The Taw-Torridge Estuaries: Geomorphology and Management Report to Taw-Torridge Estuary Officers Group

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Preface

This report was commissioned by the UNESCO Biosphere Reserve for North Devon on behalf of a local partnership to take a long term view of the evolution of the estuary. The Biosphere Reserve team in Northern Devon Coast and Countryside Service convened a study group consisting of Environment Agency, Natural England, Devon County Council, Torridge District Council and North Devon District Council to specifically explore the scientific and technical issues and how they might be combined with local knowledge to reach a common understanding of the dynamics of the shoreline in the estuary and its approaches.

This report is the result of extensive work by Professor Pethick and links to work carried out by Professor Julian Orford concerning the Pebble Ridge at Northam Burrows. It also combines the comments and observations made by local people through a series of public presentations.

We commend this work as a good example of policy development through sound science and local stakeholder interaction, and gives space for policies to be developed so that a more sustainable coast can be allowed to develop.

The report sets out our shared understanding that will be used in the derivation of the policies for the next Shoreline Management Plan which is due to be completed in 2009.

Andrew Bell

UNESCO Biosphere Reserve Co-ordinator

Contents

EXECUTIVE SUMMARY

Intention

This report presents a study of the Taw-Torridge estuary and its adjacent coast. The aim is to provide a detailed explanation of the components and function of this complex geomorphological system upon which future management decisions may be based.

The study relies upon two distinct modelling approaches: development of a conceptual model of the estuarine system and application of a series of computer-based models. The first approach offers an interpretation of the form and function of the Taw-Torridge system based upon available knowledge complied from maps, charts, aerial photos, site visits, previous studies and a specially commissioned bathymetric survey. The second approach uses a top-down modelling procedure that defines the theoretical equilibrium form of the estuary under a number of different scenarios and compares this with the actual morphology. This allows, for example, the impact of future sea level changes or of managed realignment to be assessed in a quantitative manner.

Conceptual model: Open coast

The conceptual model concluded that the open coast of Bideford Bay is dominated by a counter-clockwise tidal gyre that re-circulates sandy sediment northwards along the nearshore and coast with a southerly return in the offshore zone. This re-circulatory system explains the continued northerly movement of sediment along the coast despite the lack of any sediment inputs to the Bay, or of massive erosion of the coast. The orientation of the coastline of the Northam Burrows and Saunton Sands is such that it presents an oblique angle to incoming westerly or south-westerly waves. This forces a northerly longshore current that augments the tidal gyre and transports sediment northward along the coast: a morphology known as drift alignment. The study found however that this drift alignment was slowly changing due to erosion of the coast, so that the orientation is becoming more parallel to incoming waves. This reduces the volume of northerly drift, which could, eventually, cease altogether: a process known as swash alignment.

Conceptual model: Tidal delta

The Taw-Torridge estuary presents a major obstacle to the northerly movement of sediment along the open coast and, equally, the longshore movement of sand also tends to restrict the entrance to the estuary. This mutual antipathy is overcome by a complex morphological development: the tidal delta. The outer or ebb-tide delta is formed by the Bideford Bar; sand waves move along this Bar from south to north during extreme storms. These sand waves arrive on the Saunton Sands where they attach themselves to the upper shore, forming the pronounced headland known as Airy Point. From here some of the sand is moved, by wave action, further north into the tidal gyre, while the rest is moved by flood tide currents along the estuarine shore via Crow Point and into the outer Taw-Torridge estuary. Here the sand is temporarily deposited in a flood tide delta which is located along the Instow shore, before moving seaward on ebb currents to rejoin the outer ebb delta. This circulatory system is not, however, sediment-tight since some sand is deposited in the outer estuary so keeping pace with sea level rise that has averaged 2.8mm per year over the past century. This sand accretion represents a loss to the circulatory system in Bideford Bay and explains the gradual re-orientation of the coastline towards a swash alignment in which less sand is circulated.

Conceptual model: the Pebble Ridge

The Pebble Ridge along the Northam Burrows shore is a minor component of this overall coastal system. It seems likely that the cobbles entered the system as recently the 16th and 17th centuries, possibly emanating from major landslips at the Gore. The cobbles are subjected to the same northerly drift as described above, so that there is a loss at the distal end of the spit, possibly entering the extensive gravel spread along the southern shore of the estuary, but no corresponding input at the southern end. The Pebble Ridge is therefore losing sediment at a rate of up to $5000m^3$ per year and thus it appears to have a finite life. However, records indicate that the Pebble Ridge is itself re-orientating counter-clockwise towards a swash alignment so that northerly drift and thus loss of cobbles is progressively reducing.

Conceptual model: the Estuary

The conceptual model of the Taw-Torridge estuary concluded that both the Taw and the Torridge are still in the process of adjustment to the rapid rise in sea level after the last glaciation, during the Holocene period. This is quite distinct, for example, from estuaries on the eastern coast of Britain, where rapid adjustment took place in the early Holocene. The difference between the two lies in the relative lack of muddy sediment along the Atlantic coast of southwest Britain. The Taw, in particular, has a wide valley floor that is only slowly filling due to this lack of muddy sediment. This infill proceeds in a seaward direction starting at the inner reaches of the estuary. The study concludes that the leading edge of this progressive infill has now reached Penhill Point having passed by Barnstaple some two or three hundred years ago, causing siltation of its once prosperous harbour. The siltation of the outer estuary is likely be extremely slow since here the channel bed is over-deepened by the former river channel incised here when sea level was more than 15m below its present level some 8000 years ago.

The Torridge, in contrast to the Taw, has a very narrow valley floor and its steep valley sides constrain the width of the estuarine channel so that it is much deeper than the corresponding sections of the Taw. Here again, relative lack of muddy sediment means that the estuary is still adjusting to existing sea levels and the predicted increase in the rate of sea level rise will retard this process even more.

Regime model

The quantitative modelling of the estuaries of the Taw and Torridge provided additional information to complement that developed in the conceptual modelling stage. The basic model employed was a regime model. This defines the relationship between tidal volume and channel size using a sample of west coast estuaries and this relationship was then applied to the Taw-Torridge system. The results indicate the form that the estuary would take in response to existing tidal conditions, assuming that sufficient time, sediment and space were available: a theoretical condition that nevertheless allows the existing behaviour of the estuary to be assessed. The results showed that the equilibrium channel in the Taw would be much narrower than its valley in the section between Penhill Point and Barnstaple, would fill the existing valley (defined mainly by artificial defences) in the Chivenor reach, and would be significantly wider (by 50%) than the existing channel in the outer, mouth section. Upstream of Barnstaple the model suggests that the equilibrium channel is much wider than the existing channel implying that some stress is already exerted on tidal defences here. In the mouth of the estuary the over-deepened channel means that the tidal discharge is contained within a much narrower section than predicted by the model. Nevertheless, since any further increase in depth is not possible, any changes in the tidal discharge (for example due to sea level rise) would result in a change in width. This was shown by running the model in reverse to predict what changes would have occurred in theory over the past century when sea level rise was around 2.8mm per year. The model results showed that the channel would have widened by 1.04m per year, a result extremely close to the actual change of 1m per year in the outer estuary. Thus the outer estuary is seen as being extremely sensitive to changes in tidal discharge, in contrast to the inner estuary where the wider valley allows room for channel expansion. In the central section, that is the Chivenor reach, the model results suggest that stress on the defences may be an existing problem that will be exacerbated in the future.

In the Torridge estuary, the model results show that the equilibrium width is approximately equivalent to those of the existing channel suggesting that the estuary is in regime. However, this is contradicted by the depth data that shows the Torridge channel is much deeper than would be expected for an equilibrium estuary. In fact the model results show that the cross sectional areas of the existing channel are almost twice the size that would be predicted for an equilibrium state. Clearly the Torridge is still slowly adjusting to the Holocene rise in sea level, inhibited by the lack of sediment. Equally clearly, the predicted increase in the rate of sea level rise will not lead to an increase in channel size in the Torridge but will, instead, merely reduce the rate of infill.

Regime model: sea level rise

The study went on to predict the response of the Taw-Torridge estuary to the rise in sea level over the next 100 years, put at just under 1m by Defra. The results indicate that, taking the over-deepened channel mouth into consideration, the estuary mouth will increase its channel width by between 360m (the error term here for the model being +/- 100m) by the year 2100. At Chivenor the increase is predicted to be 119m (+/- 33m) and at Barnstaple 61m (+/-17m). For the Torridge, results are more difficult to interpret given the existing depth of the channel. If the present channel were in equilibrium the model predicts that sea level rise over the next 100years would result in channel widening of 157m at Appledore; 47m at Bideford; and 25m at the R. Yeo, again with 28% error margins. However, these increases are unlikely to occur due first to the depth of the channel here and the fact that the valley sides constrain the channel from further widening.

Regime model: managed realignment

A further set of model predictions were made to define the response of the estuary to proposed managed re-alignment of the flood defences. The proposed realignment sites were at Bishops Tawton, Anchorwood Marsh, Home Farm Marsh, Horsey Island, Northam Burrows on the Taw and Hallspill and Tennacott on the Torridge. The tidal volume that would enter these areas if flood defences were to be realigned would mean an increase in the tidal volume of the estuary channel and a corresponding increase in its size. However, the model predictions show that these increases in channel width would be modest (i.e.<10m) for most of the proposed sites. For the Horsey Island realignment however, a 33m increase in width at the mouth of the estuary is predicted while, on the Torridge, the Hallspill realignment would result in a potential width increase of 27m at the R Yeo outfall. It is interesting to note that these predictions for managed realignment must have acted in reverse during times of reclamation when the reduction in tidal volumes would have caused channel narrowing. For example, the reclamation of the Horsey Island site began in 1833, a period when accretion was noted on the shore at the lighthouse, south of Airy point, implying channel narrowing here. By 1860, however, this accretion had reversed to erosion, perhaps in response to the increase in sea level, an illustration of the sensitivity of this area of the estuary to changes in its tidal volumes and the rapidity with which such change can occur, an example that may inform management practices in the future.

Meander model

The prediction of channel width in the model assumes a symmetrical response on both banks, but this is not observed in reality since estuarine channels, in common with their fluvial counterparts, meander between banks causing problems for management and flood defence. In order to provide some estimate of this asymmetry, a meander model was developed for the study that incorporated the channel response to both tidal and fluvial discharges and their predicted increase over the next 100 years. The results showed that under existing conditions meanders in the Taw do not impinge directly on either bank, but that after 100 years of sea level rise the increase in meander amplitude will cause stress on the estuarine channel banks north of Penhill Point and at Home Farm Marsh. These impacts will be exacerbated by an increase in fluvial discharge over the same period. On the Torridge, due to the more restricted valley widths, meander bends have a greater impact on channel banks. Under existing conditions the predicted meanders impact both banks of the estuary south of the Torridge Bridge although in reality channel training on the Bideford reach has effectively removed these. Interestingly, as sea level rise occurs, these meanders south of the Torridge Bridge become less marked and bank stress would be reduced mainly due to the increase in meander wavelength under these conditions. Nevertheless, immediately north of the Torridge Bridge meanders will cause increased impact on both banks both due to sea level rise and fluvial discharge increases over the next 100 years.

Management issues

Although the intention of the study was to provide the basis for management of the estuary rather than offer management advice itself, some consideration was given to the probable status of the estuarine flood defences over the next 100 years as a result of sea level rise. At the moment, flood defence crest levels along the estuary protect against floods with a return interval of 1: 200 years, the study concludes that, unless major upgrading takes place, by 2055 this defence standard will have fallen to 1: 2 years and that, by 2100 the defences will be overtopped on most spring tides. In addition, defences will become under increased stress due to the impacts of channel widening and meander bend development as outlined above. Increased crest heights will be necessary in order to maintain defence standards, although, where possible, realignment should also be considered.

Three other management issues were briefly considered in the study. These were the erosion at Crow Point, sand accretion on the Instow foreshore and the erosion of the Pebble Ridge. The study observed that the existing spit and dunes at Crow Point may have developed in the 19^{th} century as the result of the construction of a stone weir, possibly a fishing weir. This structure has now vanished and the dunes in its lee are being rapidly eroded. The study concluded that this was an inevitable development and, since the dunes here are ephemeral features, would result in no geomorphological changes to the estuary. The sand accretion on Marine Parade, Instow was seen as part of the ongoing process of sand circulation around the tidal delta. The wind-blown sand accretion on the Instow foreshore and road has probably been exacerbated by sea level rise resulting in higher inter-tidal levels. This circulation of sand around the tidal delta of the Taw-Torridge estuary is an important process helping to maintain the entire system as described above, and the sand accretion at Instow is a vital component of this circulation. The study suggested that management should consider moving the sand back to the estuary inter-tidal zone but to the south of Instow where it will continue in the circulation pattern.

The management of the Pebble Ridge is more complex particularly in view of the multiple use of the land behind the ridge including the landfill site. If nothing is done it seems likely that the ridge will gradually deteriorate allowing increased flooding of the Burrows area. This would be geomorphologically acceptable, but would involve loss of use of the Burrows for recreation, change of conservation status and would necessitate removal of the landfill site. Present management consists of rock armouring of the northern extremity combined with some replacement of material along the ridge after severe storms. The study concluded that this maintenance was both costly and, in the long term, unsustainable. Maintaining the ridge in its present form involves prevention of the long term geomorphological development which was shown to be towards a swash alignment that would eventually reduce northerly drift of the cobbles and thus increase the lifespan of the ridge. The study suggested that this process could be enhanced if the northern end of the ridge were to be held in place by rock armour but the southern end were to be allowed to move landwards, thus increasing the counter-clockwise re-orientation of the shoreline and encouraging a swash realignment..

Conclusion

It is emphasised that the intention of this study was to provide a coherent geomorphological model of the Taw-Torridge estuary and coast upon which local planning and management decisions could be based. The work has attempted to do this and to provide appropriate quantified estimates of change over the next 100 years as a result of climate change. It is acknowledged however, that the Taw-Torridge estuarine system is an extremely complex one and that the basic model resulting from this study should be seen as only the first stage in the process of understanding this important and beautiful area.

1. BACKGROUND

This study was commissioned by the Taw-Torridge Estuary Officers Group and is an assessment of the geomorphology of the Taw and Torridge Estuaries, their interactions with the open coast and the sand dune complexes of Braunton Burrows and Northam Burrows and the pebble ridge at Westward Ho!. The work includes a series of model predictions of the probable changes in the estuaries over the next 100 years and the management implications of these changes.

The report covers the following broad topic areas:

- A conceptual model of the past geomorphological evolution of landforms within the study area;
- the probable evolution of the estuaries and associated coastline over the next 100 years;
- the implications of this evolution on the standard of flood protection afforded by the flood defences in the estuaries;
- the manner in which current management practices will affect the evolution of the coast and estuaries in the future, and assessment of possible future management strategies, including techniques such as managed retreat and sediment husbandry;
- In addition to a general review of future geomorphological evolution of the landforms within the study area, the following specific issues are addressed:
    - the future geomorphological integrity of the coastal dune system, including possible breaching of the Crow Neck and/or the Pebble Ridge at Northam Burrows;
    - impacts of management options on future (possible) managed re-alignment sites within the estuary, including at Horsey Island, Home Farm Marsh, Anchorwood Bank, Bishops Tawton, Hallspill and Tennacott;
    - Implications of the (observed) trend in loss or movement of beach material on Westward Ho! Beach on the Pebble Ridge defences and the Landfill site;
    - The geomorphological development and management of dunes and beach at Instow.

2. THE STUDY AREA

The study area, including the Taw-Torridge Estuaries and associated open coastal region is shown in Figure 1. The underlying geology of the area consists of a series of Upper Carboniferous rocks, chiefly sandstones and mudstones, extending from the Bideford Formation of the southern Torridge Estuary, through the Crackington Formation that forms the Appledore ridge and underlies the outer Taw-Torridge channel, to the Pilton Shales of Saunton Down in the north of the region.

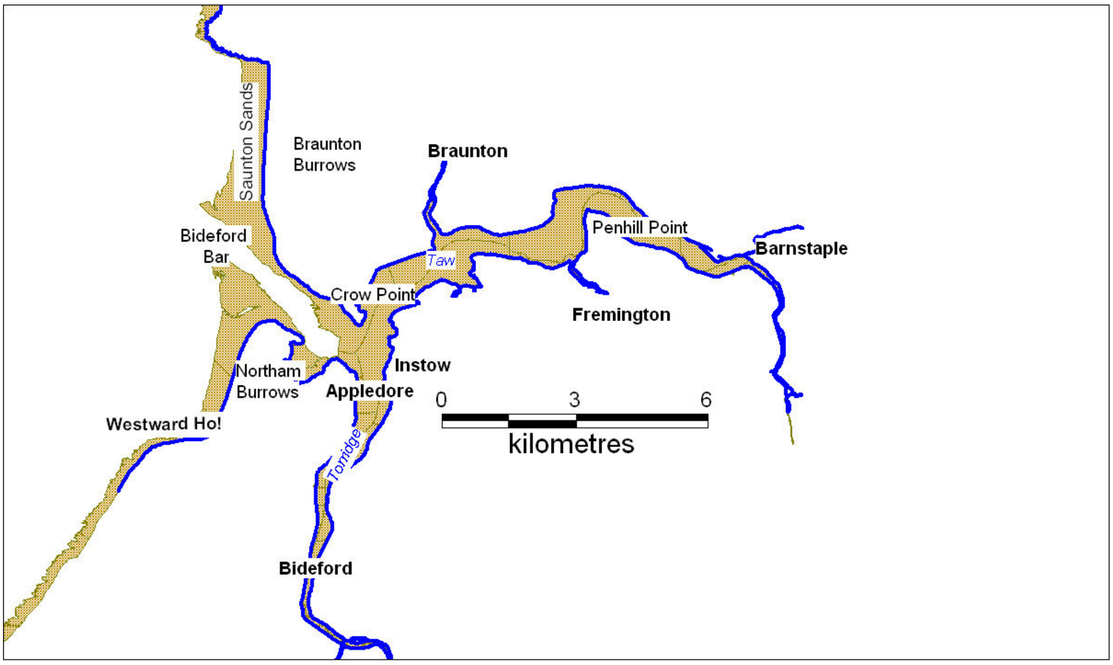

Figure 1: The Study Area showing key places mentioned in the text

The extensive sand dunes of Braunton and Northam Burrows define the coastal limits of the combined estuaries. The Westward Ho! Pebble Ridge extends for 3.5km along the western limit of Northam Burrows and is formed of pebbles, cobbles and boulders with a mean diameter of 0.3m formed from the Carboniferous rocks exposed along the coast in Bideford Bay to the southwest of the study area. At the northern end of Northam Burrows, the pebble ridge is backed by sand dunes while, to the south, an area of estuarine clays lies between the pebble ridge and the high land of the Appledore promontory and extends eastwards to the estuary where it culminates in the Skern: an inter-tidal bay with muds locally covered by salt marsh. Braunton Burrows is characterised by sand dunes extending for 5.5km south from Saunton Down to the estuary mouth and for 1.5km inland where they merge into the estuarine clays of the Braunton Marsh. Three main dune ridges are present with the highest, at 35m, along the landward limit. The dunes ridges meet the estuary at Airy Point while a narrow recurved sand dune spit, Crow Point, extends southeast from Airy Point into the estuary.

Seaward of the Northam and Saunton Burrows lies a broad inter-tidal sand beach varying in width between 400m and 700m . This beach merges into the tidal delta of the Taw-Torridge estuaries which consist of a series of sand bars inclined obliquely to the shore with the ebb-tidal delta, the Bideford Bar, running shore-parallel some 1.5km north west of Airy Point.

The outer Taw-Torridge estuary channel extends from the junction of the two estuaries at Appledore to the sea. The estuaries are macro-tidal with a 7.5m tidal range at the mouth. The outer estuary is constrained in several places by rock outcrops, notably at Cool Stone, Crow Rock and Pully Ridge. At the confluence of the two estuary channels, a shore-attached sand bar at Instow Sands may represent the flood-tidal delta of the estuary system.

The two estuaries themselves are distinct in their morphology. The Taw is a broad sandy estuary with a tidal limit 18km inland. A small tributary, the Caen, meets it landward of Braunton Burrows where former extensive inter-tidal mudflats and salt marshes have been reclaimed at Horsey Island. Landward of Penhill Point estuarine sediments become finer grained and there is some development of salt marsh, notably at Anchorwood Marsh. The Torridge estuary is narrower and shorter than the Taw and is constrained by its rock valley. Inter-tidal sediments are much finer than those of the Taw although there is little salt marsh development, mainly due to the constraints imposed by the valley slopes. The inner Torridge is characterised by a series of rock-cut meander loops.

3. THE DATA BASE

Assessment of the geomorphology of the area has relied on a data base that is not as extensive as that for many similar sized estuaries in the UK. This is perhaps due to the relatively undeveloped nature of the estuaries, with limited navigational access either in the past or at present, so that long term records of tides, waves, or bathymetric change are limited. A review of the data base that was available to the study is given here.

3.1 Bathymetry

A bathymetric survey of the two estuaries was commissioned specially for the study by the Environment Agency. This bathymetric survey was merged with a LiDAR survey of the inter-tidal and supra-tidal regions of the estuary and the Northam and Braunton Burrows areas, coverage of this combined mapping is shown in Figure 2. The resultant DTM was then used to provide a series of 53 cross sections across the two estuaries. The locations of these sections are shown in Figure 3. The sections provided the basis of all further modelling as described in section 5. The cross sections used in the study are shown in Annex 1.

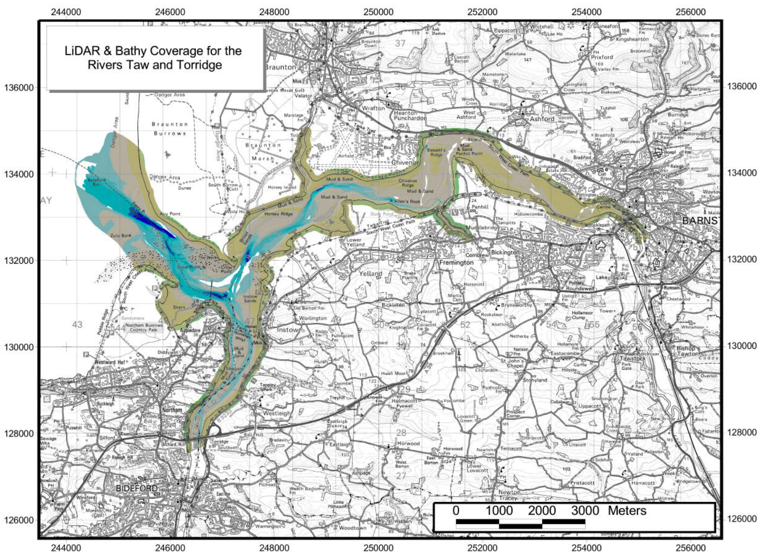

Figure 2: Bathymetric and Lidar survey coverage

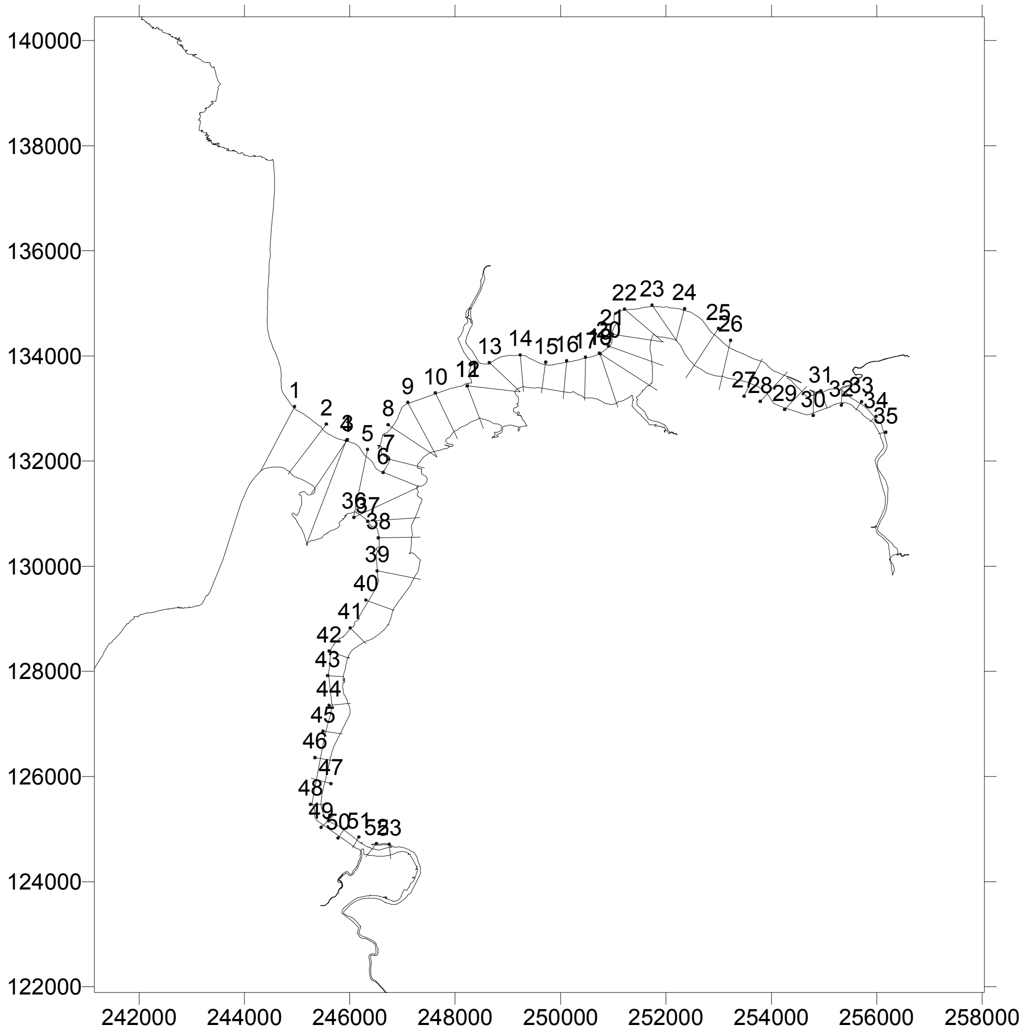

Figure 3: Locations of channel cross sections used in the study

The survey was used to provide a calculation of the tidal prism of the Taw-Torridge Estuaries. The tidal prism is the volume of water entering the estuary during a flood tide and is equivalent to the inter-tidal volume of the estuary. The bathymetric survey, combined with Admiralty predictions of high and low water along the length of the estuary, (see section 3.2) were used to calculate this inter-tidal volume (Table 1).

Tidal prisms for the Taw-Torridge Estuaries		
Area (Figure 25)	Profiles (Figure 3)	Tidal prism (m3)
Taw I	6 to 35	31,497,302.30
Torridge II	36 to 53	15,598,065.70
Mouth III	1 to 6	20,646,833.00
Total		52,144,135.30

Table 1: Tidal prism for the Taw-Torridge Estuaries.

In addition to the provision of cross section data for the estuarine channels, the inter-tidal elevation data provided by the LiDAR survey was used, in conjunction with tidal data (see section 3.2) to calculate tidal volumes of possible realignment areas within the estuary limits.

3.2 Tides

Tide gauge data was obtained for 5 stations along the two estuaries (Admiralty 1995) as shown in Table 2 and converted to OD. Using these basic data a best fit regression was calculated, relating tidal elevations to distance along the axis of each estuary. The results are shown in Figure 4.

Station	Data to Chart Datum				Data to Ordnance Datum			
	MHWS	MHWN	MLWN	MLWS	MHWS	MHWN	MLWN	MLWS
Appledore	7.5	5.2	1.6	0.2	4.32	2.02	-1.58	-2.98
Barnstaple	4.1	1.4	0.3	0.3	4.7	2	0.9	0.9
Bideford	5.9	3.6	0	0	4.52	2.22	-1.38	-1.38
Yelland	7.1	4.8	1.3	0.1	4.34	2.04	-1.46	-2.66
Fremington	5.9	3.4	0.3	0.2	4.47	1.97	-1.13	-1.23

Table 2: Tidal heights for the Taw-Torridge Estuaries (Source: Admiralty Handbook of Tides)

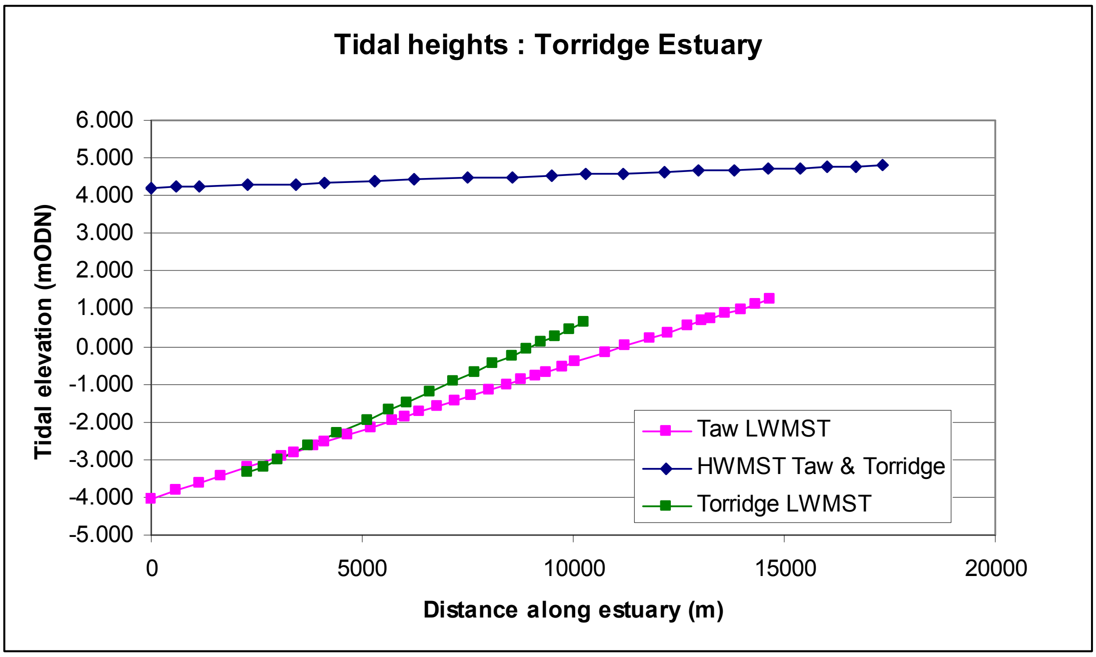

Figure 4: Tidal heights in the Taw-Torridge Estuaries

Tidal range is shown (Figure 4) to decrease from 8m at the mouth of the estuaries to 3.5m south of Barnstaple on the Taw and to 4.2m at Landcross on the Torridge, although, at any given distance from the sea, the tidal range in the Torridge is smaller than that for the Taw. These decreases in tidal range are, however, modified by the bed elevation in the Taw Estuary where drying heights exceed spring tide low water to the east of Penhill Point. This means that the Taw Estuary is entirely inter-tidal east of this point. The Torridge Estuary, in contrast, maintains a sub-tidal channel to its tidal limit at Wear Giffard. For example, at Landcross on the Torridge, the southerly limit of available bathymetric data, spring low water is 2.3m above the bed level. This marked contrast between the two estuaries is discussed in detail in section 6.4 below where geological constraints on the cross sections of the two estuaries is shown to have a major impact on their tidal dynamics.

Tidal curves for the Taw estuary are provided in HR (1990) and Kirby (1996) but in both cases these are in diagrammatic form and digital data is not available. Both sources indicate a marked flood tide asymmetry between Fremington and Barnstaple. However, the SMP (Halcrow 1998, section 3.4.3) states that the estuary mouth exhibits ebb tide dominance with maximum ebb currents of 0.45m/s and maximum flood flows at 0.2 to 0.3m/s. No information is available on the tidal asymmetry in the Torridge Estuary. It seems likely, given the morphology of the estuarine channel of the Torridge, that flood dominance would be present throughout.

3.3 Waves

Bideford Bay experiences one of the highest inputs of wave energy on the UK coast. The general north-south alignment of this coast and offshore bathymetric contours, means that the shore lies normal to the west-east tracking Atlantic waves which experience little refraction as they pass into shallow water. Atlantic Wave data for the study area was obtained from the Shoreline Management Plan (Halcrow 1998), Figure 5 illustrates the exposure of the Bideford Bay area to these ocean waves. Along the Clovelly to Babbacombe coast wave energy dissipation is marked but east of Westward Ho! a significant increase in energy is experienced although some truncation of extreme waves is shown particularly along the Saunton Sands shoreline.

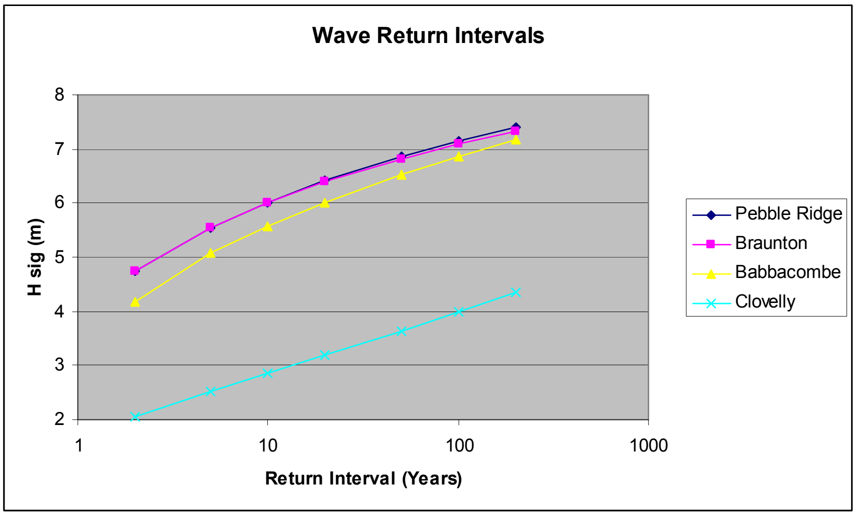

Figure 5: Wave return intervals (Hsig) for N Devon coast (source SMP 1998)

3.4 Sea level rise

Prediction of sea level rise over the next century for the south west of England are available from UKCIP (2005) and are based on three levels of CO_2 emissions. Predictions by DEFRA (2006) are linked to those of UKCIP (2005) but assume a worst case. They do, however, provide a continuous predictive curve for the next 100 years and as such are in some cases more useful than the step-wise predictions provided by UKCIP. The Defra predictions(2006) use the year 1990 as their baseline but for the purposes of the present report the baseline used is sea level as in 2005.

Table 3 shows the predictions from both sources. The UKCIP data applies to the year 2080 and by extension to 2105 to give the 100 year prediction. The Defra predictions are therefore shown both for 2080 and 2105 as well as for 2025 and 2055 (i.e. the 20 and 50 year predictions). There is a considerable discrepancy between the two data sets although this is not considered sufficient to preclude their use for geomorphological predictions. It is emphasised that the data shown in Table 3 is for changes in relative sea level rather than absolute levels.

Figure 6 shows the sea level curve for the next century using the Defra predictions for south west England.

			Change in sea level (m) by date shown		
Region	**2080 to 2105 UKCIP (2005)**	**2025 Defra (2006)**	**2055 Defra (2006)**	**2080 Defra (2006)**	**2105 Defra (2006)**
South east	0.77	0.144	0.403	0.64	1.07
South west	0.8	0.127	0.362	0.6	0.997
North	0.6	0.087	0.290	0.51	0.86

Table 3: Sea level predictions for the next century

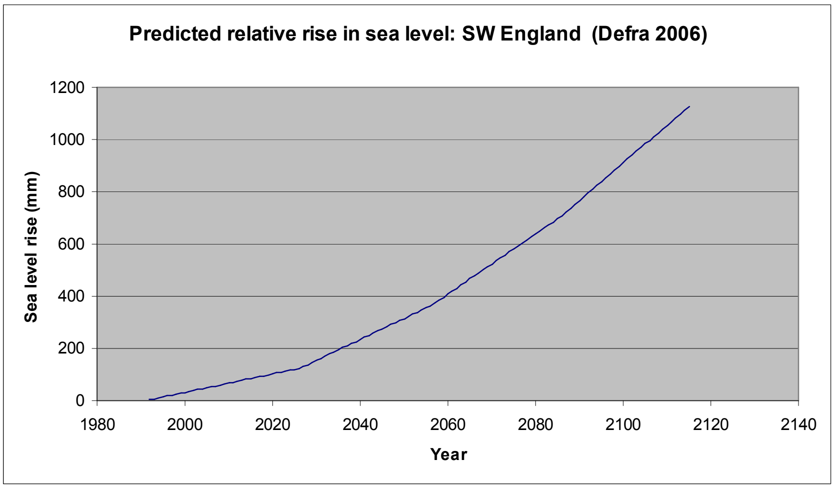

Figure 6: Sea level predictions for the next century for south west England (Defra 2006)

3.5 Extreme water levels

Return intervals for extreme water levels on the open coast (Pebble Beach) are provided in the SMP (Halcrow 1998) and are for the period to 1998 . These data are plotted as Figure 7 together with the return interval curves for the next 20, 50 and 100 year periods. These have been calculated using the Defra sea level rise predictions discussed above (section 3.4). The graph shows that the 200 year return interval extreme water level will become the 10 year flood by 2025 and the 2 year flood by 2055.

The data shown in Figure 7 are for the open coast. Within the estuaries the tidal level (HWMST) rises landward and this increase has been added to the Defra predictions for sea level rise for 2105 in Figure 8 for the Taw and Figure 9 for the Torridge. Flood defences on the coast and in the estuaries have a crest height that is designed to defend against the 200 year flood. The 200 year flood is shown in Figure 7 to be at 5.33mODN, that is 1.1m above HWMST on the open coast. Assuming that the relationship between the 200year and HWMST stays constant over the next century (i.e. the shape of the return interval curve shown in Figure 7 stays constant) this constant of 1.1m is added to the sea level rise curve and the high water mark in Figure 8 and Figure 9 to give the rise in water level along the length of the estuaries.

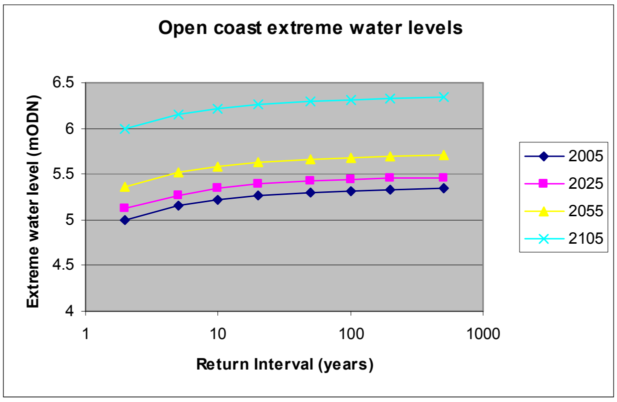

Figure 7: Extreme water level return intervals for the open coast, Northam Burrows.(source SMP 1998)

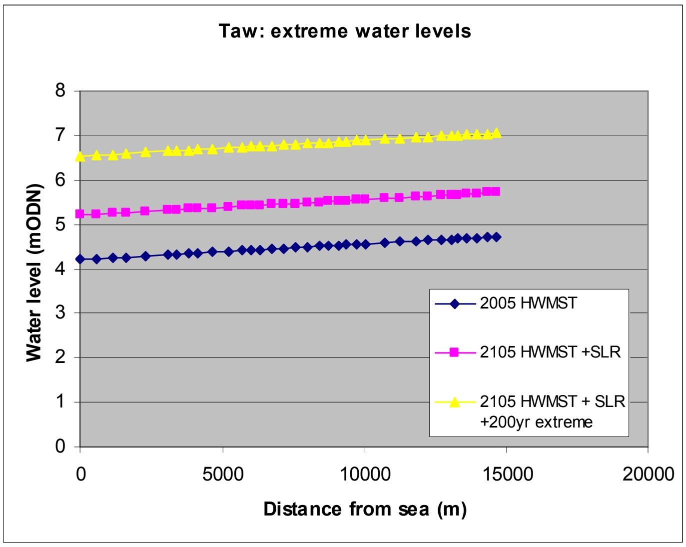

Figure 8: Extreme water levels for the Taw Estuary incorporating sea level rise and tidal gradients in the estuary.

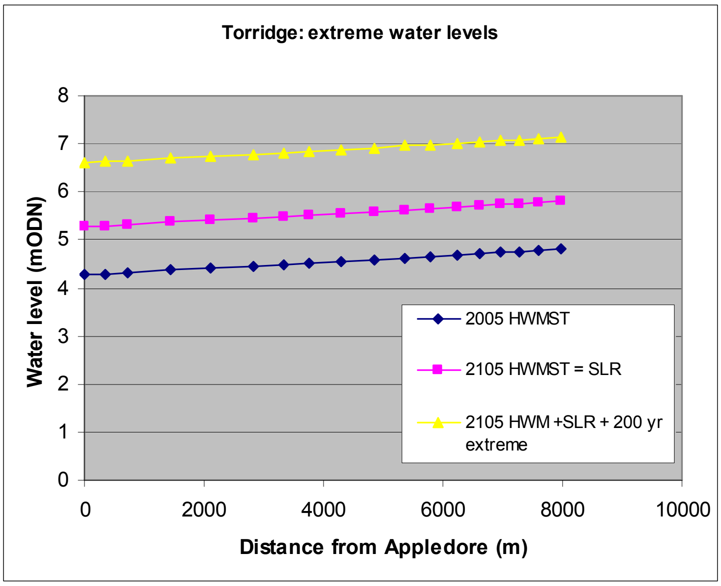

Figure 9: Extreme water levels for the Torridge Estuary incorporating sea level rise and tidal gradients in the estuary

3.6 Fluvial discharge

Fluvial inputs to the Taw-Torridge estuarine system are mainly as water discharge since relatively little sediment enters the system from the rivers (Kirby 1996).

Fluvial discharges during extreme rainfall events can have a significant impact on the morphology of the estuary channels as discussed in section 8. Flow gauges for the rivers are located at Umberleigh on the Taw, and Torrington on the Torridge. The highest monthly mean discharge over the period of record (1960-2001) was used as an indicator of dominant discharge with morphological significance (Table 4).

Station	Highest monthly flow (Cumecs)	Highest daily mean (cumecs)
Torrington (Torridge)	74	338
Umberleigh (Taw)	82	363

Table 4: Fluvial discharge data for Taw and Torridge rivers

3.7 Historic maps and charts

A review of available maps and charts showing morphological development of the Taw-Torridge estuary is provided in HR Wallingford (1990). Table 5 summarises these sources all of which were available to the present study.

Title	Date
1st Edn. Ordnance Survey	1809

Admiralty chart (Denham)	1832
Admiralty chart (Aldridge)	1855
Revision 1st Edn Ordnance Survey	1885
2nd Edn. Ordnance Survey	1905
Revision 2st Edn Ordnance Survey	1935
Admiralty chart (Lowry)	1949
Revision Ordnance Survey	1966 - 1987
Bathymetric and Lidar survey for this study	2006

Table 5: Maps and charts consulted in the study

4. APPROACH

The intention of this report is to provide a conceptual model of the geomorphology of the Taw-Torridge estuaries that can be used to assess the changes in geomorphology that might arise as a result of changes in such external factors as sea level rise, climatic change, and estuarine management. The development of a conceptual model will allow the application of a number of geomorphological models that will provide some quantification of the predicted changes in morphology. It is intended that these predictions can subsequently be used to provide guidance for the future management of the estuary.

The approach to both the conceptual and the geomorphological modelling is one based on that of dynamic equilibrium in coastal geomorphic systems. Total equilibrium or stability is, of course, unattainable for a coastal system since external factors are constantly in flux and the system must respond to these. However, if these external factors (for example waves and tides) vary within limits and experience no long term trend then the morphology will also vary around a mean value. Dynamic equilibrium is the concept of variation within limits and around a long term mean.

The concept of dynamic equilibrium assumes that the external forcing factors of the coastal system are themselves experiencing no long term trends. In its simplest form these external factors consist of three elements: energy (i.e. waves, tides, winds etc); materials (i.e. mainly sediments, but also biological materials); and human intervention in the system, often in the form of management.

In order to achieve a long term dynamic equilibrium a coastal system must achieve a balance between imports of energy and materials and exports of these. A stable coastal system is defined as one in which, over a significant time period, inputs of energy and materials are balanced by outputs.

This balance between inputs and outputs is achieved by adjustments to the morphology of the coast so that, for example, a coastline receiving sediment inputs from a river may alter its orientation to the incident waves thus increasing its sediment transport potential until river inputs equals longshore outputs .

It is recognised that such a balance between inputs and outputs is a theoretical one and can never be perfectly achieved since external factors do experience long term trends and thus coastal morphology will also be experiencing long term change as it constantly attempts to reach an equilibrium position. The morphological response of the coast to changes in energy and materials, for instance as a result of climate change, in order to maintain this balance between inputs and outputs, forms the basis of this report.

The geomorphological response of a coastal system to natural changes in energy and materials is capable of significant modification by coastal management. For example, the provision of coastal defence structures can alter the morphological response of a coastline and prevent it from attaining a dynamic equilibrium. Coastal management must be included in any evaluation of morphological change and resulting coastal hazards.

The basic model applied to the evaluation of coastal hazards in this section of the report therefore consists of four elements:

- Energy
- Materials
- Management
- Morphological response

The linkages between the three forcing elements and coastal morphology are shown in Figure 10.

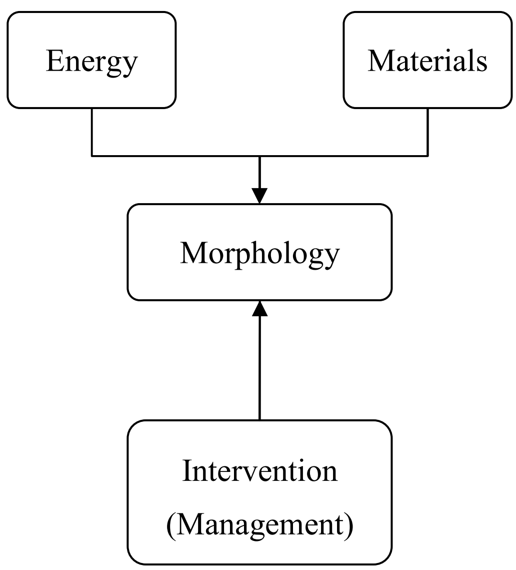

Figure 10: The controls of coastal morphology

4.1 The Estuaries

The geomorphology of the Taw-Torridge estuaries can be assessed under three major headings:

- Channel dimensions
- Channel plan

- Mouth configuration

4.1.1 Channel dimensions

The first of these attributes, channel dimensions, is the equilibrium form that the channel below HWMST must adopt in order to minimise morphological change over a medium term period. This assumes that there is no long term change in the three basic variables of energy, sediments and management. This concept of minimum morphological change, referred to above as dynamic equilibrium, is also known as estuarine regime. It assumes that minimum work by the estuarine system is the ultimate steady state and that this is achieved when no net sediment movement occurs, so that erosion and accretion tend towards zero.

In order to achieve a morphology that will minimise such change, channel bed shear stresses must be held at a level that is just below the critical erosion stress and just above the critical deposition stress. Clearly, constant variation in external forcing factors such as tidal range, freshwater discharges, storm surges, and wind waves mean that the attainment of a critical bed shear stress must be an average condition, achieved over a long period, perhaps measured in decades. Moreover, the critical erosion and deposition stresses are themselves a function of the sediments of the estuary bed and banks and are also subject to change over time. Thus although the morphology of the estuary may vary constantly this variation will be cyclical and between limits so that there will be no long term trend. Nevertheless, despite these complex variations, the concept of a regime form leading to a minimisation of morphological change has been found to be a useful one when applied to a medium term prediction of estuarine behaviour. Definitions of medium term are difficult to predict but, for macro-tidal estuaries such as the Taw and Torridge, will be in the region of decades.

The relationship between the conceptual model framework for coastal systems, discussed above, and estuarine regime models is a close one. Thus regime modelling is employed in this report to provide quantification of the morphological changes that can be expected as a result of, for example, sea level rise, climate change or management decisions. The regime model used in this assessment was developed for the Emphasys project (HR 2000) and has been successfully applied to several east coast estuaries including the Blackwater, Crouch/Roach; and Humber and west coast estuaries including the Esk; Ribble; Severn; and Parrett. A full discussion of the application of regime modelling is given in Defra (2007) and details of the model as applied to the present study are given in section 3.

4.1.2 Channel plan

Regime modelling can be used to provide prediction of the variation in channel width and depth along the length of an estuary and thus provide a reasonable indication of the estuary plan-form. It does not, however, provide any indication of the sinuosity of the estuarine channel: its meandering pattern. An understanding of meander pattern is essential for management purposes, for example flood defences are placed under stress at the apex of meander bends, and thus a geomorphological meander model has been adapted for use in this study and details are provided in section 5.

4.2 The Open coast

One of the critical issues under review in this study is the relationship between the estuaries and the open coast of Bideford Bay, including the Northam and Braunton

Burrows and the Westward Ho! Pebble ridge. No quantitative modelling has been attempted for this complex area. Instead a conceptual geomorphological model has been developed based upon existing literature providing an assessment of the qualitative manner in which the coast and estuary interact and may develop in the future.

5. MODEL SPECIFICATION

5.1 Regime model

Attempts to model the processes involved in order to predict even short term geomorphological development in an estuary have proved elusive. So-called 'bottom-up' hydro-dynamic models, which attempt to integrate physical processes to give morphology have been particularly unsuccessful over time scales of more than a few tides. 'Top-down' models that ignore processes but concentrate instead on predicting the equilibrium balance between stress and strength have been more successful in predicting time-independent forms but fail to predict short to medium term changes. Hybrid-models, incorporating elements of both 'bottom-up' and 'top-down' models are currently being developed within research programmes (Whitehouse 2001; HR Wallingford 2007).

Regime models are a form of top-down models that rely on a semi-empirical approach to give prediction of the ultimate equilibrium morphology of an estuary in response to changes in external factors. The approach does not allow any production of the rates at which estuaries may respond to changes in environmental controls.

Simple power laws connecting discharge and channel morphology have been used for many years in fluvial geomorphology where they are known as hydraulic geometry (e.g. Leopold 1964). In the coastal case O'Brien (1932, 1972, 1976) and Escoffier ((1940,1977) related tidal discharge or tidal prism (Ω) in coastal inlets, to mouth area, A_m using expressions of the type:

$$A_m = k\Omega^n$$

This approach was applied to a large sample of estuaries by Gao and Collins (1994) who derived empirical values for the k and n components of the basic power relationship. The approach has also been used by Spearman et al (1998) and Pethick & Lowe (2000).

The model developed by Pethick & Lowe (2000) uses the general inter-estuary relationship between tidal prism and cross sectional area of the estuarine mouth and applies this to the intra-estuary case. This assumes that the tidal prism/cross section relationship applied equally to each section of a given estuary as it does to individual estuaries. The resulting model allows prediction of the regime relationship between cross section area and tidal prism for any given section of an estuary.

The constants in the regime expression used in the present model were evaluated from empirical derived data from UK estuaries. Figure 11 shows the relationship for the sample of estuaries using data as set out in Table 6. Using these empirically derived constants the regime expression can be used to predict the variation in the cross sectional area of an estuary channel at any distance along its length.

Estuary Name	Tidal prism (m3)	Mouth area (m2)	Log Tidal prism	Log Mouth area
Esk	8,770,728	475	6.943	2.677
Torridge	15,598,065	7640	7.193	3.883
Parrett	16,311,000	3037	7.212	3.482
Lune	21,320,000	3475	7.329	3.541
Camel	22,321,000	7897	7.349	3.897
Wyre	26,643,000	3680	7.426	3.566
Taw	53,334,000	8483	7.727	3.929
Duddon	93,784,000	18000	7.972	4.255
Ribble	120,245,000	10985	8.080	4.041

Table 6: Sample of UK estuaries used in the analysis.

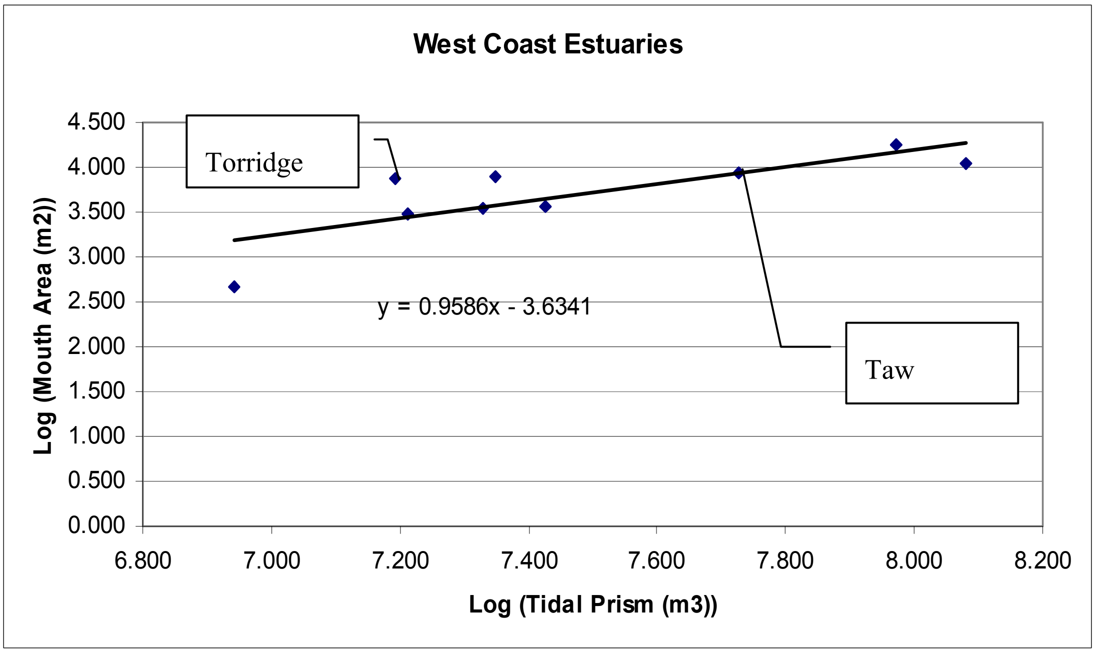

Figure 11: Relationship between tidal prism and cross section area for a sample of UK west coast estuaries as used in the model (see Table 6)

In this case the regression equation that best describes the behaviour of west coast estuaries is:

$$CA = 0.0023.TP^{0.96}$$

Where: TP = tidal prism (m^3); CA = cross section area (m^2)

This regression equation was used in the regression model to predict the cross sectional area of the Taw-Torridge estuaries at incremental distance along their length.

The cross sectional area of an estuary channel is not a particularly useful measure of estuarine characteristics, particularly for management purposes. In order to derive channel width from cross sectional area a model developed by Hughes (1999) was used that predicts the equilibrium scour depth of an estuarine channel from sediment grain size and tidal current velocity. The equation developed by Hughes is:

$$V_m = 5.12\{g(S_s\text{-}1)\}^{1/2}\ d_e^{3/8}\ h_e^{1/8}$$

Where: V_m = maximum tidal velocity; S_s = specific gravity of sediment grains; d_e = sediment grain mean diameter; h_e = mean channel depth

Using this relationship equilibrium depth was derived for each reach of the estuaries and thus channel width from:

$$W_e = CA/h_e$$

Where: We = equilibrium channel width (m)

It is this regime width, calculated for MHWNT, that is used to define the regime (or equilibrium) channel dimensions. It is emphasised that the regime model predicts width for high water neap tides (HWMNT) amd high water of spring tides (HWMST) may lie a considerable distance landward of this. This area between HWMNT and HWMST is outside the equilibrium channel and thus is a potential area for the development of salt marshes. Salt marshes will not necessarily develop in this location however; this depends on several further factors such as sediment availability and the exposure of a site to wind-generated waves. Nevertheless, the model output does provide a good indication of potential salt marsh development.

5.2 Accuracy of model prediction

The accuracy of the model depends principally on the empirical input data for the sample of estuaries shown in Table 6 and Figure 11. The 9 west coast estuaries represent the best available data set for this area and for which accurate tidal prism and mouth areas are known. Nevertheless the data set is small and this contributes to the error margins within the model.

Using standard statistical analysis the error term associated with the input data was calculated. The standard error of the data was calculated for the 5% and 95% probability levels as shown in Figure 12 . This allows the error margins to be calculated for the log/log regression data shown in Figure 12. Conversion of these log data to linear form provides a more accessible form for the error term and these are shown in Table 7.

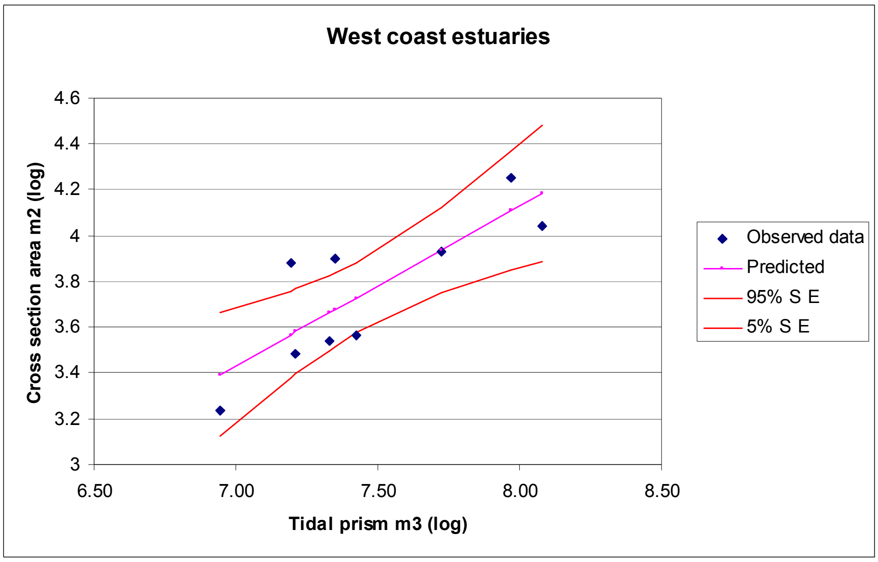

Figure 12: Standard errors (SE) at the 5% and 95% P levels for the west coast estuaries data set.

It will be noted that the error term associated with the data is not constant but increases away from the centre of the distribution. This means that estuaries that lie centrally in the distribution of tidal prism and mouth area will be associated with lower error terms than those on the margins of the distribution. In the case of the Taw and Torridge estuaries, their position lies towards the margins of the distribution so that although the minimum error term is calculated to be +/-23% the error for the Taw is +/-28% and that for the Torridge is +/-29%. These error terms are to be applied for all predictions made in this report.

	Observed data (log)		Standard error terms (log)		Linear conversion			
Estuary	Tidal prism (m3)	Mouth area (m2)	SE 5%	SE 95%	Mouth area (m2)	SE 5%	SE 95%	Error term (%)
Esk	6.94	3.24	3.19	3.60	2470	1541	3959	37.61
Torridge	7.19	3.88	3.42	3.71	3687	2631	5167	28.64
Parrett	7.21	3.48	3.44	3.72	3803	2737	5285	28.04
Lune	7.33	3.54	3.54	3.79	4583	3434	6114	25.05
Camel	7.35	3.90	3.55	3.80	4731	3563	6282	24.68
Wyre	7.43	3.57	3.61	3.85	5351	4081	7017	23.74
Taw	7.73	3.93	3.80	4.08	8674	6244	12050	28.02
Duddon	7.97	4.26	3.91	4.31	12847	8136	20285	36.67
Ribble	8.08	4.04	3.96	4.41	15273	9053	25766	40.73

Table 7: Standard error terms for estuary input data shown in Table 6.

5.3 Meander model

Three formulations are required to describe fully the shape of a meander:

5.3.1 Meander wavelength

Many empirical formulae exist for predicting the meander wavelength in freshwater flows. Ferguson (1975), for example, predicted fluvial derived wavelengths (L_f) in terms of the freshwater discharge that is exceeded 1% of the time over a minimum of 6 years (Q_f). His formula, now accepted as the classic meander wavelength model is:

$$L_f = 57Q_f^{0.58}.$$

Geyl (1976) proposed that tidal meander wavelength (L_t) increased with tidal discharge and presented an empirical formula based on measurements from tidal channels within the Dutch Wadden Sea : L_t=$132Q_t^{.49}$ where Q_t is the tidal discharge averaged through the tidal period). It is this basic expression that is used in the present model.

5.3.2 Meander amplitude or sinuosity

This is the least readily understood parameter for tidal meanders. Geyl (1976) showed that the radius of curvature of tidal channels in the Wadden Sea increased with tidal discharge. However, no further shape parameters were described and the radius of curvature together with the wavelength is insufficient to describe the meander amplitude or sinuosity.

In the absence of any published theoretical relationship between tidal meander amplitude and tidal discharge, an empirical approach is used. Tidal amplitude was measured in 7 UK estuaries for which tidal prism was known (**Figure 11**). The data were then used to calculate a relationship between mean tidal discharge (Q_t) and tidal amplitude (A_t):

$$A_t = 49.9Q_t^{0.38}$$

5.3.3 Meander shape

Langbein and Leopold (1966) presented a model for meander shape in rivers, based on minimising the variance in channel direction. This was achieved by varying the channel direction sinusoidally as follows:

$$\vartheta = \omega \sin 2\pi \frac{x}{L_*}$$

where ω is the maximum deviation and x is the distance along the channel or meander length (L_*).

6. THE CONCEPTUAL MODEL

An initial approach to understanding the future behaviour of the Taw-Torridge estuarine system and its associated coast is to develop a conceptual model of its geomorphology. In order to do so the system has first been broken down into three sub-units:

- Open coast
- Tidal delta
- Estuaries

Assessment of the geomorphology of these sub-units will be followed by a synthesis in which an overall conceptual model is proposed.

6.1 Open coast

The beaches, dunes and pebble ridge that form the open coast of the study area represent one of the highest energy shores in the UK. The 50 year wave height of 6.8m for example compares with 3.9m on the South Devon coast and 6.0m on the Gower coast in South Wales. This high wave energy input coupled with a macro-tidal range of 8.0m mean that attainment of a dynamic equilibrium state could only be achieved through major morphological adaptations.

There are two theoretical possibilities for such a morphological adaptation:

- Drift alignment
- Swash alignment

Either the system is drift aligned so that the high energy input is dissipated in sediment transport, or the system is swash aligned and the shore is parallel to the incident wave crest so that wave energy is dissipated in friction on the beach or reflection. There is, of course, a spectrum of morphological adjustments between each of these polar states, such that a system may reduce its drift alignment by re-orientation of the shore in response to a fall in sediment inputs.

The first of these theoretical possibilities appears, at first sight, to be more probable than the second. The dominant wave direction is from the west (see section 3.3) with minimum refraction in the near shore zone so that a swash aligned coast would be expected to be orientated approximately north-south. In fact the shoreline of Northam Burrows, south of the tidal delta, is orientated at 24° east of north. Saunton Sands however is orientated at 4º east of north (see Figure 1). Since sediment transport rates increase as the angle between wave crest and shore, the geomorphological implication is that there is a strong sediment movement northwards along the Northam Burrows shore but that there is a much weaker longshore sediment movement along the Saunton Sands.

This tentative conclusion is given more credence if the movement of clasts along the Northam Burrows pebble ridge is considered. Most estimates put the rate of pebble transport northwards at $5000m^3$ per year implying a strong drift alignment that must also apply to sand sized sediments on the inter-tidal beach. No estimates have been made in the literature of the potential or actual volumetric rates of the longshore movement of sand along this shore. Comparisons with similar high energy open beach systems however, suggest that it would be not unreasonable to assume that the net northward drift would be in the region of $100,000m^3$ to $250,000m^3$ per year. It is not probable that these high rates of potential transport are attained on this shore. The Northam Burrows and Saunton Sands inter-tidal beaches are reported to be veneer beaches, with a thin mantle of sand over underlying clays. The planar surface of these beaches suggests that actual sand transport is limited, perhaps by availability of material.

The orientation of the two shore systems appears, from evidence available, to be shifting slightly towards a reduction in the rate of longshore drift, that is slightly towards a swash-alignment. Two sources of evidence suggest this possibility: the map of the pebble ridge development over the past 100 years presented by Stuart and

Hookway (1954) shows that the high water mark of the Northam Burrows shore had re-orientated in a counter-clockwise direction with a pivotal point at the Sandy Mere (Figure 13). Similarly the SMP (Halcrow 1998) states that the low water mark of Saunton Sands has retreated landwards over the past 100 years by 30m in the south and 80m in the north, a slight but unmistakable decrease in drift alignment. In both cases the geomorphological implication is that there has been a slight decrease in the volume of sediment moving northwards along these shores.

Despite these strong indications of strong northwards longshore sediment transport, there are two major arguments against such a hypothesis:

- No sediment source
- No sediment sink

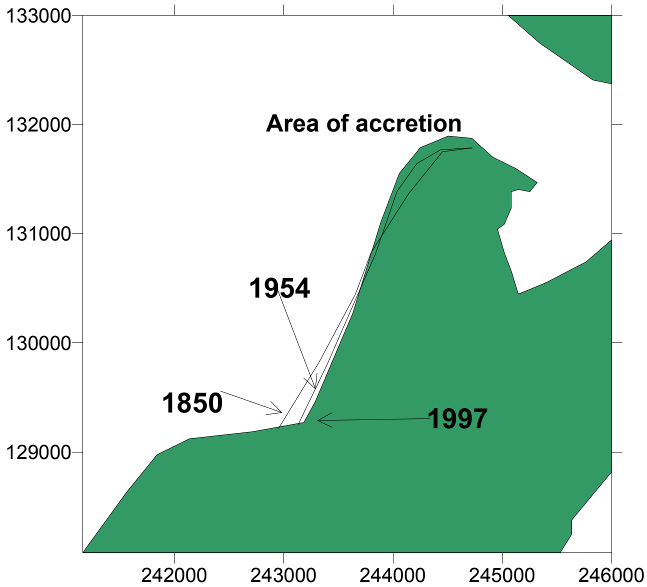

Figure 13: Movement of the pebble ridge 1850 – 1997. Data for 1850-1954 from Stuart and Hookway (1954). 1997 shore from OS 1: 25,000.

6.1.1 Sediment source

Previous studies of this shore have concluded that there is no modern sediment input into the bay. Kirby, for example, referring to the sediment contained within Bideford (or Barnstaple) Bay states that '*Barnstaple Bay appears to contain an isolated unconsolidated residual which has been passed by in the main westerly migration of the Channel feed*' and again '*Barnstaple Bay cannot hope to gain sand, only to lose it seaward or at best remain stable in future'* (Kirby 1996 p 33-35). The SMP (Halcrow 1998) confirms this view of an isolated sediment body with no modern inputs from marine or fluvial sources.

6.1.2 Sediment sink

The movement of sediment northwards within Bideford Bay is also difficult to reconcile with the lack of an obvious northern sink. Although some movement across the headlands of Saunton Downs and Baggy Point may be possible it is unlikely that any major sediment transfers take place here. Neither Saunton Sands nor Braunton Burrows sand dunes appear to have increased their sediment volume significantly over the past century although they clearly were a significant sediment sink in the mid-Holocene. The low water mark on Saunton Sands has retreated landward by between 30m and 80m over the past 100 years (Halcrow 1998) Kidson and Carr (1960) suggested that the dunes had increased in height over the period 1885 to 1960 and migrated landwards but Kidson (1989) further notes that the vegetated edge of the dunes had remained stable during the same period, implying that the increased dune height was due to internal sediment redistribution. However, comparison of the Denham (1832) chart with the OS 1997 1:25,000 Revision shows an advance of the HWMST by approximately 150m over a 2km stretch of the Saunton Sands shore, while the SMP (Halcrow 1998) estimate that this advance has been in the region of 20m to 60m over the past 100 years. Assuming an average sediment depth of 2m these observations imply accretion rates of between 800m^3 and 4000m^3 per year over the past 100 to 150 years which, it can be argued, are insufficient to account for the potential sediment transport rates on this high energy shore.

6.1.3 The double-gyre model

The SMP (Halcrow 1998) provides some explanation of these seemingly irreconcilable facts. They propose that tidal residual circulation within Bideford Bay re-circulates sediment so that neither external source nor sink is necessary. If this outline hypothesis is examined in detail several complications arise. First, the SMP bases its argument upon work by GeoSea Consulting (1997) who suggest that two gyres exist in the bay which converge along the line of the Taw-Torridge tidal delta. The southern gyre rotates counter-clockwise so that it enhances wave-driven longshore sediment transport on the Northam Burrows shore while the northern gyre rotates clockwise so opposing the weaker, northwards wave-driven drift along Saunton Sands. The convergence of these two gyres along the line of the Taw-Torridge channel through its tidal delta, is crucial to the long term stability of the system. As wave driven sand converges from the north and south within the delta so the ebb-dominant tidal discharge from the Taw-Torridge estuaries carries the converging sediment seaward where it is temporarily deposited in the centre of each gyre before resuming its pathway and re-entering the nearshore sediment movement at Westward Ho! in the south and Saunton Down in the north. Thus, assuming an efficient re-circulatory system, neither sediment source nor sink is required for long term stability of this coast.

6.1.4 The single gyre model

The double-gyre model as proposed by GeoSea (1997) may well account for the observed movements of sediment in Bideford Bay and the lack of any obvious source or sink. It does, however, present several apparent anomalies that need further examination. The first of these is the implication that sediment is transported south along Saunton Sands by a weak tidal residual within the clockwise gyre, that is in opposition to the wave-driven currents in a northward direction. Although it was shown above that the orientation of the Saunton Sands shoreline was 4º east of north so that a much lower sediment transport rate would be present here than in the Northam Burrows case, nevertheless, this shore experiences an extremely high wave energy input and it seems unlikely that the tidal residual would result in a net longshore movement south towards the Taw-Torridge delta. The second anomaly is shown in the diagrams presented as Volume 3 of the SMP (Halcrow 1998). In Maps 3 and 4 of Volume 3 of the SMP Halcrow show the results of their tidal model within Bideford Bay. The maps show a single, counter-clockwise gyre with a strong residual current flowing north east from the Taw-Torridge delta towards Baggy Point before turning south to south west and eventually north along the Northam Burrows shore.

Although the evidence presented in the SMP is contradictory there are some reasons to support a single, rather than a double, gyre model. The first is that a single gyre does not entail the opposition of the strong northward wave driven current along Saunton Sands. The second reason is the strong evidence that sand moved northwards along the Northam Burrows shore does bypass the Taw-Torridge channel and arrive on the Saunton Sands shore at Airy Point (see discussion below section 6.2). If such a movement does take place then under a double-gyre model this sediment would enter into the northern clockwise gyre. The long term result would be a transfer of sediment from the south to the north of the bay, a transfer that would result in morphological changes that, as discussed above, are not evident.

It is emphasised that the currents experienced within this tidal gyre will be tidally induced and therefore not competent to transport sediment coarser than fine to medium sands. Thus transport of cobbles along the Northam Burrows shore and into the mouth of the estuaries, is thus a result of wave driven currents in the near shore zone.

6.1.5 Conclusion

The morphology of Bideford Bay presents a strong argument for a drift alignment in which sand sized sediment is moved northwards by wave-driven longshore currents. The lack of any obvious sediment source for such a longshore movement; the closure of the sediment pathway in the north by the Baggy Point headland; and the slow rates of accretion of sediment within Braunton Burrows or Saunton Sands; can all be explained by a re-circulatory system driven partly by tidal residual currents and partly by wave-driven currents. The possibility of this re-circulatory system resulting from a double gyre within Bideford Bay is discounted here on the grounds that it would be in opposition to the wave-driven currents in the Saunton Sands area and that it would necessitate strict compartmentalisation of sand within each gyre to prevent long term morphological change. Instead a simpler, single gyre model is proposed in which sediment is re-circulated around Bideford Bay and, in so doing, bypasses the Taw-Torridge tidal delta. The mechanism for such a sediment bypass system is discussed in the following section.

6.2 The delta

The estuaries of the Taw-Torridge meet the sea in a classic tidal delta. Figure 14 taken from Carter (1988) shows the major components of such a delta. The twin barriers of Northam Burrows and Braunton Burrows define the boundaries of the ebb-delta and are an integral part of its function. The ebb ramp is formed by Bideford Bar and the swash bars are represented here by features such as the Zulu Ridge, the Middle Ridge and the North and South Tail. Within the estuary mouth the flood-delta is represented by the Instow Sands and flood ramps by features such as the Sprat Ridge.

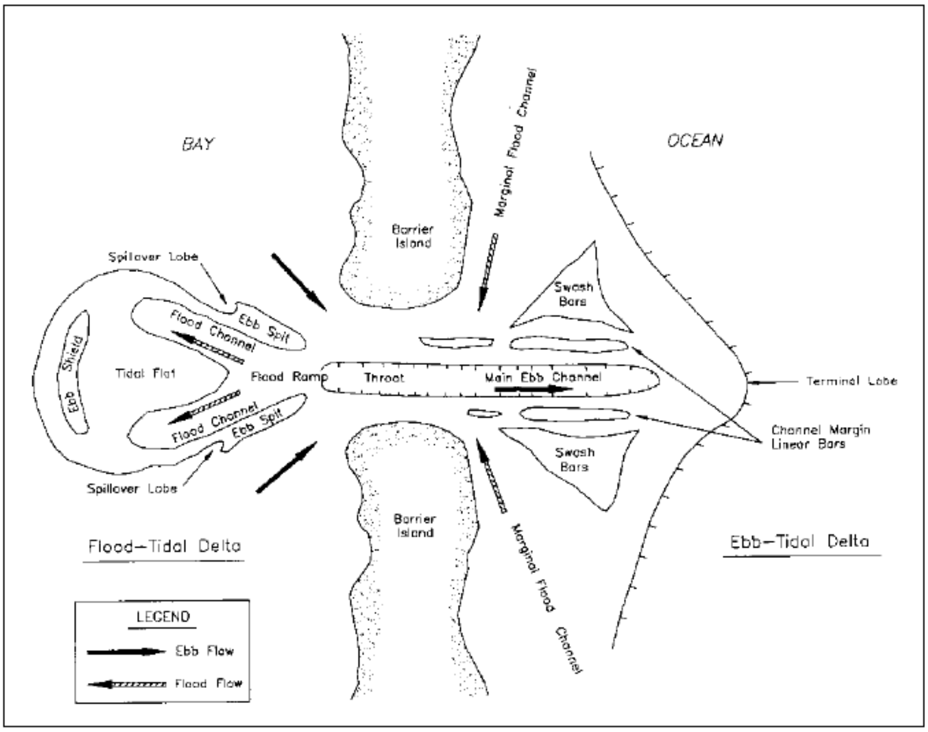

Figure 14: Structure of a typical tidal delta.

The tidal delta is a morphological response to the discharge of an estuary across an open coast sediment pathway as shown by Nummidal and Penland (1981) in their seminal work on the Frisian Islands (Figure 15). If the tidal power of the estuary is sufficiently great, as in the case of the Taw-Torridge estuaries, it can interrupt the sediment moving along the open shore. Some of the interrupted sediment moves into the estuarine channel and is carried seaward where it is deposited where tidal current velocities fall off in unconfined water – forming the ebb-ramp. Most of the interrupted sediment however builds up on the banks of the estuarine channel forming a series of sand waves or bars. These bars gradually migrate around a semi-circular pathway across the delta front, passing along the ebb-ramp and then are driven shoreward where they eventually weld onto the shore on the down-drift side of the delta. This process of sediment bypassing is event driven, that is it only occurs episodically during extreme wave events so that a single bar-transfer may take several years to complete.

The shore-welded bar on the down-drift side of the delta causes local accretion of the barrier which develops a characteristic 'leg-of-mutton' shape shown in Figure 15. Most of this sediment then continues along its longshore pathway away from the estuary mouth. Some of the shore-welded sediment, however, moves into the estuary mouth driven by flood tide currents that flow inshore of the more dominant ebb-currents in the central channel. This sediment is subsequently deposited on the flood delta within the estuary from where it is gradually re-eroded and moved seaward to the ebb-ramp by ebb-tide currents so that a minor circulatory pathway is established within the estuary mouth across which flows the uni-directional longshore sediment pathway.

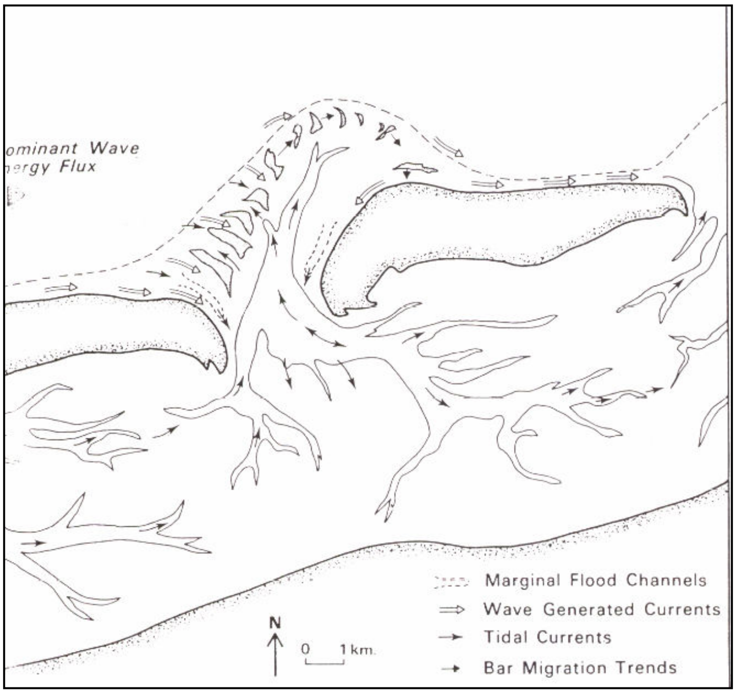

Figure 15: Sand bypassing system through tidal delta, Frisian Islands, from Nummedal & Penland (1984). Note the similarities with the morphology of the Taw-Torridge system.

The Taw-Torridge delta system displays all of the characteristics of a typical tidal delta. In particular, it is notable that Airy Point appears to be the location to which sand bars are driven and become shore-attached. Maps and aerial photographs show a series of sand bars at Airy Point and historical records show that accretion here is frequent but sporadic: typical behaviour of these deltaic systems. The intermittent accretion at Instow Sands also appears to be due to the event-driven movement of sand around the clockwise circular pathway within the estuary mouth and may be part of a sequence in which sand first arrives at Airy Point, is subsequently driven landwards along Crow Point, across the channel to Sprat Ridge and thus to Instow from where it moves west into the Skern, or seaward onto the Zulu Bank.

The critical issue here is that the sediment moving northwards along the Northam Burrows shore appears from the morphological evidence and from comparison with other similar deltaic systems, to bypass the Taw-Torridge estuary channel where most of it moves into the Saunton Sands nearshore. If this is indeed the mechanism, and assuming, as argued above, that there is no external modern source for sediment within Bideford Bay, then the sand moved into Saunton Sands must eventually be returned to the Northam Burrows longshore drift pathway. It is proposed above that this is achieved by a single tidal residual circulation system that moves sediment along the Saunton Sands shore, seaward towards Baggy Point and then returns it south and west towards Westward Ho! where it resumes its northward drift towards the Taw-Torridge delta.

The movement of sediment outlined above, along the Northam Burrows shore and passing into the Saunton Sands, means that the two barriers: Northam Burrows and Braunton Burrows, have evolved in opposite directions, Northam Burrows accreted northwards as sand arrived from the south. Braunton Burrows accreted southwards as sand arrived at the proto-Airy Point and became shore-attached. The morphology of the southern section of Braunton Burrows, with its characteristic bulge at its south west edge and its pattern of sand dune ridges, reflects this geomorphological evolution.

6.3 Estuaries

6.3.1 The Taw-Torridge system

The estuaries of the Taw-Torridge are distinct from each other in morphology yet share a common mouth, a complexity that provides some difficulty in the development of a conceptual model. Accordingly it is necessary to anticipate the results of the analysis in order to provide a coherent commentary, and to propose that the Taw estuary together with the shared mouth region is considered as the dominant component of the system. This means that the discussion will concentrate on the Taw together with the mouth region between Instow and the Bideford Bar; it is proposed to refer to this entire system as the Taw Estuary. The Torridge will be examined as a separate entity; its confluence with the Taw will be defined as a line drawn between Instow and Appledore. It is emphasised that these definitions are made for the purposes of clarity and that in fact the Taw-Torridge system cannot be geomorphologically sub-divided in this manner.

6.3.2 Incised channel

The bathymetric survey of the Taw undertaken for this study has revealed two hitherto unknown or perhaps previously disregarded morphological features. The first of these is that the outer Taw channel is characterised by a deeply incised (10m), narrow (120m maximum), channel cut into the wider bed of the estuary. It is assumed that this channel is cut into bed rock (Upper Carboniferous sandstones) and represents a former, perhaps late Devensian/early Holocene fluvial channel flowing northwards to a lower sea level.

Figure 16 shows this incised channel in the outer estuary, that is west of Appledore looking seaward. Fig 15 also shows that profiles 3 and 4 (see Figure 3 for profile location) exhibit a secondary incised channel located 320m south of the main incised channel in profile 3 and 580m south of the main incised channel in profile 4. In profiles 5,6 and subsequent profiles along the Taw and profiles 36, 37 and subsequent profiles along the Torridge no such secondary channels are shown. The conclusion drawn is that these secondary incised channels represent the fluvial river of the Torridge immediately east of its confluence with the fluvial Taw when sea level was at least -14m below present, since the most seaward incised channel bed is at -13.5 mOD. According to Long et al (2002) sea level was at -15m at 8000years BP. Figure 17 shows the confluence of the two rivers at 8000BP it demonstrates that the present Sprat Ridge lies between the two rivers at their confluence suggesting that this feature predates the estuaries of the Taw-Torridge and is an early Holocene component of the landscape. This analysis also demonstrates that the Taw and Torridge have occupied their present channels at least for the entire Holocene period and probably prior to that. This means that the possibility of alternative routes for the Taw mouth, such as that along the northern flank of the Appledore promontory towards an outfall at Westward Ho! following a linear depression in the estuarine clays, must be discounted. Instead this former channel was probably a minor marsh creek acting as a tributary to the Taw.

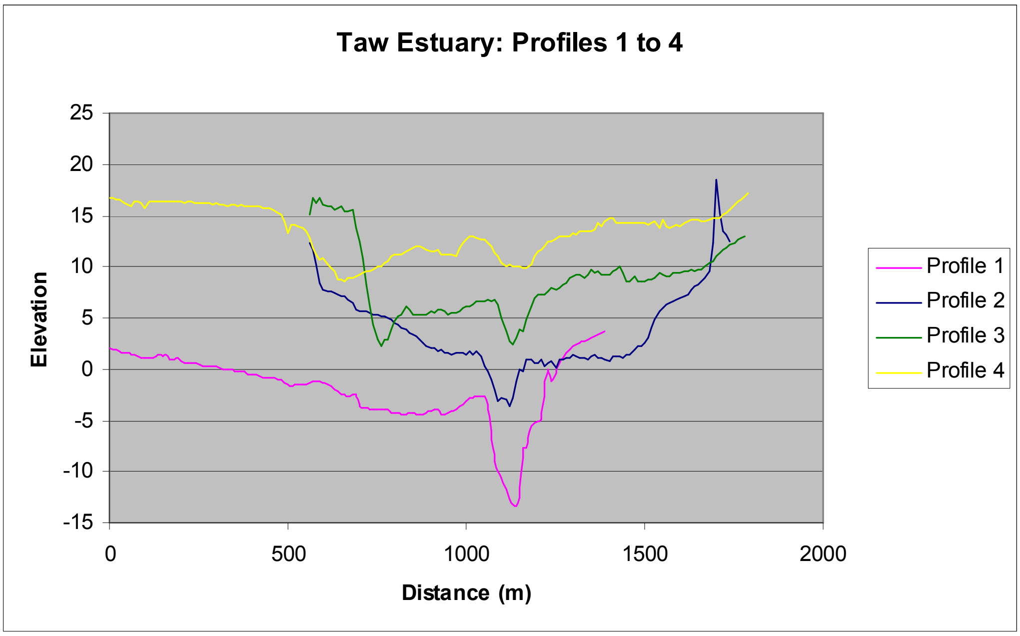

Figure 16: Cross sections across the outer Taw Estuary. Profiles are plotted at different heights for clarity and the central incised channel has been aligned. Note the secondary incised channel in profiles 3 and 4

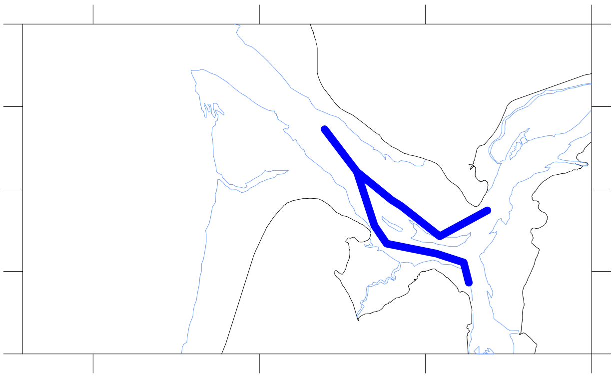

Figure 17: Confluence of the Taw-Torridge fluvial rivers at 8000years BP, mapped from bathymetric data.

6.3.3 Long profile

The second morphological feature revealed by the bathymetric survey is the unusual long profile of the Taw Estuary. Figure 18 shows that this profile is concave upwards along its fluvial section and that this concavity continues conformably into the tidal section to Penhill Point at 10,000m from the sea. This is the normal shape of both fluvial and tidal long profiles and represents the adjustment of stream gradient to the downstream increase in discharge resulting in a constant power expenditure (see for example Richards 1982). Seaward of Penhill Point, however, the profile departs from this normal concave form and becomes sharply convex. The profile also becomes irregular seaward of Penhill Point with sand bars alternating with the deep incised channel section noted above.

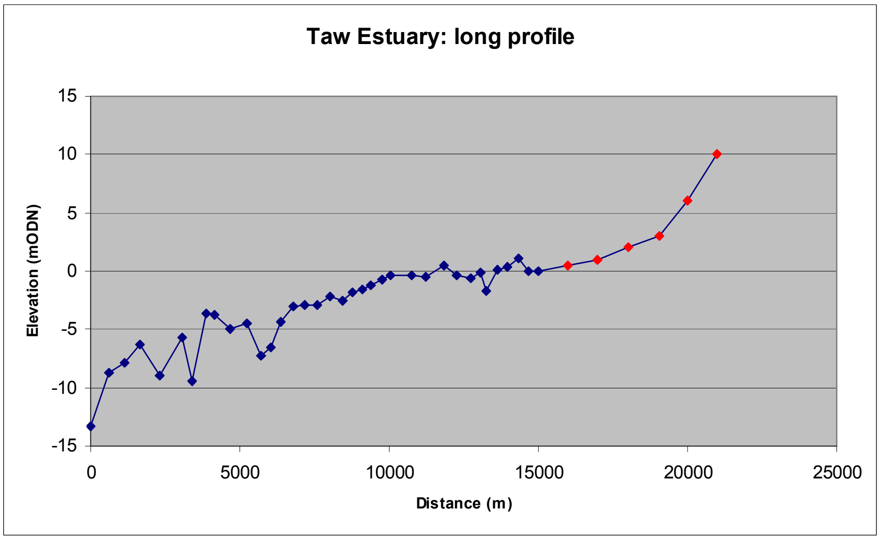

Figure 18: Taw estuary long profile. Note that red points are for the fluvial valley beyond the tidal limit. Penhill Point is located at 10,000m from the mouth.

This convexo-concave long profile appears to be a response to the extremely low suspended sediment concentrations in the tidal waters of the Taw Estuary. The relative lack of fine sediment has meant that that deposition of mud-banks has not been able to keep pace with rising sea levels during the Holocene and only the inner estuary, between 10,000m and 15,000m on Figure 18, has accreted sufficient fine sediment to produce a smooth concave long profile. Seaward of Penhill Point, that is at 10,000m from the sea, accretion has taken place but this is mainly of sand and has not yet been sufficient to produce a continuous concave profile as shown in Figure 18.

The probable Holocene sequence is shown in Figure 19. In the early Holocene between 10,000 and 8000 years BP sea level rose from -30m to -15m below its present level and a fresh water river flowed in the Taw valley and out into what is now the Bristol Channel, cutting or perhaps exhuming the channel, now seen as the incised channel in the outer estuary, and forming a smooth long profile. The probable form of this early Holocene fluvial long profile is shown in Figure 19. Accretion has subsequently taken place within the estuary and Figure 19 shows the extent and depth of this deposited sediment , with some 5m depth of sediment in the outer estuary thinning towards the tidal limit.

If sea level was to remain constant at its present level, deposition would eventually result in a smooth concave long profile reaching the sea at an elevation of -3mOD (present LWMST) and merging landward into the existing fluvial river profile as shown in Figure 19. Accretion of a further 5m of sediment in the outer estuary would be necessary to achieve this profile even without the predicted future increase in sea level. The existing profile is therefore in an early developmental stage but has taken at least 6000 years to develop thus far. It seems probable that at least a further 6000 years will be required before deposition attains a stable long profile for this estuary or longer if accelerated sea level rise is taken into account.

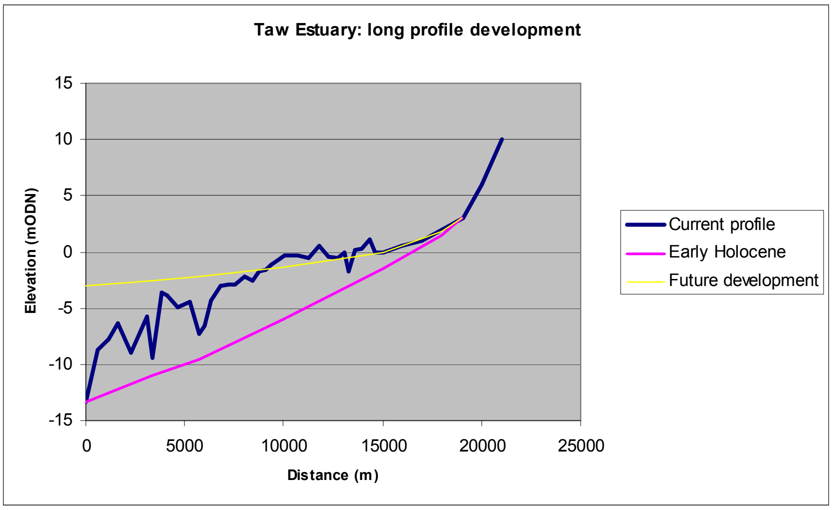

Figure 19: Probable Holocene development of the Taw long profile.

This analysis of the Holocene development of the Taw suggests that there is a fine sediment deposition-front presently at Penhill Point but moving steadily seaward. Such an hypothesis would explain the progressive siltation of the channel at Barnstaple and its abandonment as a trading port in the 19th century (SMP 1998, p1.25) and also the growth of salt marshes at Pottington, west of Barnstaple and along the Anchorwood Bank on the southern bank of the Taw in the same reach. Seaward of Penhill Point deposition has mainly been of sand although increasingly fine sediment deposition has characterised the upper inter-tidal areas. It is predicted that the fine sediment deposition front will continue to progress seaward over the long term future.

6.3.4 Outer estuary

The outer estuary presents a complex geomorphology some of which has been discussed in connection with the tidal delta morphology (Section 6.2). In order to reach the sea the Taw must first cross the high energy open coast shore with its high rate of sediment transport and this presents a major obstacle to flow. In order to maintain an open channel the estuary must resist this northwards movement of sediment, forcing it seaward to the ebb-tide delta. The necessary power needed to maintain the open channel must be provided by the tidal prism of the estuary but analysis of estuarine length conducted for Defra (Pethick 2007) suggested that estuaries with tidal lengths of less than 30km would not have sufficient tidal power to maintain their sea outfall without a number of morphological adaptations. The Taw whose tidal length, including the shared mouth section west of Instow, is 18km. However, the junction of the 11.5km long tidal Torridge with the Taw at Appledore, means that the composite tidal length of the two estuaries is 29.5km approaching the critical threshold for tidal competence at the mouth. Nevertheless, the Torridge estuary, as discussed below, has a relatively small tidal prism for its length so that the combined Taw and Torridge are not competent to maintain their shared mouth across the high energy longshore transport pathway of the open coast. As a result, the outer Taw estuary does appear to have developed two morphological adaptations that increase its competence for maintenance at its mouth.

Many estuaries, including the Taw, widen towards the sea creating inter-tidal lagoon areas. These have the effect of increasing the tidal prism within the estuary and thus providing additional power to maintain the shore crossing. In the Taw two inter-tidal lagoon areas are present: Horsey Ridge and the Skern. The tidal prism contributed by these two areas is approximately 6 x 10^6 m^3 representing over 10% of the total tidal prism of the estuary and this increases the tidal discharge within the mouth channel. These inter-tidal lagoons may have developed as a response to the part-closure of the estuarine mouth by longshore sediment movements so ponding tidal water within the estuary until sufficient discharge was available to maintain a flow across the shore. It appears from historical evidence that both areas were formerly much more extensive than they are today. Horsey Ridge was once part of the Horsey Island area that as largely reclaimed in the 19^{th} century. The Skern extended northwards into the Greysands Lake prior to its use as a landfill site. In both cases the loss of inter-tidal volume due to reclamation puts additional stress on the estuary mouth to maintain an open channel across the longshore sediment pathway.

A second morphological adaptation in the outer estuaries is the development of a narrow channel in order to increase tidal velocities. Increased tidal current velocity within the outer estuary is necessary to resist the movement of sediment into the channel from the longshore sediment pathway. This increased velocity is provided by a narrower channel than would be expected for an estuary mouth with this volume of tidal discharge as is shown by the regime modelling results discussed in section 7.0. The sub-tidal channel of the outer Taw narrows towards the sea (Figure 20) thus increasing velocities here to between 1.8m/s and 2.0m/s (SMP 1998) compared to average estuarine velocities of around 0.5m/s.

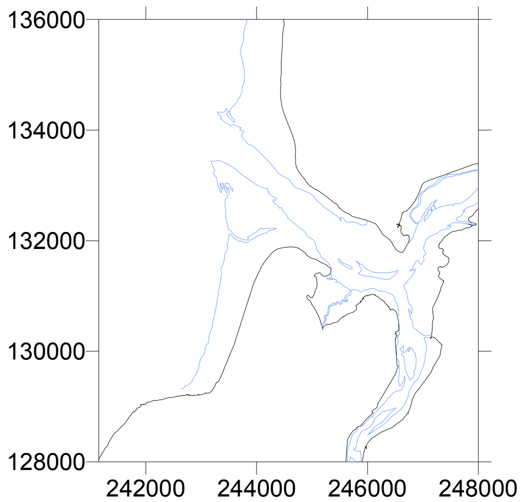

Figure 20: The sub-tidal channel of the outer Taw narrows towards the sea

These adaptations are important components of the geomorphological system of the Taw-Torridge estuaries and any management intervention that results in changes in either the width of the mouth or in the inter-tidal area landward of the mouth must be viewed with some concern. The implications are discussed in section 9.

6.4 The Torridge Estuary

The morphology of the Torridge Estuary contrasts markedly with that of its neighbour, the Taw, chiefly because of the constraints to the channel development imposed on the Torridge by its geology. This property of estuaries is often referred to as its accommodation space: that is the space available for estuarine channel development. Accommodation space is normally determined by the interaction of two factors: the geological and geomorphological rock framework in which the estuary lies and the relative sea level at any given time period. As sea level rise occurs, so accommodation space changes within the fixed geological frame.

The Torridge is bounded by steep rock valley sides with gradient ranging from 1:15 at Appledore to 1:3 in the incised gorge at Landcross. This deep and relatively narrow valley has constrained the Torridge estuary and has resulted in a distinctive channel geomorphology. However, the most obvious result of the constraints imposed by accommodation space is the relatively small tidal prism exhibited by the Torridge. The tidal prism of an estuary is a function of its tidal length. In most cases, given unrestricted accommodation space, tidal prism increases approximately as the third power of length. In the case of the Torridge the restricted accommodation space means that tidal prism is much smaller than would be expected. If the shared mouth of the Taw-Torridge estuary is omitted from the measurement, the tidal length of the Torridge from Appledore to the tidal limit at Wear Giffard is 11,500m. The tidal length of the Taw, again omitting the shared mouth, from Instow to the tidal limit at Bishop's Tawton is 15,100m. Yet the tidal prism of the Torridge is only one half that of the Taw: 15.6 x $10^6 m^3$ compared to 31.5 x $10^6 m^3$. This difference in the tidal discharge has a major impact on the morphology of both estuaries.

6.4.1 Long profile

The long profile of the Torridge lies at an almost identical elevation to that of the Taw and follows approximately the same slope as shown in Figure 21. The southern, landward section of the estuarine long profile passes conformably into the fluvial long profile in a smooth concave slope.

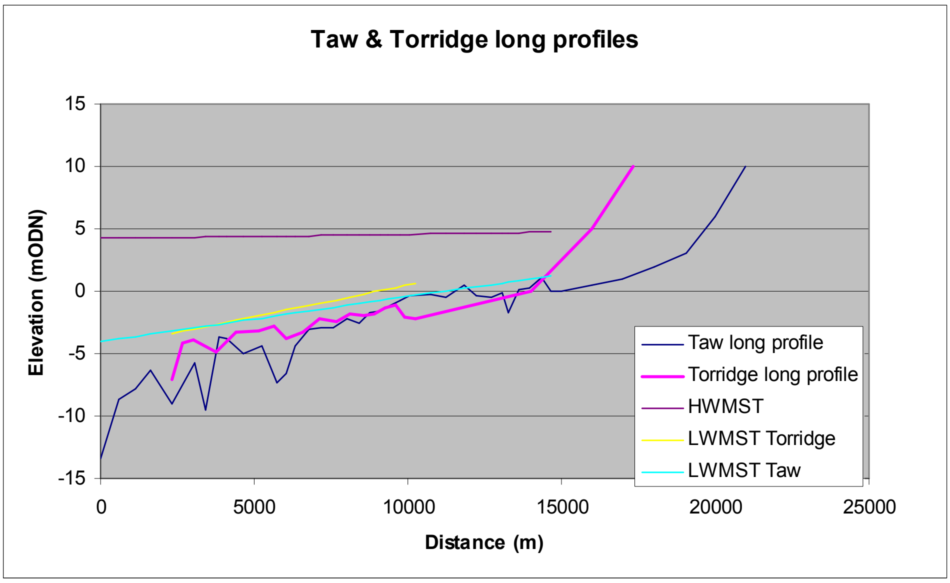

Figure 21: Comparison between the long profiles of Taw and Torridge. Spring tide high and low water gradients are superimposed .

The outer Torridge long profile, seaward of Appledore, shares the channel of the Taw and thus plunges into the sharp convexity of the outer Taw as discussed above (section 6.3.3). The middle section of the Torridge long profile therefore exhibits an almost linear slope connecting the inner concavity with the outer convexity. This central linear section of the long profile is a depositional feature and, as in the case of the Taw, represents approximately 5m of accretion laid down over the period since 6000 years BP.

These features of the Torridge long profile are similar to those of the Taw. The two estuaries depart from each other, however, in the relationship to the low water levels. Figure 21 shows that the low water gradient in the Torridge is both steeper and at a higher elevation than that of the Taw although, as shown in Figure 21, high water elevations are approximately the same, at equal distances from the sea, in both estuaries (Section 3.2). This means that the Torridge experiences a slightly smaller tidal range at any given distance from the sea than the Taw, a feature that is perhaps a result of increased frictional effects in its confined valley.

6.4.2 Channel morphology

The overall impact of these morphological and tidal characteristics is that, in order to maintain a channel cross section large enough to accommodate the tidal discharge at any point, the Torridge estuarine channel is forced by its constraining valley sides to become narrower and deeper than the channel of the Taw. This comparison may be seen in Figure 22 in which two cross sections at identical distances from the sea (8,500m) are superimposed. The Torridge section is both narrower and deeper than that on the Taw and the impact of the valley sides on the Torridge section is evident. One of the major effects of the restricted accommodation space is the lack of extensive salt marsh in the estuary. Salt marsh is present where some of the small tributary rivers and streams increase the available accommodation space (e.g. the R. Yeo) and there is a 2.5km narrow salt marsh on the inside bend of the incised meander loop south of Bideford but apart from these the estuary is notable for the restricted development of salt marsh and inter-tidal mud-banks.

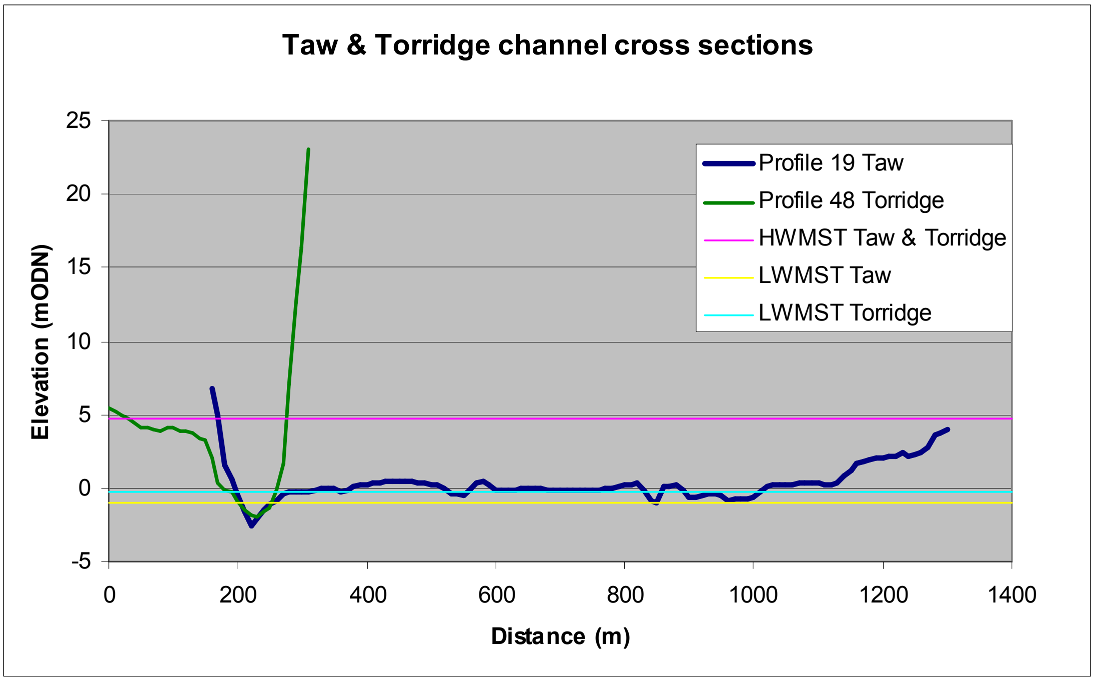

Figure 22: Comparison of Taw and Torridge cross sections at 8,500m from the sea. High and low water marks are shown superimposed.

6.5 Secondary geomorphological components

6.5.1 The Pebble Ridge

The seaward margin of Northam Burrows is characterised by the Pebble Ridge: a 3,5km long storm beach composed of gravels and boulders whose development has been the subject of considerable studies (e.g. Keene, 1996; Stuart & Hookway, 1954; Comber et al 1993, Halcrow, 1980).

There is a general consensus that the there is little or no input of coarse sediment to the Pebble Ridge. Halcrow (1980) and Orford (2004) consider that the material probably originated from a massive sediment pulse along the coast from the Gore 10km to the south, following a series of landslips. The probable date of this input is put by Orford (2004) as 16th or 17th century, so that the Pebble Ridge is a comparatively recent component of the coastal system. The repetition of such an event is, of course, not impossible, so that future inputs of sediment may occur, although Orford (2004) points out that the landward retreat of the ridge to the east of the Nose means that the coastal sediment transport pathway is now interrupted and any new inputs would have to be derived from the short west-east section of raised beach and head between the Nose and Westward Ho! or offshore cobble ridges (May & Hansom 2003).

If modern input of coarse sediment is limited or absent, then it would be expected that the storm beach would be developing a swash-aligned morphology, that is, one aligned north south so as to parallel incident west-east wave crests. The work by Stuart and Hookway (1954) showed that the Pebble Ridge has indeed been rotating counter-clockwise since 1850 as discussed above (See section 6.1) thus adopting a increasingly north-south alignment.

Although a progression towards swash-alignment is therefore observed in this system, it is also apparent that this has not yet been achieved, since eastward sediment transport continues to move gravels and boulders towards the distal end of the Northam Burrows shore. This means that although any small breaches in the ridge may infill naturally at the present time, this will become increasingly difficult in the future as the movement of cobbles reduces over time. Once at the distal end of the spit the cobbles are moved into the estuary mouth along the line of the re-entrant spit or enter the gravel spread north of the spit. However, the volume of clasts held in these sinks can only account for approximately 100 years of input at an annual rate of 5000m^3 suggesting a lower rate of longshore movement in the past. Re-cycling of this sediment from east to west has been a management practice until recently. The SMP (Halcrow 1998) reports that 60,000m^3 of material were used to re-nourish the southern end of the ridge between 1974 and 1978 and that, subsequently, a re-cycling scheme between 1981 and 1986 moved 15,000m^3 per year and 7,500m^3 per year between 1986 and 1998. Orford (2004) estimates that 5000m^3 of sediment is currently moved by natural longshore processes towards the northern end of the Northam Burrows shore, although Kirby (1996) puts this at between 3200m^3 and 5000m^3 per year. The total volume of the ridge is approximately 6 x 10^6 m^3 so that, assuming no inputs of new sediment at the southern end, output at the distal end of 5000m^3 per year would mean that the entire volume would be lost in a millennium. The reduction in ridge height would, however, be felt long before this and there is some concern that erosion of the back-barrier area of Northam Burrows will be at risk in the near future as ridge integrity is reduced.

The present rate of barrier retreat is put at between 1.5m per year (e.g. Keene 1996; Kirby 1996) and 2.6m per year (Orford 2004) but is clearly at a maximum in the south and reduces towards the north. Orford (1995) considers that a 5mm rate of sea level rise will increase the rate of retreat by 2m per year. Defra (2006) estimate the rate of sea level rise will be 8mm per year by 2026 and 14.5mm per year by 2100, suggesting that retreat rates of >2m per year will be experienced over the next 20 years and that this rate will increase exponentially over the next century. A link between sea level and the rate of retreat may account for the apparent long term reduction in the rate of longshore movement suggested by the volume of material help in the sediment sinks to the north of the distal end of the ridge as discussed above.

The impact of future changes in the Pebble Ridge morphology can be divided into two categories. On the one hand the retreat rates of >2m per year rising to perhaps 4m per year by 2100 will inevitably mean loss of an outer area of Northam Burrows, including sand dunes in the north and estuarine clays in the south. The Northam Burrows landfill site will therefore be at risk. On the other hand the reduction in height, perhaps breaching of the Pebble Ridge will allow sedimentation to take place in the Northam Burrows back-barrier areas. Such sediment may take the form of sub-aerial sand transport from the inter-tidal beach to the dunes thus increasing their height and extent. It may also take the form of fine sediment deposition on the southern estuarine clays thus increasing their surface elevation, although the rate of such deposition will not be rapid. Orford (2004) makes the point that south Northam Burrows is 'an accommodation space waiting to happen', that is an area where marine and sub-aerial deposition has been prevented both by the barrier presented by the Pebble Ridge and the artificial barrier of the eastern access road. He suggests that removal of the access road barrier or increasing the number of culverts under the road would allow increased deposition and habitat creation. Equally, it may be suggested that the progressive loss of the Pebble Ridge may stimulate back barrier geomorphological development. If the age of the Pebble Ridge is indeed c 300 years, as suggested by Orford, then the Northam Burrows back barrier dunes and marine clays were laid down before the Pebble Ridge developed and thus the ridge may have acted as to inhibit rather than protect the geomorphological evolution of Northam Burrows.

6.5.2 Crow Point

Crow Point is a sand spit, capped by a 5m high sand dune ridge, extending approximately 500m south-east from the southern tip of the Braunton Burrows sand dune area (Figure 23 and Figure 24). The feature has been a centre of some attention and concern from estuarine users for many years due to the continued erosion of its exposed estuarine channel face. The SMP (Halcrow 1998) reports that, at a Public Inquiry in 1981, the agreed rate of erosion of the estuarine shore at Crow Point was 1.0m per year. There has been a suggestion that this erosion was in part due to the extraction of between 15,000 and 80,000 tonnes per year of gravel from immediately south of Crow Point (SMP p 1.67) but this extraction has now ceased while erosion continues. The Environment Agency has undertaken some defence works here in the form of rock revetment designed to slow or halt the erosion rate.

Crow Point is an integral part of the sediment circulation pathway around the tidal delta of the Taw-Torridge estuaries as discussed above (see section 6.2). Sand waves are moved northwards along the Northam Burrows nearshore and bypass the estuary mouth during episodic storms, moving onshore to the east of the estuary mouth and welding on the shore, approximately at the location of Airy Point, which has a history of episodic accretion. Some of this sand is then moved further north along the Saunton Sands nearshore. Some, however, is moved into the estuary on the flood tides that hug the inner shore here while the stronger ebb currents occupy the central channel. This movement of sand from Airy Point into the estuary occurs along a pathway that includes Crow Point.

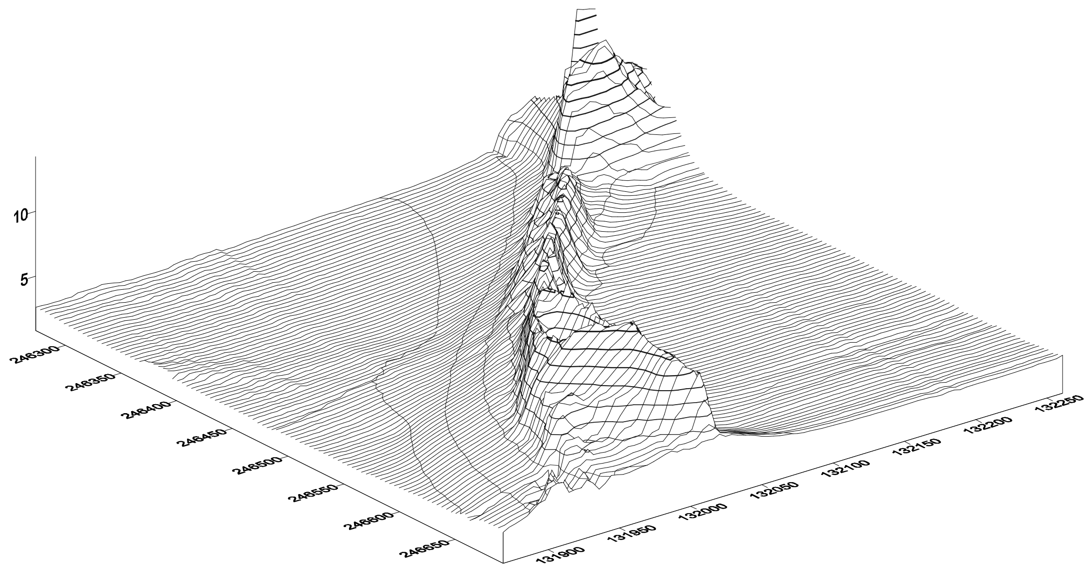

Figure 23: Crow Point, 3-D model looking north showing narrow and eroding neck.

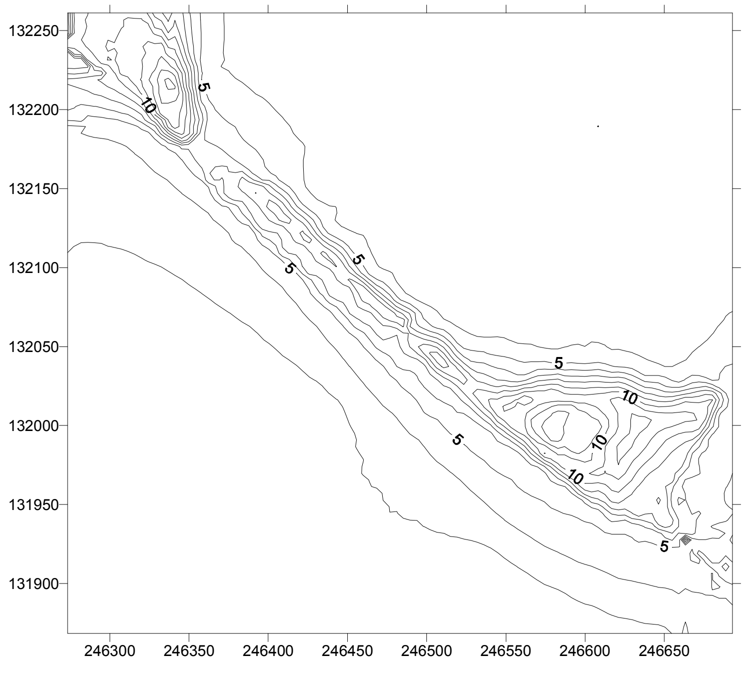

Figure 24: Crow Point surveyed in 1998

In the early 19th century Crow Point did not exist as a sub-aerial feature. The 1st edition OS map (1809) shows Crow Point as a gravel, perhaps rock, inter-tidal bank. The Denham Chart (1832) similarly shows the area now occupied by the sand dune spit as inter-tidal shore with the high water shoreline of Braunton Burrows ending in a right angle. Interestingly, the Denham Chart of 1832 also shows a 200m to 300m linear structure, labelled 'Weir' on the chart and extending parallel to the Braunton Burrows shore and between the high water mark and the Sprat Ridge. A sand bar immediately west of this 'weir' is labelled Crow Ridge on the chart. It may be that this weir was a fish weir similar to those built on the Scars of the Carmarthen coast (James 2003) in which case it would have been a stone-built structure built with the characteristic zig-zag shape as shown on the Denham chart .

It appears from this evidence that Crow Point has always been a sediment transport pathway but until 1832 this pathway had been an inter-tidal one with no sub-aerial sand dune development. Between 1832 and 1849 the presence of the weir structure immediately to the west of this sand transport pathway reduced wave energy on the upper shore so that blown sand was moved from the inter-tidal pathway to the upper shore and formed the line of sand dunes that still exist today. This hypothesis for the origin of Crow Point is confirmed by HR (1990) who note that between the 1832 Denham survey and the Admiralty survey of 1855: 'Crow Point had become established. This could have been as a result of the weir mentioned in above'.

If the sub-aerial sand dunes at Crow Point are indeed the result of an artificial structure, then since that structure no longer exists it is to be expected that the sand dunes themselves will erode away. It is not likely, however, that the inter-tidal sand transport pathway that follows the line of these sand dunes will also disappear nor the inter-tidal gravel that forms the foundation of this area.

The SMP (Halcrow 1998) suggests that 'At Crow Point the spit shelters the inner estuary to incident wave attack and so its integrity is crucial'. This seems both unnecessarily alarmist and without any geomorphological foundation. The sand dunes at Crow Point have only been in existence for 200 years. Prior to that there is no evidence to suggest that waves caused problems in the inner estuary, nor is there any geomorphological reason why, before 1832 or if the modern dunes were to erode away, significant wave energy should or could propagate across the inter-tidal gravel spread that underlies these sand dunes. The sand dunes of Crow Point do not offer any protection to the inner estuary; it is the gravel foundations of these dunes that provides this protection and provide the inter-tidal pathway for sand moving to the Instow Sands and the Horsey Ridge.

6.6 Conceptual model: Synthesis

The conceptual models for each of the components of the Taw-Torridge Estuary system may now be synthesised into an overall model of this coast. The individual component analysis has stressed several major points that may first be summarised:

- The open coast sediment is recycled around a counter-clockwise gyre forming a northerly sediment pathway within the nearshore of both Northam Burrows and Braunton Burrows;
- The common mouth of the estuaries is dominated by a tidal delta that allows longshore sediment movements to bypass the estuarine mouth while maintaining an open channel to the sea;
- The estuaries of the Taw and Torridge and their common mouth are immature systems due to relative lack of fine sediment input. The inner estuaries have accreted fine sediment but the outer estuary is sand dominated producing characteristic convexo-concave long profiles;
- A deeply incised mid-Holocene river channel is present in the bed of the common outer estuary section that controls both the direction and dimensions of this reach of the estuary;
- The twin barriers of Braunton Burrows and Northam Burrows form an integral part of the tidal delta system and define the mouth of the estuaries. They represent a considerable store of sand from the mid-Holocene;
- Some of the sediment moving across the estuary mouth via the ebb-tidal delta and Airy Point, passes into the estuary where it is retained in a temporary sink at Instow before moving seawards within the central ebb channel in a clockwise rotation.

These attributes of the coastal system demonstrate an intimate link between the estuaries and the open coast based upon the circulation of sand along the coast and into the outer estuary. Examination of historic charts of the outer estuary since 1832 show that very little change has occurred in the HWM or LWM of the inter-tidal sand bodies despite a rise in sea level over this period of approximately 0.5m. This suggests that the outer estuary is receiving sufficient sand from the open coast to maintain its inter-tidal morphology relative to tidal levels. The conceptual model however suggests that there is no new input of sand into the open coast sediment store, so that any net transfers to the estuary must be at the expense of this open coast store.

A first order calculation can be made of the volume of sand needed to keep pace with sea level rise over an outer estuary area of approximately 1000ha. Assuming sea level rise of 2mm per year the total volume of sand needed would be 20,000m^3 per year. Removal of this volume of sand from the 9km long and 500m wide inter-tidal beaches of Northam Burrows and Braunton Burrows, would mean an annual vertical erosion rate of 4mm and a horizontal retreat of low water mark of between 0.25m to 0.4m depending on the slope of the inter-tidal beach. This rate of retreat has been observed for the Saunton Sands where annual retreat rates of between 0.3m to 0.8m were noted by the SMP (Halcrow 1998).

The implications here are that the sand circulation within Bideford Bay contributes to the Taw-Torridge estuary sediment store and allows the estuary to keep pace with sea level rise, but at the expense of the open shore which is suffering erosion as a result.

7. THE ESTUARY REGIME MODEL

The intention of the model simulations is to define the impact of changes in tidal prism within Taw-Torridge estuaries due to sea level rise and managed realignment schemes. In order to demonstrate the impact of these changes to tidal prism it is first necessary to define the regime or equilibrium morphology of the estuaries under present day tidal conditions. The regime form of an estuary is a theoretical optimum and therefore not necessarily the form exhibited by the estuary. In the Taw-Torridge estuaries for example, the conceptual model has shown that the restricted fine sediment input over the Holocene has meant that insufficient deposition has occurred to allow the estuaries to attain an equilibrium long profile. It is therefore unlikely that these estuaries will have attained their regime morphology. The regime morphology is therefore the form that would develop under a given tidal regime, assuming that sufficient time was allowed to elapse. The regime model used to simulate this equilibrium form is time independent in that it does not calculate rates of geomorphological processes, but defines the ultimate equilibrium form. The model calculates the location of the high water neap tide mark (HWMNT) as the boundary to the active estuarine channel geomorphology. Areas lying between this HWMNT and the HWMST are still within the tidal environment but, since tidal flow velocities within this zone approach zero, they are characterized by sedimentation and may be expected to develop into salt marshes, assuming sufficient sediment is available.

7.1 Present day sea level

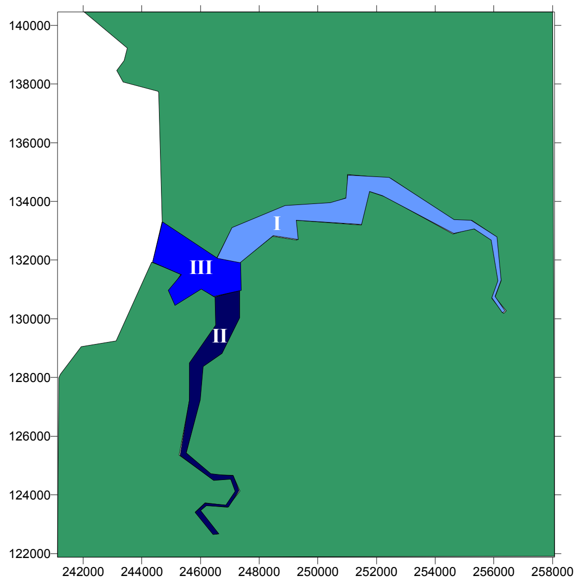

Figure 25: Division of the Taw-Torridge Estuaries for regime modelling

The development of a composite regime model for the combined Taw and Torridge estuaries was a three stage process. A model of the Taw from its tidal limits to the sea was first developed. This model incorporated the areas shown as I and III in Figure 25. The tidal prism of Area III included its own inter-tidal volume together with the inter-tidal volume of Area I: the Taw, and Area II: the Torridge. Second, a model of the Torridge was developed that incorporated the tidal prism from Area II. Finally, these two models were joined in a composite model that incorporated all three tidal prisms.

7.1.1 Tidal conditions

The existing conditions are defined by the tidal prism of the Taw as represented by the bathymetric survey described in section 3.1 . The tidal prism data input to the model is shown in Table 8.

Area (See Figure 25)	Tidal prism (m^3)
I	31,500,000
II	15,600,000
III	20600000
Total I + II + III	67,700,000

Table 8: Tidal prisms for estuarine areas shown in Figure 25.

7.1.2 Equilibrium channel form

7.2 The Taw

The regime plan form of the Taw (Areas I and III) under exiting conditions is shown in Figure 26. It is emphasised that the predicted outline (red line on Figure 26) is that of HWMNT while the observed outline (blue line on Figure 26) is that of HWMST. It is also emphasised that the model predictions are for specific cross sections only as shown in Figure 3. Thus the high water mark between cross sections is interpolated and may, in some cases, not represent the exact location of the regime form.

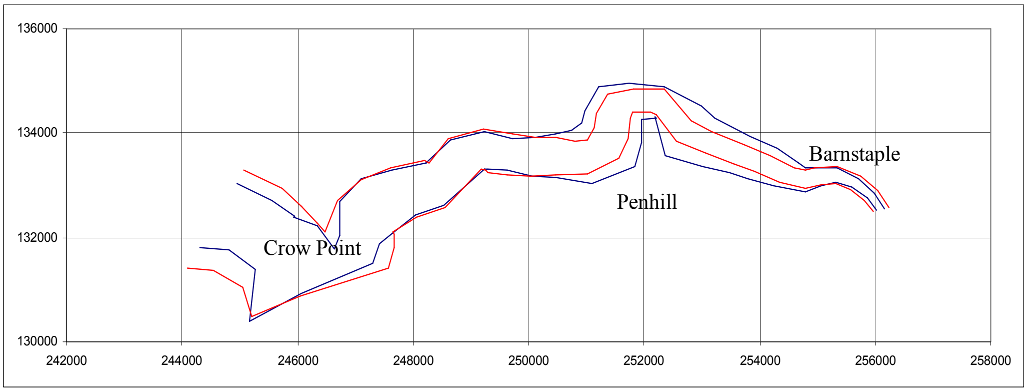

Figure 26: Predicted regime HWMNT for the Taw Estuary. Existing HWMST shown as blue line; predicted HWMNT shown as red line. Note that area between the two lines indicates either a potential for erosion (red line landwards of blue) or salt marsh development (blue line landwards of red).

The model predictions show:

- Over the inner estuary, that is between the tidal limit and Penhill Point, the observed high water channel is wider than predicted;

- In the middle estuary, that is between Penhill Point and Crow Point, the observed and predicted channel widths are similar;
- In the outer estuary, that is between Crow Point and the sea, the observed high water channel is 50% narrower than predicted by the regime model.

Table 9 shows the observed and predicted channel widths for each cross section along the Taw. Figure 27 shows the data plotted in graphical form.

It is clear from these results that there is a significant difference between the regime form of the Taw and its present morphology. The conceptual model, discussed in section 6.3.1 above, suggested that the Taw estuary has been slow to respond to rising sea levels during the later Holocene due primarily to lack of fine sediment inputs. This would account for the prediction of a much wider regime channel than is observed at present. It may be expected that this difference in widths would be gradually reduced as sediment accretion takes place and, in particular, as salt marsh development between the observed HWMST and the predicted HWMNT takes place. This does not, however, account for the difference between observed and predicted widths in the outer estuary where the existing channel is 50% narrower than predicted.

Profile Number	Distance from sea (m)	Observed width at HWMST (m)	Predicted Width at HWMNT (m)	Difference bertween Observed and predicted (m)
1	0	1395	2290	-895
2	594	1202	2159	-957
3	1132	1235	2050	-815
4	1633	2128	1956	173
5	2306	1321	1432	-110
6	3078	729	1294	-565
7	3401	701	1240	-539
8	3846	1112	1170	-58
9	4129	1179	1128	51
10	4655	969	1052	-83
11	5226	872	977	-104
12	5721	1011	915	96
13	6026	807	879	-73
14	6359	711	842	-131
15	6777	591	797	-206
16	7186	728	755	-27
17	7571	826	718	108
18	8024	1074	677	397
19	8427	1306	642	664
20	8762	1108	614	494
21	9102	973	588	386
22	9366	830	568	262
23	9756	980	539	440
24	10059	619	518	101
25	10747	1134	474	660
26	11235	969	444	525
27	11822	794	411	382
28	12250	763	389	374
29	12718	609	366	243
30	13066	477	350	128
31	13278	358	340	18
32	13613	267	325	-59
33	13968	201	311	-109
34	14337	158	296	-138
35	14650	147	284	-137

Table 9: Predicted and observed channel widths for profiles 1-35, Taw Estuary. (For location of profiles see Figure 1)

The shared outer estuary of the Taw-Torridge system is characterised by sand sized sediment that has failed to infill the deeply incised central channel derived from the fluvial river of the mid-Holocene period (see section 6.3.2). The regime model predicts the width of an estuary channel from the ratio of equilibrium scour depth to the regime cross sectional area; this assumes a mobile bed to the channel. In the outer

Taw-Torridge, however, the bed is not mobile but is incised into rock. The depth of the channel is therefore significantly greater than the equilibrium scour depth. If the predicted cross sectional area of the channel is plotted against observed, the same characteristics are observed. Figure 28 shows that the predicted cross sectional area matches the actual section from the junction with the Torridge towards the sea, but the outer three cross sections are predicted to be much larger than the actual sections. Two reasons for this outer estuary mis-match between observed and expected channel dimensions may be forwarded:

- The central section of the outer estuary is cut into rock and therefore cannot erode to create a regime channel form;
- The longshore sediment transport along the open coast has forced the channel to narrow across its mouth.

It appears that the constriction imposed by the distal end of the Northam Burrows and Pebble Ridge, and the accretion at Airy Point on the northern bank, has resulted in the part-closure of the outer estuarine channel which would otherwise have followed the line of the Skern embayment as shown in Figure 28. This means that the outer estuary channel is smaller than predicted for a regime estuary leading to higher velocities which, in a mobile bed estuary, would mean increased erosion leading to the predicted dimensions. However, in the Taw-Torridge estuary the bed of outer channel is cut into rock, preventing further erosion in the sub-tidal area while the continued pressure of longshore sediment transport at the distal end of the Northam Burrows and at Airy Point, forces the inter-tidal channel to adopt a narrower section.

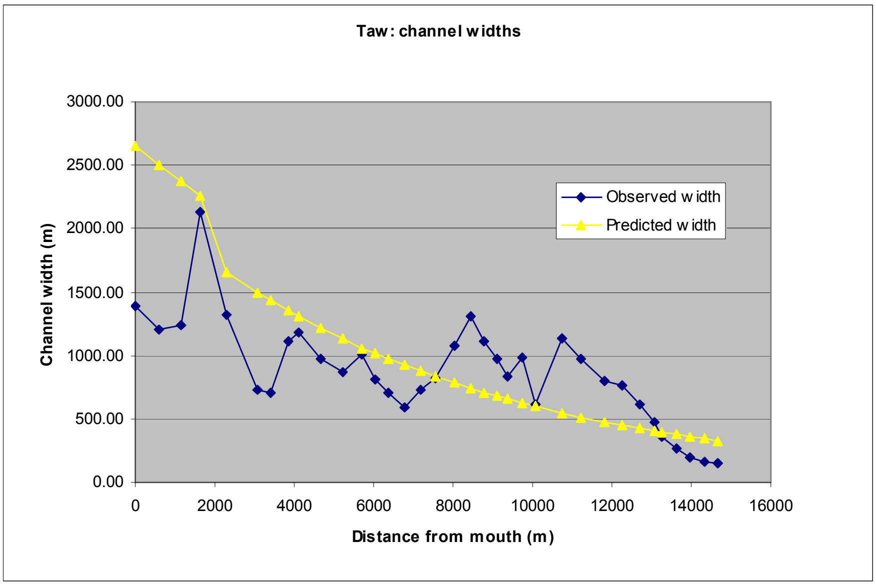

Figure 27: Observed and predicted channel widths for the Taw.

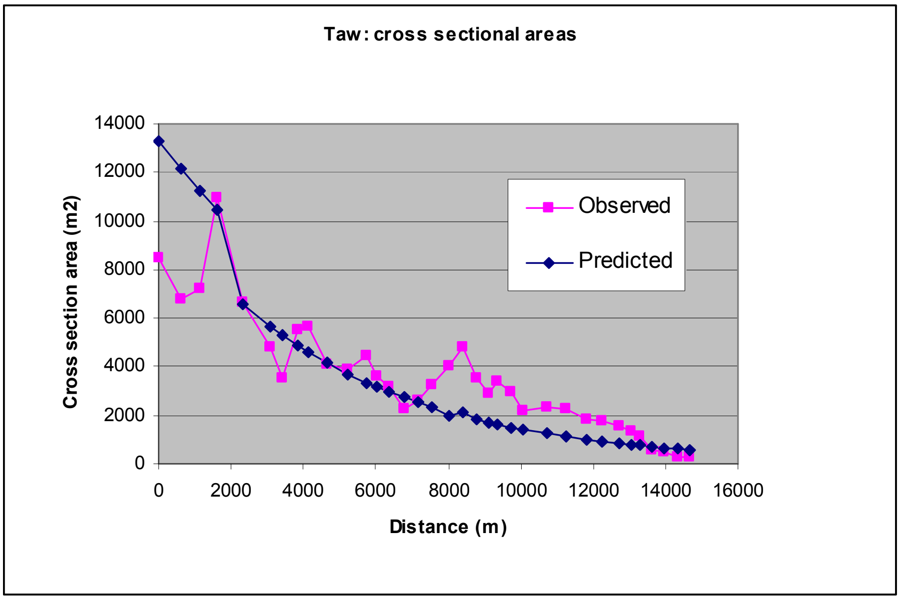

Figure 28: Observed and predicted cross sectional areas for the Taw. The Skern is located at point 4, 1600m from the sea.

7.3 The Torridge

The regime plan form of the Torridge (Area II Figure 25) is shown in Figure 29. As in the case of the Taw regime model the predicted high water mark is for HWMNT while the observed high water is for HWMST. Table 10 shows the differences between the observed and predicted widths at each cross section and these data are plotted in Figure 30.

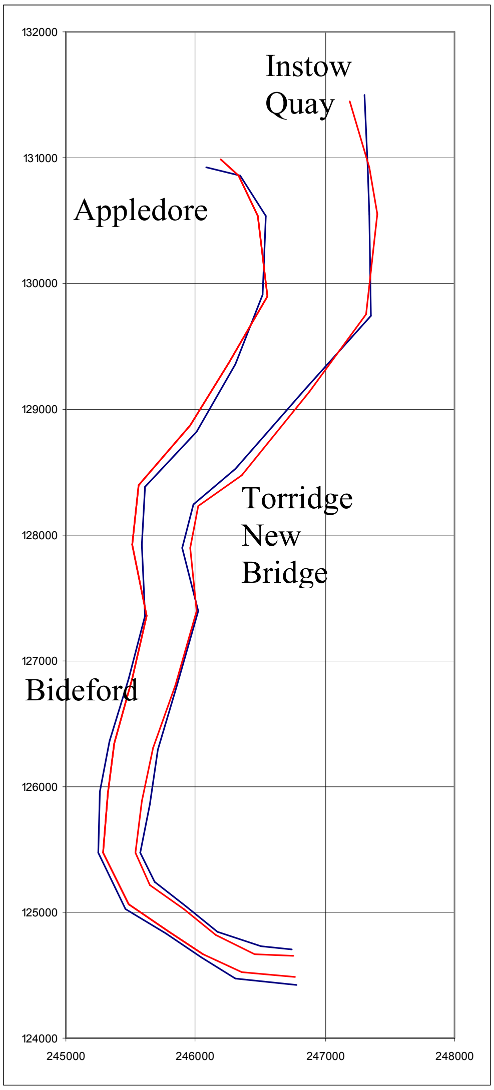

Figure 29: Regime plan for the Torridge Estuary. Existing HWMST shown as blue line; predicted HWMNT shown as red line. Note that area between the two lines indicates either a potential for erosion (red line landwards of blue) or salt marsh development (blue line landwards of red).

The model predictions show:

- In the inner estuary, between the tidal limit and south Bideford, the predicted channel width is narrower than the observed channel;
- In the outer estuary, between Bideford and Appledore, the predicted channel width is slightly wider than the observed channel.

The Torridge estuary was described in the conceptual model (Section 6.4) as being constrained by its valley slopes. This would account for the wider predicted channel in the outer estuary. It does not, however, account for the narrower predicted channel in the inner estuary. The prediction of a narrower regime channel south of Bideford does, nevertheless, agree with the observed salt marsh development here since the zone between the predicted regime HWMNT and the observed HWMST is an area where deposition and thus salt marsh may occur. However, some further explanation of this inner estuary behaviour is necessary.

Profile Number	Distance from sea (m)	Observed width at HWMST (m)	Predicted Width at HWMNT (m)	Difference bertween Observed and predicted (m)
36	0	1356	1101	256
37	357	992	1010	-18
38	716	802	926	-124
39	1433	846	779	67
40	2110	573	662	-88
41	2824	426	557	-131
42	3335	399	493	-93
43	3750	311	446	-135
44	4289	417	391	26
45	4846	371	342	29
46	5373	383	301	81
47	5793	390	272	117
48	6240	317	244	73
49	6605	314	224	90
50	6952	263	206	57
51	7276	239	190	48
52	7605	325	176	149
53	7962	285	161	123

Table 10: Predicted and observed channel widths for profiles 36-53 Torridge Estuary. (For location of profiles see Figure 1)

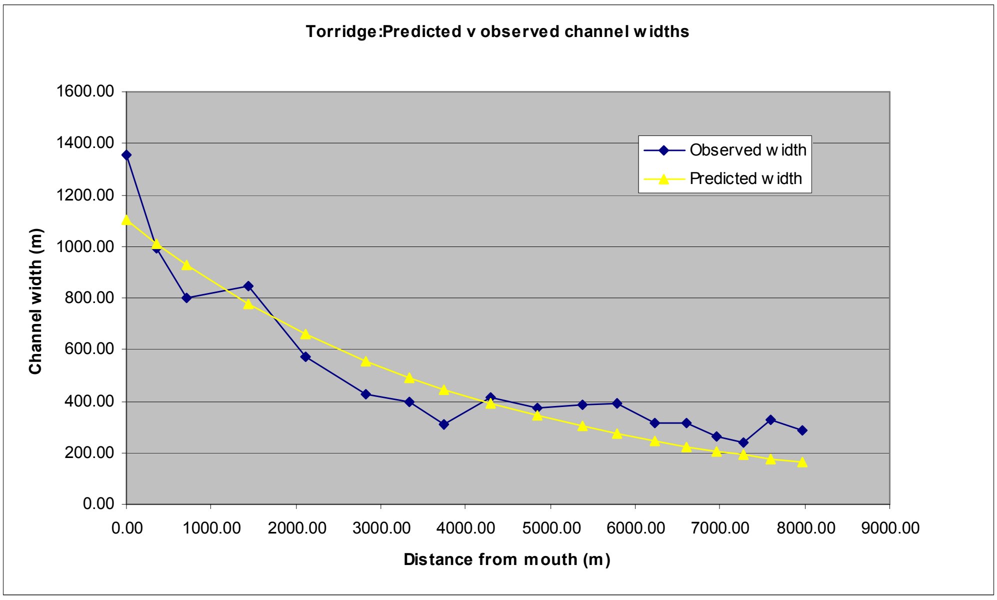

Figure 30: Observed and predicted channel widths for the Torridge estuary

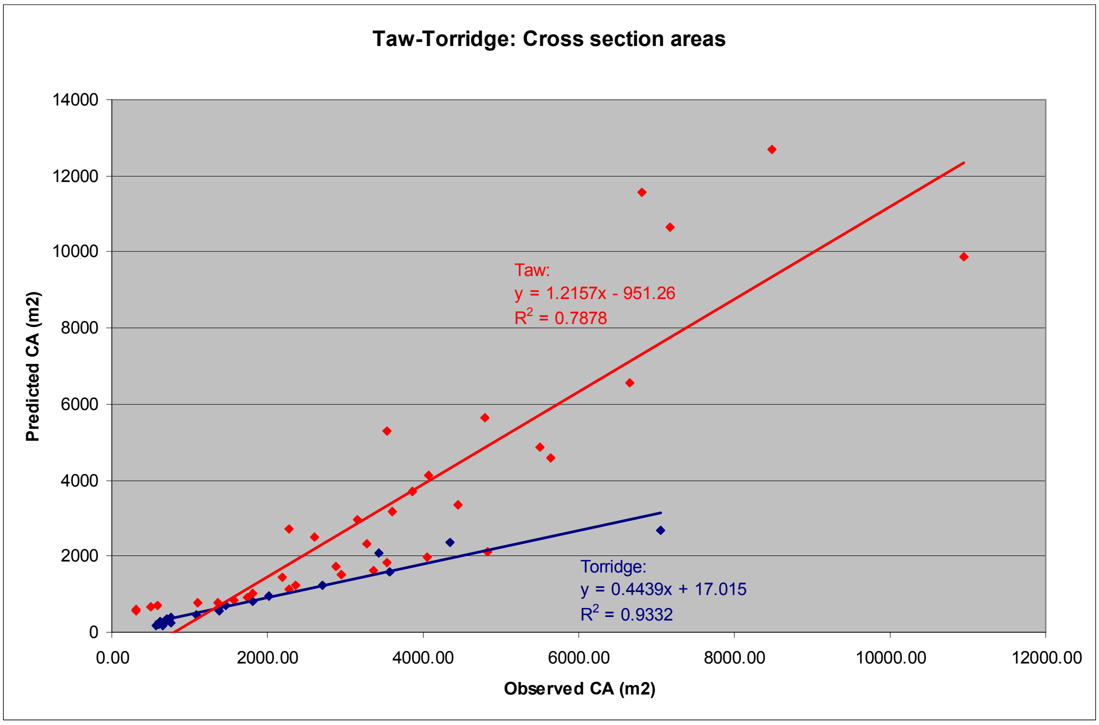

Figure 31: Predicted versus observed cross sectional areas for the Taw and Torridge Estuaries. The regression coefficient for the Taw is 1.22 indicating that, on average, predicted values are equivalent to actual values. The regression coefficient for the Torridge is 0.444 indicating that predicted values are less than half the observed values.

The conceptual model (section 6.4) proposed that the Torridge estuary is constrained by its valley side slopes and that this is reflected in its relatively deep channel sections. Throughout most of the estuary, sub-tidal average channel depths exceeded 1.0m, compared to the Taw in which average channel bed elevations were at or near low water mark – that is drying at low tide.

The model results show the impact of the constraints of the valley slopes even more clearly. One unexpected result is shown in Figure 31. The predicted cross sectional area for the Torridge is shown here to be over half the size of the actual cross section. The regression coefficient for the relationship between observed and predicted cross sectional area is 0.44. This compares with the same plot for the Taw estuary (Figure 31) which shows a regression slope of 1.22, a high degree of equivalence between observed and predicted cross sectional areas for this estuary. The large discrepancy between predicted and observed values for the Torridge contrasts with the predicted width of the estuary, shown in Figure 30 to be approximately equivalent to the actual width, although, as pointed out above, it is slightly narrower than the actual channel in the inner estuary.

It is clear that the cross sections of the Torridge are not in regime. The tidal prism volume is extremely small for the tidal length due to the constriction imposed by valley sides, as discussed above (section 6.4.1) and this should result in a small channel. Yet the channel is relatively deep and has not accreted sufficient sediment over the Holocene to reduce its dimensions accordingly. The relatively large channel sections mean that velocities are much lower than would be expected within regime morphology so that deposition of sediment would be expected to be rapid. The lack of available fine sediment however has led to a low rate of deposition and the result is a deep sub-tidal channel, one that may be expected to infill over the long term – but with a time frame perhaps measured in millennia.

7.4 The composite model

The regime model for the Taw-Torridge estuary system as a whole is shown in Figure 32 plotted on a map of HWMST for the two estuaries. It is noted that the mapped high water in Figure 32, derived from the OS 1:25,000, 1997 survey, differs from the high water established from the bathymetric/Lidar survey for this study in 2006 which was used, together with Admiralty predictions of tidal heights, to derive the tidal height locations on the cross sections input to the model and to plot the diagrams shown as Figure 26 and Figure 29. The map shown in Figure 33 appears to show the predicted channel for the mid-Taw estuary as wider than the actual channel particularly at Home Farm Marsh and Instow, although the plot using bathymetric/Lidar data (Figure 26) shows predicted and actual width as equal along this stretch of the channel. Similarly, the predicted channel in the inner Torridge, at the confluence with the R Yeo, is shown as matching the actual channel width, whereas the plot using the bathymetric/Lidar data (Figure 29) shows predicted as narrower than actual width along this stretch of the channel. These discrepancies are due to differences in the definition of the high water mark in the existing estuaries rather than any differences in the model predictions. This difference between mapped high water marks is critical but cannot be finally resolved in this study. It is assumed that the 2006 bathymetric/Lidar survey provides the most accurate definition of the high water mark although this cannot be established from the evidence available at the moment.

Despite these difficulties of defining the present day estuary form, the main conclusions of the regime modelling are:

- The mouth of the estuary system is predicted to be significantly wider and shallower than the actual channel, but is held at its present dimensions by the incised rock channel and the pressure imposed by longshore sediment transport. Any decrease in the longshore sediment transport rate, for example, due to an increase in swash alignment of the open coast, would lead to erosion at the estuary mouth;
- The inner Taw is predicted to be narrower than the actual channel, but slow deposition rates in the Holocene have restricted its development. It is predicted that deposition will continue to slowly infill the channel with a deposition front moving seawards from its present position at Penhill Point.
- The Torridge is predicted to be shallower than its actual channel, although its predicted regime width is approximately equivalent to the observed values. Infill of the sub-tidal channel is predicted to continue, again at a slow rate.
- In both estuaries the lack of sediment means that a sedimentary response to sea level rise over the next century will be restricted, leading to increased tidal prisms and potential widening of the predicted channel. The major stress points are located along those sections of the estuary where predicted values are already equivalent to, or greater than actual values. These are:

- The outer estuary between Crow Point and Airy Point;
- The mid-Taw between Horsey Ridge and Chivenor Ridge;
- The outer Torridge between Bideford and Appledore.

The implications of sea level rise on the morphology of the estuaries is considered in detail in section 8 in which the results of the regime models incorporating sea level rise scenarios are discussed.

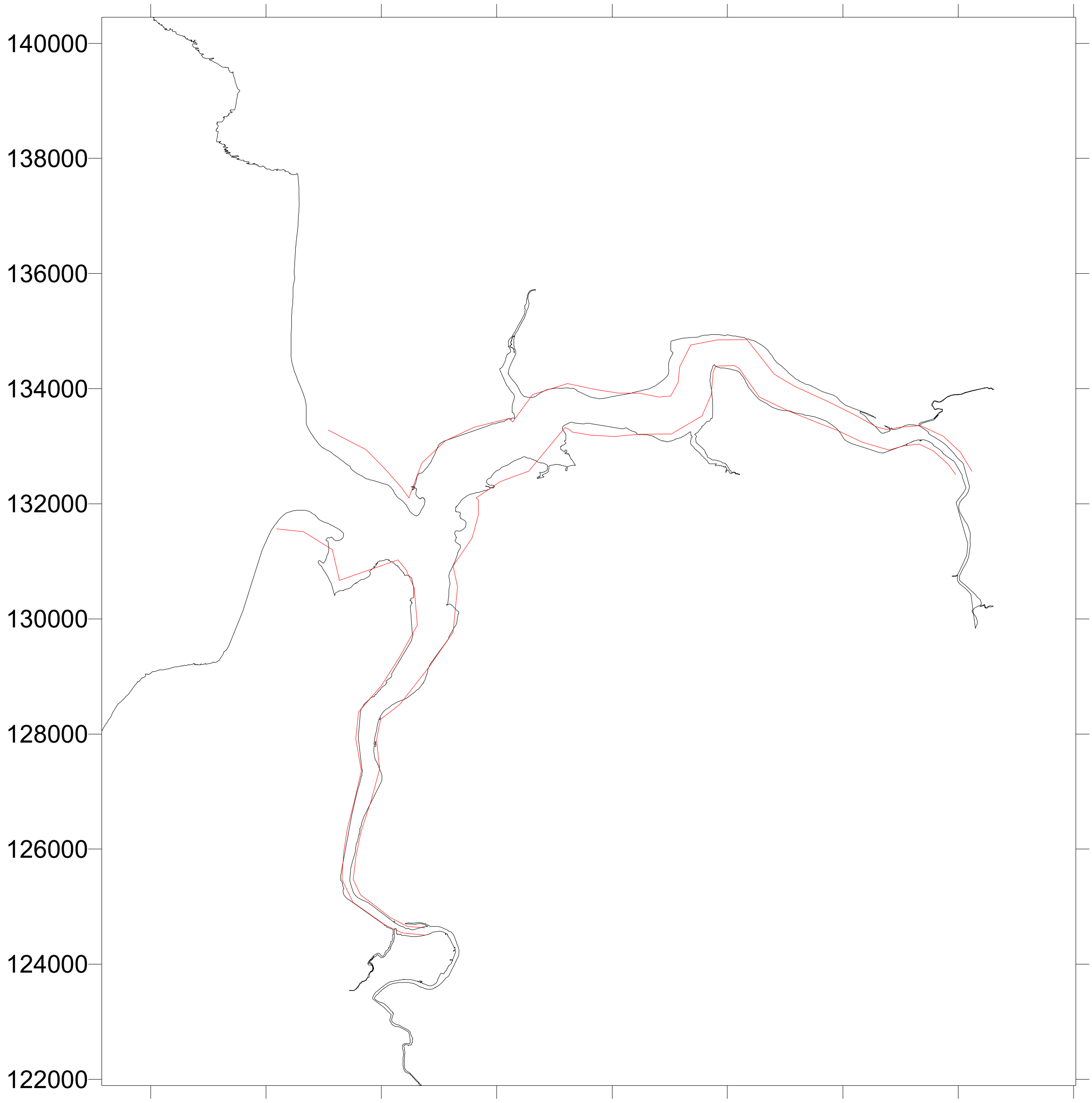

Figure 32: Regime model of Taw and Torridge estuaries for existing tidal conditions. Existing HWMST shown as black line; predicted HWMNT shown as red line. Note that area between the two lines indicates either a potential for erosion (red line landwards of black) or salt marsh development (black line landwards of red).

8. SEA LEVEL RISE: MODEL PREDICTIONS

The predictions for sea level rise over the next 100 years used in the model simulations are based upon those provided by DEFRA (2006) for the south west of England as discussed above (Section 3.4). It is acknowledged that these predictions are higher than similar predictions, for example by UKCIP, and therefore can be regarded as a worst case scenario.

Three sea level rise scenarios are considered here for the years 2025, 2055 and 2105. The Defra (2006) predictions for the increase in sea level by each of these dates are: 0.122m; 0.362m and 0.997m respectively.

The regime models for the Taw and Torridge were run for each of these scenarios and comparison made between the predicted regime morphology under existing sea level conditions and the predicted regime morphology assuming the increased sea level.

The increase in sea level over the next 100 years will result in a change the tidal prisms of the Taw-Torridge estuaries only if sedimentation keeps pace with the sea level rise. In this case the increase in water levels would not be associated with any increase in the inter-tidal volume and changes in estuarine morphology will result only from a re-location of the high water mark. In the case of the Taw-Torridge estuaries, however, this study has concluded that very little sediment has been available for deposition over the Holocene period and this is unlikely to increase in the future. Thus it is extremely unlikely that deposition will keep pace with the predicted accelerated sea level rise and as a result tidal prisms are likely to increase.

In view of the difficulties of predicting future inter-tidal deposition rates, the model predictions presented here assume that no inter-tidal deposition will occur over the next 100 years, a worst case scenario. Increased tidal prism was calculated using the inter-tidal area of each estuary and the predicted annual rate of sea level rise given by Defra (2006). For an estuary with no inter-tidal area, for example one with a rectangular cross section defined by training walls, increased sea level is not associated with increased tidal prism and the tidal frame merely rises without change in volume.

8.1 Historic rates: model verification

In order to provide some verification of the model to support its use for the prediction of morphological responses to future sea level rise, a hind-casting procedure was used to predict historic morphological changes using past rates of sea level rise.

Over the last 200 years sea level rise in the Bristol Channel has been estimated to have been between 2.23mm per year (Allen 1991) and 3.3mm per year (Allen and Duffy 1998), an average of 2.76mm per year. Comparison of the Denham 1832 chart of the outer Taw-Torridge Estuary with the modern OS 1: 25,000 1997 survey and the 2006 bathymetric/Lidar survey conducted for this study showed that the outer estuary widened from 1100m in 1832 to 1300m in 2006, an increase of 200 m at an average erosion rate of 1.14m per year. This compares well with the rate of erosion at Crow Point that was agreed at a Public Inquiry in 1981 (SMP 1998) to be 1m per year as discussed above (See section 6.5.2).

The regime model hind-cast simulation was performed using a rate of sea level rise of 2.76mm per year and the inter-tidal area of the Taw and Torridge Estuary (1743ha) to give an annual rate of change in the tidal prism. This was calculated as 47,8900m^3 per year. The increase in estuary width at profile 1 in the outer estuary, using this annual rate of change in the tidal prism, was 1.038m per year, again showing good agreement with the observed increase in width here.

Although the use of historical charts for accurate measurement is open to many criticisms nevertheless this comparison between predicted and actual rates is extremely close and it is assumed therefore that the use of the model for the prediction of future morphological responses to sea level rise is justified.

8.2 Future morphological response

The relatively small changes in the width of the estuary channel in response to rates of sea level rise predicted for the next 100 years are difficult to represent in map form. Instead, the changes predicted by the model are shown here in tabular format. Three representative locations were chosen in each estuary to illustrate the magnitude of response to sea level rise at each time period. Table 11 shows these data for the Taw estuary at Airy Point, Chivenor and Barnstaple. In each case the predicted regime channel width for existing sea level is compared with the predicted width for the increased sea level and with the actual, that is observed, width at each point. At the mouth of the Taw-Torridge estuary the impact of sea level rise is to cause erosion, widening the predicted regime channel by 361m by the year 2105 at an average rate of 3.61m per year.

Comparison with the actual channel width shows that by 2105 the estuary mouth will erode by over 1km at an average rate of 12m per year. However, as noted above, the mouth channel is unlikely to widen by this amount owing to the constraints imposed by the rock channel and the longshore transport pressure here.

Profile	Location	Predicted width post-sea level rise (m)	Difference from predicted pre-sea level rise (m)	Difference from existing width (m)
Year 2007		Sea level 0		
1	Airy Point	2290	0	-895
16	Chivenor	755	0	-27
28	Barnstaple	389	0	374
Year 2025		Sea level +0.122m		
1	Airy Point	2336	-46	-941
16	Chivenor	771	-15	-43
28	Barnstaple	397	-8	366
Year 2055		Sea level +0.362m		
1	Airy Point	2425	-134	-1030
16	Chivenor	800	-44	-72
28	Barnstaple	412	-23	351
Year 2105		Sea level +0.997m		
1	Airy Point	2651	-361	-1256
16	Chivenor	875	-119	-147
28	Barnstaple	450	-61	313

Table 11: Model predictions for channel width changes in the Taw Estuary under 3 sea level rise scenarios

Table 12 shows the predictions for the Torridge estuary at Appledore, Bideford and at the River Yeo confluence. The outer estuary is predicted to widen by 157m by 2105 at an average rate of 1.57m per year, almost half the rate of erosion predicted in the outer common mouth of the estuary.

In contrast, the differences between the predicted and the actual channel widths for the Torridge as a response to sea level rise show that in every case the channel will decrease in width after sea level rise. This reflects the constraints on the Torridge imposed by its accommodation space as discussed above (sections 6.4.1 and 7.3) rather than the response to sea level rise. The channel is larger than would be expected at the present time and the increased tidal prism due to sea level rise by 2105 will not be sufficient to offset this. Thus the Torridge channel is predicted to accrete over the foreseeable future and the effect of sea level rise will be to reduce this accretion rather than reverse it and cause erosion.

Profile	Location	Predicted width post-sea level rise (m)	Differencefrom predicted pre-sea level rise (m)	Difference from actual (m)
Year	2007	Sea level 0		
37	Appledore	1010	0	346
46	Bideford	301	0	81
53	R Yeo	161	0	123
Year	2025	Sea level +0.122m		
37	Appledore	1030	-20	326
46	Bideford	307	-6	75
53	R Yeo	165	-3	119
Year	2055	Sea level +0.362m		
37	Appledore	1068	-58	288
46	Bideford	319	-17	63
53	R Yeo	171	-9	113
Year	2105	Sea level +0.997m		
37	Appledore	1167	-157	189
46	Bideford	348	-47	34
53	R Yeo	186	-25	98

Table 12: Model predictions for channel width changes in the Torridge Estuary under 3 sea level rise scenarios

8.3 Conclusions

The results of the regime modelling incorporating sea level rise over the next century have shown that the morphological response of the estuary will be significant. The Taw is predicted to increase its width at Airy Point by 360m over the next 100 years, a rate of erosion some three times the present rate. The Torridge is predicted to increase its channel width at Appledore by 157m.

It is emphasised that these predictions are for changes in the regime, or equilibrium, form of the estuaries. It can be argued that, since the estuaries have not yet attained equilibrium, these predicted morphological responses will not apply. There are two arguments to counter this suggestion:

- The hind cast verification, reported in section 8.1, resulted in a rate of channel widening over the past 100 years that closely matched the recorded rates. It appears that the estuary, although not in equilibrium throughout its length , nevertheless responds to changes in its tidal prism when its existing morphology is either similar to, or smaller than the predicted morphology.

This is the case at the mouth of the estuary where the predicted width is significantly wider than the actual channel so that here the estuary is extremely sensitive to changes in its tidal characteristics. This sensitivity of the width of the channel is due to the relative difficulty of increasing cross sectional area by scour so that changes in depth are small and responses to tidal prism variation are confined to width alone. It would also appear that the presence of the cobble re-entrant spit on the south bank of the channel mouth will mean that most of the change in width will be accommodated by changes to the north bank where such armouring is not present.

- In contrast to the outer estuary , in the inner Taw and Torridge channels where the existing form is wider than the predicted equilibrium, the estuary will be less sensitive to external changes and responses to increased tidal prism will be seen as a reduction in accretion rather than a reversion to erosion.
- The morphological responses predicted by the regime model are potential responses only. Thus predicted channel widening at any point will only occur if the banks of the estuary are capable of erosion so that if, for example, the banks are protected by hard defences, no erosion or widening will occur. The model predictions for potential widening in this case will result in increased stress on these defences.

9. ESTUARINE RESPONSE TO MANAGED REALIGNMENT

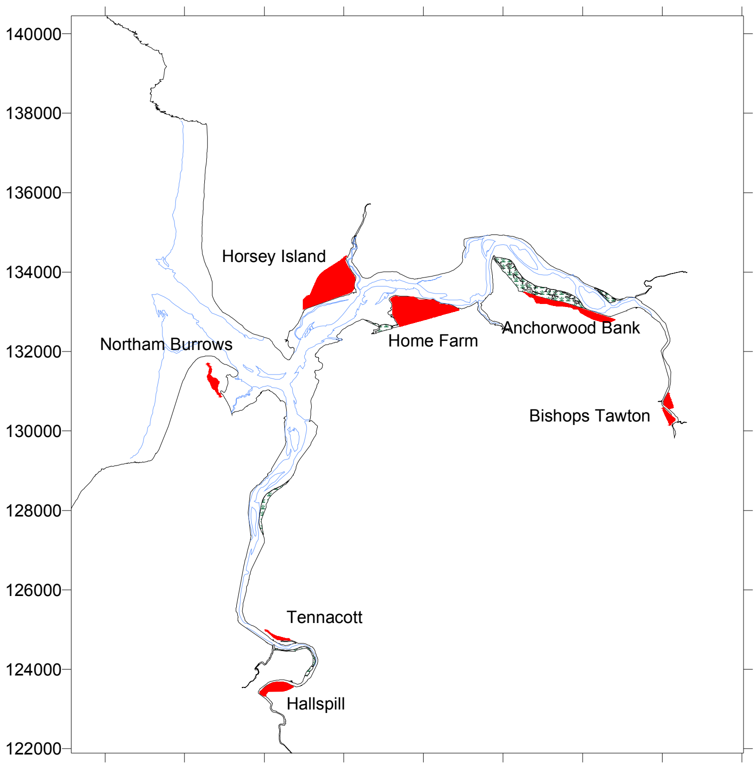

Figure 33: Potential realignment sites in the Taw-Torridge Estuaries

Several former inter-tidal areas in the Taw-Torridge Estuaries have been proposed as potential managed re-alignment sites. The cost-benefit ratios of maintenance of estuarine shore defences versus agricultural land returns or the conservation benefits of increased natural habitat are not within the boundaries of the present study. The concern here is the potential impact on the estuaries of an increase in inter-tidal area and the potential future development of the realigned site if left to natural estuarine processes.

Realignment site	Tidal volume(m$^{3)}$
Taw Estuary	
Anchorwood	231414
Bisphops Tawton 1	37652
Bishops Tawton 2	23688
Home farm Marsh	386388
Horsey Island	1512054
Northam Burrows	20834
Torridge Estuary	
Hallspill	212118
Tennacott	53891

Table 13: Tidal volumes of potential realignment sites

The potential sites are shown in Figure 33. The tidal volumes that would enter each site on a high water spring tide is shown in Table 13. These values were used as inputs to the regime model and added to the existing tidal prism downstream of the locations of each site.

Results of the modelling are again shown in tabular form rather than as mapped outlines since the predicted changes are too small to be shown on large scale maps.

9.1 Taw realignment sites

Results for the Taw realignment sites are shown in Table 14. Changes in channel width at three representative locations are shown. In most cases predicted changes in channel width are small when compared to the predicted regime widths but large if the existing channel is used as a baseline but these include the future development of the estuary as well as the impact of managed realignment. The results comparing predicted regime channel changes are therefore to be regarded as representative of the impact of the realignment alone. Overall the changes in width are in the order of -1m but the realignment of the large Horsey Island site is predicted to result in 33m of erosion at the estuary mouth. No changes are of course predicted for the inner estuary which will not be affected by the realignment of Horsey Island.

For the inner estuary sites: Anchorwood Bank, and the two Bishops Tawton sites, it is noteworthy that the inner estuary channel is predicted to widen more than the channel in the outer estuary. The Anchorwood site for example would result in 10m of erosion at Chivenor but only 5m at the estuary mouth.

Profile	Location	Predicted width post-realignment(m)	Difference from predicted pre-realignment(m)	Difference from actual (m)
Northam Burrows	Tidal prism =	20,834.11		
1	Airy Point	2291	-1	-896
16	Chivenor	755	0	-27
28	Barnstaple	389	0	374
Horsey Island	Tidal prism =	1,512,053.74		
1	Airy Point	2323	-33	-928
16	Chivenor	755	0	-27
28	Barnstaple	389	0	374
Home farm Marsh	Tidal prism =	386,387.84		
1	Airy Point	2299	-9	-904
16	Chivenor	755	0	-27
28	Barnstaple	389	0	374
Anchorwood	Tidal prism =	231,414.46		
1	Airy Point	2295	-5	-900
16	Chivenor	765	-10	-37
28	Barnstaple	389	0	374
Bisphops Tawton 1	Tidal prism =	37,652.27		
1	Airy Point	2291	-1	-896
16	Chivenor	757	-2	-37
28	Barnstaple	391	-3	361
Bishops Tawton 2	Tidal prism =	23,687.88		
1	Airy Point	2290	-1	-896
16	Chivenor	756	-1	-29
28	Barnstaple	390	-2	372

Table 14: Model predictions for channel width changes in the Taw Estuary as a response to managed realignment.

9.2 Torridge realignment proposals

The two potential realignment sites in the Torridge estuary are both located in the inner estuary. The impact of realignment at these sites is shown in Table 15. The comparison between the predicted regime channels before and after realignment is again regarded as indicative of the impact of realignment since the comparison with the existing channel width includes long term estuary development with the realignment. The results of the modelling show that the relatively large Hallspill site will have a significant impact on channel width in the estuary resulting in a potential maximum widening of 27m reducing to 20m at Bideford. As discussed above, however, due to the undersized regime channel in the Torridge the predicted wider channel will be reflected not in erosion but in a reduction in the amount of accretion that the channel will experience.

Profile	Location	Predicted width post-realignment(m)	Difference from predicted pre-realignment(m)	Difference from actual (m)
Hallspill	Tidal prism =	212118		
37	Appledore	1110	-9	246
46	Bideford	321	-20	61
53	R Yeo	188	-27	96
Tennacott	Tidal prism =	53891		
37	Appledore	1103	-2	253
46	Bideford	306	-5	76
53	R Yeo	168	-7	116

Table 15: Model predictions for channel width changes in the Torridge Estuary as a response to managed realignment.

9.3 Conclusions

The impact of the managed realignment, at the scales proposed, on the channel morphology of the Taw Estuary is relatively small. The most significant impact would result from the realignment at Horsey Island which is predicted to increase the channel width at Airy Point by 33m. The impact of the potential sites within the Torridge estuary is rather more marked. The Hallspill realignment site for example is predicted to result in 20m of channel widening at Bideford. Although as pointed out above, this would be realised not as erosion but as a reduction in accretion, nevertheless the potential impact on this small estuary must be regarded as significant.

Perhaps of greater concern than the direct impact of realignment on channel morphology is the indirect effect brought about through sediment sequestration in a realigned site. The 150ha site at Horsey Island for example would create a sediment demand of 13,500m^3 of fine sediment per year in order to keep pace with sea level rise , assuming an average sea level rise for the next century of 9mm per year (Defra 2006). A conservative estimate of the total of fine sediment deposition in the Taw over the Holocene period is $25x10^6$ m^3 or less than 5000m^3 per year. It is unlikely therefore that the Horsey Island managed realignment site would be able to keep pace with sea level rise and thus instead of salt marsh habitat it would develop into a low elevation mudflat. At the same time abstraction of sediment from the estuary into this area would reduce the deposition rate elsewhere and thus reduce the capacity of the estuary to respond to sea level rise.

It is interesting to note that the reclamation of Horsey Island took place between 1832 and 1855 (HR Wallingford 1990). By 1855 the lighthouse at Airy Point was surrounded by accreting sand causing some concern to harbour managers; however by 1860 this accretion has reversed to erosion (Kirby 1996). This does not mean that the impact of reclamation over the previous 30 years was cancelled out in 5 years but merely that the accretionary trend was reversed. The model predictions for a channel widening of 33m as a result of realignment apply equally in reverse, so that reclamation would result in 33m of channel narrowing. This may have been the cause of the accretion at the mouth in the years following reclamation of Horsey Island with reversion to erosion occurring as sea level rise re-established the former channel dimensions.

10. CHANNEL PLAN: MODEL PREDICTIONS

The prediction of a regime channel morphology for the Taw-Torridge estuaries does provide an indication of the future behaviour of the channel and allows some consideration of the management implications for the estuary. One aspect of estuarine geomorphology that is often overlooked when considering management implications, however, is the meandering plan form of an estuary. Estuarine meanders pose important problems for flood protection, navigation and conservation. Flood defences at the apex of meander bends, for example, are under significantly greater stress than those between meander apexes.

The meander model used in this study has been described in section 5.2 above. It consists of two components: a tidal meander model and a fluvial meander model. The model has been applied to the Taw and the Torridge and results are discussed in the following sections.

10.1 The Taw

The tidal model for the Taw estuary is based on the existing tidal prism. The output from the model is shown in Figure 34. Tidal wave length and amplitude increases towards the sea. Within the outer estuary the wave length for the Taw is in the range 5000m to 6000m and its amplitude ranges between 400m to 500m. Random variations in the predicted form are the result of sampling distance and do not reflect actual variations.

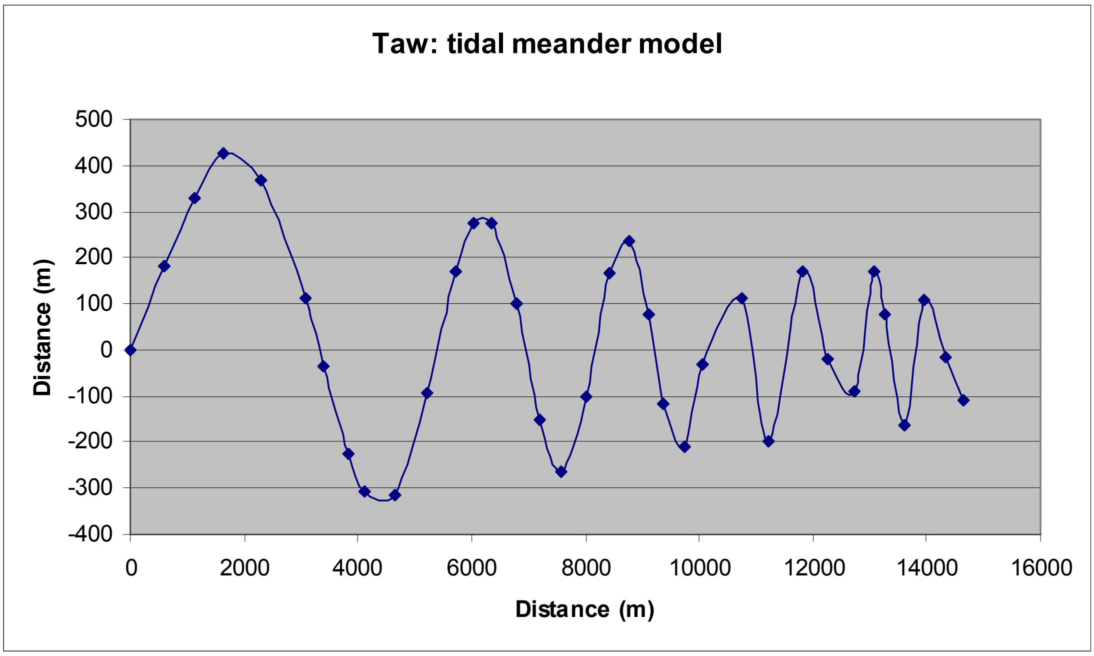

Figure 34: tidal meander model for the Taw Estuary based on present day tidal prism.

The fluvial meander is based upon the highest average monthly fluvial discharge over the recording period (1960-2002) at Umberleigh: 72m^3 s^{-1}. Since this discharge does not increase significantly within the tidal limits of the Taw, the predicted meander has a uniform wave length and amplitude throughout its length as shown in Figure 35.

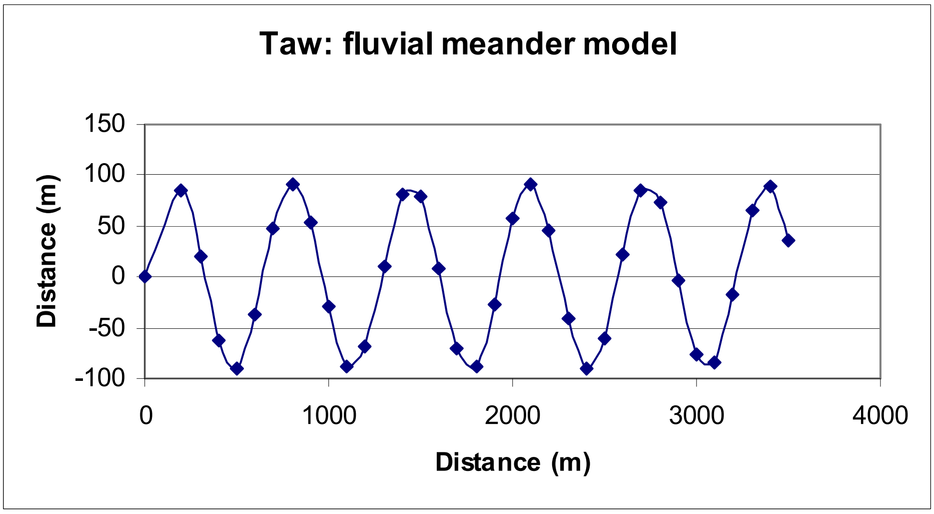

Figure 35: Predicted fluvial meander for the Taw

Addition of these two meander forms results in the plan form shown in Figure 36. The random variations in this plan form are partly due to the addition of the two wave lengths and partly due to sampling distances since the sample points were determined by the cross section data available for the study.

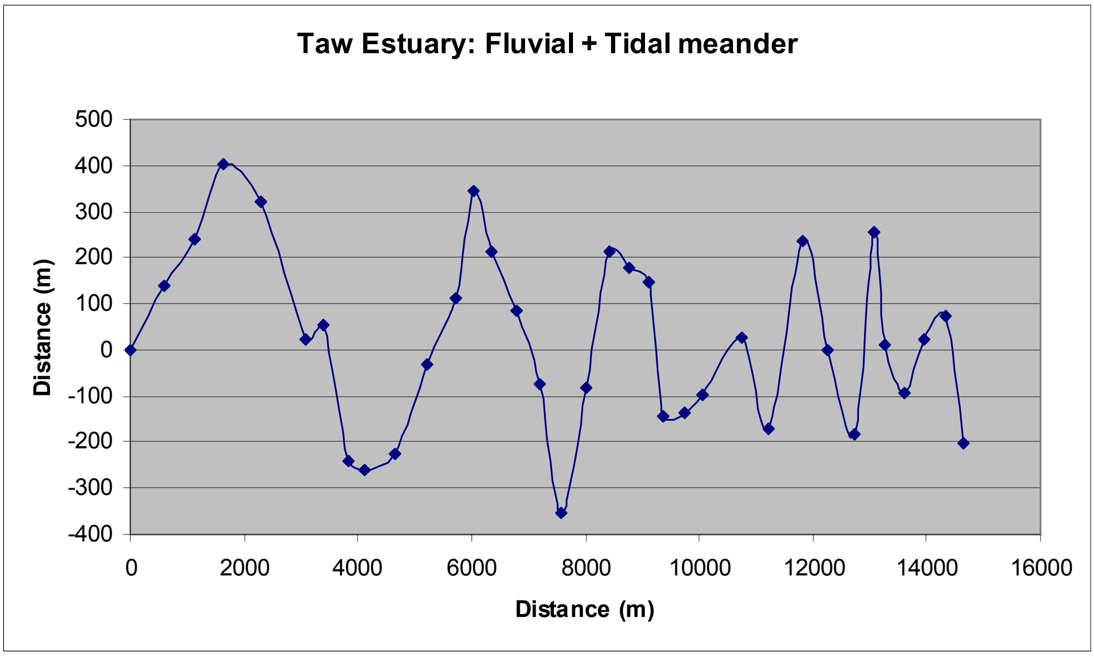

Figure 36: Predicted tidal plus fluvial meander for the Taw

10.2 The Torridge

The meander modelling for the Torridge estuary followed a similar process to that of the Taw. The results are again shown as a series of diagrams indicating the tidal meander (Figure 37) , the fluvial meander (Figure 38) and the composite addition of the two (Figure 39).

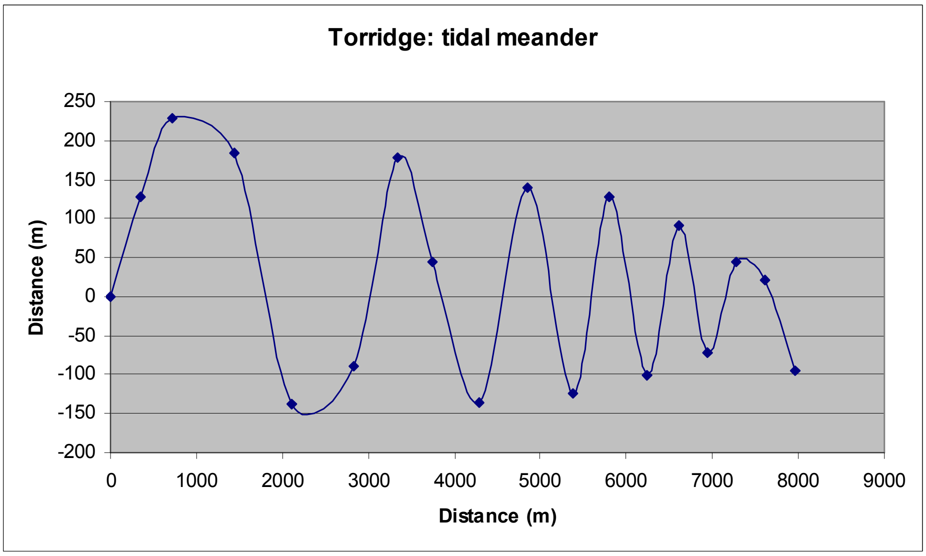

Figure 37: Predicted tidal meander for the Torridge Estuary

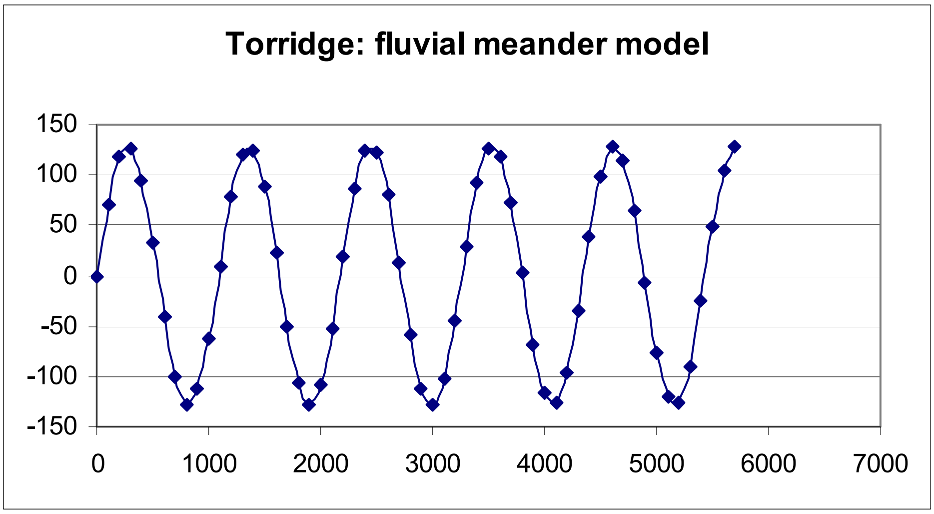

Figure 38: Predicted fluvial meander for the Torridge

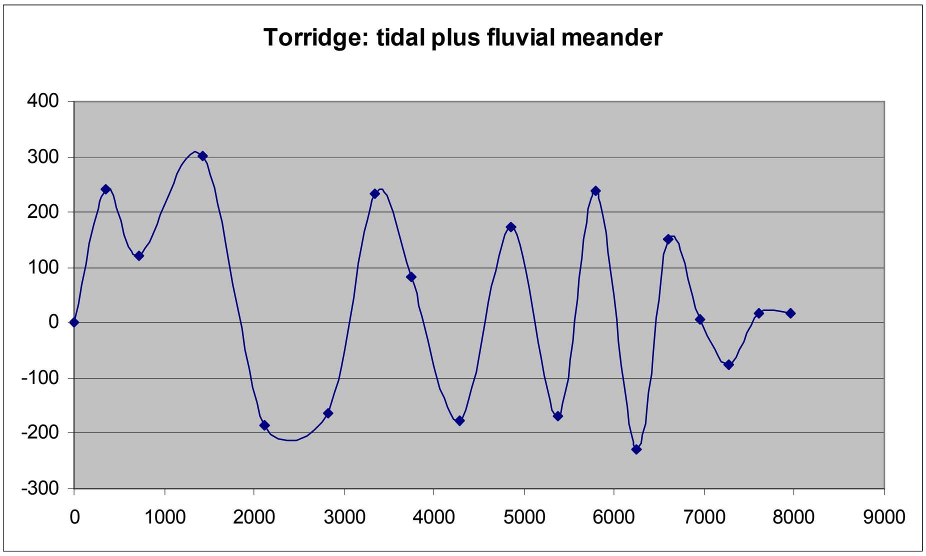

Figure 39: Predicted tidal plus fluvial meander for the Torridge

10.3 The Taw-Torridge meander model

The results of the meander models for both Taw and Torridge estuaries as shown above were fitted to the existing morphology of the estuaries to provide a map of the predicted plan form. Figure 40 shows the tidal meander only. The predicted channel pathway follows the existing low-tide meanders extremely well with the exception of the mid-Torridge where the predicted meander loop contrasts with the straight channel section along the Bideford frontage. It may be that this is due to channel modification along this reach of the estuary, since the 1st edition OS map does show a meander bend here that has subsequently disappeared.

Figure 41 shows the predicted tidal plus fluvial meander for both estuaries. The increase in amplitude over that for the tidal meander alone is particularly noticeable in the Torridge where the apex of each meander falls landward of the high water mark indicating considerable stress on banks and flood defences. In the Taw the much wider channel accommodates the meander within the inter-tidal area but nevertheless the results do indicate stress points at Bickington south of Barnstaple, along the Anchorwoodbank marsh edge and at Chivenor. It is emphasised that the meander pathway shown in Figure 41 is the mid-point of the channel and not the full channel width so that stress on banks will extend further landwards than indicated by the map.

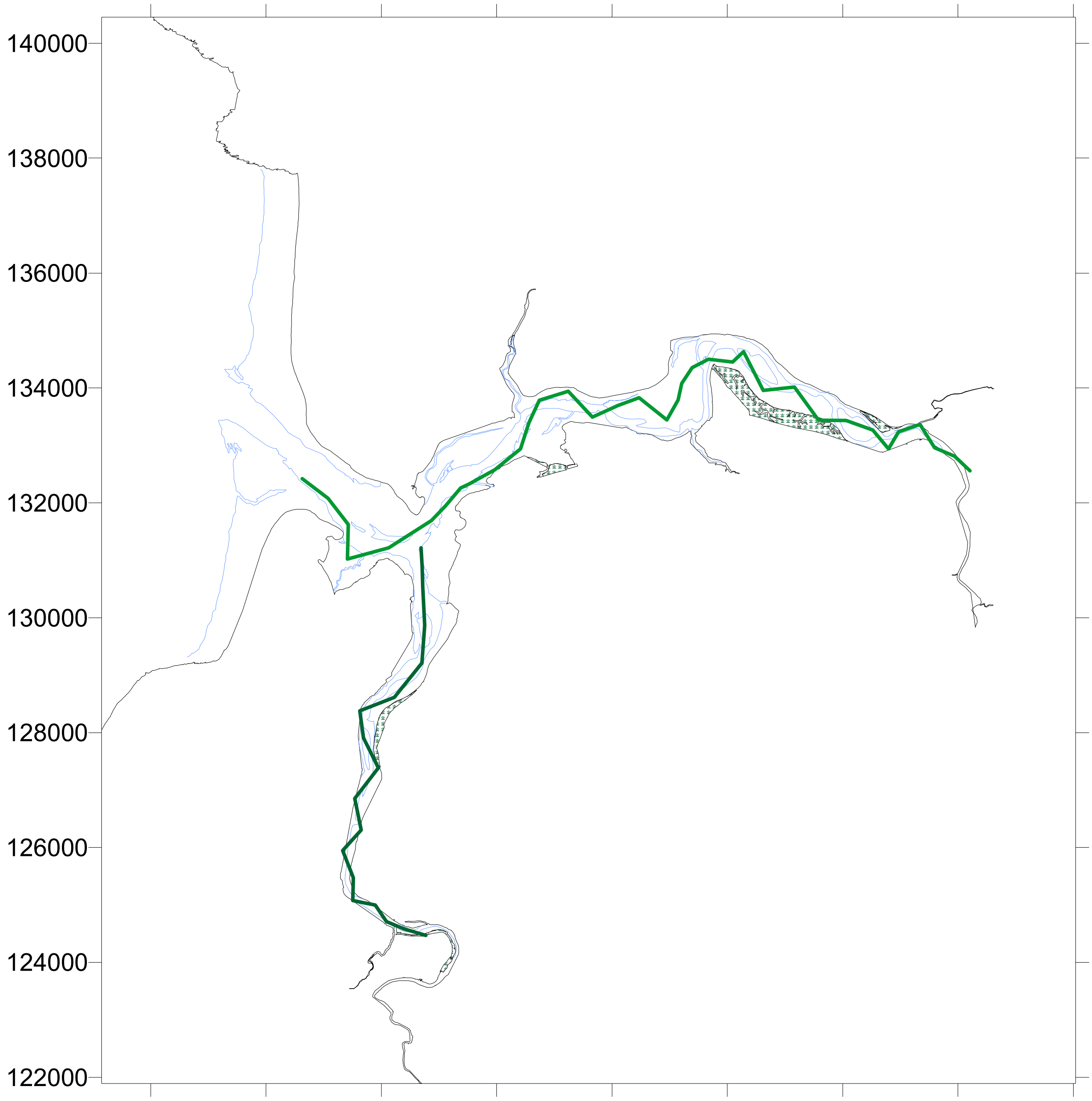

Figure 40: Predicted tidal meander pathway (green line) for the Taw-Torridge Estuaries.

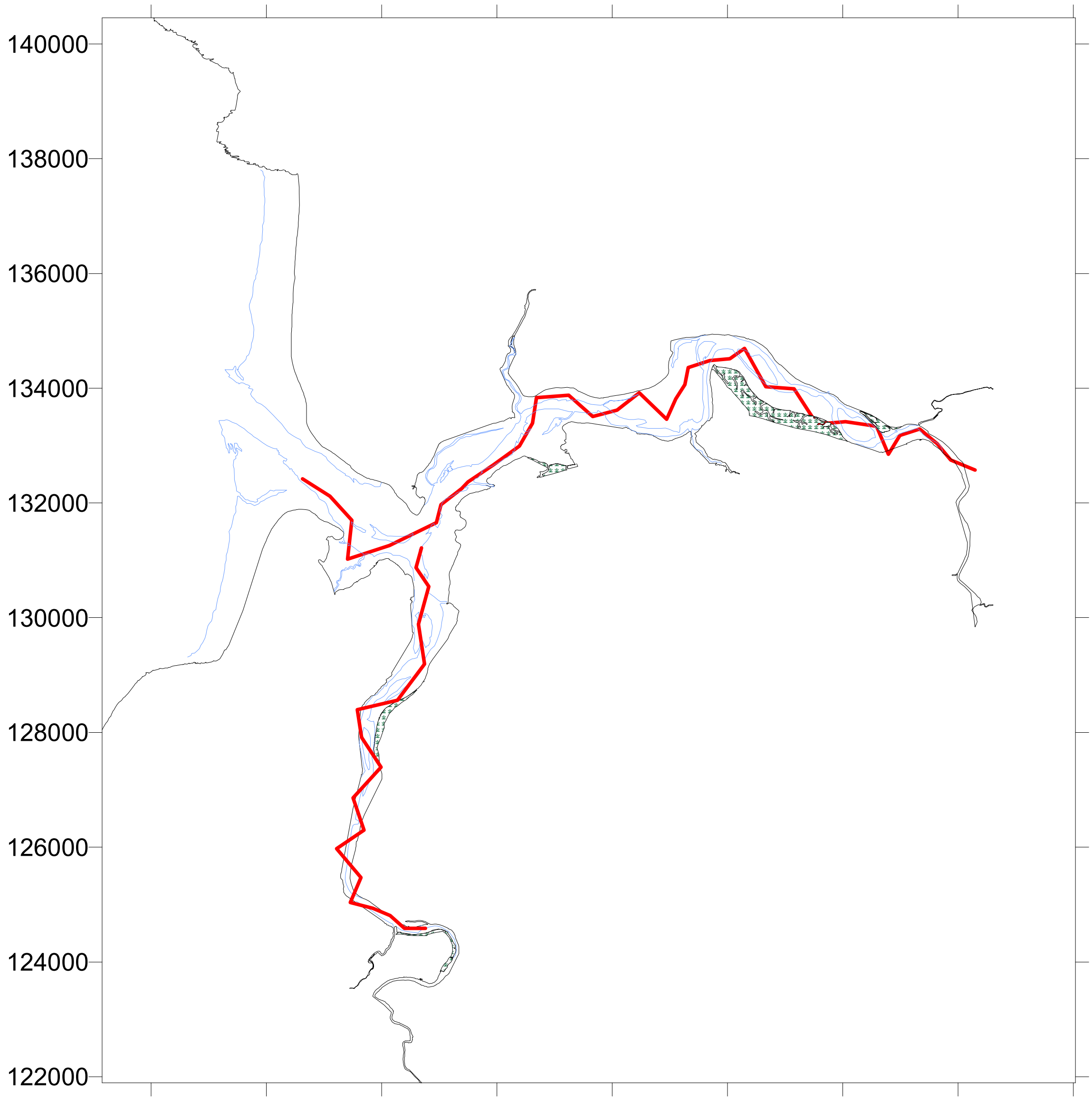

Figure 41: Predicted combined tidal and fluvial meander (red line) for the Taw-Torridge Estuaries.

10.4 Meander response to sea level rise

The meander model so far developed indicates those areas of the Taw-Torridge Estuaries that lie at the apexes of meander bend and therefore will experience increased erosion stress. This analysis may be useful, for example, to flood defence management or conservation planning. The model can now be extended to predict the impact of sea level rise on the meander pathway and therefore the impact on channel banks.

The tidal plus fluvial meander model was re-run incorporating one future sea level rise scenario – that for the year 2105. Sea level by this time is predicted to have risen by 0.997m (Defra 2006). The fluvial discharge is set at 72cumecs for the Torridge and 84 cumecs for the Taw, unchanged over the 100 year time period. This is perhaps unrealistic since some predictions of increased rainfall due to climatic changes have been made. However, these predictions have not been quantified and cannot be used for modelling purposes. It is emphasised however that an increase in fluvial discharge in the Taw or Torridge catchments would result in an increase in meander amplitude and wave length in the estuaries.

The tidal prism associated with a 0.997m rise in water level was calculated under the assumption, discussed above, that sediment deposition does not keep pace with sea level rise.

10.4.1 The Taw

The predicted meander for the Taw estuary by 2105 is shown in Figure 42. The dashed line indicates the predicted meander under existing conditions (sea level as at 2005) while the full red line shows the meander as at 2105.

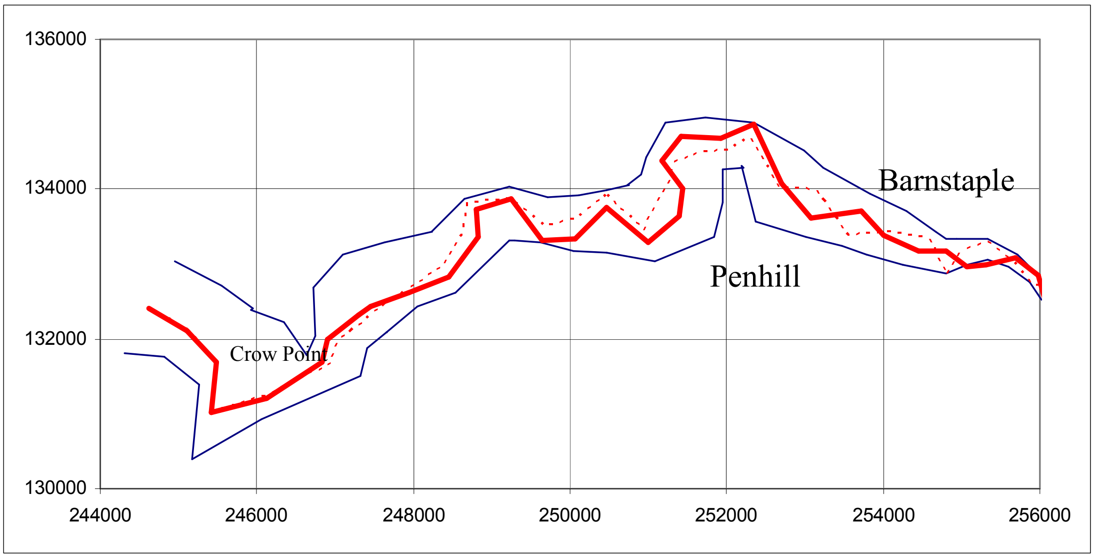

Figure 42: Changes in the combined tidal and fluvial meander for the Taw estuary over the next century assuming a 1m sea level rise. The meander under present day sea level is shown as dashed red line and after 1m sea level rise by 2105 as a continuous red line.

The predicted change shows some interesting variations, for example at Chivenor the meander has moved south so reducing the stress on flood defences there. On the other hand, the meander apex at West Ashford has moved north by over 150m while at Home Farm Marsh a 200m southerly movement of the apex is predicted and indicates increased erosion along this section of the estuary bank. The Bickington frontage south of Barnstaple also exhibits an increase in stress due to the easterly movement of the meander apex here.

10.4.2 The Torridge

The predicted meander for the Torridge assuming a 0.997m rise in sea level by 2105 is shown in Figure 43, again compared to the predicted meander for current sea level. The major implication is seen at the location of the Torridge Bridge. On the west bank the meander is predicted to have shifted almost 100m landwards immediately north of the bridge, on the east bank the meander apex has shifted landwards at Westleigh. Further south the meander has shifted away from the Bideford frontage and runs in the mid-channel from Bideford south to the R Yea confluence where again some stress on both banks is indicated.

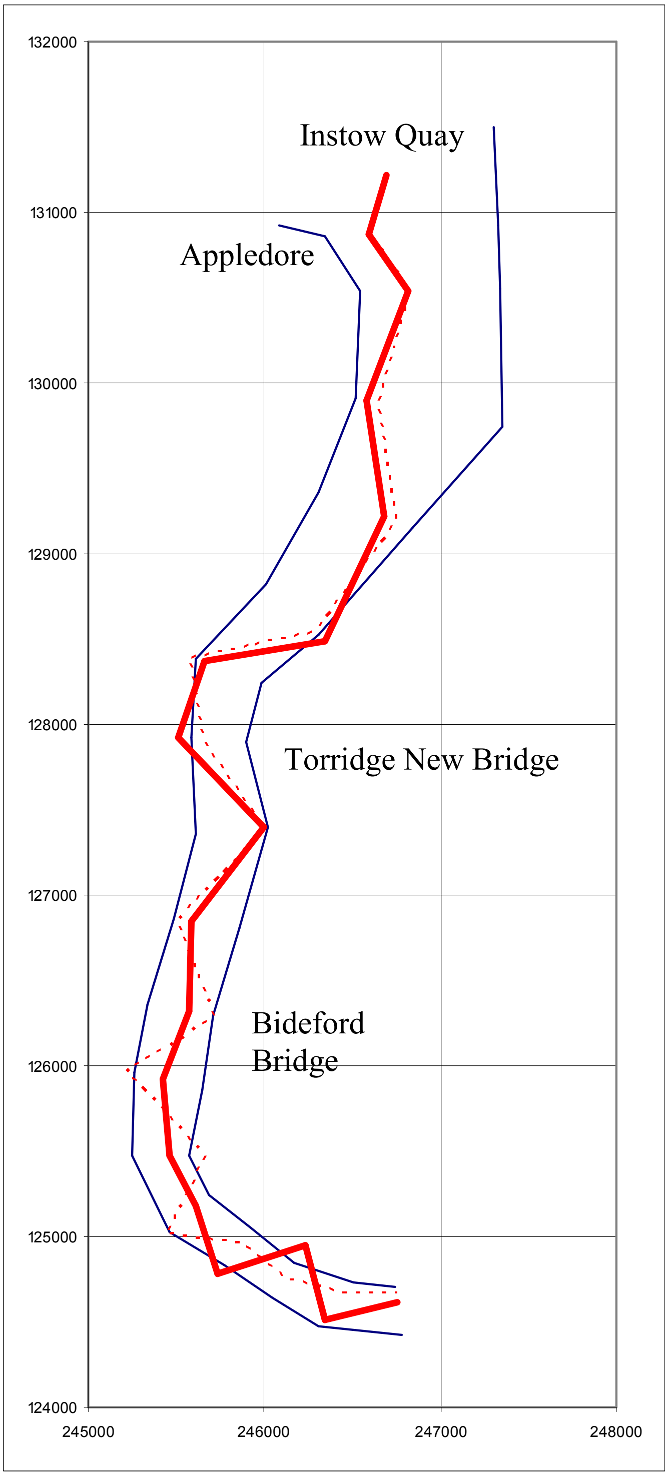

Figure 43: Changes in the combined tidal and fluvial meander for the Torridge estuary over the next century assuming a 1m sea level rise. The meander under present day sea level is shown as dashed red line and after 1m sea level rise by 2105 as a continuous red line.

11. COASTAL AND ESTUARINE DEFENCES

11.1 Existing defence standards

Standards of defence along the Taw estuary and outer Torridge estuary are provided in the SMP (Halcrow 1998) but no other information was available to this study. Defence standards are for the 200 year return interval and crest heights are in the range 6.0m to 7m ODN but with urban defence crest locally rising to 9.6m to 10.0m (e.g. at Appledore).

Reference to Figure 7 to Figure 9 Section 3.5, shows that, without defence crest increases, the standard of defence will be reduced from 1:200 years at present to 1:10 year by 2025 and 1:2year by 2055. By 2105 the predictions shown in Figure 7 to Figure 9 indicate that the defences in the estuaries will be overtopped on most spring high tides.

11.2 Future stresses on defences

In addition to the predicted increases in water levels over the next century, flood defences also are threatened by changes in the morphology of the estuary channels.

The results of the regime modelling indicated that sea level rise in the Taw estuary would result in an increase in channel width, unless sediment deposition in the inter-tidal zone keeps pace with sea level rise. Since the amount of fine sediment in the estuaries is already limited this seems unlikely. The resultant increases in channel width are shown in Table 11 and Table 12 in section 8.2. In the outer estuary at Airy Point channel width is predicted to increase from 46m by 2025 to 361m by 2105. This implies an increase in the present rate of erosion, put at 1m per year, to 2.3m by 2025 and 3.6m by 2105. Further landwards in the Taw, the predictions are for an 8m increase in channel width at Barnstaple by 2025 increasing to 61m by 2105. It is assumed that the flood defences at Barnstaple and other urban frontages will be maintained throughout this period so that the predicted channel widening here will be prevented. Nevertheless, the potential for channel widening will exist and will increase stress on these hard defences resulting in an increased maintenance effort.

The regime model for the Torridge estuary shows that, over the next 100 years, the channel will decrease in width due to the constraints imposed by its accommodation space rather than the response to sea level rise. The channel is larger than would be expected at the present time and the increased tidal prism due to sea level rise by 2105 will not be sufficient to offset this. Thus the Torridge channel is predicted to accrete over the foreseeable future and the effect of sea level rise will be to reduce this accretion rather than reverse it and cause erosion so that stress on defences here will be minimised.

The impact of channel meanders on flood defences as a result of sea level rise has been discussed above (section 10.4). It was noted that several sites along the Taw, including West Ashford, Home Farm Marsh and Bickington, were predicted to have increased stress on defences due to meander bend migration by 2105. On the other hand, in the Torridge estuary stress on the Bideford frontage is predicted to decrease due to meander migration away from the frontage into the central channel. Further north in the Torridge, however, at the location of the Torridge Bridge, additional stress on the west bank from meander movement is predicted and on the east bank at Westleigh. The inner Torridge, at the confluence of the R Yeo is also predicted to suffer increased erosion on both banks as shown in Figure 43.

11.3 Management issues

The development of the open coast along Northam Burrows and Braunton Burrows over the next century will be characterised by increased shore retreat as sea levels rise. This retreat is predicted to be accompanied by a re-orientation of the shore, a process already observed to be occurring. This will reduce the rate of sediment transfer along the coast and may affect deposition rates in the estuaries. The implications for the Pebble Ridge are discussed below. Along the Braunton Burrows frontage the main implications are loss of dune habitat especially of embryo and fore dunes. The impact of a number of human interventions in the natural system, including the construction of an offshore wind farm and the possibility of a tidal barrage are also considered in this section.

Consideration of any management intervention in the Taw-Torridge system is the function of the Shoreline Management Plan (SMP) and any specific scheme proposals or strategies that may arise from it. The SMP will be a transparent process where data and reports will be gathered, from all sectors of the community. There is a new prescribed methodology from DEFRA that ensures local viewpoints will be listened to. Ultimately the plan will be considered and, if approved, adopted by Local authorities and government agencies. Conflict resolution is an integral part of the prescribed procedure from DEFRA, where there is accountability for the development of the policies. There is legislation in place that sets the priorities for the types of area that need to be protected and the presumption towards natural processes.

11.3.1 The Pebble Ridge

The Pebble Ridge is re-orientating in a counter-clockwise direction with a retreat rate of 1.5m per year at its southern end. Northerly transport of the clasts has been at rates varying between 3000 m^3 and 5000m^3 per year but this is predicted to fall as the ridge re-orientates itself towards a swash-alignment. The re-orientation process is predicted to continue until movement of pebbles to the north is reduced to a minimum.

The possibility of successful management intervention in this development is difficult to envisage. Construction of groynes, for example, would be counter-productive since any interruption of the existing northward drift of cobbles would lead to accretion on the south side but a deficit on the north side leading to a breach. This may be seen at present at the small concrete sleeper bridge over the pebble ridge.

If losses of sediment from the distal end to the nearshore sink are allowed to occur the ridge will lose integrity and overtopping and breaching frequencies will increase. However, a recycling process that re-nourishes the ridge on its seaward side or on its crest merely reverses the process of swash orientation, so increasing drift rates and losses towards the distal end of the ridge. Orford (2004) therefore recommends that if any management is considered necessary then this should involve re-nourishing the ridge on its landward edge thus increasing the rate of counter-clockwise movement and increasing the rate of swash realignment.

If this process of back-edge re-nourishment is combined with continued maintenance of the existing defences (rock armour) at the distal end, the ridge will swing counter-clockwise with a fulcrum at the distal end. This would result in a minimum overall retreat rate and eventually achieve swash-alignment, minimising sediment losses at the distal end. Nevertheless, retreat would be necessary at increasing rates towards the south in order to achieve the counter-clockwise rotation and the eventual reduction in northerly sediment transport. A management programme designed to provide the precise retreat rate necessary for each location commensurate with the rotation rate of the ridge as a whole will be necessary. This may be achieved by using front-edge re-nourishment for the section of the shore, between Sandy Mere and the distal end, where the pebble ridge is backed by dunes. Given this programme of intervention, the most vulnerable section of the ridge will be located at Sandy Mere, where maximum rates of retreat will be experienced in the front-nourished section and careful planning will be needed to calculate the precise rate of retreat necessary. Management of the southern end of the ridge will also present difficulties as the ridge retreats. Flooding across the shore here may result in a re-opening of the tidal channel that connects to the Skern. Although such a process would result in increased fine sediment deposition here it would cause access problems to Northam Burrows. As pointed out above, management of this area for recreational use is in conflict with its natural coastal processes. Flood protection of the developed area of Westward Ho! must be an integral part of any such management process and would be considered within the Shoreline Management Plan.

11.3.2 Northam Burrows landfill site

Removal of the landfill is of course the theoretically optimum solution for this area but remains a high-cost and difficult operation. If the overall management plan for the Pebble Ridge follows the outline given above, then the distal end of the Pebble Ridge would be held by hard defences together with a programme of continued maintenance. This will reduce, and may eliminate, erosion to the frontage and thus the potential risk to the landfill site along its north east flank. However, the proposed management plan for the Ridge assumes a counter-clockwise rotation with a fulcrum at the distal end. This means that retreat of the Ridge and thus erosion of the sand dunes, will occur at increasing rates towards the south away from the distal end. The vulnerability of the shore at Sandy Mere due to this rotation has already been stressed. Management would involve nourishment of the front face of the ridge with recycled boulders and cobbles from the distal end so as to allow retreat but at rates consistent with the exact location on this rotating shoreline. Failure to achieve the correct rate of retreat between Sandy Mere and the distal end could result in catastrophic erosion during an extreme storm event and thus threaten the landfill site.

The proposed realignment of the northern area of the Skern and Grey Sand Lake (see section 9.1) would involve allowing tidal propagation across the access road to the landfill site. This could be achieved either by removal of the road, thus inhibiting any future plans for removal of the landfill, or by establishing multiple culverts under the road. The impact of this realignment on the estuary mouth is predicted to be minor amounting to 1m of erosion (section 9.1). The realignment would allow accretion within the site, mainly of sand but with some finer sediment so that some salt marsh may develop. This would act as a form of natural protection for the south east flank of the landfill site but might at the same time increase the tidal water table levels in the landfill and thus allow some exudates to move into the estuary. Overall, it is concluded that the realignment proposal for this area has a neutral impact on the landfill problem.

11.3.3 Crow Point

The origin and development of Crow Point have been discussed above (section 6.5.2). It was concluded that Crow Point resulted from an artificial structure in the 19th century and will inevitably erode away over the next few decades. This is not seen as posing any problems for the estuary since the basement of the area remains as inter-tidal gravel which will act to dissipate any wave propagation entering the estuaries across the outer delta. The presence of this inter-tidal gravel basement, prior to the development of the Crow Point sand-dune spit, is shown on the Denham chart of 1832. This suggests that sand moving into the estuary from Airy Point was moved across this gravel basement by wave and tidal action so that no net accretion occurred. The effect of the construction of the weir along this section of the foreshore, shown in the Denham Chart, was to reduce wave energy at the upper shore and allow sand deposition and thus provide a source for wind blown sand that formed the dune spit. Thus, not only does the gravel basement to Crow Point act to dissipate wave energy, but in so doing it allows rapid sand transport into the estuary and into the temporary store at Instow Sands. Although this accumulation of sand at Instow may be seen as a management problem in fact it is a crucially important process for estuarine stability as discussed below (Section 11.3.4)

It may be concluded that the threat to this area of the inner estuary would not be from the erosion of the Crow Point sand dunes but rather from any renewed gravel extraction from the inter-tidal area, a process now discontinued.

11.3.4 Instow Sands

The geomorphology of the Instow Sands was discussed in section 6.2. They form an integral part of the tidal delta of the Taw-Torridge estuarine system, representing the flood delta rampart. A clockwise, circular sand-transport pathway links the ebb-tide delta (the Bideford Bar) with the Instow Sands via Airy Point and Crow Point. Sand is temporarily stored at Instow before moving seawards along the ebb-dominated central channel. This sand movement results in some net input to the estuary, calculated above as around 20,000m^3 per year. This sediment is deposited in the outer estuary and has allowed the inter-tidal area to keep pace with sea level rise. It is predicted that the accelerated rates of sea level rise over the next century will mean that this input of sand will be insufficient to maintain relative inter-tidal levels and some erosion of the outer estuary will result. It is therefore imperative that sand continues to arrive at the Instow Sands. This causes some problems for shore management here since blown sand on the shore road must be removed. Removal must and should be continued, but the sand should be re-deposited within the sediment pathway on the down drift side, that is to the south of Instow or, if possible within the outer estuary channel. This will allow sand to continue circulation without re-entering the Instow shore area and allow the outer estuary to respond to future environmental changes.

11.3.5 Offshore wind farm

The wind farm is expected to be situated to the north and west of Lundy. The implied circulation of the Bideford Bay is tightly confined and will not be affected. The wind farm is lies closer to the pathway of sediment that is moving down the Bristol Channel and past Bideford Bay.

11.3.6 Tidal barrage

Recent research has shown that estuaries need to have a critical length for the volume exchange of water in and out of the mouth of estuary during a tidal cycle: that is the tidal prism as defined in section 3.1 above. A tidal barrage would reduce that volume exchange and result in a reduction in velocity at the estuary mouth. This decrease in velocity will, in turn, mean that the estuary is no longer able to scour its mouth section as longshore sediment enters it from the west. The mouth will therefore become narrower and shallower causing an increase in velocity and stability will once again be resumed. Thus the major outcome of a barrage would be deposition in the entrance to the Taw-Torridge estuaries. There will be other issues concerning sediment migration upstream, water quality and flood defence that detailed studies would need to address.

12. TECHNICAL SUMMARY

- **The conceptual model.** This study has developed a conceptual geomorphological model of the Taw-Torridge Estuaries and their adjacent coast. The major conclusion of the model is that the estuaries and the open coast are sediment-starved systems whose morphology has therefore not attained a geomorphological equilibrium at this stage in the Holocene Interglacial. This can be seen in the changing orientation of its open coast shorelines as it swings towards a swash-alignment. It can also be seen in the gradual seaward progression of a deposition front in the estuaries, particularly the Taw, as fine sediments slowly infill the deeply incised early-Holocene river channel cut into the bed of the estuaries.
- **The tidal delta.** The connection between the estuaries and the open coast, its tidal delta, is seen as the critical component of the entire system. Sediment is circulated counter-clockwise around the open coast bay. Within the nearshore, this sediment bypasses the estuary mouth in a series of episodic, south to north, sand-wave movements across the tidal-delta frontal lobe. Some of this bypassed sediment is moved along the Saunton Sands and then north and west to complete the sediment gyre in the bay. Some of the bypassed sediment at the delta front moves into the estuary along a clockwise pathway passing from Airy Point, along Crow Point and through the Instow Sands before moving back to the open shore. A small percentage of this sand is retained in the estuary and has, in the past, allowed the outer estuary to keep pace with sea level rise.
- **The outer estuary.** The outer estuary channel is constrained both by its rock-cut incised channel and the pressure of long shore sediment transport along the open coast. This has resulted in a relatively narrow mouth and the growth of the two barrier beaches on either bank: the Northam Burrows and the Braunton Burrows. Both these sand dune and marine clay barriers represent a major sediment store from the early to mid-Holocene and are likely to remain as stable features over the long term future despite minor changes in the position of their open shorelines and the width of the estuary mouth between them, resulting from sea level changes and a gradual reduction in sediment circulation. Independent of this entire system, a pulse of coarse gravel and boulder sized sediment entered Bideford Bay in the 16th or 17th centuries and

formed the Pebble Ridge along the upper shore of Northam Burrows. This ridge receives no new sediment but, under natural processes, is losing sediment to the north and will eventually be removed from the coastal system altogether.

- **The inner estuaries.** In the inner estuaries, the sandy outer channels merge into finer grained muds. This fine sediment is derived from marine sources and is in short supply. The estuaries therefore have not yet achieved the smooth long profiles and extensive inter-tidal salt marshes of a mature system. Instead the wide Taw estuary has a limited extent of marginal salt marsh and a long profile that exhibits a sharp break is slope as the inner muddy estuary channel passes into the outer sandy channel. In the Torridge estuary, the confining valley slopes together with the lack of fine sediment have produced a relatively deep and narrow channel with little salt marsh development. As a result, it is predicted that the inner Torridge channel width will continue to decrease slowly over the next 100m years despite an increase in the rate of sea level rise. In both cases it is expected that fine sediment will eventually infill the channels but that this process may take centuries even millennia to accomplish.
- **Management implications**. The implications of the conceptual model for coastal and estuarine management of this area are centred on the realisation that the system has been, and remains, in a state of flux, even before the predicted changes over the next century in sea level, storm frequency, extreme water levels and fluvial discharges. Management of such a volatile system must rely on a detailed knowledge of the long term outcome of the natural processes of change, so that human intervention, if necessary, may attempt to work with, rather than contest, the natural evolution of the system.
- **Regime modelling**. In order to provide some quantification of the long term evolutionary pathway for this coastal and estuarine system, a series of geomorphological models has been employed. These have resulted in prediction of the probable morphology of the estuaries, first assuming that no change occurs in their external forcing factors and second assuming changes associated with global warming, principally sea level rise. The main conclusions of the geomorphological or regime modelling are as follows:
- **The outer estuary equilibrium**. The theoretical, equilibrium, mouth of the estuary system is predicted to be significantly wider, (by 900m) and shallower than the actual channel, but is held at its present dimensions by the incised rock channel and the pressure imposed by longshore sediment transport. This area of the estuary channel is, however, shown to be extremely sensitive to changes in energy or sediment inputs. Thus, reclamation of the Horsey Marsh in the 19th century may have caused a temporary narrowing of the mouth, while sea level rise over the past 200 years has resulted in a steady widening of the mouth by approximately 1m per year.
- **The inner Taw equilibrium.** The inner Taw is predicted to be narrower than the actual channel: by between 300m to 500m, but slow deposition rates in the Holocene have restricted its development. It is predicted that deposition will continue to slowly infill the channel with a deposition front moving seawards from its present position at Penhill Point.

- **The inner Torridge equilibrium.** The Torridge is predicted to be shallower than its actual channel, although its predicted regime width is approximately equivalent or slightly wider than the observed values in the outer estuary , that is between Bideford and Appledore. South of Bideford the predicted channel is narrower than the actual width. Infill of the sub-tidal channel is predicted to continue, again at a slow rate.
- **Predicted stress points.** The major stress points are located along those sections of the estuary where predicted values are already equivalent to, or greater than actual values. These are:
    - The outer estuary between Crow Point and Airy Point;
    - The mid-Taw between Horsey Ridge and Chivenor Ridge;
    - The outer Torridge between Bideford and Appledore.
- **Sea level rise.** The results of the regime modelling incorporating sea level rise over the next century, rising by almost 1m by 2105, have shown that the morphological response of the estuary will be significant.
    - The Taw is predicted to increase its width at Airy Point by 360m over the next 100 years, a rate of erosion some three times the present rate.
    - The Torridge is predicted to increase its channel width at Appledore by 157m.
    - These increases in width will place existing flood defences under considerable stress and are a matter of some concern for estuary management.
- **Managed realignment.** The results of the regime modelling incorporating a series of potential managed realignment sites in both estuaries have shown that the impact, at the scale of realignment proposed, will be relatively minor.
    - In the Taw Estuary following the Horsey Island realignment a maximum of 33m of erosion at Airy Point is predicted. All other realignment sites result in widening of <10m and in most cases <2m throughout the channel.
    - The impact of realignment within the Torridge estuary is similar in absolute terms to that of the Taw, but in the much smaller estuary channel its relative impact is greater. The Hallspill realignment site for example is predicted to result in 20m of channel widening at Bideford. Since the inner Taw is already wider than predicted this impact of realignment would be realised not as erosion, but as a reduction in accretion.
    - Perhaps of greater concern than the direct impact of realignment on channel morphology is the indirect effect brought about through sediment sequestration in a realigned site. This is likely to result in poor habitat development in the realigned site and a reduction in deposition elsewhere in the estuaries.
- **Meander modelling**. The results of the regime meander modelling incorporating sea level rise of 1m over the next century, has predicted that

several locations will experience increased bank stress due to the movement of the apex of meander bends. These locations include:

  - West Ashford on the Taw where a landward movement of the meander apex of 150m is predicted;
  - Home Farm Marsh on the Taw where a 200m southerly movement of the apex is predicted;
  - The Bickington frontage south of Barnstaple where a 300m easterly movement of the meander apex is predicted.
  - Torridge Bridge, west bank where a meander is predicted to move 100m landwards immediately north of the bridge;
  - Torridge Bridge, east bank, a meander apex is predicted to shift 200m landwards at Westleigh.
  - Bideford frontage is predicted to experience a decrease in bank stress as the meander bend moves away and into the central channel.

- **Management Issues**
  - **Estuarine flood defences.** The crest heights of existing flood defences in the Taw-Torridge estuaries are shown to be inadequate given the predicted rate of sea level rise over the next century. Analysis of tidal gradients, existing extreme water levels and sea level rise predictions indicate that the 200 year return flood water level will, by 2105, become the 2 year return interval event. Maintenance and increased crest standards will be essential. In addition, the meander modelling results have shown that at several locations along both estuaries, meander migration will cause increased stress on flood defences, again demanding increased maintenance.
  - **The Pebble Ridge.** The Pebble Ridge represents an ephemeral and peripheral landform component of this coast. Under natural processes the Ridge will gradually erode away and its component gravels, cobbles and boulders moved northwards. The lack of any new sediment inputs means that the ridge is rotating counter-clockwise towards a swash-alignment that will eventually reduce northerly transport to a minimum. If management is deemed necessary to retain the integrity of the ridge, for example in order to maintain the recreational use of Northam Burrows, then it is recommended that the counter-clockwise rotation towards swash-alignment is accelerated by nourishing the back edge of the southern ridge with recycled cobbles and by holding the present line of the distal end. In the intermediate section between Sandy Mere and the distal end this management programme must nourish the front edge of the ridge in such a way as to allow it to continue rotation.
  - **Northam Burrows Landfill.** The management programme outline for the Pebble Ridge will provide protection for the landfill site. This will remain extremely vulnerable however, especially from erosion along the Sandy mere section. The proposed realignment site at Greysands

Lake is not seen as providing any additional protection for the landfill site.

- **Crow Point.** The sand dune spit appears to be the result of an artificial structure built in the 19th century and now removed. As a result the sand dunes at Crow Point will eventually erode away. This is not seen as providing any additional risk to the inner estuary or to Instow from wave propagation.
- **Instow Sands.** The accretion of sand along the Instow frontage is a result of wind-blown sand from Instow Sands - the flood tide delta of the estuary. Although sand accumulates on this flood tide ramp, there has been no long term change in its morphology and thus sand is stored here temporarily before moving seawards. The process of sand circulation around the estuary mouth area is crucial to the estuarine response to sea level rise. If any attempt were made to inhibit this movement, the reduction in sand accretion in the inner estuary would result in increased wave erosion along the shoreline.

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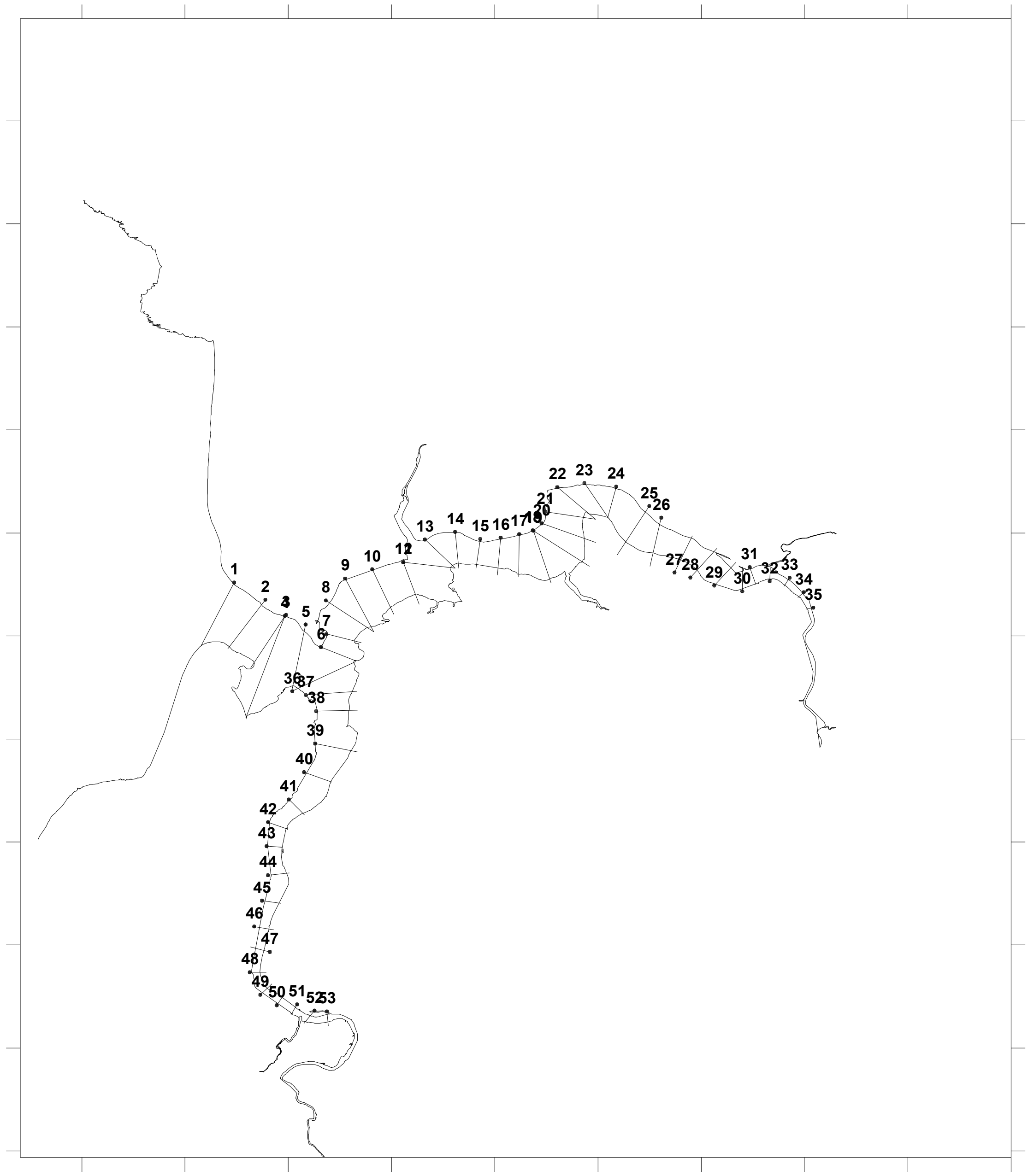
ANNEX I

TAW-TORRIDGE ESTUARY BATHYMETRIC PROFILES. SURVEYED MAY 2006.



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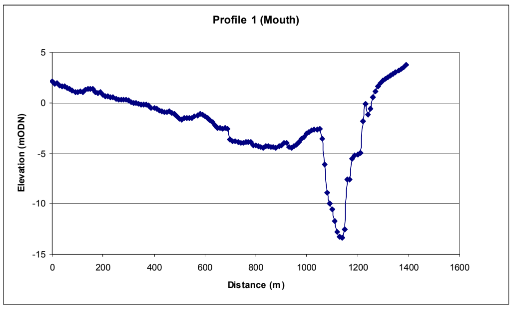
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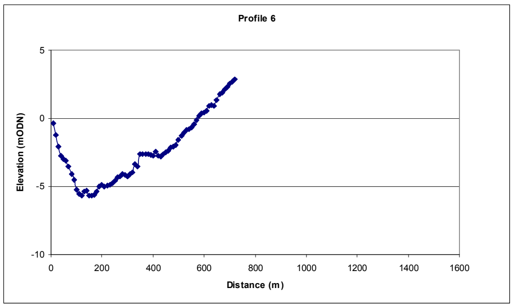
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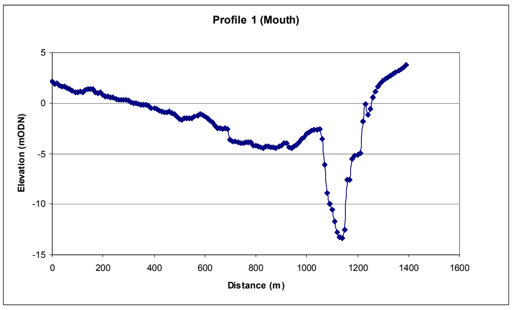
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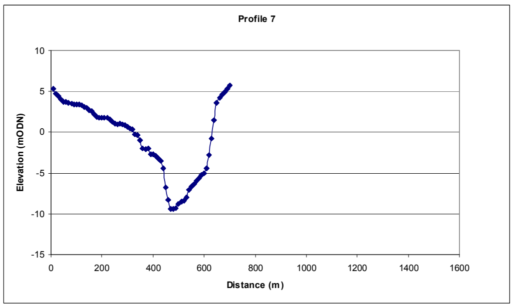
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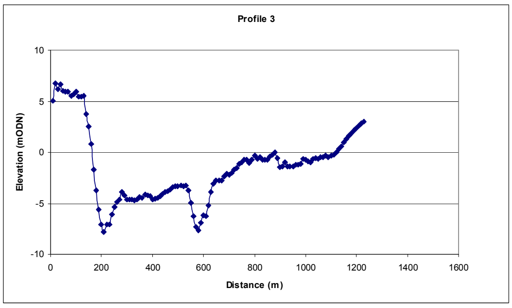
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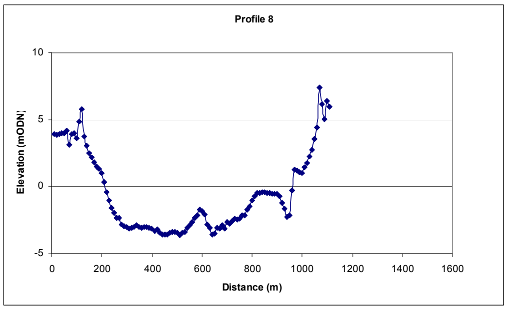
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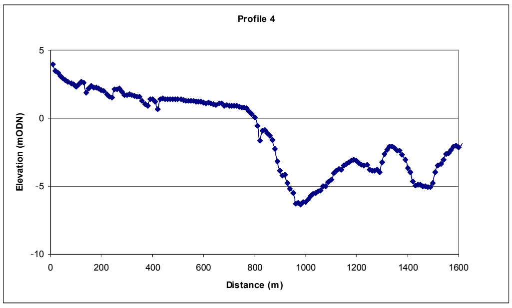
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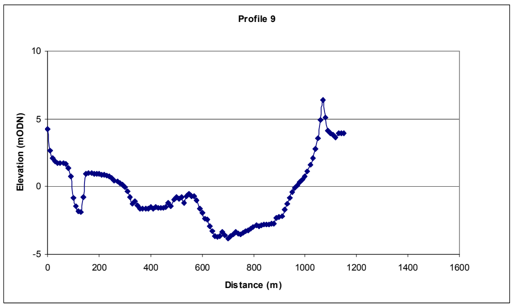
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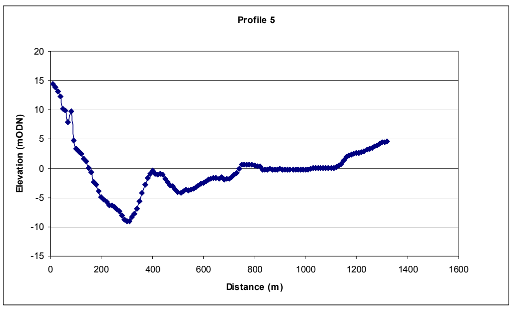
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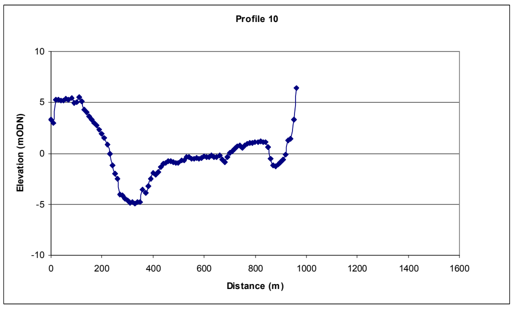
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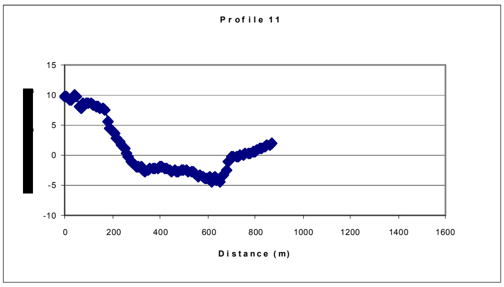
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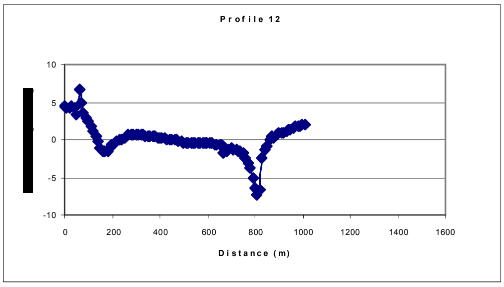
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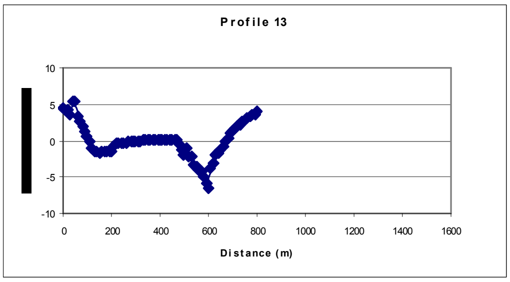
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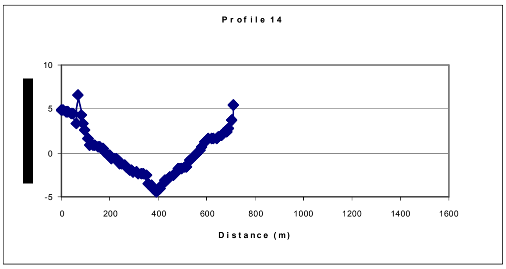
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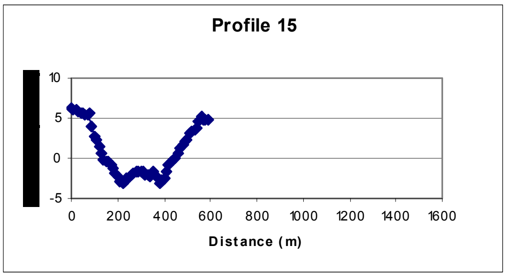
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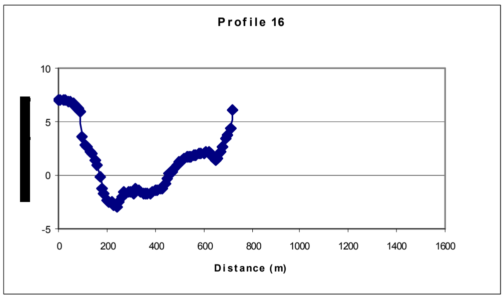
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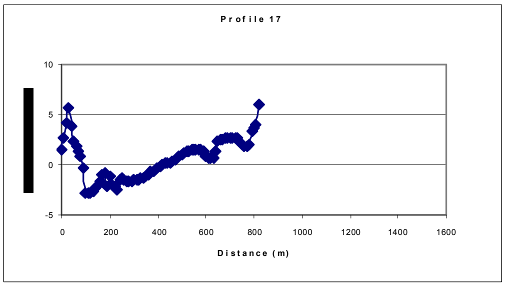
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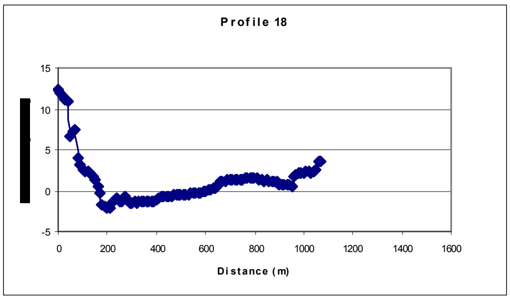
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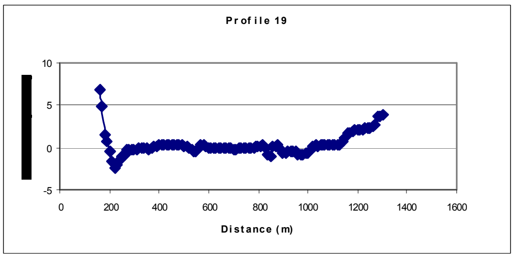
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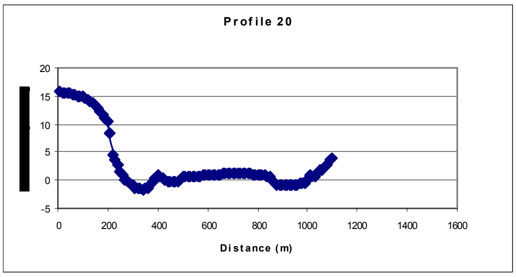
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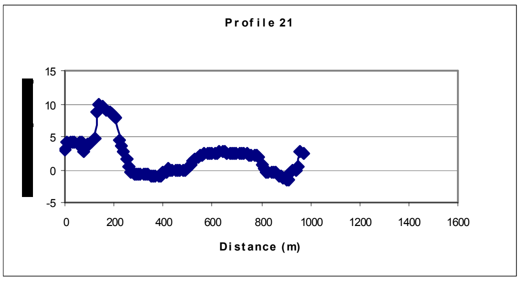
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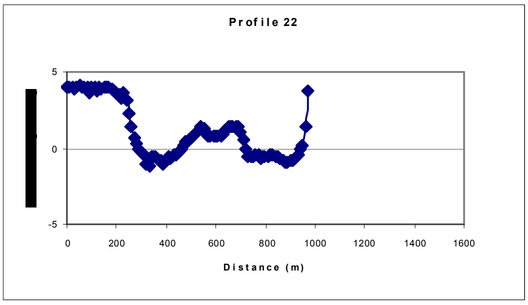
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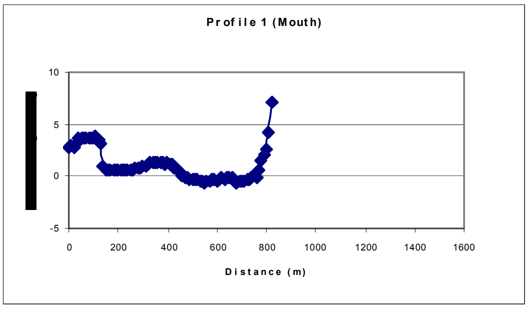
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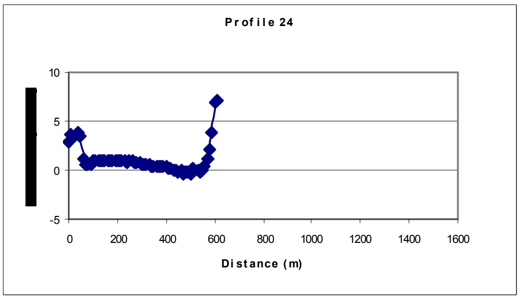
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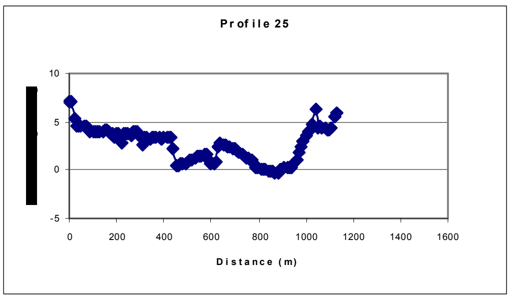
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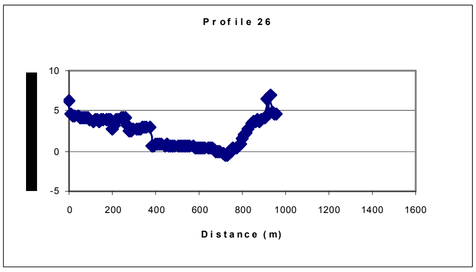
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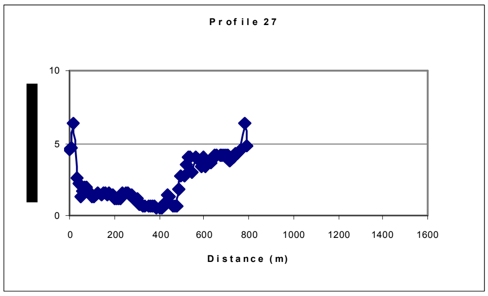
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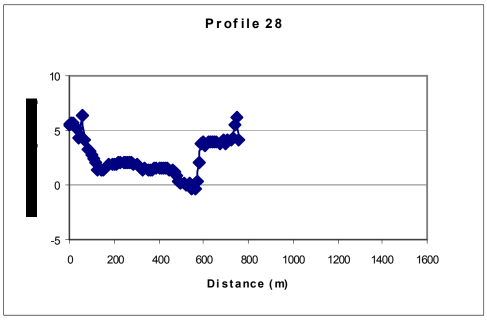
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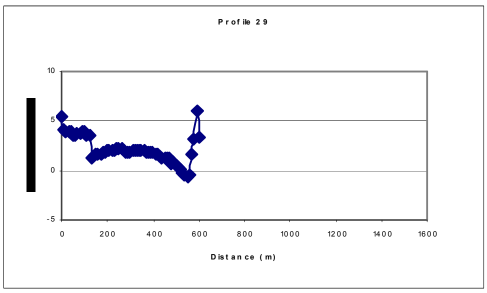
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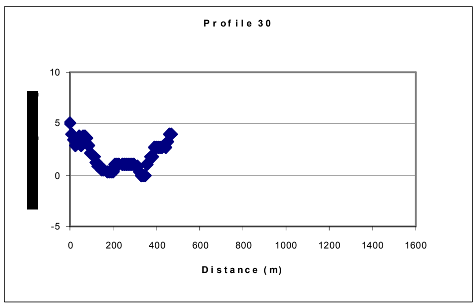
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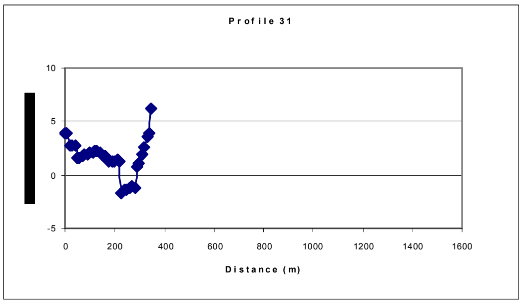
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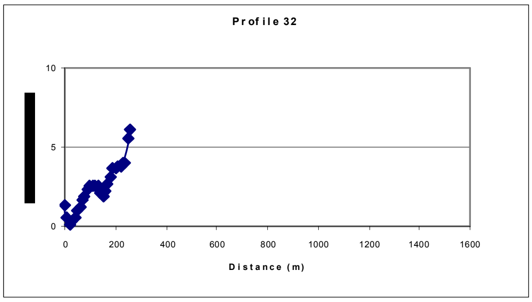
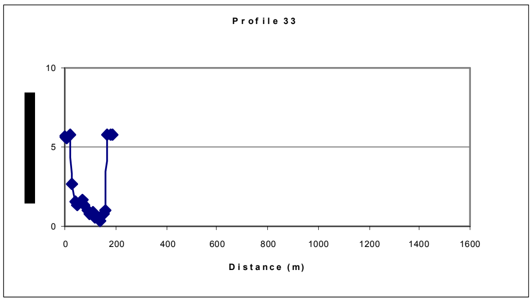
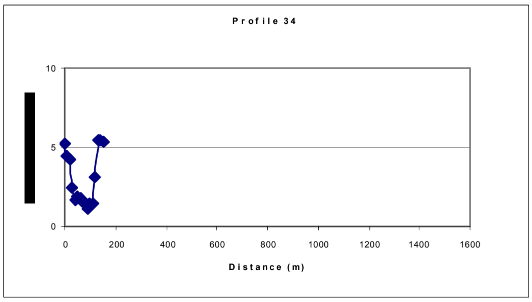
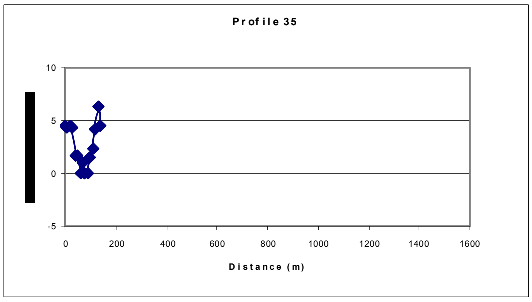
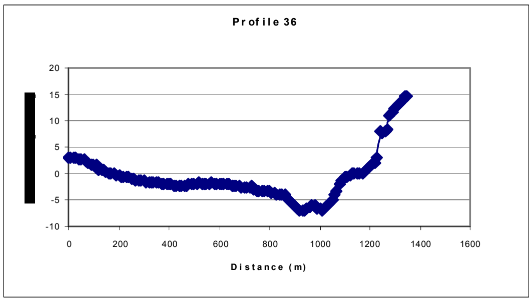
Distance (m)

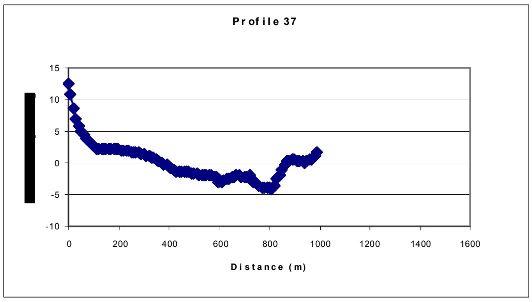

Profile 32
Distance (m)

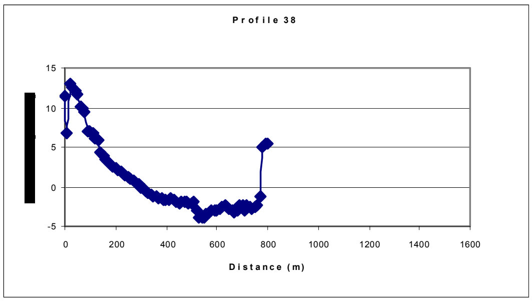

Profile 33
Distance (m)

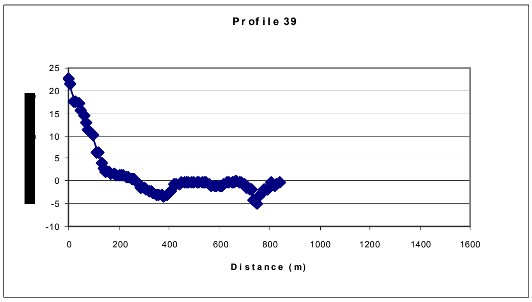

Profile 34
Distance (m)

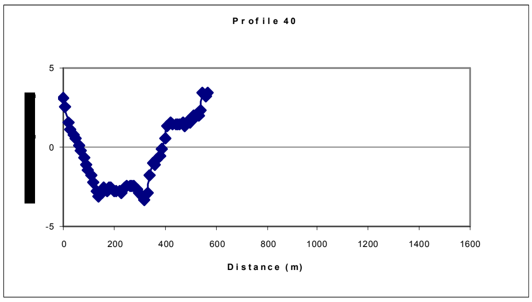

Profile 35
Distance (m)

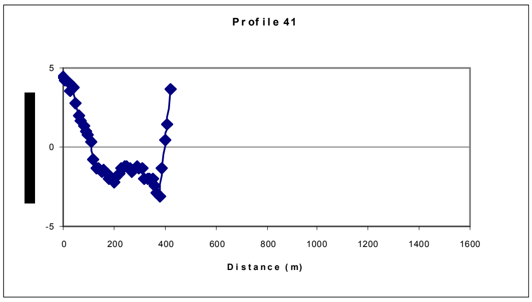

Profile 36
Distance (m)


Profile 37
Distance (m)


Profile 38
Distance (m)


Profile 39
Distance (m)


Profile 40
Distance (m)


Profile 41
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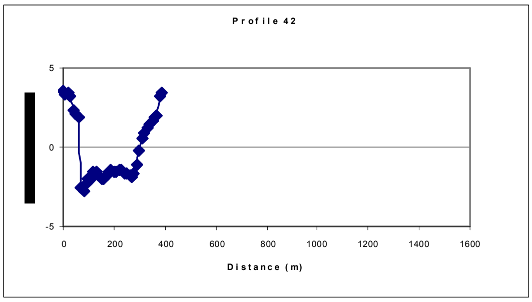
Distance (m)


Profile 42
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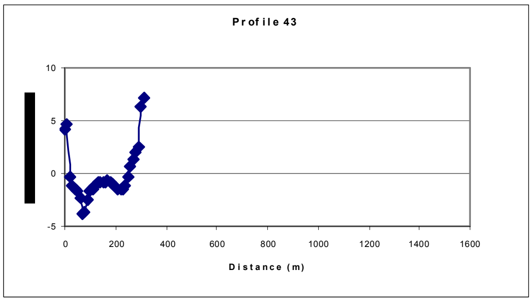
Distance (m)


Profile 43
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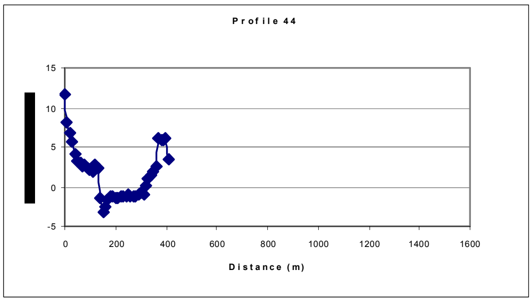
Distance (m)


Profile 44
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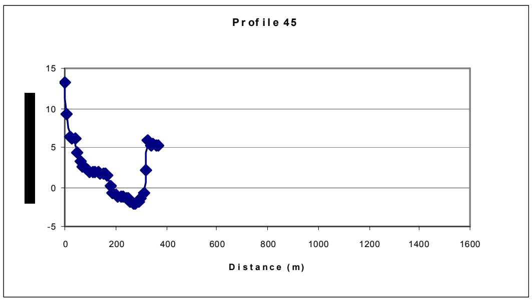
Distance (m)


Profile 45
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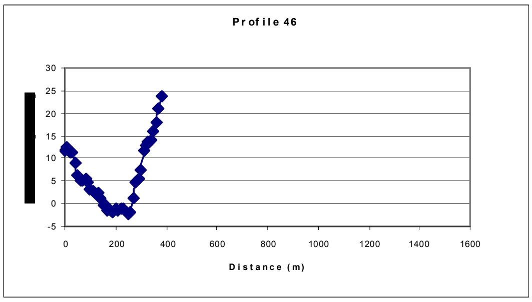
Distance (m)


Profile 46
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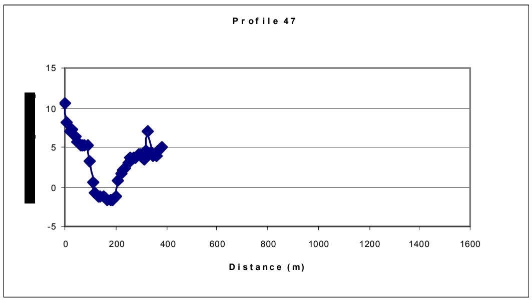
Distance (m)


Profile 47
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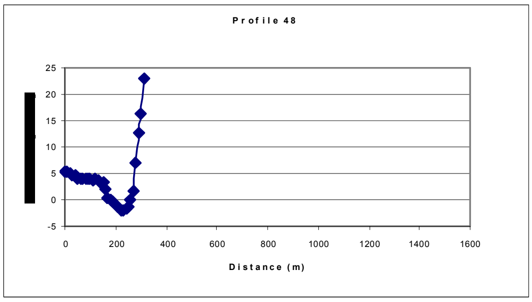
Distance (m)


Profile 48
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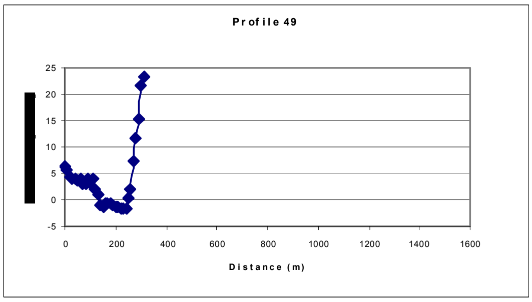
Distance (m)


Profile 49
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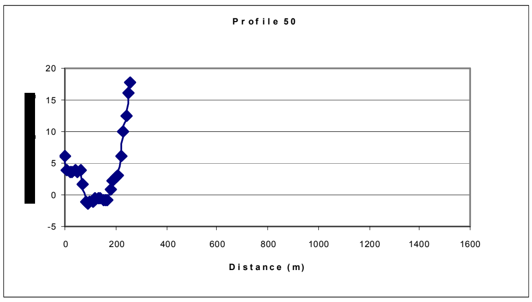
Distance (m)


Profile 50
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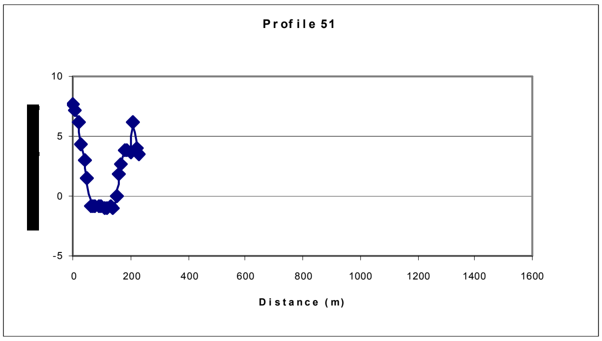
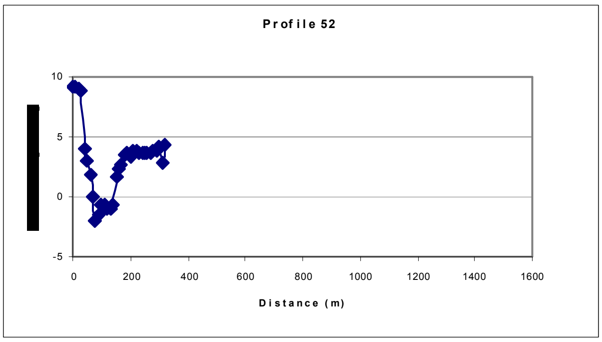
Distance (m)


Profile 51
10
5
0
-5
0
200
400
600
800
1000
1200
1400
1600
Distance (m)


Profile 52
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0
-5
0
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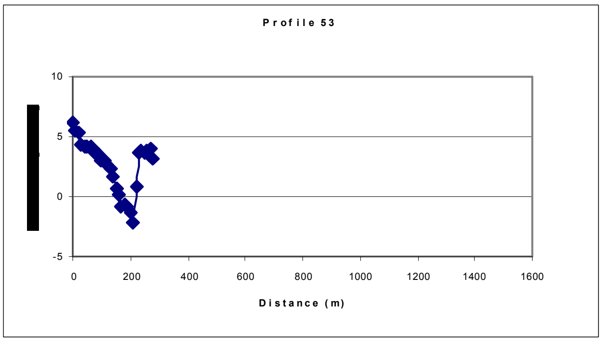
600
800
1000
1200
1400
1600
Distance (m)


Profile 53
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-5
0
200
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600
800
1000
1200
1400
1600
Distance (m)