Geomorphological change and its impact on habitats in the Camel Estuary, Cornwall, UK

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The Camel Estuary, Cornwall, UK, supports a diverse range of habitats which are of primary marine biological importance. This paper describes how the extent and distribution of these habitats are influenced by the morphological evolution of the estuary and considers their likely future evolution within the context of morphological change. Historical trend analysis shows that in the late 1920s, the main subtidal channel switched from the western to the eastern side of the outer estuary, leading to changes in the distribution of sandflat and sand dune areas. Since then, the outer estuary has remained relatively stable with a positive sediment budget. The main changes to the morphology of the inner estuary have been caused by human impact. Areas of saltmarsh are stable or very slowly accreting, but there appears little scope for future expansion within the current estuary boundaries. Large areas of previous saltmarsh have been isolated from tidal flow and are now freshwater marshes and grazed farmland. Long-term potential acceleration of sea-level rise will increase pressure on habitats, particularly in the inner estuary, where they are dependent on a limited fluvial sediment supply and are restricted by artificial stabilisation.

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Introduction

The Environment Agency South West Region has identified the need to improve our understanding of morphological change in the Camel Estuary, Cornwall, UK, in relation to mobile Biodiversity Action Plan (BAP) habitats, including saltmarsh, mudflat, sandflat, subtidal channels, grazing marsh and sand dune (Royal Haskoning, 2005). The Camel Estuary is a dynamic system within which these habitats are prone to changes in shape and extent, through their interaction with sediment supply and loss. Muddy and sandy sediments accumulate to build mudflats and sandflats, respectively. Sediment from the sandflats is reworked by currents and wave action or blown onshore to feed sand beaches and dune systems. These interactions occur gradually over decades or by catastrophic change during extreme storm events (John Merefield, personal communication, 2009). Accreting mudflats support the development of saltmarsh communities. A combination of tidal flows and sediment redistribution across intertidal areas drives migration of subtidal channels (Royal Haskoning, 2005).

This paper provides analysis and interpretation of historical and contemporary geomorphological data (historical trend analysis) to construct a conceptual understanding of the estuarine functioning of the Camel. This provides the background against which the likely future evolution of morphological features and habitats in this estuary can be predicted.

There is a clear relationship between geomorphological and ecological change in estuarine systems. This paper provides one example of how that link can be studied using historical trend analysis. Although this study is specific to the Camel Estuary, the trend analysis methodology can be tailored and/or adopted to, deliver solutions to similar concerns in other dynamic estuarine (and coastal) settings.

Sedimentary environments

The Camel Estuary is a deep valley that has been drowned by post-glacial sea-level rise, extending 15 km upstream from Trebetherick Point (Figure 1). The bulk of the estuary is now shallow and sandy, only deepening at its mouth (Padstow Bay), with a narrow meandering low-water channel that shifts position across the intertidal flats. The total intertidal area is around 6 km^2 with 92% of this being intertidal flat (Buck, 1993). For ease of description, the estuary is divided into outer, middle and inner reaches (Figure 1).

The north-facing mouth of the estuary is approximately 1 km wide and dominated by Doom Bar, a large intertidal sandflat connected to the west bank (Figure 1). The subtidal channel flows between Doom Bar and intertidal sandflats of Daymer Bay along the east side of the estuary. Two main areas of sand dune exist in the outer estuary, on the east bank north-west of Rock and in Harbour Cove on the west bank, south of Doom Bar. These dunes support rich calcareous vegetation and a diverse invertebrate fauna and associated rare plant species (Gill and Mercer, 1989; ABP Research and Consultancy, 1995).

The estuary narrows upstream from Brea Hill and then widens again into the middle estuary (Figure 1). Here, the subtidal channel currently follows the east bank, passing close to the Rock shoreline. The west side of the middle estuary is dominated by two large intertidal sandflats known as Town Bar and Halwyn Bank. On the south margin of Town Bar, Little Petherick Creek drains into the estuary.

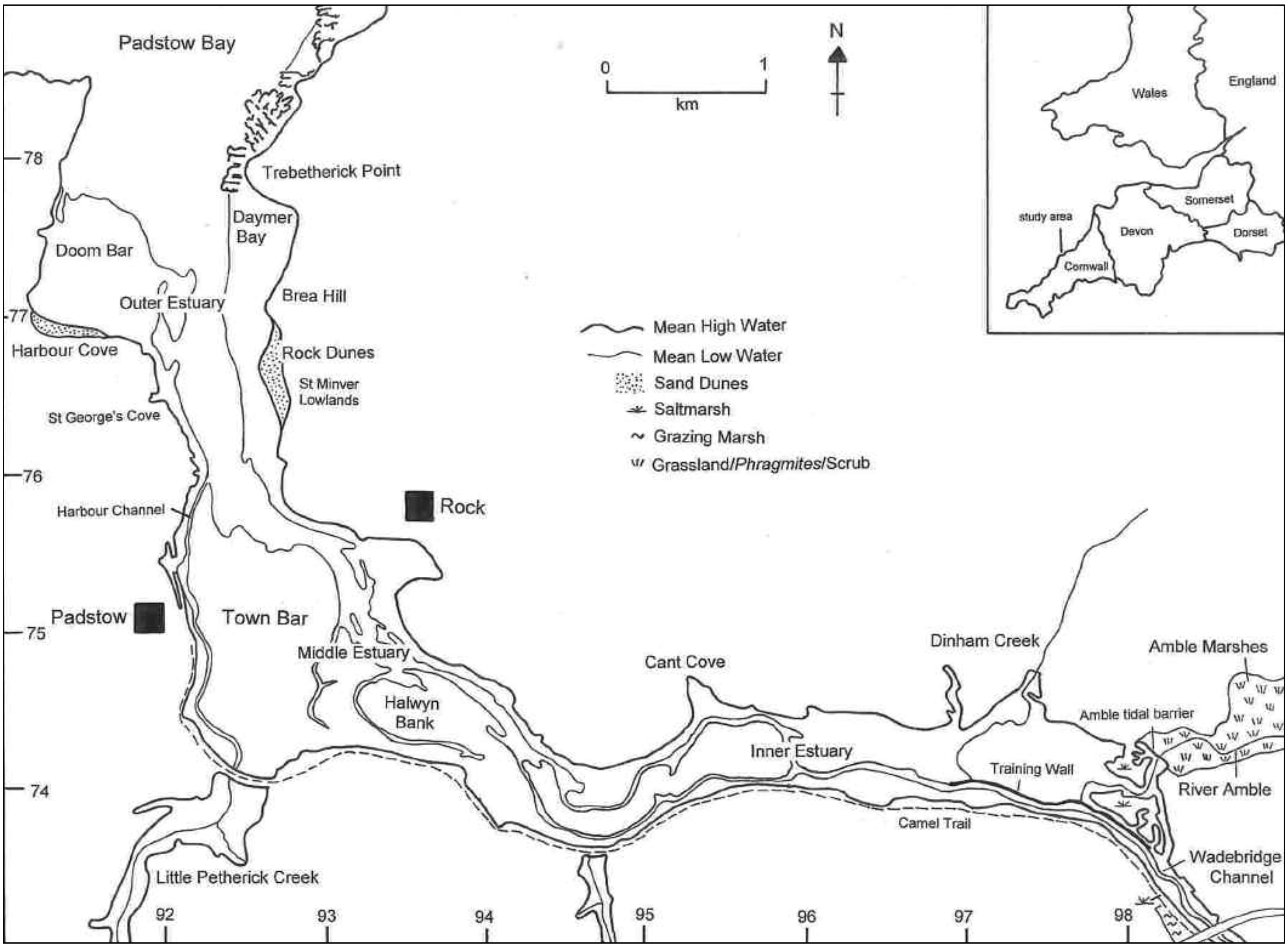

Figure 1. *Location map of the Camel Estuary, west Cornwall showing locations mentioned in the text..*

Sediments on the sandflats in the outer and middle estuary have relatively uniform mean particle sizes of 0.2-0.25 mm (fine sand) (McMullen & Associates and Herrington Geoscience, 1989). The sediments contain high levels of marine-derived calcium carbonate (mainly between 60 and 80%), in the form of shell fragments (Merefield, 1982). In the channels, coarser sand is present along with shells and gravel. In contrast to the sandy composition of the middle and outer estuary, Little Petherick Creek is mud dominated.

The channel in the inner estuary meanders through sandflats in a narrow valley between Halwyn Bank and the confluence with the River Amble. Upstream of Cant Cove, the character of the estuary changes from sand- to mud-dominated. Saltmarsh becomes more common, and the estuary narrows from around 500 m to 100 m upstream into Wadebridge Channel (Figure 1). This narrowing is partly caused by a 1000-m long training wall built in 1870 on the north side of the channel and embankments further upstream in Wadebridge. Grazing marshes have formed where the low-lying land has been isolated from tidal inflow by the embankments.

In 1952, a tidal barrier was built at the confluence of the River Amble and Camel Estuary (Figure 1) to protect upstream farming land from flooding. The barrier excludes tidal inflow to a large area (0.5 km^2) of previously saltmarsh and intertidal mudflat (Amble Marshes). Now the Amble Marshes consist of a number of different habitats including grassland, open water, *Phragmites* marsh, scrub and marginal vegetation (Gill and Mercer, 1989; ABP Research and Consultancy, 1995). A significant amount of saltmarsh (including *Spartina* stands) has developed on the mudflats between the Amble barrier and the channel training wall. Approximately 0.05 km^2 of saltmarsh is also isolated from the estuary by a tidal barrier at Dinham Creek.

Physical processes

The spring and neap tidal ranges at Padstow are around 6.5 m and 3.0 m, respectively. The tidal prism of the estuary is calculated to be around 16.5 million cubic metres on a neap tide and 32 million cubic metres on a spring tide (McMullen & Associates and Herrington Geoscience, 1989). Ebb tidal current velocities on a spring tide at Rock can reach 1.5 ms^{-1}. Strong ebb flows continue further downstream with velocities up to 1.15 ms^{-1} near St George's Cove. Flood velocities off Rock can reach 1 ms^{-1} and hence tidal current dominance here is ebb-dominated. Ebb and flood velocities are approximately equal near Trebetherick Point with values up to 0.8 ms^{-1} in the channel. Velocities over Doom Bar are lower, between 0.3 and 0.5 ms^{-1}. Halcrow (2002) provided a measure of the tidal asymmetry in the form of the 'Dronkers gamma'. The small value for the Camel Estuary (0.074) indicates that the estuary is ebb-dominated supporting the velocity measurements. The influence of wave action is mainly confined to the outer estuary particularly at Doom Bar, where it may be responsible for periodic sweeping of sediment into the subtidal channel.

Sedimentary processes

The main supply of sand-sized sediment to the estuary is from offshore sources (Merefield, 1982). Sea bed sediments immediately offshore of the mouth comprise mixed sand and gravel (British Geological Survey, 1987). The sediments generally occur as extensive sheets of less than 1 m thickness overlying a comparatively smooth bedrock surface. Little bedload sediment is supplied to the estuary through freshwater discharge. However, freshwater supplies of suspended sediment (and possibly coarser sediment) probably contribute to the inner estuary and the creeks along the south shore. The concentration of suspended sediment in the estuary increases in an upstream direction. Average concentrations recorded between 1992 and 1995 were less than 20 mgl^{-1} in the outer estuary, increasing to less than 40 mgl^{-1} in the middle to inner estuary. The highest levels (around 100 mgl^{-1}) were measured in Little Petherick Creek (ABP Research and Consultancy, 1995).

Historically, the natural supply of sediment to the estuary was temporarily increased by the release of waste from upstream hard rock mining in the late 19th and early 20th centuries. Pirrie *et al.* (2000) collected cores from intertidal areas in front of the Amble barrier and described relatively high concentrations of heavy metals in the middle of the cores decreasing to the sediment surface. They suggested that the heavy metal peaks represent pulses of mine waste into the catchment, tailing off towards the top of the cores after closure of the mines in the 1920s and 1930s.

Direct measurement of tidal currents and analysis of estuary dimension suggest that the Camel Estuary is ebb-dominated (McMullen & Associates and Herrington Geoscience, 1989). This would imply a net sand transport out of the estuary, and in the absence of a major fluvial supply, a net sand deficit. Such a sediment deficit is not consistent with the historical evidence, particularly the apparent resilience of the estuary to ongoing sediment removal by dredging (McMullen & Associates and Herrington Geoscience, 1989). Large quantities of sediment have been removed by dredging, but there is no evidence of a long-term loss of sediment. Current and past extraction activities appear to be insufficient to counteract sediment supply. In addition, asymmetrical bedforms on the intertidal sandflats of Doom Bar, Town Bar and Halwyn Bank indicate flood-dominated transport. These bedforms do not appear to reverse during the ebb tide and suggest sediment transport into the estuary.

Methods and data for historical trend analysis

Historic bathymetry provides a key dataset for any study assessing morphological behaviour. Due to the presence of Padstow Harbour, there is good temporal coverage of bathymetric surveys. Admiralty Charts are available for 1839, 1903, 1931, 1954, 1961, 1981 and 1983, with an additional bathymetric survey undertaken in 1988 (McMullen & Associates and Herrington Geoscience, 1989). Most of these charts only cover the outer and middle estuary as they concentrate on the approaches to Padstow Harbour. Aerial photographs provide a more recent source of information. Oblique aerial photographs of the estuary exist for 1993, 1995, 1996, 1999 and 2000, with vertical aerial photographs taken in 1998. LiDAR flown in March 2003 provides information on the extent and elevation of intertidal areas and the adjacent floodplain.

Historical change in the outer and middle estuary

The earliest reliable chart used in this study is from 1839 (Figure 2). This survey shows that the main subtidal channel was along the west side of the outer estuary. In 1839, Doom Bar was located on the eastern side of the estuary, extending into the estuary from Daymer Bay.

The 1931 chart illustrates one of the most significant changes to the outer estuary. The main subtidal channel had switched to the eastern side and Doom Bar was now connected to the west shore. McMullen & Associates and Herrington Geoscience (1989) suggested this change occurred in 1929 and was caused by the development of surge channels by breakers which breached Doom Bar to create space for the present main channel. The configuration of the outer estuary largely established in 1929 has remained relatively stable up to the present day (Figure 2).

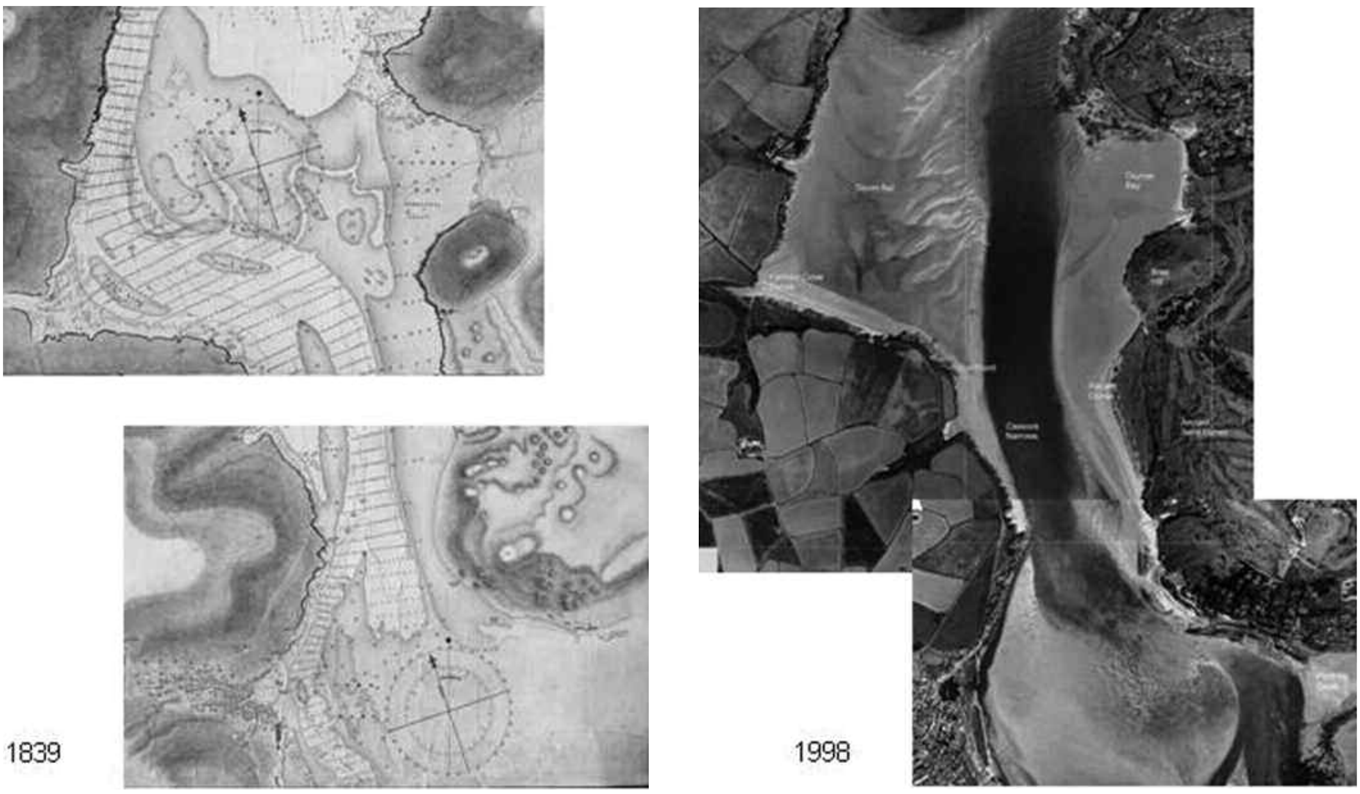

Figure 2. *Comparison of the hydrographic chart of 1839 and the vertical aerial photograph of 1998 showing the shifting position of the subtidal channel, intertidal flats and sand dunes of the outer and middle estuary.*

Further upstream, the main channel in 1839 flowed adjacent to Padstow Harbour (Harbour Channel) (Figure 2). By 1947 a significant change in the middle estuary occurred with the main subtidal channel shifting from the west bank (adjacent to Padstow) to the east bank (flowing past Rock), which is its current position (Figure 2). McMullen & Associates and Herrington Geoscience (1989) cited anecdotal evidence suggesting that this switch took place around 1942, but no cause was provided. It is possible that the 1942 switch was a delayed response to the 1929 change in orientation of the main channel in the outer estuary. Associated with this switch was the lateral movement of Town Bar with erosion by the new channel on its eastern margin and accretion in the old Harbour Channel. Harbour Channel continues to infill, and is maintained for navigation by ongoing dredging.

In 1839 there were no dunes mapped north of Rock on the east shore of the estuary (Figure 2), and their growth in this location probably began once the shift in channel position had taken place. Between 1931 and 1988 these dunes advanced seaward by around 140 m. Between 1988 and 1998, Rock Dunes accreted by up to a further 30 m, with little change between 1998 and 2002. The good health of the dunes suggests an adequate supply of sand from the adjacent sandflats and the necessary winds (predominantly south-westerly) to transport it from one to the other. The easterly shift in the main subtidal channel also resulted in the retreat of the shoreline at Rock by 135 m between 1931 and 1961 (McMullen & Associates and Herrington Geoscience, 1989) leading to protection measures being put in place along this bank in 1985.

In 1839, coastal dunes were also absent at Harbour Cove on the west bank of the estuary (Figure 2), as there was no supply of sediment from sandflats when the main channel was aligned close to the west shore. It is likely that the dunes now present at Harbour Cove began to form in response to an increased source of sand associated with the attachment of Doom Bar to the western shore of the estuary. These dunes have grown more slowly than Rock Dunes, because their development is dependent on a less dominant wind direction. It is likely that transport of sand from Doom Bar to Harbour Dunes occurred both gradually over the long term and by short-term movement during storm events.

The timing of the migration of the main subtidal channel coincides with changes in the configuration of Padstow Harbour (Wroe, 2008). Between 1910 and the 1930s, the shore-parallel West Quay, railway jetty (with 'bull-nose' breakwater), and North Quay breakwater were completed. Given that the size of these structures is very small compared to the scale of the geomorphological features, there is unlikely to be a link between their construction and the changes to the outer and middle estuary.

Historical change in the inner estuary

The 1839 chart shows that the River Amble and Dinham Creek were in a relatively natural state, with significant areas of intertidal mudflat (Figure 3). Similarly, all the creeks on the south side of the estuary contained intertidal mudflats and unrestricted flow to the body of the estuary. There is no indication of saltmarsh in any of the inner creeks of the estuary on the 1839 map.

The most significant changes to the inner estuary have been induced by anthropogenic activity, particularly the construction of the 1870 training wall and the 1952 Amble tidal barrier. The combined effect of their construction (and the Dinham tidal barrier) influenced the sediment regime in two ways. Tidal flows from the Amble and Dinham rivers were removed and a more 'stable' regime was established (less prone to influence from channel migration) north of the training wall. This allowed accumulation of mud, leading eventually to the saltmarsh habitat seen today. Aerial photographs show that these areas of saltmarsh have increased slightly between 1988 and 2002. The slow spread of saltmarsh most likely reflects the limited input of fine sediment to the system. This supply is critical to the continued development of these areas and their stability in the face of future sea-level rise.

Future evolution of subtidal channels and sandflats

The main subtidal channel in the outer estuary underwent major changes in the first half of the 20th Century, when the main channel switched from the western side of the estuary to the eastern side, where it has remained to the present day (Figure 2). This change was followed by channel movements in the middle estuary. The channel and sandflats in the outer estuary have remained relatively stable since the 1930s, and there is no morphological evidence to suggest that major changes are likely to occur in the near future. This is because: (1) There is no evidence of progressive changes to the main channel in the outer estuary, (2) large sand waves are consistently present on Doom Bar, indicating a positive sediment budget and associated stability, (3) Rock Dunes appear stable and are slowly accreting. Similarly, dunes at Harbour Cove appear currently stable. (4) McMullen & Associates and Herrington Geoscience (1989) indicated an increase in the elevation of Doom Bar leading up to 1988, further supporting a positive sediment budget and stability of the Bar. (5) Ongoing dredging in the navigation channel assists in stabilising the channel path, making migration less likely.

Future evolution of sand dunes

Dune habitat became established after 1929 north of Rock and in Harbour Cove when changes in the main subtidal channel provided space and the source of sand to build dunes. However, the same changes drove erosion of the early 20th Century dunes at Rock. The historical record indicates that dune habitat is limited and potentially temporary in the Camel Estuary. The habitat is sensitive to channel movements and sediment supply and will not form or accrete in an area where supply is limited.

The dunes north of Rock are likely to continue to accrete until a balance is reached with the position of the channel and adjacent intertidal area. The reduced rate of dune building observed after 1998 suggests that this balance may have nearly been reached, and that further horizontal accretion of this dune system will be limited. Dunes in Harbour Cove appear to have undergone very little change over the last 15 years and may be in equilibrium with the current conditions.

Future evolution of mudflats, saltmarshes and grazing marshes

There are limited areas within which mudflats and saltmarshes can spread in the Camel Estuary. The area of mudflat fronting the Amble tidal barrier is becoming increasingly covered by saltmarsh, although very slowly, due to a low input of fine sediment. In many areas, saltmarsh has colonised suitable mudflat, and there is little potential for any increase in its extent. For example, further accretion of saltmarsh fronting the Camel Trail is prevented by the presence of the channel in front and the embankment behind. Here, areas suitable for the colonisation of saltmarsh have largely been isolated from tidal inundation by human influence, and exist as grazing marsh. These areas would potentially revert to mudflat and saltmarsh if tidal inflow was reintroduced (Royal Haskoning, 2005).

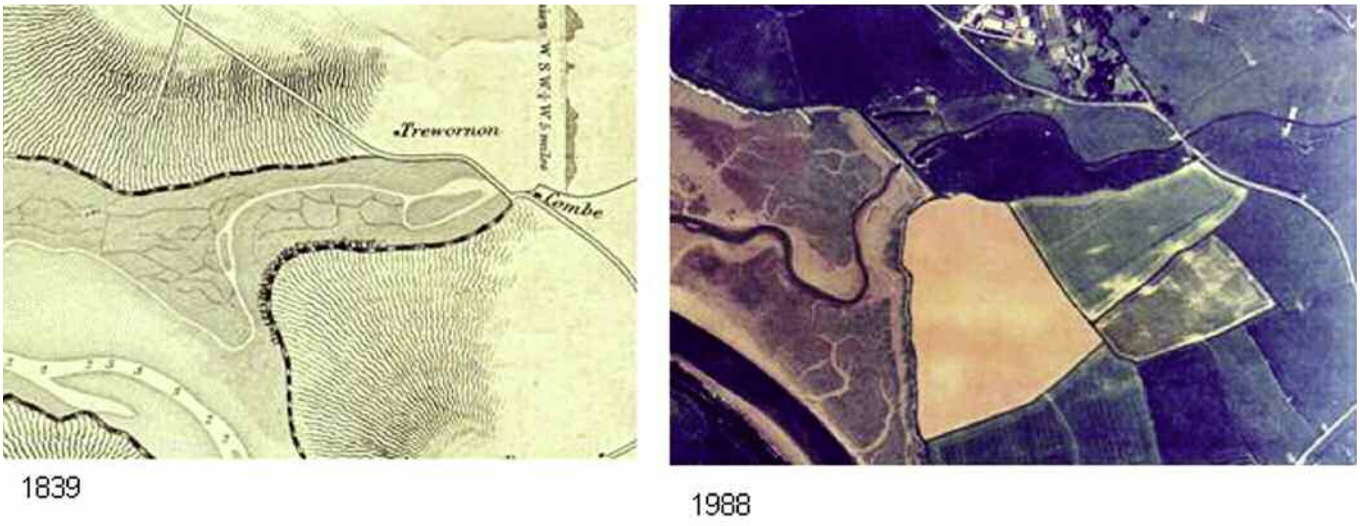

Figure 3. *Comparison of the hydrographic chart of 1839 and the vertical aerial photograph of 1988 showing the change in habitats at the Camel Estuary/Amble River confluence.*

SEA-LEVEL RISE

Woodworth *et al*. (1999) analysed tide gauge records for Newlyn, and calculated a relative sea-level rise of 1.69 mm/yr (between 1916 and 1996). In comparison, Shennan and Horton (2002) suggested a long-term relative sea-level rise (based on geological data over the last 4000 years) of 1.12 mm/yr. These data provide an indication of past rates, whereas future sea-level rise may be a key factor for the development of the estuary. Guidance on future predictions of sea-level rise along the United Kingdom coast is provided by DEFRA (2006). For south-west England, the DEFRA (2006) allowance for sea-level rise is 3.5 mm/yr between 1990 and 2025, and 8.0 mm/yr between 2025 and 2055.

Future sea-level rise may result in a reduction in the overall area of intertidal sandflat and mudflat, unless sediment supply is sufficient to support accretion to keep pace with sea level. The present-day positive sediment budget indicates that in the long-term sandflats and dunes may be able to evolve to keep pace with accelerating sea-level rise. However, the relatively low input of fine sediment from fluvial sources may mean that mudflat development (and associated saltmarsh habitat) will be slow (as observed in the past), and will be prone to loss, particularly where the shoreline cannot migrate landward due to embankments.

CONCLUSIONS

This paper presents information on the mobile physical habitats in the Camel Estuary and an interpretation of past and present estuary behaviour, as well as an assessment of likely future evolution of these habitats. Historical trend analysis shows that there have been major changes in the outer and middle estuary since the mid 19th Century. The main subtidal channel has switched from the western to the eastern side of Padstow Bay. These changes to the channel and sandflat configuration allowed for the development of sand dune areas north of Rock and at Harbour Cove, and caused their erosion further south at Rock. There is no evidence that further significant change in the subtidal channel and sandflats in the outer estuary will take place in the foreseeable future. The outer estuary is exhibiting signs of stability and a positive sediment budget, and the sand dune habitats are currently stable or slowly accreting. While the adjacent channel and sandflats remain stable, they will continue to provide protection and sand supply to the dune environment. The middle estuary is dynamic with ongoing channel switching and migration but overall the intertidal area has remained relatively constant.

The most significant changes to the inner estuary have been those induced by human impact. Large areas of saltmarsh have historically been isolated from tidal flow and are now freshwater marshes and grazed farmland. These areas would be likely to return to saltmarsh if re-opened to the tide. Existing areas of saltmarsh appear to be either stable or very slowly accreting, but there is very little mudflat for expansion of saltmarsh within the current estuary boundaries.

The Camel Estuary appears to have a positive sediment budget with a marine sediment supply that has been sufficient to balance sand removed by dredging. The overall area of intertidal sandflat has remained relatively constant, and will continue to be so if the sediment budget of the estuary is sufficient to exceed the rate of sediment removal by dredging and natural processes. Long term acceleration of sea-level rise will increase pressure on habitats, particularly in the inner estuary, where they are dependent on a limited fluvial sediment supply and are restricted by artificial stabilisation.

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