Annex A1:
Coastal Processes and Shoreline Behaviour of Estuary Dominated Systems in Swansea Bay and Carmarthen Bay (prepared by Professor Ken Pye, May 2009)
Coastal processes and shoreline behaviour of estuary dominated systems in Swansea Bay and Carmarthen Bay

Report prepared for Halcrow Group Ltd

by

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Contents

1. Report scope and purpose ........................................ 10

2. Geological framework and general character of the coast .... 11

3. Offshore bathymetry and seabed sediments .................. 13

4. Environmental controls on coastal processes ................. 14
   4.1 Mean sea level .............................................. 14
   4.2 Tidal regime ................................................. 14
   4.3 Wind regime ................................................. 15
   4.4 Wave regime ................................................ 15
   4.5 Storm surges ................................................. 16
   4.6 Temperature, rainfall and surface runoff .................. 17
   4.7 Sediment transport ........................................... 18
   4.8 Human impacts .............................................. 19

5. Shoreline evolution and morphology ........................... 21
   5.1 Giltar Point to Burry Holms .............................. 21
   5.2 Pendine to Ginst Point .................................... 24
   5.3 Ginst Point to Tywyn Point (Three Rivers Complex) .... 26
   5.4 Tywyn Point to Burry Port ................................ 30
   5.5 Burry Inlet .................................................. 32
   5.6 Whiteford Point to Burry Holms ......................... 37
   5.7 Burry Holms to Worms Head ................................ 38
   5.8 Mumbles Head to Porthcawl Point ........................ 39
   5.9 Porthcawl Point to Nash Point ............................ 43

6. Conceptual model of shoreline evolution - past, present and future 45

7. References ...................................................... 48
Tables
Table 1  Tidal levels for ports along the coast of South Wales, in metres relative to Ordnance Datum Newlyn. Data sources: figures in italics from NTSLF; figures in regular type from Admiralty Tide Tables 2008

Table 2  Summary characteristics of four South Wales estuaries. Figures in italics are estimates. Data source: Bristow and Pile (2003).

Figures
Figure 1  Major geological features of South Wales and the Bristol Channel, based on British Geological Survey maps and Tappin *et al*. 1994). A = Variscan Front Thrust, B = Central Bristol Channel Fault Zone. Also shown are the limits of the SMP2 study area and defined limits of the Outer, Central and Inner Bristol Channel (after Posford Duvivier and ABP, 2000)

Figure 2  Generalised bathymetry of the Bristol Channel and Severn Estuary showing the position of operative wave buoys and tide gauges. Also shown are the limits of the Inner, Central and Outer Bristol Channel, after Posford Duvivier and ABP (2000).

Figure 3  Seabed sediment distribution in the Bristol Channel and surrounding areas. Modified from BGS (1986) and Pantin (1991).

Figure 4  Sea level index points for three locations around the Bristol Channel, plotted as calibrated age against change in sea-level relative to the present (m), after Shennan and Horton (2002). The solid line indicates the best estimate of the late Holocene relative sea level trend. The dashed line indicates the predicted relative sea level from model 4 described by Shennan *et al*. (2002).

Figure 5  Annual mean sea level recorded at six tide gauge stations: (a) Newlyn; (b) Avonmouth; (c) Newport; (d) Mumbles; (e) Milford Haven (Hakin); and (f) Fishguard. Data source: PSMSL.

Figure 6  Annual mean tide, wind and wave parameters in the Bristol Channel. Maps generated from gridded datasets compiled for the Atlas of UK Marine Renewable Energy Resources from average measurements of the Met Office UK Waters Wave Model for the period 01/06/2000 to 31/05/2007 (BERR, 2008).

Figure 7  Comparison of tidal levels recorded at three stations in South Wales during October 2008. Date source: NTSLF

Figure 8  Wind and sand rose diagrams calculated from records for Pembrey Sands between 1994 and 2000: (a) Wind rose, unshaded segments refering to all winds, shaded segments refering to winds > 11 knots. Arrows indicate resultant wind direction for all winds. (b) Sand rose, showing Drift
Potentials (DP, in vector units) calculated using the Fryberger and Dean (1979) equation. Arrows indicate Resultant Drift Potential (RDP, in vector units) and Resultant Drift Direction (RDD). Data source: Pye and Saye (2005).

Figure 9  Rose diagram of mean wave height and direction recorded at the CEFAS waverider buoy situated on Scarweather Bank (51° 26'N 3° 56'W, water depth of 30 m), calculated from 30 minute observations of significant wave height and peak wave direction between May 2005 and March 2009.

Figure 10  Average monthly minimum and maximum temperature for the period 1971-2000 at: (a) Cardiff and (b) Tenby. Average monthly rainfall and number of rain days for the period 1971-2000 at (c) Cardiff and (d) Tenby. Data source: Met Office.

Figure 11  Schematic representation of major net sediment transport pathways in the Bristol Channel, based on information from various sources.

Figure 12  Carmarthen Bay map.

Figure 13  LiDAR DEM of western Carmarthen Bay.

Figure 14  Composite aerial photography of the Laugharne and Pendine Burrows frontage and the Taf Estuary, western Carmarthen Bay, flown in 2006. The dashed line shows the position of the dune toe or marsh edge from the first edition County Series OS Map surveyed in 1887.

Figure 15  LiDAR DEM of Laugharne and Pendine Burrows. Cross-sectional profiles are shown in Figure 16.

Figure 16  Cross-sections shown in Figure 15.

Figure 17  Historical changes in the position of the coastline, Mean High Water and Mean Low Water at Laugharne and Pendine Burrows from available Ordnance Survey maps dating from 1887, 1905, 1949 and 1970. The base map is dated 2002. The location of the shore-normal profiles used to calculate the width changes is also shown.

Figure 18  LiDAR DEM of the Three Rivers Estuary (Taf, Tywi and Gwendraeth).

Figure 19  Composite aerial photography of the Tywi and Gwendraeth Estuaries, eastern Carmarthen Bay, flown in 2006. The dashed line shows the position of the dune toe or marsh edge from the first edition County Series OS Map, surveyed in 1879.

Figure 20  Composite aerial photography of the Pembrey frontage and the adjoining Gwendraeth and Loughor Estuaries, western Carmarthen Bay, flown in 2006. The dashed line shows the position of the dune toe or marsh edge from the first edition County Series OS Map, surveyed in 1879.
Figure 21  LiDAR DEM of Pembrey Burrows

Figure 22  Cross-sections shown in Figure 21

Figure 23  Burry Inlet and the Gower Peninsula map.

Figure 24  LiDAR DEM of Burry Inlet

Figure 25  Composite aerial photography of Burry Inlet and the Loughor Estuary, western Carmarthen Bay. Flown 2005-2006. The dashed line shows the position of the dune toe or marsh edge from the first edition County Series OS Map, surveyed in 1879/1883.

Figure 26  Composite aerial photography of Whiteford Burrows and Rhossili Bay, flown in 2005. The dashed line shows the position of the dune toe or marsh edge from the first edition County Series OS Map, surveyed in 1883.

Figure 27  LiDAR DEM of Whiteford Burrows

Figure 28  Cross-sections shown in Figure 27.

Figure 29  Historical changes in the position of the coastline, Mean High Water and Mean Low Water at Whiteford Burrows from available Ordnance Survey maps dating from 1878, 1915, 1950 and 1970. The base map is dated 2002. The location of the shore-normal profiles used to calculate width changes is also shown.

Figure 30  LiDAR DEM of Rhossili Bay

Figure 31  Swansea Bay map

Figure 32  Composite aerial photography of Swansea Bay, flown in 2006. The dashed line shows the position of the dune toe or marsh edge from the first edition County Series OS Map, surveyed in 1876.

Figure 33  LiDAR DEM of Swansea Bay

Figure 34  Composite aerial photography of Margam Burrows, Kenfig Burrows, and Merthyr-mawr Warren, flown 2005-2006. The dashed line shows the position of the dune toe or marsh edge from the first edition County Series OS Map, surveyed in 1876.

Figure 35  LiDAR DEM of Kenfig Burrows

Figure 36  Cross-sections shown in Figure 35.

Figure 37  Historical changes in the position of the coastline, Mean High Water and Mean Low Water at Kenfig Burrows from available Ordnance Survey maps
dating from 1876, 1897, 1914 and 1963. The base map is dated 2002. The location of the shore-normal profiles used to calculate width changes is also shown.

Figure 38  LiDAR DEM of Porthcawl and Merthyr-mawr Warren

Figure 39  Cross-sections shown in Figure 38.

Figure 40  Historical changes in the position of the coastline, Mean High Water and Mean Low Water at Merthyr Mawr from available ordnance survey maps dating from 1877, 1897, 1934/1950 and 1966. The base map is dated 2001. The location of the shore-normal profiles used to calculate width changes is also shown.

Appendix 1  Results of Beach Profile Analysis
Coastal processes and shoreline behaviour in Swansea Bay
and Carmarthen Bay

1. Report scope and purpose

The purpose of this report is provide a review of the background geological factors and physical processes which is intended to inform the assessment of policy options in the second generation Shoreline Management Plan for the area between St. Ann's Head and Lavernock Point. Particular attention has been given to the estuaries and intervening shorelines in Swansea Bay and Carmarthen Bay.

The review has drawn on published literature, unpublished reports and new analysis of lidar data, aerial photographs and beach profile data carried out specifically for this study. This information has been used to develop a conceptual model of the past, present and likely future geomorphological development of the area.
2. Geological framework and general character of the coast

The fundamental geomorphological character of the South Wales coast is controlled by relatively resistant rock outcrops which give rise to a series of headlands, sections of cliffed coast with intertidal shore platforms, and intervening bays backed by sandy beaches, dunes and back-barrier marshes (Evans, 1995a,b). In terms of tidal energy regime, the entire open coast between St Ann's Head and Lavernock Point can be classified as a high energy environment. Wave energy regime on exposed parts of the open coast is also high, but is moderate to low in more sheltered areas. Low wave energy environments are restricted mainly to the larger estuaries, including those of the rivers Taf, Tywi, Gwendraeth and Loughor.

The geological framework is fundamentally controlled by Variscan structures which formed at the end of the Carboniferous Period (c. 290 million years ago). The Variscan Thrust front runs across the area from a point near Newport towards St Bride's Bay (Figure 1). North and south of the Thrust Front are a series of east-west trending folds and fault zones, the largest of which is a syncline whose axis runs through the centre of the South Wales Coalfield, the Burry Inlet, northern Carmarthen Bay, and south Pembrokeshire. Superimposed on this pattern is a series of NW-SE trending secondary folds and faults which are responsible for many of the main topographic features along the coast (Owen & Bridges, 1980; Price & Brooks, 1980).

The bedrock which outcrops along the coast between Milford Haven and Lavernock Point ranges in age from Silurian to Cretaceous (Figure 1). Due to regional-scale tilting there is a general transition from exposures of older rocks in the northwest to younger rocks in the southeast. Superimposed on this trend are a series of WNW - ESE trending structures which give rise to two elongate basins, the South Wales Coalfield Basin and the Bristol Channel Basin. The structures impart a general WNW-ESE strike to coastal rock outcrops. A major syncline and fault zone extends along the axis of the Bristol Channel (North, 1964; Tappin et al., 1994). South Pembrokeshire, northern Carmarthen Bay and the Gower are dominated by relatively hard rocks of Silurian to Middle Carboniferous age. Eastern Carmarthen Bay is dominated by rocks of Middle and Upper
Carboniferous age, while the coast between eastern Swansea Bay and Lavernock Point is dominated by softer rocks of Triassic to Lower Jurassic age (Evans, 1995a).

The bedrock is mantled by a patchy, generally thin cover of glacial drift and solifluction deposits (Head), most of which were deposited during the Wolstonian and Devensian, glaciations (Bowen, 1970), and by alluvial and coastal deposits of Holocene (Flandrian) age. Glacial Drift extends to the coast in relatively few places, and soft sediment cliff exposures are restricted in their occurrence (Campbell & Bowen, 1989; Howe, 2002). The valleys of South Wales owe their origin and overall form mostly to fluvial action during the Tertiary Period, but have been significantly modified by Pleistocene glaciation (Price & Brooks, 1980; Bowen, 1995). Outwash sands and gravels of Pleistocene age are of significant extent in some locations, including the northwestern part of Swansea Bay. Borehole and geophysical investigations have also indicated that outwash deposits and in situ till are present beneath the cover of Holocene marine sediments in offshore areas of Swansea Bay and elsewhere (Price & Brooks, 1980; Culver & Bull, 1980).

The hinterland is relatively high along most of the coast, areas below 10 m OD generally being restricted to the margins of the major estuaries and areas behind the larger coastal barriers. In terms of broad-scale morphology, the north coast of the Bristol Channel can be classified as a headland and bay coast. To the east of Ogmore-on-Sea, cliffs and shore platforms dominate. Between Ogmore-on-Sea and the western end of Swansea Bay, sandy beaches and dunes dominate, although large areas have been built on (Evans, 1995b). The south and western sides of the Gower Peninsula are characterised by rocky headlands and intervening small sandy bays, backed by dunes. The Burry inlet is fringed by extensive tidal flats and saltmarshes, significant parts of which have been reclaimed. The northern and eastern parts of Carmarthen Bay east of Pendine are fringed by large sandy barrier systems and back-barrier marsh areas, now mostly reclaimed. An extensive estuary system (the Three Rivers complex, comprising the Taf, Tywi and Gwendraeth) occupies the north-central part of the bay. Between Pendine and Angle at the entrance to Milford Haven the coast is mostly cliffed, with intervening pocket beaches backed by dunes. Milford Haven itself is a deep rocky inlet,
sometimes described as a ria, characterised by narrow beaches and localised areas of saltmarsh.

3. Offshore bathymetry and sea bed sediments

The Bristol Channel is relatively deep, with maximum depths of 50 - 60 m near its entrance, decreasing eastwards to about 20 - 30 m near Lavernock Point. A shallower shelf area, ranging in width from 4.5 to 20 km, extends along the northern side between the Gower Peninsula and Lavernock Point (Figure 2). Three large, east-west oriented linear sand banks (Nash Bank, Scarweather Sands and Helwick Bank) extend seawards from headlands at Nash Point, Porthcawl and Port Eynon Point, respectively (Britton & Britton, 1980; Rowlands, 1981; Schmitt et al., 2007).

Much of the floor of the Bristol Channel is relatively flat, although there are large sandwave fields south of St. Govan's Head and Carmarthen Bay. Individual sand waves are 2 - 5 km in length and have an amplitude of 10 - 20 m, with a general north - south crest orientation, transverse to the principal tidal current flow directions (Stride, 1963; Stride & Belderson, 1990).

The seabed sediments in the Outer Bristol Channel consist mainly of sands and gravelly sands, the central area is dominated by sandy gravels and muddy sandy gravels, while much of the Inner Bristol Channel sea floor is swept bare of significant sediment accumulations by strong tidal currents. Areas of slightly muddy sands occur in northern Swansea Bay (British Geological Survey, 1986; Pantin, 1991; Figure 3). The thickness of sediments exceeds 20 in some places but is generally <10 m. The coarser grained sediments are characterised by low amplitude dune forms and mega-ripples, whereas areas of medium to fine sand exhibit either higher dune forms or plane bed features, depending on the local near-bed current speeds (Harris, 1984; Collins, 1993).

Significant quantities of mud and fine sand are supplied to the Bristol Channel by the main river systems (principally the Severn), and there is additional supply from coastal
cliff erosion, but the principal source is provided by reworking of Quaternary sediments in the offshore zone.

4. Environmental controls on coastal processes

4.1 Mean sea level

Radiocarbon dating of sea level index points round the Bristol Channel, principally on the English side, has allowed the construction of a composite sea level curve for the area (Heyworth & Kidson, 1982; Shennan & Horton, 2002; Figure 4). Mean sea level rose from c. -14 m OD around 9000 years ago to c. -2 m OD around 2500 years ago. There are few data for the period after 2500 yr BP, but the available evidence suggests continuing sea level rise from 2500 yr BP to the present, albeit at a diminishing rate. The available data suggest average net relative land subsidence in the area over the last 4000 years of -0.2 to -0.5 mm/yr (Shennan & Horton, 2002), but the rate has probably declined over this period. There are no long-term tide gauge records for the area, but available data from Newlyn, Avonmouth and stations along the South Wales Coast suggest an average regional upward trend in mean sea level of the order of 2 mm/yr over the last century (Figure 5).

4.2 Tidal regime

The Bristol Channel experiences a macrotidal regime. The dominant tidal component is the lunar semi-diurnal $M_2$ component, which contributes approximately 72% of the overall tidal amplitude at Swansea (Wilding & Collins, 1980). Mean spring tidal range increases up the Bristol Channel from 6.3 m at Milford Haven to 11.2 m at Cardiff (Figure 6a, Table 1). Correspondingly, the elevation of the highest spring tides relative to Ordnance Datum (OD) increases from <3.0 m OD at Milford Haven to c. 6.5 m OD at Newport and Cardiff (Figure 7). Mean neap tidal range shows a corresponding increase from 2.7 m to 8.3 m (Figure 6b). Peak spring tidal current velocities are high in the Inner Bristol Channel (>2.4 m/s), but relatively low in Swansea Bay, Carmarthen Bay and Milford Haven (<0.5 m/s), (Figure 6c). Peak neap velocities are significantly
lower, ranging from c. 1.5 m/s in the Inner Channel off Nash Point to <0.2 m/s in Swansea Bay and Carmarthen Bay. The tidal excursion (distance travelled by a water particle on a single tide) is relatively large (10 to 22 km), but the net distance travelled is relatively small (Shaw, 1980). Ebb and flood dominance (in terms of peak and average current speeds) varies with position within the Bristol Channel. Some of the deeper parts show ebb dominance but flood dominance is characteristic over many of the shallow sub-tidal and intertidal areas.

4.3 Wind regime

The prevailing regional winds blow from the southwest, and wind speeds over the Bristol Channel can be high. However, velocities close to the coast are lower due to increased frictional drag over the land area, and there is considerable local variation in wind speed and direction due to the effects of topography and coastal orientation. Long-term wind records are rare; patchy long-term data sets exist only for Rhoose (Cardiff) and Pembrey (northeast Carmarthen Bay). Average wind speeds across the area are shown in Figure 6e & f and an average wind rose for Pembrey for the period 1994-2000 is shown in Figure 8.

4.4 Wave regime

The wave climate of the Bristol Channel is influenced both by swell waves from the Atlantic and by locally-generated wind-waves. The maximum fetch to the southwest is more than 6000 km, allowing swell generated as far away as the South Atlantic to reach the shore. Long-period swell waves occur throughout much of the year. They typically have a low H/L ratio and their overall effect is to move sediment landwards. Wind waves are more sporadic in their occurrence and are more variable in direction. They are mostly generated over a shorter fetch and tend to have a higher H/L ratio. They are frequently destructive during the winter months when breaking of steep waves erodes sediment from the upper beaches and move it seawards to form nearshore bars.

Average wave height and wave power decrease up the Bristol Channel, being greatest at the shoreline near the entrance to Milford Haven and lowest near Lavernock Point.
(Figure 6g & h). As waves approach the shore they undergo transformation due to refraction, diffraction and frictional energy dissipation. In areas where relatively deep water occurs relatively close the shore, as around many of the headlands, the waves break against the cliffs at high tide and a proportion of the wave energy is reflected. Wave reflection is also significant on the steeper beaches and those backed by hard defences. In the shallower bays and stretches of open coast with wide sandy beaches, most or all of the wave energy is dissipated before it reaches the backshore area, and there is no wave reflection. Interference between incident and reflected waves can play a significant role in offshore bar development, and may lead to the formation of edge waves which produce rhythmic three-dimensional topographic features. Where waves approach the shore obliquely, longshore sediment drift is likely to be important due both to the asymmetric nature of swash - backwash motion in the surf zone and to the generation of strong longshore currents in the nearshore zone.

No long-term measured wave data are available for inshore areas along the north coast of the Bristol Channel, although data are available for Scarweather Sands for a 12 month period in the 1970s (Fortnum & Hardcastle, 1979a) and since 2005 (Figure 9). Short-term observations along the eastern Swansea Bay shoreline have recorded extreme wave heights of >7 m, and 5 to 6 m is not uncommon during storms (Fortnum & Hardcastle, 1979b). Extreme nearshore wave heights generally decrease eastwards up the Channel. At most locations in south Wales there is a strong domination of waves of all heights from a westerly or southwesterly direction, demonstrated by wave records from the waverider buoy on Scarweather Sands (Figure 9).

4.5 Storm surges

The Bristol Channel is affected by storm surges which are generated by the passage of Atlantic depressions across the UK, and especially those which take a more southerly track across Ireland which generate strong southwesterly winds and drive water up the Bristol Channel (Lennon, 1963). Storm surges of >3.5 m have been recorded in the Severn estuary and Inner Bristol Channel, but surges in this area are generally of short duration, affecting only one tide, and surges of >1.5 m rarely coincide with high spring tides (Proctor & Flather, 1989). The most serious tidal flooding event on record
occurred on 30th January 1607. Devastation was most severe along the Welsh side of
the Channel between Laugharne and Chepstow, and an estimated 2000 people were
killed. It has been suggested that this event could have been a tsunami (Bryant &
Haslett, 2002; Haslett & Bryant, 2004), but analysis of tidal predictions and
documentary evidence of meteorological conditions around the time suggests it is much
more likely that the flooding was due the coincidence of storm surge and a high spring
tide (Horsburgh & Horritt, 2006; Risk Management Solutions, 2007).

4.6 Temperature, rainfall and freshwater input

The climate of the area can be classified as transitional between full maritime and
continental (Sumner, 1997). Average monthly maximum and minimum temperatures at
Cardiff (Rhoose) and Tenby for the period 1971-2000 are shown in Figures 10a & b.
Monthly maximum temperatures at Cardiff are 1 to 2.5°C higher than at Tenby, while
the monthly minimum temperatures are about 1°C higher at Cardiff.

Mean annual rainfall on the South Wales coast is moderate (900 - 1250 mm) but
increases inland over the higher ground (1250 - 2500 mm; Sumner, 1997). Significant
rainfall occurs throughout the year but principally in the months of December to March.
The average monthly rainfall and number of rain days at Cardiff and Tenby over the
period 1971-2000 are shown in Figures 10c & d.

There is a large freshwater input from the River Severn, whose catchment covers a large
part of central Wales and the border counties of England. The combined freshwater
input from the Rivers Wye, Usk, Rhymney, Neath, Tawe, Afan, Loughor, Taf, Tywi,
Gwendraeth and Cleddau is also significant. The effect is to significantly lower the
salinity in the eastern and northern Bristol Channel, especially during periods of high
winter flow. Partial stratification of the water column can develop periodically in the
Severn Estuary Inner Bristol Channel, with implications for fine sediment transport.
Average maximum surface water salinities in winter vary from c. 35 per mil in the outer
Bristol Channel to <20 per mil at the landward limit of the Inner Bristol Channel and
Severn Estuary. Average salinities in summer are slightly higher within the Central and
Inner Bristol Channel and Severn Estuary. Average sea surface temperatures vary from a minimum of c. 5°C in February to a maximum of c. 19°C in August.

4.7 Sediment transport

Marine sediment transport pathways and transport rates in the area are governed by a combination of currents and wave action. The overall pattern of residual water circulation in the area is determined by a combination of tidal action, wind drift, gravitation forces associated with the Coriolis effect, and density differences due to salinity, temperature and sediment loading. There is significant short to medium term variability and a complex spatial pattern. However, the general pattern is one of easterly residual depth-averaged flow along the coast between Carmarthen Bay and Nash Point, and net westward depth-average flow in the centre of the Bristol Channel (Hamilton, 1973; Heathershaw & Hammond, 1980a; Uncles, 1982; Collins & Ferentinou, 1984).

Studies of seabed sandwave morphology and modelling of tidal currents and near-bed sediment transport have suggested the presence of a major bedload sediment parting zone in the deeper parts of the Inner Bristol Channel (Pingree & Griffiths, 1979; Stride & Belderson, 1991). However, other evidence indicates a net landward movement of near-bottom sediment drift in the shallower water closer to the coast (Barrie, 1980; Hamilton et al., 1980; Collins & Ferentinou, 1984; Harris, 1984; Harris & Collins, 1985, 1991; McLaren et al., 1993; Cooper & McLaren, 2007).

Finer grained suspended sediments can either move landwards or seawards, depending on the water depth and particular combinations of tide and wind conditions (Culver & Banner, 1979; Culver, 1980a; Collins, 1983, 1989). Owing to the strong tidal currents, suspended sediment concentrations remain high, and the quantity of sediment in suspension at any time has been estimated to be approximately equivalent to 3 or 4 years of annual river sediment supply (Collins, 1983). In more sheltered shallow water areas deposition and re-suspension of mud is strongly influenced by wind and wave conditions (Parker & Kirby, 1981, 1982).
A conceptual model of the regional sediment transport regime, based on a synthesis of available published and unpublished information, is shown in Figure 11.

4.8 Human impacts

The morphology and sediment transport regime along the South Wales coast and neighbouring parts of the Bristol Channel have been influenced by several human activities, including land reclamation, port and harbour construction, dredging and the construction of hard defences in several areas.

Dredging for aggregate extraction within the SMP area has taken place mainly at Culver Sands in the Inner Bristol Channel, at Nash Bank near the eastern limit of the Central Bristol Channel, and at Helwick Bank in the eastern part of the Outer Bristol Channel (Figure 3). The main areas of dredge spoil dumping, principally of material derived from navigation approach channels to Barry, Port Talbot, Swansea and Milford Haven, have been to the west of Nash Bank and to the south of St Ann's Head.

The principal areas of harbour development in the area are at Barry, Port Talbot, Swansea, Pembroke and Milford Haven. In each of these areas land has been claimed from the sea by construction of areas of made ground, breakwaters, and wharfs. Burry Port is an area with potential for significant redevelopment as it is part of the Carmarthenshire County Council regeneration area. Significant areas of former marshland have also been claimed for agricultural, urban and industrial development around the major estuaries, notably on the eastern and northern sides of the Burry Inlet around Llanelli and Burry Port, and in the Three Rivers area of Carmarthen Bay. Hard coastal defences have been built along most of the urban frontages, including Barry, Porthcawl, Aberavon to Baglan, Swansea to Mumbles, Llanelli and around Tenby.

Futurecoast (Halcrow, 2002) divided the Swansea Bay and Carmarthen Bay SMP II study area into three Coastal Behaviour Systems (CBSs):

(1) Bristol Channel North (Penarth to Worm's Head)
(2) Carmarthen Bay (Worms Head to Giltar Point)
Within these Coastal Behaviour Systems a number of Shoreline Behaviour Units (SBUs) were identified:

1. Penarth to Nash Point  
2. Nash Point to Porthcawl  
3. Porthcawl to Mumbles Head  
4. Mumbles Head to Worms Head  
5. Worms Head to Burry Holms  
6. Burry Holms to Pendine  
7. Pendine to Giltar Point  
8. Giltar Point to Studdock Point

A number of smaller-scale Geomorphological Units (GUs) were also defined within each Shoreline Behaviour Unit. However, the Burry Inlet (Loughor Estuary), Three Rivers complex (Taf-Tywi-Gwendraeth) and Milford Haven estuaries were not included in the study.

In the following sections this framework is broadly followed to present a more detailed discussion of the geomorphological character and evolutionary trends. Particular attention is given to the soft sediment-dominated shorelines of Carmarthen Bay and Swansea Bay, including the Burry Inlet and the Three-Rivers Estuary Complex.
5.0 Shoreline evolution and morphology

5.1 Giltar Point to Pendine

Carmarthen Bay is a relatively wide (50km), shallow (0 to 20 m) embayment which is bounded by Giltar Point and Caldey Island in the west and by the Gower Peninsula in the east (Figure 12). The western side of the Bay is characterised mainly by rocky cliffs and small bays which contain pocket beaches, but the northeastern and eastern sides are dominated by large estuaries and associated sand barrier systems.

Giltar Point and the area of high ground on which Tenby is situated are composed of Carboniferous Limestone outcrops. Between the two promontories lies Tenby South Beach which is backed by a 50 - 300 m wide dune barrier and the Tenby to Pembroke railway line. Behind the South Beach dune barrier is a significant area of low-lying land which represents the former estuary of the River Ritec (Figure 13). The mouth of the estuary was blocked off during construction of the railway line in the mid 19th century and the river was diverted through a culvert. Significant accretion of beach and dune sediment occurred after that time, forming a much larger belt of dunes. Until the early 1990s the dunes were subject to heavy visitor pressure and exhibited a number of large blowouts. Loss of windblown sand inland led to lowering of the upper beach and erosion of the dune toe by waves during storm tides. Gabions and localised rock revetment were emplaced in at attempt to limit erosion, and a policy of dune management, including marram planting, fencing and boardwalks, was implemented in the 1990s. Since that time the seaward dunes have become largely stabilized and the old coastal defence structures have been buried by sand. However, the dune belt remains relatively low at the Giltar Point end of the barrier, where part of the more landward dune area is occupied by Tenby Golf Club and the rifle range.

South Beach faces southeast and is strongly influenced by wave refraction and diffraction around Caldey Island and Woolhouse Rocks. It is relatively wide and flat and effectively swash aligned. Sediment transport occurs mainly in an onshore-offshore direction; offshore sand movement is relatively infrequent and associated mainly with
occasional storms from the east and southeast. Under such conditions sediment may also move along the beach from Tenby towards Giltar Point. However, the intertidal beach which fronts the cliffs between South Beach and St Catharine’s Island is a relatively stable feature. Evidence from historical maps and air photographs indicates there has been only limited morphological change over the past century and the frontage has a relatively low sensitivity to changes in environmental forcing factors.

Analysis of beach profile data for the period 1999-2008 showed that South Beach has experienced only relatively limited variability in levels and form over the past decade (see data and figures in Appendix 1), and there has been little net change in the position of mean high water spring (MHWS) and highest astronomical tide (HAT). The positions of the mean high water neap (MHWN) and mean low water neap (MLWN) elevation contours have shown a variable pattern of landward and seaward advance at different profile positions, but the overall net change in the width and slope of the mid beach has been small (see Table 3 in Appendix 1).

Under a ‘business as usual’ scenario (i.e. with present levels of management intervention and a similar rate of sea level rise to present) the position of the dune toe is considered unlikely to show a major change in the next 20 years but will show an increasing tendency for landward recession on 20 - 50 and 50 - 100 year timescales, since supplies of new sediment are limited. Under a scenario of ‘no active intervention’, blowouts are likely to develop in the frontal dunes due to visitor pressure on a timescale of 0 - 20 years, and dune toe recession is likely to be more rapid over 20 - 50 and 50 - 100 year timescales. If sea level rise accelerates significantly (i.e. approaches or exceeds a total of 1 m by the end of the century), dune toe erosion and the risk of breaching at the southern end of the barrier will increase. However, if it is allowed to roll back the dune barrier is likely to maintain its integrity and continue to provide an effective tidal flood defence. The beach fronting the cliffs at Tenby will be unable to roll back and may lose sediment volume due to increased wave reflection, but a significant increase in the rate of cliff erosion is unlikely.

Between Tenby and Monkstone Point the coast consists of a crenulated cliff-line cut into Millstone Grit and Lower Coal Measures. Behind Tenby North Beach the cliff toe
is protected by hard defences fronted by a wide intertidal beach. Between North Beach and Monkstone Point the cliffs are fronted by alternating intertidal rock platforms and narrow stretches of sandy beach. The cliffs are mostly stable and historically have shown only low rates of retreat. Beach levels and positions in this area have shown some temporal and spatial variability over the past decade, but little significant net change (Appendix 1). It is unlikely that there will be a significant increase in cliff recession rates over the next 100 years although there may be localised erosion if sections of the defences fail.

Between Monkstone Point and Pendine the coast is also mostly cliffed with alternating intertidal sandy beaches and rocky shore platforms. There are small barrier beach systems at locations where the cliffs are broken by small coastal valleys, as at Saundersfoot, Pleasant Valley and Amroth (Figure 13). Bedrock promontories at Coppet Hall Point, Telpyn Point, Ragwen Point and Gilman Point act as hard points which control the form and position of the intervening pocket beaches. There are also lengths of hard defences at Saundersfoot, Wiseman's Bridge and Amroth. The beach profile data (Appendix 1) show that at most profile locations the position of the MHWS contour has moved landward over the period 1999-2008 (most notably at Monkstone Point North and Summerhill). The central part of the beach between the MHWN and MLWN levels has also shown a tendency for steepening at most profile locations.

There is limited opportunity for the beaches to move landward where they are backed by natural cliffs or man-made defences, and under conditions of rising sea level some further steepening and/or loss of beach volume is likely at these locations over coming decades. However, it is unlikely that there will be any major increase in cliff erosion rates over the next 20, 50 or 100 years, even if there is a rise in sea level of up to 1m, since the cliffs are mainly composed of relatively resistant lithologies. If current defences are maintained the risk of flooding due to over-topping and/or breach-type failure may be expected to increase. If the defences are not maintained they can be expected to fail over the next 100 years, resulting in high tide flooding of the areas of low-lying land behind. Where not effectively constrained by defences, the sand and gravel beaches will show a tendency to roll landwards.
5.2 Pendine to Ginst Point

The coast to the east of Pendine (Figure 14) consists of a large (10 km long, 0.5 to 1 km wide) barrier spit complex which developed over the course of the later Holocene as a result of net sediment drift from the west. The inner part of the western end of the dune-capped barrier system (Pendine Burrows) overlies glacial deposits and probably began to form around the time sea level reached its present position around 5500 years BP (Walley, 1996). This area consists of a series of irregular hummock dunes and parabolic dunes which attain a height of > 20 m OD in places (Figure 15). The inner part of the eastern half of the system (Laugharne Burrows) is younger and may have formed in the later Holocene on a detached sand bank separated from Pendine Burrows by a tidal channel. This channel (the Witchett Inlet) was progressively blocked off from the 17th century onwards as the land behind the barriers was reclaimed. Since that time new dune ridges have developed along the entire length of the Pendine - Laugharne frontage.

Behind the dune barrier is an extensive area of reclaimed marshland up to 2 km wide, behind which lies a degraded fossil cliff cut into Lower Old Red Sandstone. The marshes have evolved over the past 5000 years in response to the development of the barrier system. Tidal flooding of the eastern end of Laugharne East Marsh, north of Ginst Point, is now prevented by a low ridge of dunes and an earth embankment, seaward of which lies active saltmarsh.

The first sea banks were constructed as early as 1660AD across the Witchett Inlet and between Sir John's Hill and the eastern end of Laugharne Burrows (Walley, 1996). The Lower Marsh was embanked in the late 18th century and further embanking of tidal creeks occurred in the 19th century. The resulting loss in tidal prism encouraged sediment accumulation within the Taf estuary and further eastward extension of the barrier system at the estuary mouth (Bristow & Pile, 2003).

Analysis of historical maps and charts by Pye & Saye (2005) indicated seaward movement of the dune toe along most of the Pendine - Laugharne frontage between 1887 and 1970, except near Ginst Point (Figure 16). Progradation increased from west to east and was particularly rapid at Laugharne Burrows between 1905 and 1970. Since
that time there has been variable accretion and erosion along the central and eastern ends of the system and a tendency for net erosion at the western end of the system.

Pendine village is protected by hard defences, but erosion affects the dunes immediately beyond the eastern limit of the defences. Erosion of the dune frontage in the late 1960s and 1970s prompted the Ministry of Defence to undertake dune creation works and place rock armour in several areas (e.g. Colquhuon, 1968). The lengths of rock armour now act as hard points which strongly influence the behaviour of the adjoining sections of unprotected shoreline. Ginst Point continues to be a dynamic area with continued growth of spit recurves into the entrance of the Taf estuary (Figures 15 & 16).

The present beach at Pendine and Laugharne is wide (1 to 1.5 km), relatively flat, and composed of medium to fine, well sorted sand. It experiences a relatively high wave energy regime and significant easterly longshore currents (Jago & Hardisty, 1984). The beach system as a whole can be classified as a high energy dissipative system.

Analysis of the beach profile data (Appendix 1) showed a net landward movement of the MHWS contour at most profiles along the Pendine - Laugharne frontage between 1999 and 2008. Slight landward movement of the HAT contour also occurred at most profiles, related to dune toe erosion, although recession was prevented or limited in areas where defences are present (e.g. near Pendine village). Further to the east up to 40 m of frontal dune erosion occurred during the period (Profiles 33, 34 and 36). Along the Laugharne Burrows part of the barrier, the pattern and rate of dune toe erosion has been more variable, reflecting the local influence of slipways and rock armour placed by the Ministry of Defence.

Under a ‘business as usual’ scenario (i.e. with present management, slowly rising sea level and no large-scale input of new sand to the system) there is likely to be continued slow loss of upper beach volume near Pendine village and erosional pressure on the dune toe will increase along most of the dune frontage. However, the present of hard defences, rock armour bastions and lengths of rock revetment will continue to slow the overall rate of dune recession. Shallow embayments are likely to develop between the
hard points. These will act to funnel wind blown sand and transgressive dunes or sand sheets may develop behind these areas.

Under a scenario of ‘no active intervention’ the coastal defences features will deteriorate on a 50 – 100 year timescale but are likely to continue to play a role in holding the position of the shoreline. A major breach in the dunes, leading to flooding of extensive areas behind, is considered unlikely, even if there is a significant increase in the rate of sea level rise, since the dunes are relatively wide and high (Figure 17). However, without maintenance to the flood banks between Ginst Point and Laugharne, the risk of flooding to the East and West Marsh areas will significantly increase, and in the event of a permanent breach parts of the reclaimed marsh area are likely to revert to active saltmarsh.

With or without management, further sediment accretion is likely to occur in the Ginst Point area as sediment is transported eastwards along the shoreline by waves and longshore currents. Repeat topographic surveys over the past 10 years have shown very rapid accretion in this area (Figures A1 and A4 in Appendix 1), and this process is likely to continue, although the position of the end of the spit is likely to move north-eastwards over time.

5.3 Ginst Point to Tywyn Point (Three Rivers Estuarine Complex)

The Three Rivers Estuarine Complex comprises the estuaries of the Afon Taf, Tywi and Gwendraeth. The western outer limit is defined by Ginst Point and the eastern outer limit by Tywyn Point (Figures 18 & 19). The main physical characteristics of the three estuaries are compared with each other, and with the Burry Inlet (Loughor Estuary), in Table 2.

The Afon Taf enters the sea via a glacially over-deepened valley cut into Old Red Sandstone. The valley is partially filled with glacial drift and post-glacial alluvium. The low water channel presently lies on the eastern side of the estuary mouth, close to a
steep slope formed of Old Red Sandstone which terminates at Wharley Point. To the east of this promontory lies the estuary of the Afon Tywi which occupies a similar glacially-modified valley cut into the Old Red Sandstone. Near the estuary mouth parts of the bedrock are mantled by glacial drift. Reworking of these deposits by wave and current action in the intertidal zone has formed boulder lags (St Ishmael's Scar, Salmon Point Scar and Pastoun Scar) at the confluence of the Tywi and Gwendraeth estuaries. Elsewhere the intertidal zone at the mouth of the three estuaries is dominated by medium sand (Jago, 1980). To landward of the boulder scars is a narrow belt of dunes backed by a low-lying area of till and alluvium. These deposits represent a small barrier spit and back-barrier marsh area which has formed by NW-SE sediment drift into the mouth of the Gwendraeth estuary. Part of this area is now occupied by the Carmarthen Bay Holiday Centre and a caravan park.

The Afon Taf is tidal as far upstream as the outskirts of St. Clears. Parts of the meandering tidal channel abut bedrock slopes while others are fringed by fresh to brackish marsh, in places offered partial protection from flooding by earth embankments. Significant areas of saltmarsh are restricted to the estuary downstream of the Afon Taf - Afon Cywyn confluence. Between this point and Laugharne new marsh has developed in recent decades to seawards of the older established marshes, mainly as a consequence of the introduction and spread of Spartina (Bristow & Pile, 2003).

Analysis of historical maps and OS Landline data allowed Bristow & Pile (2003) to identify changes in the position and morphology of the tidal channels over the period since 1876. The normal tidal limit was found to have moved upstream by 368 m, but little change in channel position was identified in the upper estuary. In parts of the mid and lower estuary reductions in channel width and position were identified, associated with spread of saltmarsh and a reduction in overall sinuosity. This is opposite to the expected effects associated with rising sea level, and indicates that sediment accretion in the Taf estuary has so far been able to outpace the effects of sea level rise.

The Afon Tywi has a relatively large freshwater discharge compared with the Taf and Gwendraeth. The river is tidal as far as a point approximately 3 km upstream of Carmarthen. The central part of the estuary is confined between steep slopes cut into
bedrock, and by the Llanelli to Carmarthen railway line, but the upper estuary widens out to form a wide floodplain near Carmarthen. In this area the tidal river is confined by low flood banks, on either side of which are freshwater grazing marshes (Figure 19). Active saltmarsh occurs mainly in the lower estuary but is relatively restricted in extent compared with the total intertidal area. There has apparently been little change in the position and sinuosity of the main river channel between 1876 and 2000 (Jones, 1977; Bristow & Pile, 2003).

The Gwendraeth estuary is fed by two small rivers, the Gwendraeth Fach which flows through Kidwelly and the Gwendraeth Fawr which flows eastwards to the south of Kidwelly. The Gwendraeth Fawr is today little more than a stream which is tidal only below Commissioner's Bridge, south of Kidwelly. The Gwendraeth Fach is somewhat larger and is tidal as far as the A484 north of Kidwelly. The intertidal area of the estuary was formerly much larger but became restricted following the construction of the Llanelli to Carmarthen railway line and development of the A484 as a main highway. Large areas of the former estuary west of the railway line were also embanked and reclaimed in the early to mid 19th century and the area was used for many years as an airfield (RAF Pembrey). The entrance to the estuary has been progressively constricted over the past 120 years by the northward growth of the Tywyn Point spit (Figures 20 & 21). As a consequence of these changes, the tidal prism and associated tidal current velocities were reduced and sedimentation within the remaining area of active outer estuary was enhanced, leading to significant expansion of saltmarsh (Bristow & Pile, 2003).

Bristow & Pile (2003) reported a downstream shift in the normal tidal limit of 60.3 m and an increase in the channel sinuosity of the Gwendraeth Fawr between 1876 and 2000. They suggested this may have been a consequence of canalisation in the upstream reach of the river.

Hydrodynamic modelling reported by BMT Ceemaid (1986, 1987, 1989), Barber & Thomas (1989) and Posford-Duvivier and ABP (2000) indicated a small residual ebb flow in all three estuaries. Based on sediment grain size trend analysis, Posford Duvivier and ABP (2000) also concluded that there is net sediment transport out of the
Taf and the Tywi but net import into the Gwendraeth estuary. Based on this methodology, a complex sediment circulation pattern within Carmarthen Bay was suggested, involving radiating sediment transport pathways which emanate from three major sediment parting zones in Carmarthen Bay and three major meeting zones. It was suggested that extreme events are required to load the parting zones with sediment, following which regular transport processes produce the observed patterns of transport (Posford Duvivier & ABP, 2000; Cooper & McLaren, 2007). It was also suggested that extreme events are responsible for dispersing sediment from the convergence zones, and that the existence of the parting and convergence zones may be related to resonance features produced by the prevailing hydrodynamics (tidal, wave and wind-driven) in the Bristol Channel as a whole. It was concluded that there is little modern day input of sediment to Carmarthen Bay from rivers or from offshore, although there is apparently some supply from the Bristol Channel around Helwick Bank; the Bay therefore acts almost as a closed system, with recycling of sediments already in the bay during and following major storm events. However, these suggestions have not been confirmed by independent methods.

Repeated topographic surveys by Jago (1980) indicated that the Taf estuary is experiencing net vertical sediment accretion at a rate of 0.13 m/yr. Short term process studies by Ishak (1997) also indicated that net flood-tide directed transport of suspended sediment in the Taf is 10-30% greater than the net ebb transport, which translates into a vertical accretion rate of 1.2 to 1.6 cm/yr. Vertical sedimentation rates on active saltmarshes within the Taf were also found to range from 0.4 to 1.7 cm/yr. Mineral magnetic studies of the Gwendraeth estuary sediments (Booth, 2002; Booth et al., 2005) suggested Carmarthen Bay as the dominant source of sediment (c. 77%), but that contributions from land-based sources via the Gwendraeth Fach and Gwendraeth Fawr are also significant (13% and 10%, respectively). Bristow & Pile (2003) reported from an analysis of historical map evidence that the combined area of the Three Rivers estuarine complex at MHW level decreased from 2080 ha in 1876 to 1787 ha in 2000. The largest reduction in area occurred in the Taf estuary, followed by the Gwendraeth estuary, although only a slight reduction was found in the Tywi estuary. The balance of evidence therefore suggests that the Taf and Gwendraeth are significant net sediment sinks at the present time, while the Tywi is closer to a net sediment balance.
Beach profiles 37 - 44 within the Tywi estuary show variable movements in the position of MHWS over the period 1999-2008, although there was significant progradation at Ferryside (profile 44 near the mouth of the estuary). Slight net progradation was also recorded on the north shore of the Gwendraeth estuary.

Over the next 100 years it is likely that the onshore movement of sediment from Carmarthen Bay into the estuaries will continue, driven by rising sea level, wave processes, and long-shore drifting from the spits on either side of the Three Rivers system. Sediment accretion within the estuaries is likely to keep pace with sea level rise, even if the rate of rise increases significantly, although landward transfer of sediment from the outer parts of the estuaries towards the inner parts is likely as the estuary forms tend to 'rollover' in the landward direction. Further marsh expansion and vertical growth can be anticipated in some areas, providing greater protection for flood defences within the estuaries. However, there is likely to be an increasing risk from overtopping during periods of extreme high water level, and of flooding due to localised breaching if defences are not maintained. The tidal limits on the Afon Taf and Afon Tywi are likely to move landwards by several hundred metres and some bank erosion can be expected as tidal meanders migrate upstream and possibly develop greater sinuosity. This will create a greater risk of toe erosion along some sections of embankment near the estuary heads.

5.4 Tywyn Point to Burry Port

The western side of the Gwendraeth estuary is protected from wave action by a broad (1-2 km) belt of sand dunes, parts of which are used as a firing range and as forestry plantations. These dunes form part of a large barrier system which extends some 10 km south-eastwards to Burry Port on the northern side of the Burry Inlet. To the west of Pembrey village the belt of wind blown sands is almost 3 km wide and is fronted by a wide sandy beach (Figures 21 & 22). Much of the area is now part of Pembrey Forest but the southern area, once the location of a Royal Ordnance factory, is now occupied by Pembrey Country Park.
The age and stratigraphy of the Pembrey dune complex have not been investigated in detail, but interpretation of lidar digital elevation models and aerial photographs of the area suggest that the dune system may have originated on an emergent offshore bank during the Little Ice Age (c.1300 - 1600 AD) and subsequently grew both seawards and alongshore due to accretion of sand supplied from the floor of Carmarthen Bay.

The northern end of the Pembrey Forest frontage has been eroding for several decades. Hydrodynamic modelling results (Barber & Thomas, 1989) suggested that the change from accretion to erosion in this area may have been caused by changes in the bathymetry in neighbouring Carmarthen Bay, although changes in wind/wave regime may also have played a role.

The beach monitoring data (Appendix 1) show that dune erosion and landward movement of HAT continued along the northern part of the Pembrey Forest frontage between 1999 and 2008, but there was continued seawards accretion near Tywyn Point (Figures A2 and A4 in Appendix 1). Accretion also occurred on the central part of the Pembrey Forest frontage at profiles 49 to 52 over this period. Net erosion occurred along the north-central part of the Pembrey Country Park frontage, with further marked accretion between the southern end of the Country Park and Burry Port. The tendency for erosion along the Country Park frontage has undoubtedly been exacerbated by visitor pressure around the main beach access points, although this is unlikely to be the only cause.

Until the early 19th century Burry Port lay on the open coast, but since that time it has been cut of from the sea by south-eastward growth of a larger multiple spit system to the south of Pembrey village. At Pembrey Burrows there has been more than 1 km of progradation since the late 19th century (Figure 21), much of it in the last 30 years (May, 2003a). The beach monitoring data show that beach levels have continued to rise in this area over the past decade, with development of new foredune ridges and back-barrier depressions (Figures A3 and A4 in Appendix 1). Accretion in the area between Pembrey and Burry Port over the last century has been encouraged by the building of Pembrey Harbour and the Burry Port Outer Harbour, by the construction of the Burry
Port to Kidwelly railway line, and by the south-eastward longshore drifting of sediment from the Pembrey Forest frontage.

Under a ‘business as usual’ scenario, and in the absence of significant changes in the offshore bathymetry or rate of sediment supply from offshore, the north-central part of the Pembrey barrier is likely to continue to erode slowly. Longshore drift to the north and south will continue at a relatively slow rate, with further accretion likely at Tywyn Point and between Pembrey Country Park and Burry Port. If the rock armour buttresses on the north-central part of the Pembrey Forest frontage are not maintained, their effectiveness is likely to diminish over time, leading to slightly higher rates of erosion along this part of the frontage and higher rates of accretion at the extremities. Owing to the great width and height of the barrier there is a very low risk of breaching or storm tide overtopping over the next 100 years.

Amongst the biggest uncertainties are the potential effects of possible changes in the bathymetry of Carmarthen Bay, in average wind-wave conditions, and in the frequency and magnitude of major storms. While an increase in the frequency of moderate storm events may lead to further beach and dune erosion on exposed sections of the coast along the central part of the barrier, increased incidence of major storms could increase the transfer of sandy sediment from the deeper parts of Carmarthen Bay, below normal wave base, towards the coast. Previous studies have suggested that major storms are the main mechanism by which sediment is transported into Carmarthen Bay from deeper water, while smaller magnitude events are responsible for re-distributing the sediment in nearshore and intertidal areas (Posford Duvivier & ABP Research, 2000; Cooper & McLaren, 2007).

5.5 Burry Inlet

The Burry Inlet (Figure 23) is a large (area c. 45 km$^2$), shallow inlet, lying on the north side of the Gower Peninsula, which owes its origin partly to structural control and partly to selective erosion of weaker Lower Coal Measures strata on the southern side of the South Wales coalfield basin. The basic form of the Burry Inlet was probably established by weathering and fluvial erosion in Tertiary times, but the ancestral valley of the River
Loughor was significantly modified by ice action during the Pleistocene. The areas may have been influenced by Irish Sea ice moving up the Bristol Channel during the Wolstonian glaciation, but during the Devensian glaciation Welsh ice descending from the north and northeast occupied the area (Bowen, 1970, 1995). The line of maximum Devensian ice extent lay NW - SE across the Gower Peninsula, passing through the Hills Tor area and across Carmarthen Bay towards Saundersfoot. Following the retreat of the ice, Carmarthen Bay was progressively flooded by the sea which reached its maximum inland extent around 5500 years ago (Bridges, 1977a; Carling, 1978; Culver, 1980b). Since that time the Inlet has been progressively infilled by sand derived mainly from Carmarthen Bay, and in a few more sheltered areas by mud derived both from the Bristol Channel and the rivers which enter the Inlet.

The southern side of the Inlet was at one time formed by steep coastal slopes, locally cliffed, extending between Hills Tor, Llanrhiddian and eastwards to Gowerton. A barrier beach and dune system (Whiteford Burrows), linking Hills Tor with a glacial drift scar at Whiteford Point, has developed during the later part of the Holocene, restricting the mouth of the Inlet and encouraging the development of Landimore Marsh and Llanrhiddian Marsh (Figure 24).

The northern side of the Inlet was formerly defined approximately by the 7 m OD contour, but there has been extensive reclamation along the shore between Burry Port and the Loughor Bridge over the last 150 years. According to Plummer (1960), some 1800 ha on the north side of the estuary had been reclaimed for industrial purposes by 1850. Reclamation has been less extensive on the south side of the estuary, although Cwm Ivy Marsh in the lee of Whiteford Burrows was reclaimed for agriculture in the 17th century (Kay & Rojanihipart, 1977). It is now considerably lower than the active marsh on the outside of the sea wall. There were also significant reclamations around the head of the estuary east of Loughor and Gowerton in the 18th and 19th centuries (Plummer, 1960).

*Spartina anglica* was introduced to Landimore Marsh in 1935 and has since spread throughout the estuary (Bridges, 1977b; Figure 25).
Two principal rivers enter the head of the Inlet. The largest is the River Loughor (Afon Llwchwr) which joins the Inlet from the north at Loughor Bridge. The Loughor is tidal as far as Pontarddulais, approximately 6km from the Loughor Bridge. According to Bristow & Pile (2003), the tidal limit moved 302 m downstream between 1876 and 2000. On the east side of the Loughor estuary the limit of high water spring tides is formed mostly by naturally rising ground, but on the west side the Llanelli to Ponterddulais railway lines forms an artificial limit. There are extensive areas of high saltmarsh and brackish marsh on both sides of the estuary, much of which remains un-embanked. The lower intertidal zone is mostly sandy except near the head of the estuary.

Approximately 2 km to the southeast of the Loughor Bridge, the Inlet is joined by the Afon Llwi / Afon Llan river system at Island Bridge, which forms the present normal tidal limit. Extensive salt and brackish marshes occupy the southeast corner of the Inlet between Loughor, Gowerton and Crofty (Plummer, 1960). The combined average freshwater input (c. 1.10 x 10^3 m^3 per tide) is small compared with the tidal flushing volume (c. 1.40 x 10^9 m^3 on springs and 1.04 x 10^9 m^3 on neap tides; Moore, 1976).

Both the tidal area at MHW and the tidal prism of the Burry Inlet are much larger than that of the Three Rivers estuaries, despite a reduction in area from 8254 ha in 1876 to 7060 ha in 2000 (Bristow & Pile, 2003; Table 2). Modelling by BMT Ceemaid (1989) and Posford-Duvier & ABP (2000) suggested a small residual ebb flow from the Inlet, and other studies have indicated increasing ebb current dominance in the main channel upstream from the mouth (Moore, 1976). However, field measurements in the small channels and over the intertidal flat areas have indicated flood dominance, with surface flood and ebb velocities of 0.9 m/s and 0.7 m/s on neap tides and 1.7 m/s and 1.2 m/s on spring tides (Elliot & Gardiner, 1981; Carling, 1981).

Salinity characteristics (Moore, 1976) indicate that the estuary is relatively well mixed, with only minor freshwater input (4-5 x 10m^3/day) relative to the tidal exchange volume. The sediments of the intertidal flats and saltmarshes are predominantly fine sands (modal size 125 um), and muddy sedimentary facies are poorly developed (Carling, 1981). The presence of abundant sponge spicules, shell fragments and echinoderm spines amongst a predominantly quartzose sand indicates the predominant
sediment source is marine reworking of fluvio-glacial and glacial sediments on the floor of Carmarthen Bay (Bridges, 1976a).

To seaward of the estuary mouth is a well-developed ebb-tidal delta composed of medium to fine sand, and the area just inside the mouth shows many of the characteristics of a flood tidal delta (Elliott & Gardiner, 1981). The entire estuary is tidally dominated. Waves approach the estuary mouth from Cardigan Bay but their energy is mostly dissipated by the ebb tidal delta. The few long-period waves which enter the estuary break on the most seaward bars. Within the mid and inner estuary the wave regime is dominated by short-period internally-generated wind waves. The sandy intertidal flats are dominated by megaripples and sandwaves produced by the flood and ebb tidal currents (Elliot & Gardiner, 1981; Figure 25).

The tidal curve is generally symmetrical near the mouth but becomes progressively more asymmetrical towards the head; the asymmetry is accentuated on spring tides. Maximum flood and ebb tidal current velocities occur approximately mid way between low and high water (Moore, 1976), which is characteristic of a standing tidal wave (Dyer, 1973). Towards the head of the estuary the tidal wave is modified slightly and takes on characteristics of a progressive wave, with the ebb tide much longer than the flood. The spring tidal length of the estuary from mouth to tidal limit is approximately 16 km. There is some evidence that the main low water channels are flood dominated in terms of maximum velocities, while the secondary channels are ebb dominated (Moore, 1976).

Based on sediment trend analysis, Posford Duvivier & ABP (2000) and Cooper & McLaren (2007) suggested there is an active sediment transport pathway from eastern Carmarthen Bay into the Burry Inlet, although the flux was not quantified. Cramp et al. (1995) reported that net sediment flux within the Burry Inlet is almost zero, but comparison of historical map data led Bristow & Pile (2003) to conclude a net reduction in area of the Inlet from 8254 ha in 1876 to 7060 ha in 2000. A significant part of this reduction can be explained by land claim, but map, chart and aerial photographs also provide clear evidence of significant vertical accretion and saltmarsh spread, particularly along the southern side of the Burry Inlet.
The channels and intertidal sand banks of the Burry Inlet have historically been highly mobile, and the channel pattern has changed considerably since 1830 due both to natural processes and human interventions (BMT Ceemaid, 1990; Cramp et al., 1995). In 1882 a training wall was built across the main channel of that time to direct the flow along the northern side of the Inlet and to maintain a navigation channel into Llanelli docks and Burry Port docks. The wall was extended in 1918 to further restrict the flow. This encouraged sediment accretion on the southern side of the estuary and was a major factor contributing to the spread of saltmarsh at Llandrhiiddian (Plummer, 1960; Pye & French, 1993). The wall was breached and repaired on a number of occasions between 1935 and 1945, but during World War II it fell into disrepair. Serious breaches occurred in 1951 and 1965 and were not subsequently repaired (BMT Ceemaid, 1990). As a result of these breaches, the main low water channel has moved back towards the centre of the estuary and now flows through the training wall. The channel leading to Llanelli docks has remained but moved landwards during the 1980s, causing steepening of the beach and threatening to undermine the seawall behind. Collapses of the wall occurred in two places during storms in the 1990s. Following these events a series of rock breakwaters was constructed to keep the channel away from the shore.

The Burry Inlet is still adjusting following significant human interventions over the last 200 years. The tidal channel system is currently re-establishing a higher degree of dynamic behaviour following the breakdown and abandonment of the channel training walls, but in recent decades the estuary has continued to show a tendency to import sediment, leading to a continuing reduction in tidal volume and marsh growth along the southern side. It is likely that this trend will continue over the next 50 – 100 years, although probably at a reduced rate, due to the combined effects of sea level rise and an overall flood-dominant sediment transport regime.

Beach monitoring has demonstrated that coastal defence works at Llanelli since the early 1990s have succeeded in reversing the previous erosion trend in that area (data in Appendix 1). However, rising high water levels will increase the risk of overtopping of defences, notably along the north side of the estuary. If embankments and other defences are not maintained significant areas of reclaimed industrial and agricultural
land will be at risk from flooding and some areas are likely to revert to active saltmarsh, notably between Pen-clawdd and Loughor.

5.6 Whiteford Point to Burry Holms

The 3 km long dune-capped barrier which extends from Hills Tor to Whiteford Point (Figures 26 & 27) is founded on a glacial moraine of Late Devensian age (Bridges, 1977a; Bowen, 1995; May 2003a). A 'scar' of residual cobbles is exposed in the intertidal zone northwest of Whiteford Point. The main line of highest dunes is located 50 - 100m inland from the shore and reaches up to 16 m in elevation (Figure 28). To seaward of this ridge is a line of dune slacks and a second ridge of lower, younger dunes (Davies et al, 1987). The southern end of the system has experienced a complex history of accretion, erosion and renewed progradation in the last 20 - 30 years following beach accretion on the eastern side of Hills Tor. However, most of the central and northern parts of the dune frontage experienced slow net erosion during the later 20th century (Pye & Saye, 2005; Saye & Pye, 2007; Figure 29).

There is significant longshore drift along the beach, with sediment deposited in the form of a series of recurves at the Whiteford Point end of the system. The spatial and temporal pattern of frontal dune erosion and accretion is closely dependent on changes in the nearshore bathymetry, notably movements of the low water channel leading into the Burry Inlet. The past decade has seen offshore movement and infilling of this channel, leading to rising beach levels and foredune ridge development along the central and southern part of the barrier (see data in Appendix 1). However, this trend could be reversed at any time.

South of the short cliffed section between Hills Tor and Prissen's Tor lies another wide sandy beach in Broughton Bay (Figure 26). This beach is backed by a raised beach of last interglacial age, multiple till deposits of Devensian age, and by overlying windblown sediments of Holocene age (Campbell & Bowen, 1989). To the southwest of Broughton Bay there are low cliffs, partially buried by blown sand, which extend to the rocky islet of Burry Holms (May, 2003a). The blown sand in this area is a mixture of
sediment derived from Broughton Bay and sand transported by southwesterly winds across the headland south of Burry Holms from Rhossili Bay.

The intertidal zone fronting Broughton Bay and the southern half of Whiteford Bay is characterized by a series of large sand bars which are oriented at an oblique angle to the high water mark. Migration of these features plays an important role in transporting sand alongshore towards the mouth of the Burry Inlet. Continuation of this process will be dependent on continued dominance of wave action from the southwest.

5.7 Burry Holms to Worms Head

Llangennith Burrows consists partly of climbing dunes and partly of hummocky dunes and transgressive parabolic dunes which cap the sand barrier system linking the headland east of Burry Holms with the northern end of Rhossili Down (Figure 30). Erosion of the solifluction terrace deposits which form cliffs in the southern part of Rhossili Bay has provided a local source of sediment which compliments a second source of sand from Carmarthen Bay which approaches the shore via the northern side of the Helwick Bank. The beach has a high degree of exposure to waves from the west and southwest which generate net northerly littoral drift. The rock-bound embayment at the northern end of the system has acted as a long-term local sediment sink for sand and finer-grained sediment (Llangennith Burrows, Hillend Burrows and Llangennith Moors).

The beach monitoring data (Appendix 1) show that beach levels in Rhossili Bay have shown very limited variability over the past decade, although there has been a slight landward movement of both HAT and MHWS over the period.

Over the next 100 years, further recession of the high water mark is likely in Rhossili Bay, and under conditions of accelerating sea level rise and increased wave attack rates of recession are likely to be higher than those experienced over the past 100 years. The risk of flooding to parts of Llangennith Moors is likely to increase, although the dunes will show a natural tendency to roll landwards, maintaining or even increasing their sediment volume.
5.8 Mumbles Head to Porthcawl Point

Swansea Bay *sensu stricto* is a broad, shallow embayment whose limits may be defined as Mumbles Head on the eastern Gower Peninsula and Porthcawl Point (Figure 31). Both Mumbles Head and the Hutchwns Point - Porthcawl Point area are composed of relatively resistant Carboniferous Limestone which form 'anchor points' for the coastline. The northern, central and much of the eastern sides of Swansea Bay are backed, and underlain, by less resistant Coal Measures strata. The higher ground around the bay is mantled with glacial till, while the low-lying areas are covered by outwash sands and gravels, former lake deposits, alluvial silts, and Holocene marine deposits.

The belt of Holocene coastal sediments is widest on the east side of the Bay south of the Afon Neath and is narrowest between Mumbles Head and Black Pill on the west side of the Bay (Figures 32 & 33). These deposits accumulated after the sea reached its most landward extent around 5500 years ago (Culver, 1980b). The Holocene sequence essentially consists of a series of sandy barrier beaches, capped to varying degrees by dunes, behind which lie marsh and tidal flat deposits. The main source of sediment was provided by marine reworking of glacial and paraglacial sediment on the floor of Swansea Bay (Culver & Bull, 1980; Blackey & Carr, 1980).

The broad-scale coastal configuration of Swansea Bay was established by 3500 years ago. Low-lying areas in the valleys of the rivers Tawe, Neath and Afan were flooded by tidal waters, and extensive areas of saltmarsh and brackish marsh developed. Flooding of these areas during storms was a relatively frequent occurrence.

During the 12th to 17th centuries much of the shoreline of Swansea Bay experienced erosion and active dunes and sand sheets migrated up to several kilometres inland at Kenfig (Higgins, 1932, 1933; Evans, 1960; Carr and Blackley, 1980). The main driver for erosion and inland sand incursion appears to have been increased frequency of severe storms which transported new supplies of sand onshore from the floor of Swansea Bay and provided the wind energy to drive active dunes and sand sheets inland.
Further dramatic changes to the shoreline have occurred in the last 150 years as a result of human activities. These included construction of Swansea docks (mainly after 1870), the River Neath training walls in 1870 and Port Talbot Harbour in 1969 (Jackson & Norman, 1980). Sea walls and promenades have also been built along most of the northern and northeastern parts of the Bay since the late 19th century. The combined effect of these works has been to disrupt the natural pattern of sediment circulation in the northern part of the bay, and to limit the capacity of the beach-dune systems to respond to natural storm events.

There is a general clockwise residual current and suspended sediment transport circulation pattern around Swansea Bay (Collins *et al.*, 1979; Heathershaw & Hammond, 1980b; Uncles, 1982) which today appears to operate as a closed sediment system with limited input of new sediment from deeper parts of the Bristol Channel, or from the rivers Taw, Afan and Neath. Stratigraphic evidence in the form of foreshore peats provides evidence for the long-term landward migration of the coastal barrier in the Black Pill area, with very limited natural input of new sand to this part of the system (Collins *et al.*, 1979; 1980). However, there is evidence that severe storm events are capable of moving significant quantities from deeper water in the outer parts of Swansea Bay towards the shoreline on the eastern side of the Bay, where it becomes available for re-distribution by 'normal' wave and longshore current processes.

Significant quantities of sediment have accumulated in Port Talbot Outer Harbour after such events, requiring removal by dredging (Jackson & Norman, 1980). Although Swansea Bay is a high tidal energy area, wave processes play a very important part in transporting sediment across the sea bed and around the major offshore banks (Collins *et al.*, 1980; Pattiarachi, 1985; Pattiarachi & Collins, 1988).

The beach monitoring data (Appendix 1) show that there was a slight landward movement of HAT and MHWS, and a general reduction in beach levels, between Mumbles and West Cross, in western Swansea Bay, between 1998 and 2008. Similar landward movement of HAT / MHWS and beach lowering occurred along the frontage between Swansea University and Swansea Docks, although there was a slight seaward movement on the Lower Sketty frontage (believed to be entirely attributable to sand nourishment and foredune growth in this area). There were was also significant
landward movement of HAT along the Crymlyn Burrows frontage, although a more variable pattern of movement in MHWS. Significant beach and frontal dune erosion occurred at Profile 216, on the west side of the River Neath entrance breakwater, although frontal dune accretion took place over the same time period on the Baglan side of the river entrance (Profile 217).

The rest of the coastal frontage between Baglan Burrows and the Afon Kenfig, south of Margam Burrows, showed a landward movement of MHWS (and in many cases HAT) over the period 1998-2008. Most profiles along this frontage showed an overall fall in beach levels, especially in the northern and central parts of the area (Aberavon Sands).

Lying to the south of the Afon Kenfig, the Kenfig dunefield overlies a low-lying area of Mercia Mudstone Bedrock at relatively shallow depth (Figure 34). The bedrock surface rises gently inland towards the M4. The dune system originated as a bay fringing system which evolved into a transgressive climbing dune system during the Little Ice Age (Saye, 2003; Pye et al., 2007). Dunes advanced almost 4 km inland to reach a point which today lies on the landward side of the M4 motorway (Figures 35 & 36). Analysis of historical maps indicated slow retreat of the dune frontage over the last century, despite protection offered by a natural shingle revetment (Pye & Saye, 2005; Saye et al., 2005; Figure 37). Up to the 1970s the dunefield was relatively active, with a high proportion of bare sand, but since the implementation of strict management measures in the 1980s most of the dunes have become stabilized.

The monitoring data (Appendix 1) indicate that at most of the Kenfig profiles the HAT contour moved landwards between 1998 and 2008, although the trend in the MHWS contour was more variable. The MHWN and MLWN contours both showed seawards advance at the two most northern profiles, with a variable pattern of retreat or no movement at the three more southerly profiles.

Under a ‘business as usual’ scenario (i.e. continued maintenance of defences), relatively little change in shoreline position is likely to occur around northern and eastern Swansea Bay due to presence of the hard defences. However, the existing beaches on the northern side are likely to come under increasing pressure as sea level rises but
natural supplies of new sediment are limited. Dune erosion and flooding due to wave overtopping of the promenade are therefore likely to become increasing problems during storms. If the defences in this area were allowed to fail as a result of a policy of no active intervention, significant areas of low-lying ground behind the Black Pill - Swansea Marina promenade, and in the lower Tawe valley, could be flooded. Similar flooding would result from failure of defences around the Afon Neath and Afon Afan. One wider potential effect of regular tidal flooding of these low-lying areas would be to increase the tidal flows into and out of northern Swansea Bay. Small ebb tidal deltas might develop at the mouths of each reactivated estuary system, resulting in localised beach progradation, but beach drawdown and shoreline recession would be more likely around the entrances to the re-activated estuarine areas.

It is unlikely that over the next 50 years the position of the dune frontage at Kenfig will change to a major extent, owing to the fact that the Sker Point natural hard point and the protected frontage to the north will act to hold the overall coastal position, and the shoreline and frontal dune system now appears to have established a condition of dynamic equilibrium. This section of the shoreline is almost swash aligned and longshore sediment drift rates are low. At the present time supply of new sand from offshore is limited. Unless there is a significant increase in the magnitude of onshore sand supply, significant seaward progradation is highly unlikely. A change in the degree of frontal dune instability, due to visitor pressure and/ or deliberate dune management policy, would favour landward transfer of sand from the frontal dunes to the hind dune area, and would increase the susceptibility of the frontal dunes to erosion under storm conditions and in the face of sea level rise. In the longer term (50 - 100 years), sea level rise will increase the erosional pressure on the frontal dune system. However, owing to the relatively high degree of wind exposure it is expected that much of the sand in the frontal dune system will be conserved as shoreline recession proceeds and the frontal dunes retreat by rollover.

To the south of the Kenfig dunefield, the coast between Sker Point and Porthcawl Point is mostly backed by rocky cliffs, although a wide beach is exposed in Rest Bay at low tide. The beach profile data show that the HAT and MHWS contours have not changed much in terms of position, although average beach levels in Rest Bay dropped between
1998 and 2008 (Appendix 1). The land behind the shore is relatively high and there is unlikely to be any significant flooding or erosion risk over the next 100 years.

5.9 Porthcawl Point to Nash Point

Between Porthcawl and Ogmore on Sea lies a relatively large area of windblown sand, formerly known as Newton Burrows but more recently as Merthyr-mawr Warren. The blown sand belt extends 1 to 3 km inland and consists mainly of climbing dunes, sand sheets with localised development of foredune ridges, and hummock dunes behind the southern part of Traeth yr Afon. Urban development has covered much of the blown sand near Porthcawl and Newton, but between Newton and the Afon Ogmore the dunes retain much of their original character (Figures 38 & 39). The belt of blown sand also continues as an undulating sand sheet on the south side of the Ogmore River. The total area of blown sand is more than 932 ha.

The Merthyr-mawr dunes originated as a bay-fringing dune system but involved into a transgressive climbing dune system during stormy periods of the Little Ice Age (Higgins, 1932, 1933; Pye et al., 2007). Dune development began at least 2500 years ago and has continued episodically to the present day. Blowing sand and dune migration posed a significant problem until the 1960s, largely due to uncontrolled use of the dunes for recreation and sand extraction (Williams & Sothern, 1986; Gilham, 1987; Posford Duvivier Environment, 1996). Between 1937 and 1973 sand and gravel was extracted commercially from the frontal dunes, and recreational use was intense. However, analysis of historical maps has shown that the position of the dune toe moved only a small distance inland between 1877 and 1966 (Pye & Saye, 2005; Figure 40). For the past 25 years the dune system has been heavily managed and a variety of stabilization measures has been employed. Active blowouts are now restricted to the most accessible areas and the frontal dune toe is protected by a relatively wide natural gravel revetment.

The beach monitoring data (Appendix 1) indicate a general trend for slight landward movement of the MHWS contour at Porthcawl between 1998 and 2008, but little overall change in average beach levels. The MHWS contour showed a variable but dominant
seaward movement at Newton and Merthyr-mawr. The trends in MHWS are generally reflected in the movements in the HAT contour, but the changes in MHWN and MLWS contours show a more variable pattern. Significant development of a new 11 m high foredune ridge occurred at the southern end of the Merthyr-mawr system over the period.

Although some frontal dune erosion along the Merthyr Mawr frontage may occur in the future due to rising sea level or increased storminess, the main part of the dune system, which consists of climbing dunes overlying bedrock, is unlikely to be affected. Erosion within the smaller bays at Newton and Porthcawl is likely to be very limited, whether or not the present defences are maintained, owing to the presence of numerous rocky scars which anchor the shoreline.

The coast between the Afon Ogmore and Nash Point consists mainly of cliffs, shore platforms and residual rock pinnacles. The cliffs range in height from <30 m to 62 m and are composed of lower Jurassic rocks (mainly limestones and interbedded shales of the Blue Lias) which are relatively hard and have exhibited low rates of erosion in recent centuries (0.02 to 0.1 m/yr according to Williams & Davies, 1987). They are near-vertical with overhangs and collapse features in many places, and are fronted by platforms 200 to 250 m wide (Trenhaille, 1969; 1972; Williams & Davies, 1987; May, 2003b).

Possible increases in sea levels and storminess over the next 100 years may cause some increase in cliff erosion rates along this section of coast, but major changes are unlikely owing to the relatively resistant nature of the rocks and the high nature of the ground.
The historical development of the coast in the Swansea Bay and Carmarthen Bay area can be summarised as follows:

Last glacial period - advance of Welsh ice from the north; deposition of till and outwash deposits on what is now the coastal plain and adjoining nearshore areas; sea level lowered by up to 130 m; shoreline lay well to the southwest of the present coast at glacial maximum.

Early to mid-Holocene - disappearance of ice; sea level rose to reach approximate present level by 5500 yr BP; submergence of alluvial, glacial outwash and lake deposits; partial reworking of sediments on the floor of Carmarthen Bay and Swansea Bay by marine processes; marine inundation of what are now land areas around the heads of the major estuaries

Mid- to Later Holocene - landward movement of sediment from the sea bed towards the shoreline; development of sand barrier systems with sandy beaches, dunes and back-barrier marshes; increasingly episodic sediment transport from the offshore area and episodic aeolian activity in response to climatic change (especially increased storminess during the Little Ice Age).

Middle ages - embanking and reclamation for agricultural land in parts of the main estuaries; reduction in estuarine tidal prism leads to further sediment accretion by positive feedback.

Industrial period - reclamation for industrial and port development both on the open coast and in estuaries; construction of training walls to improve navigation within estuaries; disruption to natural coastal sediment
transport pathways; enhanced accretion within estuaries; movement of sediment from tidal deltas and open coast beaches into estuaries; construction of sea walls and groynes on the open coast.

Late - industrial - abandonment of some training walls in estuaries; re-establishment of more mobile estuarine tidal channels in some areas; stabilization of dune systems; beginning of accelerated sea level rise.

At the present time the Three Rivers estuarine complex and the Burry Inlet continue to act as long-term sinks for sediment transported by tidal currents and wave action from Carmarthen Bay. Most shoreward movement from deeper water takes place during major storms, with re-distribution alongshore and into the estuaries occurring under more typical wave and tide conditions. Similar periodic landward transfer from the deeper parts of Swansea Bay also occurs during major storms, although the total amount of sediment moved is considerably less than in Carmarthen Bay. The dune systems in northern and eastern Swansea Bay, notably Crymlyn Burrows, Baglan Burrows, Margam Burrows and Kenfig Burrows, act as significant sediment sinks. A significant proportion of the sand which is moved shorewards by natural processes is removed by dredging from the major harbours and is re-deposited offshore. Sand is also extracted (mined) from the major offshore linear banks (Scarweather and Helwick Banks) but there is little evidence that these activities have yet had a significant impact on the sediment budget of the mainland beaches.

In the absence of significant climate change and sea level rise over the next century, it is unlikely that there would be major changes in the pattern of sediment transport and shoreline evolution in the area. Local changes in shoreline erosion and accretion would take place due to changes in channel and bank morphology in nearshore areas and within estuaries. Erosion is likely to continue on more exposed sections of the open coast where rates of onshore sediment supply are lower than rates of landward transport by wind or longshore transport by marine processes, but accretion would be likely to continue at the down-drift ends of littoral sediment transport cells.
The effect of a significant increase in the rate of sea level rise would be to increase the erosional pressure on beaches and dune systems, and on coastal defences where they are present. In lower energy settings, offshore and/or alongshore movement of eroded sand is likely, but on exposed shores a significant proportion of the eroded sand would be likely to be reworked landwards by wind action, thereby conserving the sand volume of landward-moving frontal dunes. Where landward movement of beaches and dunes is impeded by coastal defences, a reduction in beach / dune sand volume is likely to occur over the longer term, placing increased stress on the defences.

Even if the rate of sea level rise accelerates substantially by the end of the century, it is likely that sedimentation rates within the major estuaries will be able to keep pace owing to the strongly flood-dominant nature of the estuarine sediment transport regimes and the potential availability of large quantities of sediment around the estuary entrances and in neighbouring parts of Carmarthen Bay. Cannibalization of sediment stored in the existing estuary mouth barrier systems and back-barrier areas can be expected, with transfer of sediment into the more landward parts of the estuaries.

A modest increase in storminess would also be likely to result in further beach lowering and frontal dune erosion. However, an increase in the frequency and magnitude of major storm events could increase the movement of sand from the offshore zone towards the coast, resulting in the formation of larger nearshore banks and bars. Subsequent movement of this sediment onto the beaches under fair weather conditions could result in the formation of extensive transgressive dune systems (by analogy with conditions which apparently existed during the Little Ice Age). Such a major increase in storminess would also be likely to increase the rate of sedimentation within estuaries, leading to more rapid vertical, and possible lateral, growth of saltmarshes, although greater wave erosion of the saltmarsh edge would be expected in more exposed estuarine situations.
7.0 References


Shoreline Management Partnership (2006) *Swansea Bay and Carmarthen Bay Coastal Group Beach Profile Monitoring (Sample Analysis Undertaken for the City and County of Swansea)*. Shoreline Management Partnership, Rossett, Flintshire.


