examination. SCE results in Oyedotun (2016) presented a measure of total change in shoreline movements, considering all the available shoreline positions and reporting their distances without reference to the along transect yearly changes (Thieler and Danforth 1994a, 1994b; Thieler et al. 2009; Oyedotun 2014). The results presented here, however, evaluate the historical changes and the trends of individual selected transecs (the discrete alongshore positions) as examples of the time-series of specific change in the distinct compartmentalised locations along the coastline of the two bays (i.e., St Ives and Padstow bays). These transects were examined and plotted in graphs for both Mean Low Water (MLW) and Mean High Water (MHW), with 'year' plotted along the x-axis and the corresponding cumulative change in shoreline positions plotted on the y-axis with respect to year 1845 shoreline for St Ives-Hayle and to 1880 for Padstow-Camel systems, respectively.

Table 1 Spatio-temporal geomorphic responses of the coastal systems

System	Phase 1	Phase 2	Phase 3	Phase 4
St Ives / Hayle	Disequilibrium *-constant form, probability that processes maintain balance in space and time (based on Gilbert 1877);* *-equilibrium over decade scales*	Dynamic Equilibrium *-complex response;* *-increasing shoreline erosion in some parts;* *-minimal changes*	Dynamic metastable equilibrium *-response to extrinsic or intrinsic forcing;* *-altercation of threshold jumps, both in forms and processes*	Steady-state Equilibrium *-low variability;* *-small-scale shifts in shoreline positions*
Padstow / Camel	Phase 1 Disequilibrium *-high variability;* *-small changes in shoreline positions;* *-equilibrium over decadal time scales*	Phase 2 Equilibrium *-response to either extrinsic or intrinsic forcing;* *-minimal variability;* *-insignificant changes in shoreline positions;*		Phase 3 Steady-state Equilibrium *-low variability;* *-small scale in shoreline positions;* *-equilibrium over decadal time scales*
Forcing*				
Sea-level rise	1.69 mm yr.$^{-1}$	1.69 mm - 1.78 mm yr.$^{-1}$		>1.78 mm yr.$^{-1}$
NAO Index	1.00–2.25NAOi	1.25–2.25 NAOi	1.00–2.00 NAOi	1.25–2.25 NAOi
Human Interventions	Mining activities; port development; dredging activities	Reduction in mining/port activities limited dredging	Cessation of mining activities & training wall constructions	Establishment of some sites as SSSI
Year	1800–1900	1901–1940	1941–1980	1981–2013

NB: The definitions and description of the geomorphic processes are taken from Bracken and Wainwright (2006: 168–170)

*See Oyedotun (2016) for further details

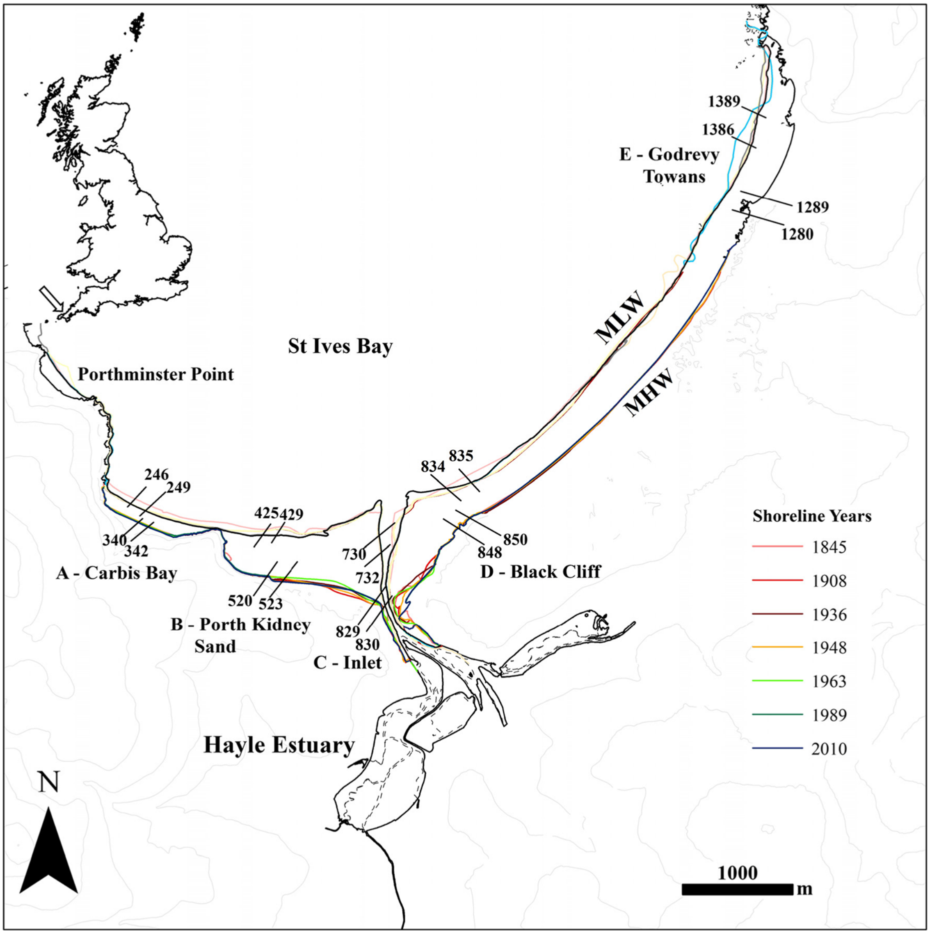

Fig. 1 St Ives Bay coastline showing the position of transects shortlisted for cumulative examination. Inset: Map of Great Britain showing the location of the bay

3 Results

3.1 Temporal Characteristics of Shoreline Change

3.1.1 St Ives Bay

Shoreline changes are spatially and temporally varied (Fig. 3). There is a very little change in MHW at the Port Kidney Sand (Fig. 3b), inlet (Fig. 3c) and the northern beaches (Godrevy Towans) (Fig. 3e) but a landward retreat of MLW of over 30 m throughout the history is observed here. However, progressive recession (> −40 m) of both MHW and MLW is evident at Carbis Bay (Fig. 3a) and more so at Black Cliff (Fig. 3d) over the same time scale in the mid-1900s. The western shorelines in Carbis Bay (Fig. 3a) show a general retreat, but this is mostly associated with 20-30 m of erosion between 1845 and the subsequent survey in 1909, which may be a result of the North Atlantic pressure systems of between 1899 to 1911 (see Fig. 7 in Oyedotun 2016). Here most transects show a landward shift, but close to the inlet at

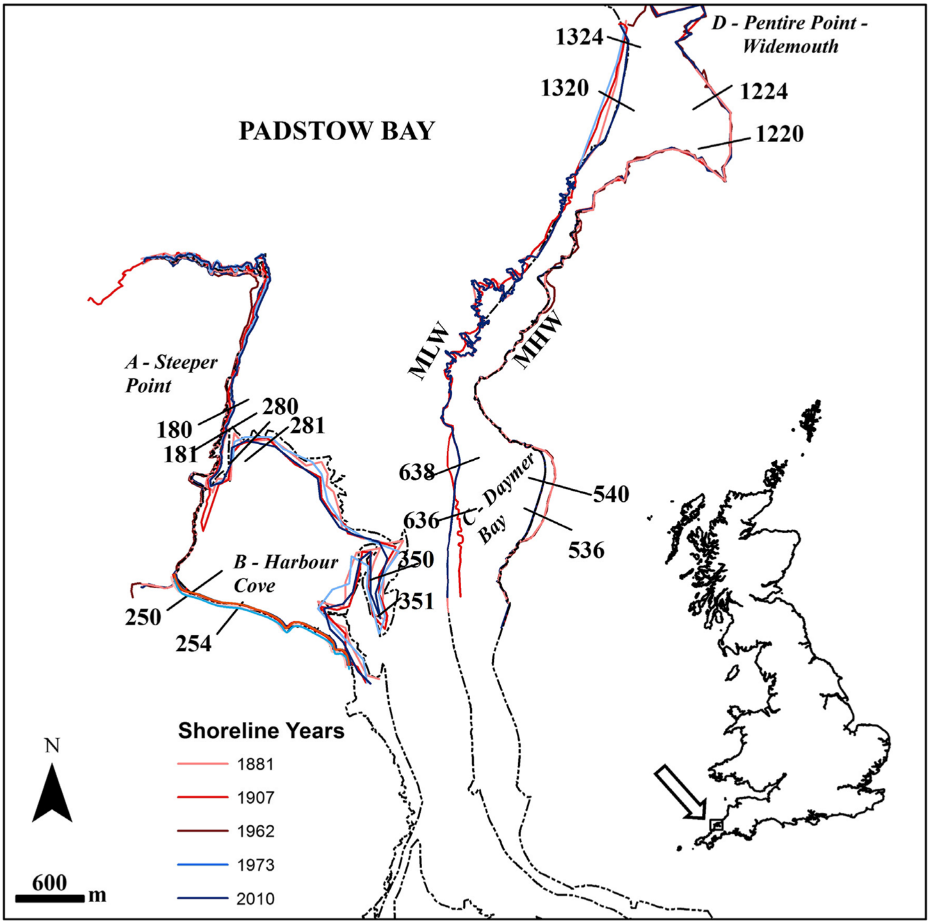

Fig. 2 Padstow Bay coastline showing the position of transects shortlisted for cumulative examination. Inset: Map of Great Britain showing the location of the bay

Port Kidney Sand (Fig. 3b), although the net change is negligible, this masks episodes of advance and retreat in the 1930s and the 1960s. This pattern of movement is also evident in transects on the western margin of the inlet at Black Cliff (Fig. 3d), but is almost inverse of the small-scale shifts in the Inlet (Fig. 3c), where small erosion-accretion episodes are shown. At Black Cliff (Fig. 3d) the 1940s to 1960s (mid-century) dynamics are superimposed on a general trend of retreat. At Godrevy Towans (Fig. 3e), again very small-scale change in the MHW position comprises slight retreat until the early 1900s followed by minor advance in the mid-1900s.

The cumulative change in shoreline position reported here shows a decrease in erosion in the 1950s and reported accretion at high water coastlines in the 1960s. The accretion (advance) rate of 0.01–1.00 m yr.$^{-1}$ previously reported (see Table 3 in Oyedotun 2016) and the evidence of reported accretion at Black Cliff (Fig. 3b) between 1908 and 1936, and 1948 to 1963, as well as at Godrevy Towans (Fig. 3e) during the same period, show that the overall historical evolution of the shorelines in the region is not all about erosion. This result, therefore, confirms what has been observed elsewhere. Especially for the observation of sparse accretional

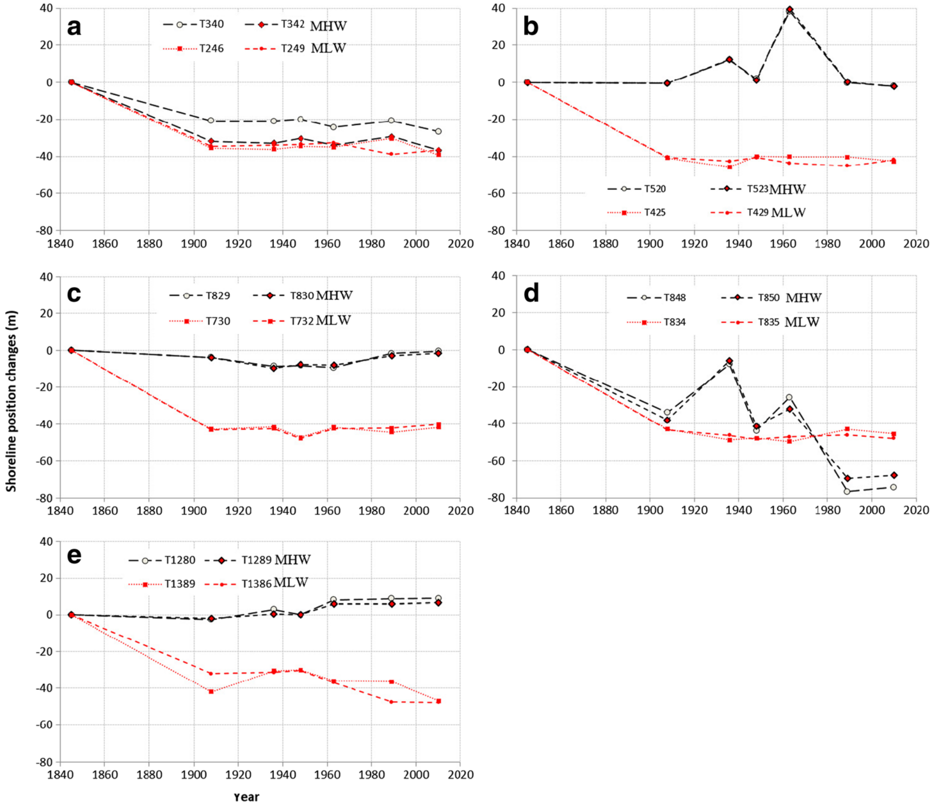

Fig. 3 Cumulative change in shoreline position along transects (**a**) T340 & T342 (MHW) and T246 & 249 (MLW) (Carbis Bay), (**b**) T520 & T523 (MHW) and T425 & T429 (MLW) (Port Kidney Sand), (**c**) T829 – T830 (MHW) and T730 & T732 (MLW) (Inlet), (**d**) T848 & T850 (MHW) and T834 & T835 (MLW) (Black Cliff) and (**e**) T1280 &T1289 (MHW) and T1389 & T1386 (MLW) (Godrevy Towans). Positive change shows accretion; negative change reflects erosion. (Within graph presentation: MHW – Black colour line, MLW – Red colour line)

shoreline behaviour in some locations along Great Britain coasts in the mid-twentieth century. For example, Montreuil and Bullard (2012) reported north Lincolnshire beaches undergoing accretion up to 2.7 m yr.$^{-1}$. The historical time-series plots of St Ives-Hayle Bay provide a clear example of the coastal system responding to forcing associated with more than just a climatic influence, as discussed in Oyedotun (2016). Most of the MLW and MHW shoreline positions have been showing recession all through the historical time considered until the 1970s. About 80% of the shoreline (MHW especially) shows erosion between 1845 and 1960, verifying that the more important change in shoreline trend was observed from the 1970s (Fig. 1).

3.1.2 Camel-Padstow Bay

In Padstow Bay, transects at Steeper Point (Fig. 4a, T180 and T181) and Harbour Cove (Fig. 4b, T251 and T255) at the west margin exhibit relative stability in the high water shoreline throughout the historical timescale considered (Fig. 4). At the eastern margin, the high water shoreline at Daymer Bay (Fig. 4c, T537 and T538), closer to the inlet, advanced minimally from the 1960s while Pentire Point - Widemouth (Fig. 4d, T1220 and T1224) shows

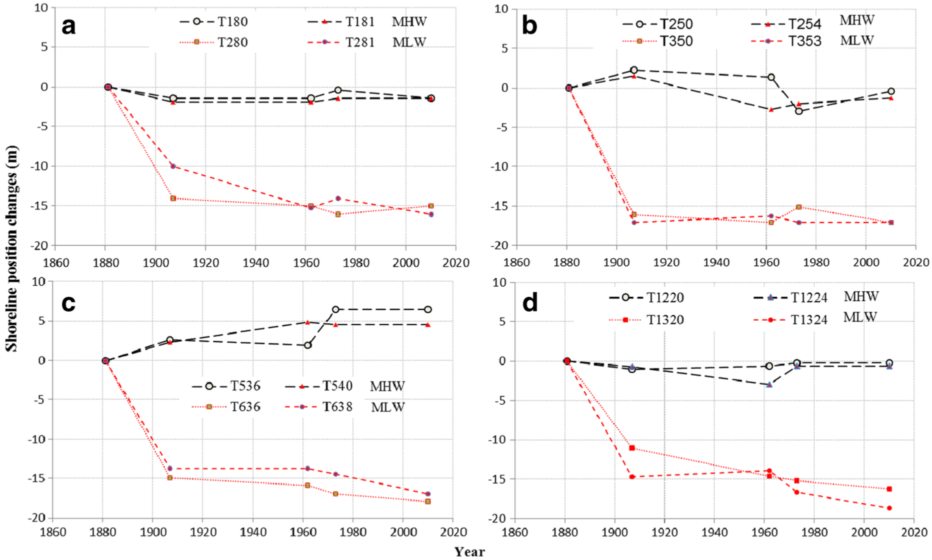

Fig. 4 Cumulative change in shoreline position along transects (**a**) T180 & T181 (MHW) and T280 & T281 (MLW) (Steeper Point), (**b**) T250 & T254 (MHW) and T350 & T353 (MLW) (Harbour Cove), (**c**) T1229 & T1230 (MHW) and T636 & T638 (MLW) (Daymer Bay) and (**d**) T1220 – T1224 (MHW) and T1320 & T1324 (MLW) (Pentire Point - Widemouth) in Padstow Bay. Positive change shows accretion; negative change reflects erosion. (Within graph presentation: MHW – Black colour line, MLW – Red colour line)

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.

4 Discussion

All environmental systems (geomorphic systems inclusive) are known to be both complex and complicated (Wainwright and Mulligan 2003; Bracken and Wainwright 2006). The unforeseen and unpredictability of response of geomorphic systems to the combination of one or more environmental factors is a hallmark of the complexity, while their complicated nature is an indication of the difficulties in their investigation (Bracken and Wainwright 2006). However, in the case of the systems investigated in Oyedotun (2016) and with the further addendum presented here, four phases of geomorphic response can be specifically identified in the St Ives/Hayle system and three phases in the Padstow/Camel system. These geomorphic evaluations consider the spatio-temporal variability of the individual systems' shoreline sensitivity and are summarised in Table 1.

Despite the exposure of the systems to the same regional climatic and environmental conditions, they respond differently over the historical time-scale. The only constant response in all of the estuaries is landward recession of the low water shoreline. Prior to the late nineteenth century, there is no available map evidence to suggest that systems in the southwest England might have existed in a condition of dynamic equilibrium. This is the situation wherein the processes operating in a geomorphic system act in a way to minimise the impact of the change on the landscape morphology (Gilbert 1877). The key feature of this geomorphic response is "constant form" while the "processes" strive to maintain balance (Gilbert 1877; Bracken and Wainwright 2006). This geomorphic situation (phase 1) is assumed to have characterised the nineteenth century in both the St Ives-Hayle and Padstow-Camel systems, although no evidence is available to suggest this state. The second phase for St Ives-Hayle is characterised by complex response to extrinsic factors (i.e., waves, wind, tides, sea level, etc.) or intrinsic forcing (e.g., accommodation space) (Oyedotun 2016), causing minimal variability of morphological changes, with increased shoreline erosion in some parts of the estuary and along the coastline. This scenario strives to maintain balance, a dynamic equilibrium response. Crucially, the nineteenth century was a period of anthropogenic activities, and the coastal systems were controlled by these activities during this time period. But in the twentieth century, these activities gradually ceased (Noall 1984; Pascoe 2005; Knight and Harrison 2013), leaving the system to respond more naturally to impose controls in the context of a changing climate. The consequence of this geomorphic response is a third phase described as dynamic metastable equilibrium. This condition, according to Schumm (1975), can be described as a "model of equilibrium". This describes the cumulative response of the coastline morphology of St Ives-Hayle in the mid-twentieth century period. During the same period, the Padstow-Camel morphodynamic behaviour implies a system characterised by minimal sensitivity to either extrinsic or intrinsic forcings as the minimal shoreline movements are noticed or the equilibrium over the decadal time scales are obvious for this period. The description which fits this second phase in the Padstow-Camel system is "equilibrium". The post-1980 response in all the systems is described as "steady-state equilibrium," as low variability to morphological changes and relative minimal change in shoreline movement are observed.

A combination of several factors is possible driver of different geomorphic response of the meso-scale morphodynamics at the study sites. These include the combinations of environmental forcing factors like the observed sea level rise of the century, the wave climate and storm surge frequency, tidal regime or the historical human activities (such as training wall construction, port development, channel dredging, sluicing, etc.) discussed in Oyedotun (2016). The post 1980s in the estuaries could be described as the current phase of the geomorphic response. This phase is characterised by steady-state equilibrium in the region with similar level of variability (Figs. 3, 4 and Table 1). The relative stability in shoreline positions post 1980s is suggested to be the outcome of mining activities cessation and reduction in channel dredging and training wall constructions during the preceding decades. In the 18th and 19th centuries, the harbours in the region were busy as they served very important ports activities. However, from the 1950s, there has been a progressive decline in the local engineering and metal ore mining industries, especially since the closure of metal foundries in 1903 and cessation of commercial shipping in the late 1960s/early 1970s (Noall 1984; Pascoe 2005). The decline has reduced the harbours to local fishing and recreational activities, leading to a reduction in dredging and other large scale anthropogenic activities. After decades of being constantly impacted and managed by human activities, the estuaries subsequently have a period of natural adjustment to this legacy, involving small-scale shifts in shoreline positions. The reduction in large scale anthropogenic activities post 1980s encouraged the estuaries to respond to natural action of waves, winds, rivers and tides solely in driving the processes in the estuaries, without being actively guided by human intervention. Another anthropogenic factor which contributes to the low variability of geomorphic response in the region is the designation of parts of the estuaries as Sites of Specific Scientific Interests (SSSIs). In 1981, the part of Hayle Estuary and Carrack Gladden were designated as SSSI, and then re-notified in 1993 to include Copperhouse (Natural England 2010). There are five sites along River Camel in Camel Estuary which have been designated as SSSIs, which include Harbour Cove, Rock Dunes, Trebetheric Point and Pentire Peninsula (with the whole River Camel) designated by the Joint Nature Conservation Committee (JNCC) as Special Area of Conservation (JNCC, URL) (Bere 1982). This requires that such sites are managed in such a way that their specific biological, geomorphological and geological features are favourably conserved - this includes the restriction and prohibition of any human activities that involve digging, harbouring or any form of access to the designated sites in the estuary. These restrictions are some of the factors which might have contributed to the reduction in significant human activities since the 1980s.

5 Conclusions

The changing nature of coastal environment is expressed in significant shifts in wave and wind climates, which are key drivers of coastal change. Apart from the key drivers of coastal processes which exert control on estuarine and coastal morphology, the inherited antecedent framework such as drainage patterns, valley character, accommodation space, sea-bed geology and human intervention also exert control on the geomorphic evolution on the coastal-estuarine system. It has been shown that understanding the evolution of coastal landscape (e.g., shoreline position) is an important medium by which disturbances in processes or geomorphic phases of coastal-estuarine environment can be well understood.

This study has examined, evaluated and compared the morphodynamic behaviour of coastal systems in north Cornwall, Southwest England. The historical analysis of shoreline has provided a long-term perspective, but the paucity of evidence over these longer time-frames make it difficult to draw direct connections between forcing and geomorphic response. Furthermore, the lack of topographic information in earlier surveys precludes any significant volume based analysis. The continued development of a lidar and aerial photography database, however, presents an excellent opportunity to explore 3D morphological change over the longer term. This has some way to go before we can achieve a clear understanding of decadal scale morphodynamics, but in the meantime, further work using the lidar data or other available Ordnance Survey maps to derive sediment budget calculations would certainly help to understand the year to year balances in morphological changes identified. The role of inherited structural framework on geomorphic behaviour is perhaps one of the most interesting elements of this research, and further work to evolve some of the ideas presented here would be useful. Certainly, the coastal systems of north Cornwall have provided a useful starting point, but the work could be expanded across equivalent systems across the southwest of England to develop conceptual models of the relative roles of bedrock controls on coastal morphodynamics.

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