Morphological Characterisation of the Severn Estuary and Solway Firth

Natural England

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Final Report
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SUMMARY
The Severn Estuary and Solway Firth are large estuary systems that support a variety of habitats designated within Special Areas of Conservation (SAC). These estuarine SACs are subject to a number of pressures including coastal squeeze and development, which could affect the whole-estuary condition. The challenge for this study was to characterise the landscape-scale functioning and degree of morphological equilibrium of the estuaries to support judgements about their condition (health), in accordance with Common Standards Monitoring (CSM) guidance of JNCC.

To define the condition of an estuary as favourable means that the special features of the designated areas are in a healthy state and are being conserved for the future by appropriate management. In order for this condition to be maintained over the long term, there must be confidence that the estuary can sustain adequate habitat of the appropriate quality, within an overall morphological equilibrium.

Morphological equilibrium in the Severn Estuary and Solway Firth was analysed using Regime Theory, which defines empirical relationships between estuary tidal prism and cross-sectional area. Equilibrium in these estuaries is seen as a dynamic state in which constant adjustments take place to their overall morphology so they are able to function effectively. The observed form of the estuary was compared to the predicted equilibrium form to determine how far from equilibrium each estuary is. Integration of natural (geological) and human-induced constraints then allowed an appraisal of reasons for disequilibrium.

The critical data upon which the Regime Theory method used in this project relies are bathymetry and tidal datum elevations. In this study, a limited number of bathymetry datasets were received covering different parts of the estuaries, including Admiralty Chart data, LiDAR and multibeam echosounder. These datasets were evaluated and those that were considered to best represent the current bathymetry were integrated and used in the analyses. The data was quality assured to check for gaps and inconsistencies which were filled and rectified as appropriate.

The results for the Severn Estuary and Solway Firth are generally similar. Both estuaries are under-sized compared to their predicted forms in their inner parts; the observed channels are narrower than predicted for the present-day tidal regimes. This means that to obtain an equilibrium form they have to widen from their current forms. They should erode by loss of intertidal habitat because in both estuaries the high water mark is constrained by coastal defences which do not allow it to migrate landwards. In contrast, both outer estuaries are over-sized compared to their predicted forms; the observed channels are wider than predicted for the present-day tidal regimes. Here, they should accrete and develop further intertidal habitat by natural processes. The central parts of the estuaries are tending towards equilibrium whereby their observed and predicted widths are similar.

In addition to considering the key requirements for a baseline measure of morphological equilibrium, a monitoring strategy was developed so that these requirements can be met through future condition assessments. The strategy includes recommendations for monitoring of bathymetry and changes in position of morphological boundaries, particularly between mudflat and saltmarsh, and protocols for data management.

CONTENTS

1 INTRODUCTION

An assessment of the condition of the interest features and attributes of an estuary needs to take account of the relationship between its broad-scale physical form and function. Local measurements of physical parameters, such as signs of erosion or accretion, aid the condition assessment of each feature attribute, but they should be viewed within the context of the broader-scale estuary processes that are contributing to change. This is particularly so for the Severn Estuary and Solway Firth, which are large and dynamic systems and potentially subject to longer-term fluctuations in morphology, reflecting estuary evolution processes as well as responses to past or present human interventions.

Both the Severn Estuary and Solway Firth support a variety of habitats including subtidal sand banks and intertidal sandflats, mudflats and saltmarsh, which are designated within Special Areas of Conservation (SAC). These estuarine SACs are subject to a number of pressures including coastal squeeze due to coastal erosion and/or sea-level rise and development such as coast protection, ports and marinas (land claim and/or dredging). These pressures can affect the whole-estuary condition.

1.1 Objectives

This report describes a desk study characterisation of the Severn Estuary and Solway Firth to support judgements about estuary condition. Existing data was used to characterise the two estuaries under five headline parameters:

- bathymetry;
- tidal regime;
- extent of estuary;
- area of intertidal habitat; and
- most importantly for the objectives of this project, (whole-estuary) morphological equilibrium.

The key requirements for a baseline measure of morphological equilibrium were considered using an approach aligned with that used for the Healthy Estuaries 2020 project (Natural England, 2015). Recommendations for a monitoring strategy have also been made in the study so that these requirements can be met through future condition assessments.

The main stages of this study in support of an assessment of morphological equilibrium in the Severn Estuary and Solway Firth were:

- collate the essential data which are bathymetry up to the foot of flood embankments or mean high water spring (MHWS) if no defences are present, and tidal datums (MHWS, mean high water neap - MHWN, mean low water spring - MLWS);
- develop a series of cross sections from the upper estuary to the estuary mouth and measure the current form and predict the equilibrium form of the estuaries at each section;

- identify any natural (geological) and human-induced constraints to estuary form; and
- provide a preliminary assessment of the condition of the morphological equilibrium attribute, in accordance with Common Standards Monitoring (CSM) guidance (JNCC, 2004) (Table 1.1).

Table 1.1. Factors involved in condition of morphological equilibrium attribute

Attribute	Measure	Target	Comment	Method
Extent	Total area of estuary feature	No decrease in extent from the established baseline due to human-induced changes	Extent is an attribute on which reporting is required by the Habitats Directive	Extent to be established using highest astronomical tide (MHWS is used in this study, see Section 2.4). This ties in with the use of spring tidal datums to establish tidal prism in Regime Theory (Appendix A)
Morphological equilibrium	Tidal prism/cross-sectional area (Tp/Cs) relationship	No significant deviation from the intra- and inter- estuarine Tp/Cs relationship.	The relationship between Tp and Cs provides a measure of the equilibrium of an estuary which is fundamental to the way it adjusts to tidal energy and is reflected in rates of deposition and erosion. Substantial changes in this relationship may indicate that human-induced factors are taking effect and this would trigger more detailed evaluation of potential problems	Bathymetric survey every 12 years, or sooner if saltmarsh boundary measurements indicate a deviation away from standard limits of natural variation
	Long-term trends in the position of the boundary between the saltmarsh and mudflat	Subject to natural change, no significant deviation from the long-term average	Monitoring the lower saltmarsh boundary (approximately mean high water neap) is a practical means of securing data which may indicate changes in the Tp/Cs relationship Deviation from long-term trends would act as a trigger for a second tier response involving detailed bathymetric survey and evaluation of changes in the Tp/Cs relationship In the absence of saltmarsh, vertical change in mudflat elevation can act as a surrogate for saltmarsh (it may be used as well)	Annual fixed point survey every September, aerial photography and LiDAR

2 METHODS

Existing data have been used to characterise the key baseline geomorphological parameters of the Severn Estuary SAC and Solway Firth SAC. These are bathymetry, tidal regime, extent of estuary and area of intertidal and subtidal habitats. Other parameters were then derived from these basic elements in order to determine how close to morphological equilibrium each estuary is (see Section 2.5). These derived components include spring tidal prism (the volume of water that enters and leaves the estuary at a defined section during a spring tide), cross-sectional area and width.

2.1 Extent of Study Areas and SACs

2.1.1 Severn Estuary

The Severn Estuary is the largest coastal plain estuary in the United Kingdom and one of the largest estuaries in Europe. The overall area of the European and international conservation designations is about 740km^2 of which roughly two thirds is composed of subtidal habitats (sandbanks and mobile gravel, sand and mud) and one third is composed of intertidal habitats (mud and sand, saltmarsh and rocky shores). The estuary has been a focus for human activity; a location for settlement, a source of food, water and raw materials and a gateway for trade and exploration. The estuary and its coastal hinterland support the cities of Cardiff, Bristol, Newport and Gloucester. Today, major industries are sited along the estuary's shores, including port installations, chemical processing plants and nuclear power stations. Aggregate extraction also occurs within the estuary.

Alongside all these competing activities, the estuary also supports a wide array of habitats and species of international importance for nature conservation.

http://jncc.defra.gov.uk/protectedsites/sacselection/sac.asp?EUCode=UK0013030

Human activity has increasingly influenced the character of the marginal mudflats and saltmarshes, with extensive land claim occurring since the Roman period. The morphology of the estuary is constantly changing due to the complex hydrodynamics. The Severn Estuary CHaMP (ABPmer, 2006) predicts losses of intertidal flats and saltmarsh habitats over the next 100 years in response to rising sea-level against fixed sea defences along much of the shoreline.

The defined boundary of the Severn Estuary SAC occupies the water course from Awre downstream to a line across the estuary between Lavernock and Lilstock. However, for the purposes of this analysis, the study area has been extended outside the bounds of the SAC to understand if there are wider implications of disequilibrium within the SAC, and how it could be potentially mitigated outside the SAC. Hence, the Severn Estuary is defined from Longney, about 15km upstream of Awre, downstream to a line between Aberthaw and Chapel Cleeve, about 15km downstream of the SAC boundary (Figure 2.1).

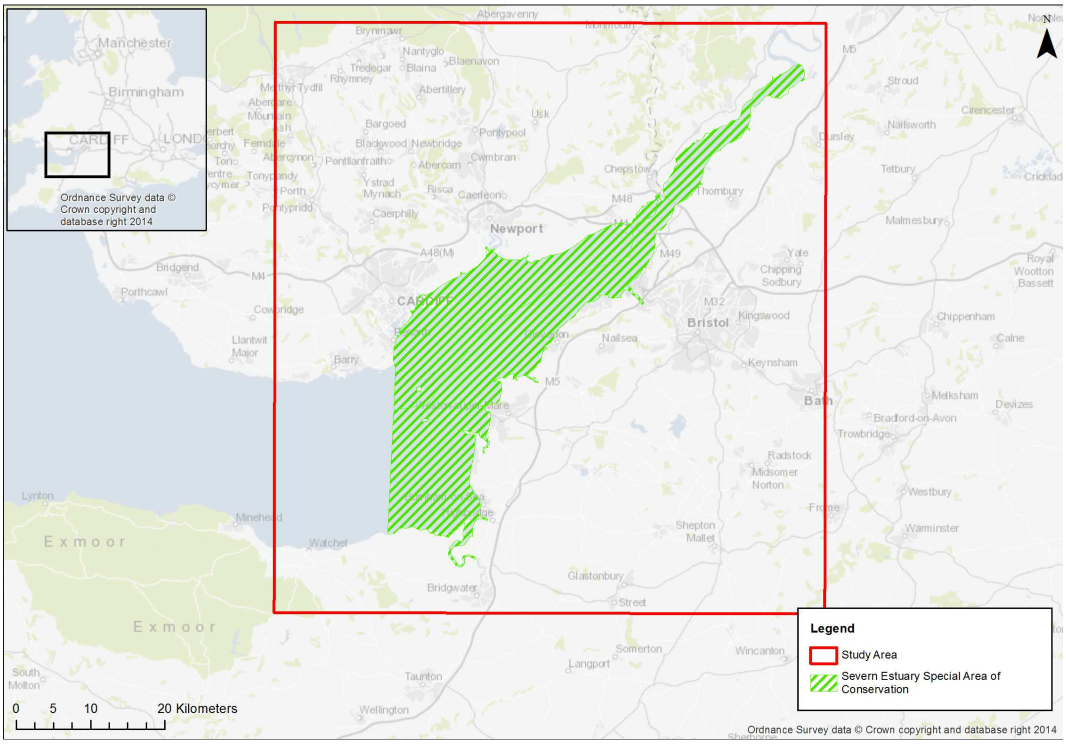

Figure 2.1. Severn Estuary study area and SAC boundary

2.1.2 Solway Firth

The Solway Firth is a large shallow estuary formed by a variety of historical physical influences including glaciation, river erosion, sea-level change and geological controls. It is one of the least industrialised and most natural estuary systems in Europe. Located on the west coast of the United Kingdom, it straddles the border between England and Scotland, forming an extensive system draining into the Irish Sea. The estuary supports extensive areas of saltmarsh, both pioneer and Atlantic salt meadow, as well as large areas of intertidal mudflats, reefs and sandflats, and subtidal sandbanks, each of which are of international importance in their own right.

http://jncc.defra.gov.uk/protectedsites/sacselection/sac.asp?EUCode=UK0013025

The defined boundary of the Solway Firth SAC occupies the water course from around Gretna downstream to a line across the estuary between Sandyhills and Mawbray. However, for the purposes of this analysis, the Solway Firth is extended about 15km beyond the seaward boundary of the SAC to a line across the estuary between Barlocco Bay and Siddick (Figure 2.2). The study area has been enlarged beyond the SAC boundary for the same reasons as the Severn Estuary.

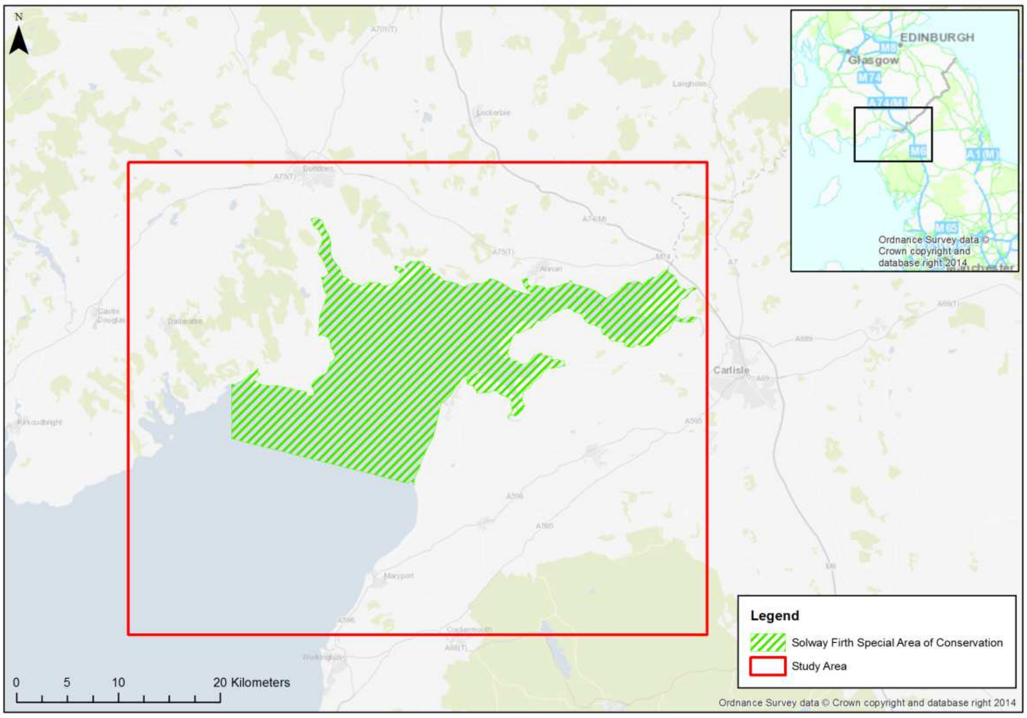

Figure 2.2. Solway Firth study area and SAC boundary

2.2 Bathymetry

Digital bathymetries were compiled from various sources, collected using several different methods. The best available bathymetry data for each estuary was compiled, as far as possible (described in Sections 3.1 and 4.1 for the Severn Estuary and Solway Firth, respectively). The bathymetry data covers all intertidal and subtidal areas up to the seaward face of the front-line defences or up to the MHWS datum where the coastal plain rises naturally into the hinterland, and stretches from as close to the upstream tidal limit(s) as possible to the defined downstream boundaries (Figures 2.1 and 2.2). The bathymetries in both the Severn Estuary and Solway Firth have been composited from two or more surveys that cover different parts of the estuaries. The bathymetry data was quality assured to check for gaps and inconsistencies which have been filled and rectified, accordingly.

2.3 Tidal Regime

Although there are several methods available to determine the tidal regime in an estuary, the simple use of the predicted tidal levels published in the 2015 UK Admiralty Tide Tables is opted for here, in line with the Healthy Estuaries 2020 approach (Natural England, 2015). The tidal datums were used as a characterisation tool in their own right, but were also used along with bathymetry to calculate tidal prism and cross-sectional area for the morphological equilibrium analysis (see Section 2.5). The critical tidal datums for the analysis were MHWS, MHWN and MLWS.

2.4 Estuary Extent and Area of Intertidal Habitat

MHWS was adopted as the datum to define estuary extent, rather than highest astronomical tide. This is because MHWS is a predicted datum (2015 Admiralty Tide Tables) at numerous points along the estuaries and so can be more readily and accurately mapped. In addition, highest astronomical tide only occurs very infrequently and is not the datum that truly represents the upper limit of intertidal habitat within an estuary.

The area of intertidal habitat has been mapped between the MHWS and MLWS datums. The original intention (in the original scope) was to screen existing data, to obtain two specific datasets; one that has mapped intertidal areas at or close to the time of designation (2005 for the Solway Firth and 2009 for the Severn Estuary) and one that is as recent as possible. This has not been possible to achieve because baseline surveys are not available (as far as we know) at the time of designation. Hence, due to the lack of consistent available data, it is only possible to determine the extent of intertidal habitat based on merged bathymetry data collected from different years. A time series of intertidal habitat change has not been achieved.

An estimate of saltmarsh change along the southern shore of the Severn Estuary Special Protection Area from 1995 (date of designation) to 2004 was carried out by Natural England (2006). They estimated an increase of about 0.2km^2 over the nine year period.

2.5 Morphological Equilibrium

The overall condition of an estuary can be founded on the relationship between its physical form and function (to accommodate an energy exchange by redistributing water and sediment), and so the estuary should be in dynamic equilibrium with natural wave, tidal and sediment transport processes. Condition can thus be explained by overall morphology of which the most easily measured attribute is planform (the outline of the estuary as seen from above).

The best way to determine how far the estuary system is from the equilibrium state is through morphological methods, which measure the long-term response of an estuary to natural changes in forcing, and also account to a varying degree, for changes in morphology following human interference such as land claim, engineering works or dredging. One of the most commonly used methods is Regime Theory (adopted by Healthy Estuaries 2020, Natural England, 2015), which uses empirical relationships between estuary gross morphology and tidal prism, through simple power-law equations. Indeed, the morphological equilibrium of an estuary as defined by the CSM guidance for estuaries and coastal saltmarsh (JNCC, 2004) is the relationship between cross-sectional area and tidal prism at the estuary mouth.

Over time, an estuary will have had its dynamic equilibrium morphology changed in some way by human interference and different parts of its form are likely to be at different stages of adjustment to natural process inputs. Hence, an estuary will seek to reach a steady state over the long term by oscillating around theoretical equilibrium morphologies over the short term to medium term. The width and depth of the estuary will therefore change over time towards a state of dynamic equilibrium or 'most probable state'. Regime Theory predicts the equilibrium width of an estuary, which when compared with the observed width can be used to determine, at a high level, how far an estuary is from an equilibrium form. How close an estuary is to morphological equilibrium defines the condition of this attribute.

Regime Theory was applied to the Severn Estuary and Solway Firth through use of GIS and Excel spreadsheet platforms, which allow step-by-step data input and calculations developed by Healthy Estuaries 2020 (Natural England, 2015). The method relies on bathymetry data (Section 2.2) and tidal datum data (Section 2.3) as inputs into the GIS. Details of the principles of Regime Theory and the specifics of how the methodology is used here are provided in Appendix A.

3 RESULTS FOR THE SEVERN ESTUARY

3.1 Bathymetry

The best available bathymetry for the Severn Estuary was obtained in two different formats from the Environment Agency Geomatics Group. These were LiDAR at 2m resolution and Admiralty Chart data in vector format. These were the only two datasets used in the analysis (a list of all bathymetry data that was received is provided in Appendix B). Both datasets required processing and manipulation before being 'stitched' together to create the final bathymetry. The following procedure was followed:

- The LiDAR data, in Ordnance Datum (OD), was processed from single ASCII files into a mosaicked dataset covering the shallower parts of the Severn Estuary (Figure 3.1).

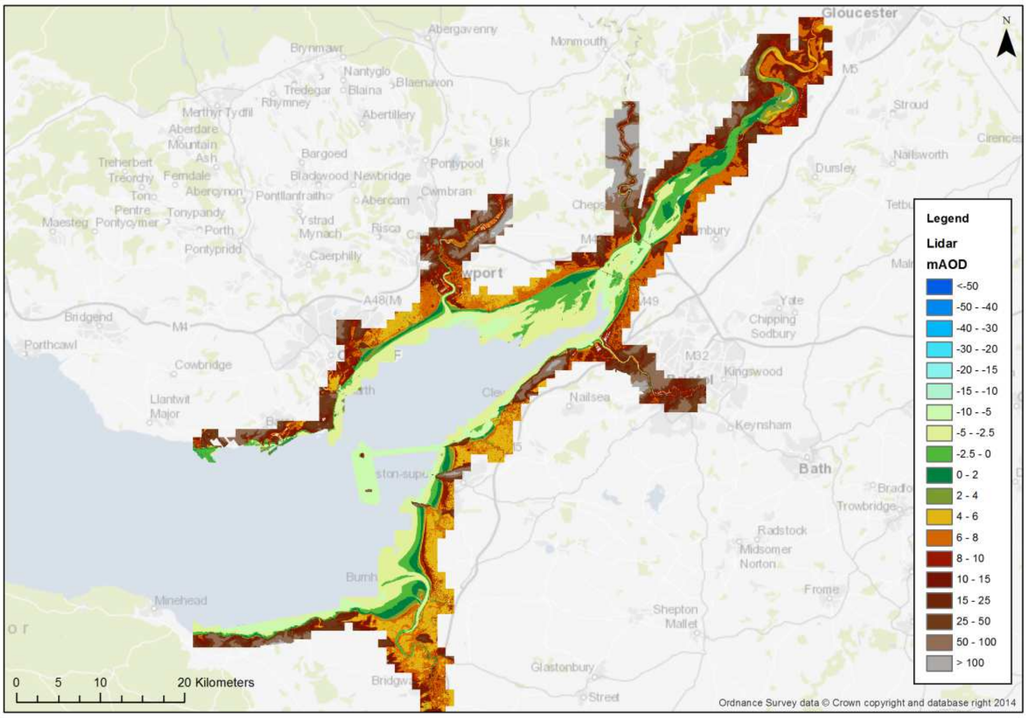

Figure 3.1. LiDAR data in the Severn Estuary

- The Admiralty Chart data was converted into a raster (Figure 3.2) and clipped to the study area extent. These data were converted from Chart Datum (CD) to OD using the conversion factors in the 2015 Admiralty Tide Tables.

Figure 3.2. Admiralty Chart bathymetry data in the Severn Estuary

- The Admiralty Chart bathymetry and LiDAR data elevations were compared along the length of the estuary. The LiDAR data was judged to be more accurate in the shallower areas upstream of the M4 road bridge and was used in this part of the estuary. Subsequently the Admiralty bathymetry was removed upstream of the M4 road bridge.
- Admiralty Chart data was used downstream of the M4 road bridge as it provided a wider coverage than the LiDAR data. However, where appropriate the Admiralty data was substituted by LiDAR data to provide greater accuracy and resolution. If the elevation difference between the two datasets was too great (greater than 1m) it was considered that the Admiralty Chart data should be used as the source to avoid large ‘steps’ in the overall data.
- The resulting Severn Estuary bathymetry, combining Admiralty Chart and LiDAR data, used in our analysis is shown in Figure 3.3.

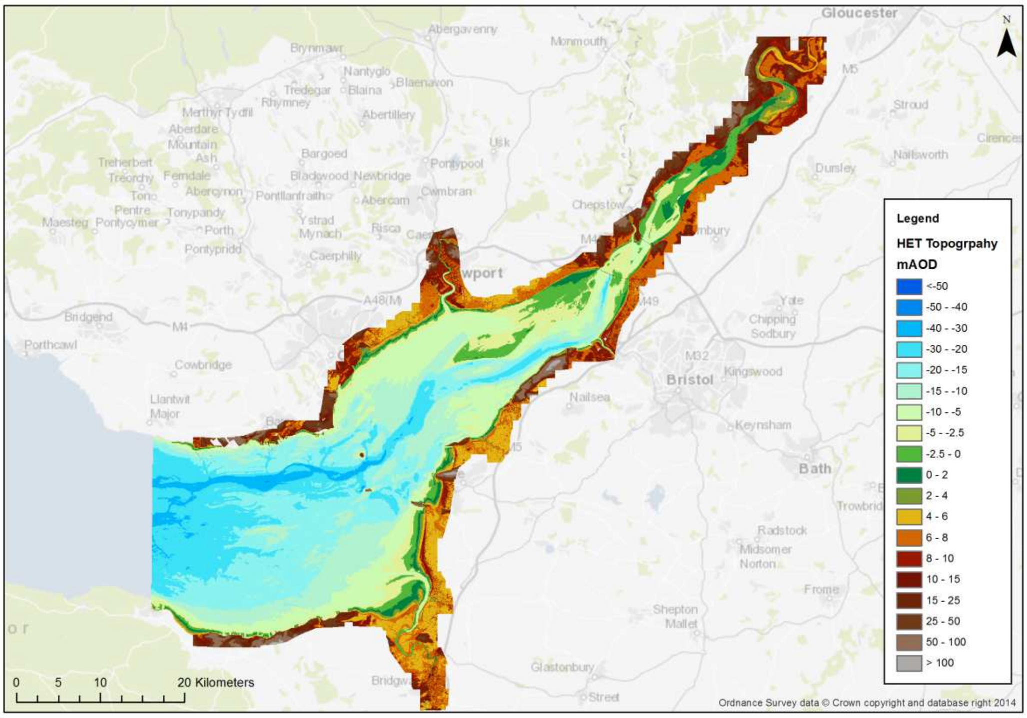

Figure 3.3. Severn Estuary bathymetry created by combining Admiralty Chart data with LiDAR data (in OD)

3.2 Tidal Regime

In order to calculate the spring tidal prism and cross-sectional area of the Severn Estuary it is necessary to know the elevations of tidal datums. Table 3.1 presents the MHWS, MHWN and MLWS tidal datum elevations at tidal stations along the Severn Estuary.

In order to delineate the plan positions of these datums, their elevations were overlain on to the Severn Estuary bathymetry. The elevations of the datums change with distance upstream (Table 3.1) and to create a surface that represents them along the estuary, the individual datum heights at each tidal station were linearly interpolated. Figure 3.4 shows the tidal datum surfaces after they have been transposed on to the bathymetry of the Severn Estuary. Note that upstream of Sharpness in the upper estuary, there is no data in the Admiralty Tide Tables for datums lower than MHWS.

Table 3.1. Tidal datums in the Severn Estuary (2015 Admiralty Tide Tables)

Tidal Station	Coordinates		Mean High Water Spring Tide (m OD)	Mean High Water Neap Tide (m OD)	Mean Low Water Neap Tide (m OD)	Mean Low Water Spring Tide (m OD)
	Easting	Northing				
Barry	311945.11	165317.10	5.60	2.60	-2.30	-4.90
Cardiff	319500.00	173055.00	6.00	2.80	-2.30	-5.10
Newport	331916.82	183920.27	6.49	3.09	-2.21	-5.01
Sudbrook	350439.01	187041.84	6.90	3.40	-2.80	-5.40
Beachley	356232.50	189212.83	6.90	3.50	-2.80	-5.40
Inward Rocks	357433.76	194763.72	7.02	3.52	-2.78	-4.78
Narlwood Rocks	358586.84	194754.12	7.03	3.53	-2.77	-4.07
White House	362062.81	196951.22	7.15	3.65	-2.85	-3.05
Berkeley	365543.36	200262.87	7.27	3.77	-1.73	-1.63
Sharpness Dock	366709.89	202479.46	7.47	3.77	-1.33	-1.23
Wellhouse Rock	366717.26	203591.64	7.58	3.88	-0.82	-0.72
Epney	372454.22	200220.27	8.30	No data	No data	No data
Minsterworth	373682.01	214672.54	8.00	No data	No data	No data
Llanthony	375989.72	216885.38	7.80	No data	No data	No data
Shirehampton	352644.85	175898.42	6.70	3.30	-2.80	-4.80
Sea Mills	354959.61	175877.35	6.80	3.30	-2.90	-4.10
Cumberland Basin Entrance	357246.27	172520.96	6.95	3.45	-3.35	-3.35
Portishead	348038.13	178167.97	6.60	3.20	-6.50	-6.50
Cleavdon	339874.28	172696.84	6.30	3.10	-2.50	-5.50
Weston-Super-Mare	331618.26	161678.33	6.00	2.80	-3.00	-5.20
Burnham-on-Sea	330275.86	148349.22	5.77	2.77	-2.73	-5.23
Bridgwater	330124.62	137228.76	6.10	3.20	1.50	1.50
Watchet	306901.80	143158.64	5.50	2.50	-1.90	-4.70
Minehead	297671.37	147784.12	5.20	2.50	-1.80	-4.40

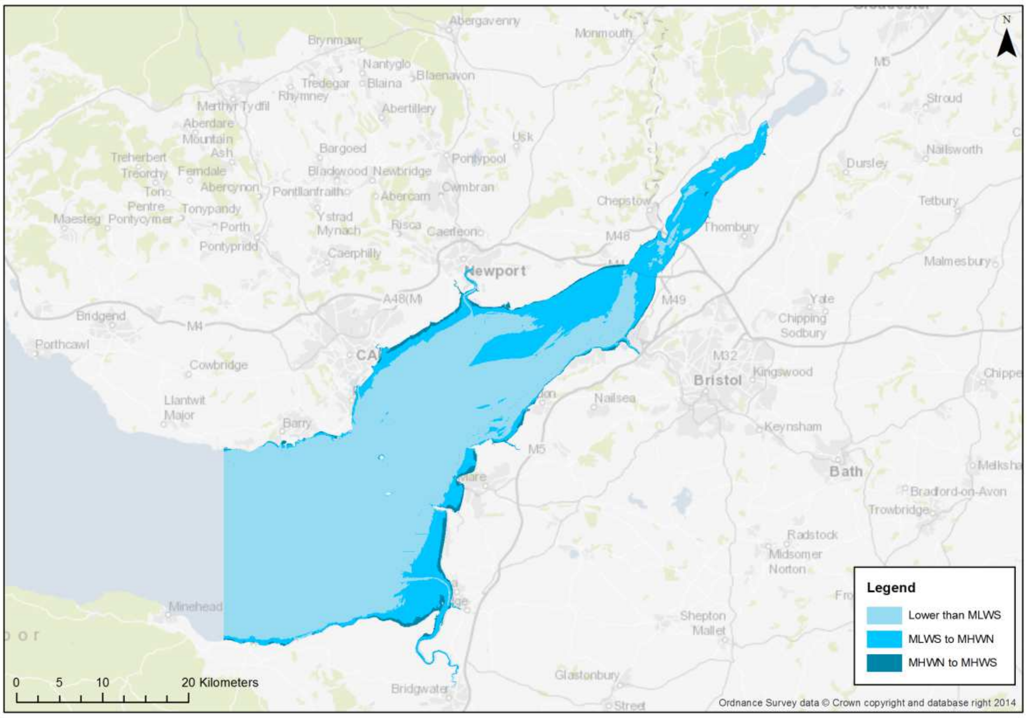

Figure 3.4. Tidal datums in the Severn Estuary

3.3 Extent of Estuary and Area of Intertidal Habitat

The extent of the estuary (total area of estuary feature) was mapped using MHWS. The intertidal area was calculated by subtracting the plan area at MLWS from the plan area at MHWS (Figure 3.5). The area where saltmarsh could potentially form was mapped by subtracting the plan area at MHWN from the plan area at MHWS (Figure 3.6). These areas, which apply to the entire study area chosen (not the SAC specifically), are presented in Table 3.2.

Table 3.2. Planform extent of the Severn Estuary and its intertidal and subtidal areas. Note these extents are for the entire study area, not just the SAC. Also note the upper reaches of the SAC (upstream of Sharpness) have no area data

Parameter	Area (km^2)
Estuary extent below MHWS	1,050
Intertidal area between MHWS and MLWS	250
Subtidal area below MLWS	800
Potential saltmarsh area between MHWS and MHWN	25

Due to the absence of data for MHWN and MLWS upstream of Sharpness, this reach of the estuary is excluded from the intertidal and subtidal analysis. This reach is also excluded from the estuary extent calculation for consistency (even though MHWS data is available).

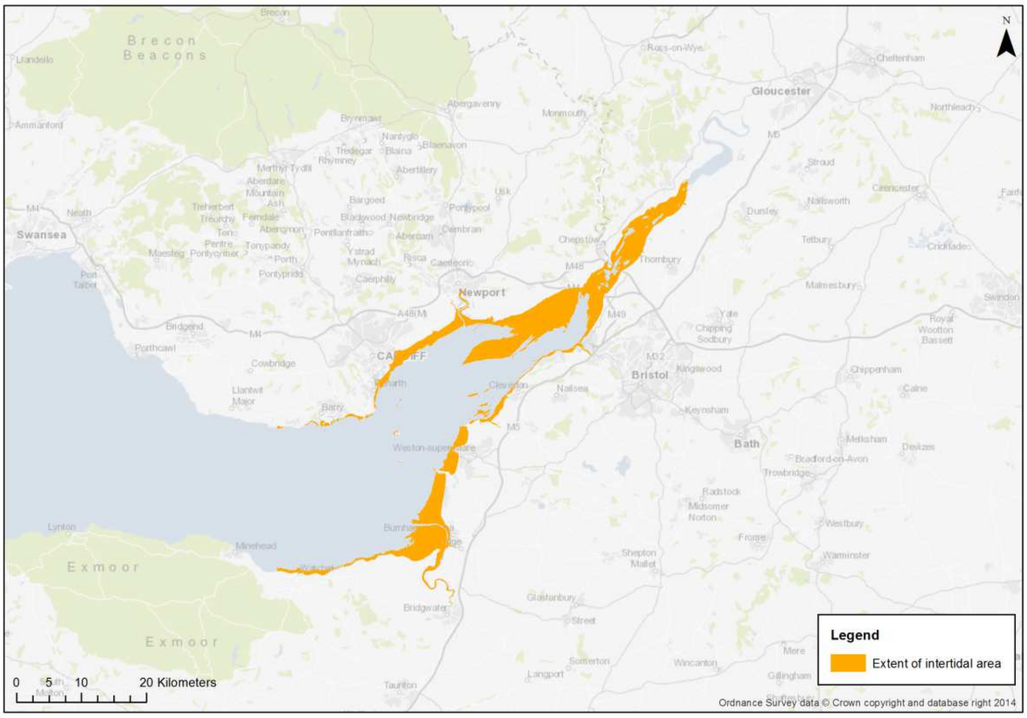

Figure 3.5. Area of intertidal habitat in the Severn Estuary (area between MHWS and MLWS datums)

Figure 3.6. Intertidal area in the Severn Estuary where saltmarsh could potentially develop if the substrate was suitable for development of this type of habitat (area between MHWS and MHWN datums)

The actual area of saltmarsh in the Severn Estuary (as defined in this study) was calculated using the saltmarsh polygons of the Land Classification Mapping (LCM) carried out in 2007. The LCM estimated area of intertidal saltmarsh was 7.5km^2 (Figure 3.7). The NVC survey of saltmarsh habitat completed in 1998 reported a total area of about 15km^2 within the SAC (Dargie, 1998).

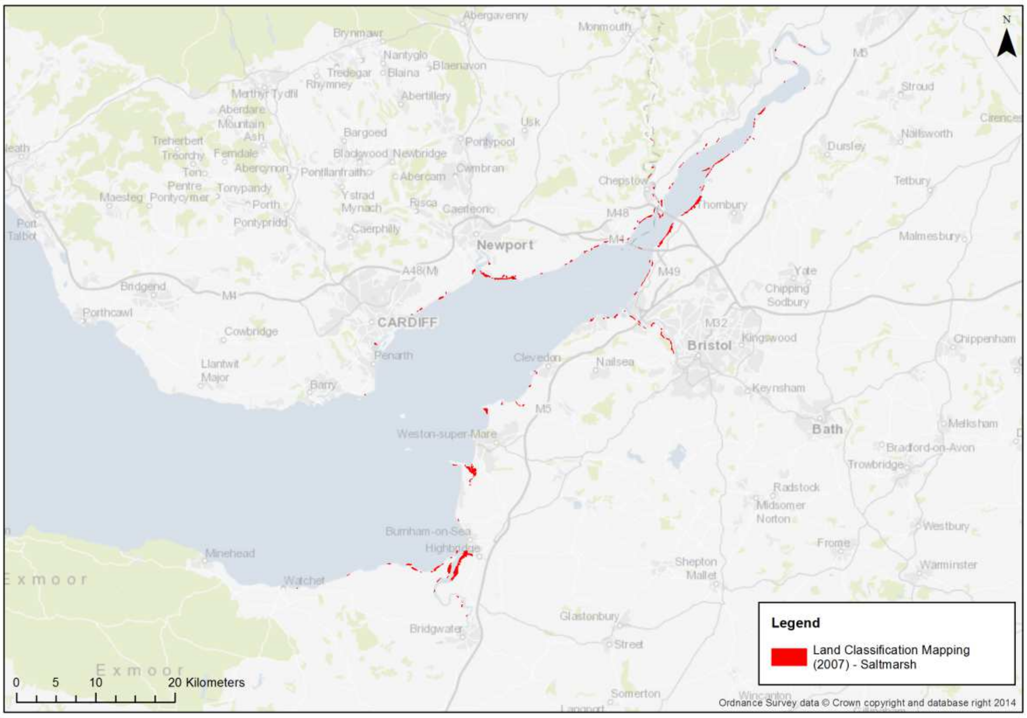

Figure 3.7. Saltmarsh in the Severn Estuary (2007 Land Classification Mapping)

3.4 Morphological Equilibrium

3.4.1 Observed Estuary Form

Using the bathymetry and tidal datums in a GIS, each of the following parameters were measured at sections spaced about 2km apart along the estuary to quantify its observed form:

- cross-sectional area beneath MHWN;
- width at MHWN;
- mean depth beneath MHWN; and
- spring tidal prism upstream of each section.

The locations of the sections where the observed form is measured are shown in Figure 3.8 and the data at each section is presented in Appendix C. Note that observed parameters are absent upstream of Section 1-280 (upstream of Sharpness) because no data for MHWN or MLWS were available.

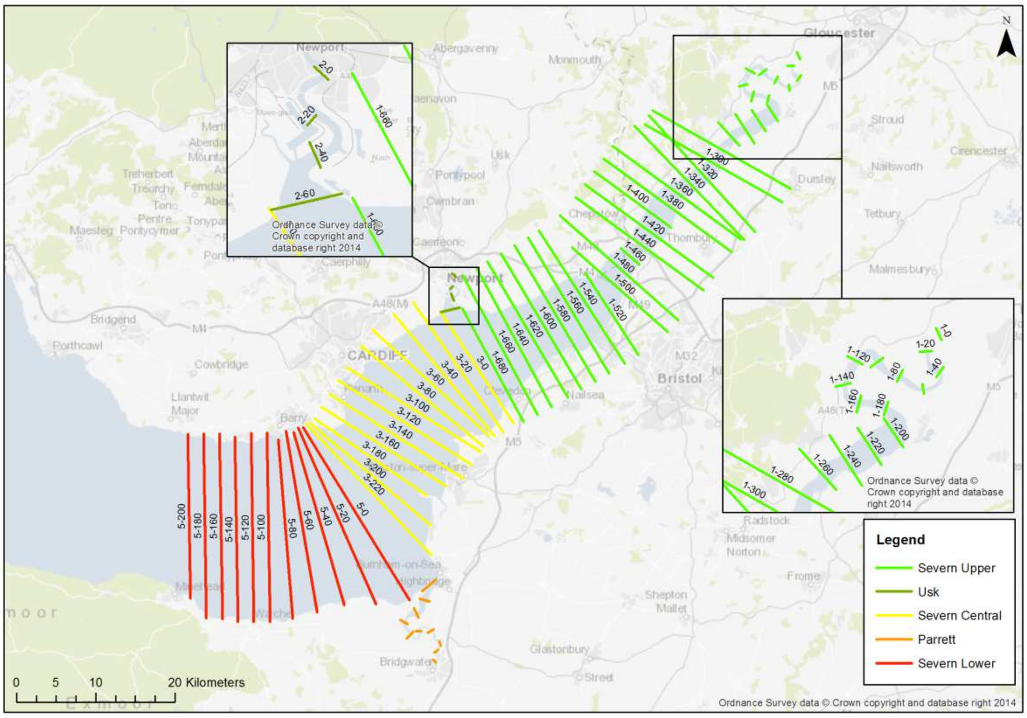

Figure 3.8. Position of the sections in the Severn Estuary where the observed form is measured

3.4.2 Predicted Estuary Form

The regime relationship that was used to predict estuary form is between spring tidal prism and the cross-sectional area at MHWN tide at each of the sections defined in the assessment of observed form (in line with Healthy Estuaries 2020, Natural England, 2015) (Appendix A, Section A.1). Two steps developed in Healthy Estuaries 2020 were followed to determine morphological equilibrium. Details of these steps are provided in Appendix A and they are only briefly summarised here.

The first step was to predict cross-sectional area from the re-distributed tidal prism (Appendix A, Section A.2.3). The regime equation that encapsulates all United Kingdom estuaries was used.

$$CSA = 0.024.P^{0.71} \ (r^2 = 0.75)$$

where:

CSA = cross-sectional area (MHWN); and
P = upstream spring tidal prism.

The second step was to calculate planform width from cross-sectional area. Several different methods were tested in Healthy Estuaries 2020 to develop a robust way of estimating planform width from cross-sectional area. It was concluded that the most reliable was the ‘constant evolution’ method (Appendix A, Section A.2.5), and this was adopted here. Using these two steps, the equilibrium form of the Severn Estuary was predicted at each section, presented in Appendix D.

3.4.3 Comparison of Predicted Equilibrium Widths with Observed Widths

The results were interrogated using GIS to compare the predicted equilibrium widths (Appendix D) with the observed widths (Appendix B) at each section. In this way, reaches of the observed estuary which are narrower or wider than their predicted form were mapped. The comparison for the Severn Estuary is shown in Figure 3.9.

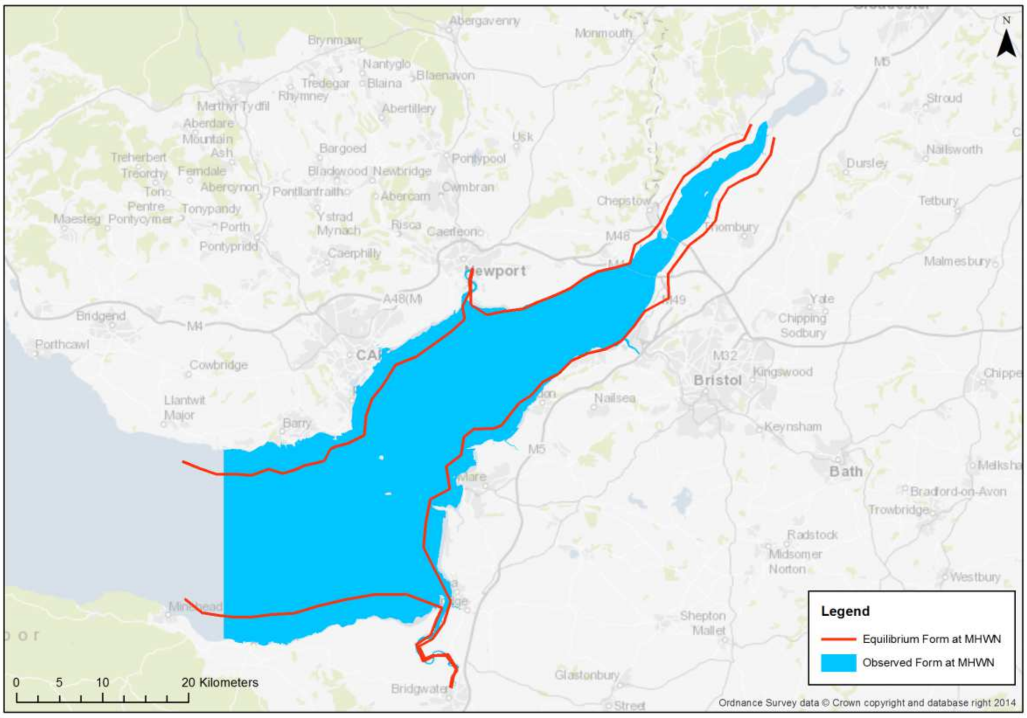

Figure 3.9. Observed and predicted forms of the Severn Estuary using the regime equation for all United Kingdom estuaries and the 'constant evolution' method

The observed widths compare with the predicted equilibrium widths in the Severn Estuary in one of three ways. The estuary upstream of the M4 road bridge is under-sized compared to its predicted form (i.e. the observed channel is narrower than predicted for the present-day tidal regime) (Figure 3.9). The estuary downstream of a line between Goldcliff and Clevedon is over-sized compared to its predicted form (i.e. the observed channel is wider than predicted for the present-day tidal regime). The estuary between the M4 road bridge and a line between Goldcliff and Clevedon has observed and predicted widths which are similar, suggesting that the observed form is close to equilibrium.

The reaches of the estuary upstream of the M4 road bridge are pressure points in the estuary. This means that here the estuary form should be wider than it actually is and to obtain equilibrium the estuary has to widen from its current form (i.e. it should erode resulting in loss of intertidal habitat if the high water mark is unable to migrate landwards). Future sea-level rise will exacerbate this trend for erosion. Where the channel is over-sized, downstream of a line between Goldcliff and Clevedon, it exceeds its predicted equilibrium width and over the long term there should be a tendency for development of intertidal habitat by natural processes.

3.5 Physical Constraints to Morphological Equilibrium

The three distinct predicted equilibrium states of the Severn Estuary suggest that different parts are at different stages of adjustment to natural process inputs.

3.5.1 Under-sized Reaches

Upstream of the M4 road bridge, the estuary is predicted as under-sized and processes will be attempting to widen the channel to establish an equilibrium form. However, it may not be possible for the estuary to widen here because of constraints such as land use (flood embankments and bridges) and geology (rock cliffs and shore platforms).

The shores of the Severn Estuary upstream of the M4 road bridge are dominated by intertidal mudflats bordered by former floodplains, which are protected from inundation at high water by flood embankments. The flood embankments currently artificially constrain the natural widening of the upper estuary. Also, the locations of the two bridges at the seaward end of the under-sized part of the estuary represent geological constraints to widening as they are bounded by rock cliffs and shore platforms. Several other shoreline reaches also contain higher ground in the form of cliffs.

Upstream of the M4 road bridge, the intertidal parts of the estuary have accreted over the past 100 years (ABPmer, 2006, 2009). This is difficult to reconcile given the significant landscape-scale morphological disequilibrium predicted, which should correlate with a trend of erosion. It is possible that the high suspended sediment concentrations (peaking at Sharpness, ABPmer, 2009) and long residence times in this part of the estuary and subsequent deposition on the intertidal flats is counteracting the effect of the disequilibrium.

3.5.2 Reaches in Near-equilibrium

Between the M4 road bridge and a line between Goldcliff and Clevedon, the estuary appears to be a state of near-equilibrium. According to ABPmer (2006, 2009) the net trend of erosion or accretion in the central part of the estuary (however, this does extend further downstream than the zone of equilibrium) is not clear, although net erosion is evident. This variability in erosion-accretion is in keeping with its near-equilibrium form, suggesting that the estuary is in a constant state of short- to medium-term adjustment to maintain this form.

3.5.3 Over-sized Reaches

In the predicted over-sized part of the estuary downstream of a line between Goldcliff and Clevedon, the bed of the estuary is partially rock outcrop which constrains the channel from deepening. The geology is sufficiently hard so that the bed is resistant to physical processes so the estuary does not conform to the regime relationship. Here, the width of the estuary is over-sized (wider) to compensate for the relatively shallow depths caused by the geological constraint. The over-sized part of the estuary also correlates with a large volume of mudflat accretion over the past 150 years (ABPmer, 2009) suggesting gradual infilling to reduce width.

3.5.4 Overall Condition of the Morphological Equilibrium Attribute

The results of Regime Theory in the Severn Estuary SAC show that only the central part is close to morphological equilibrium. The estuary has developed into a more exaggerated 'trumpet' shape that would be expected if it was in morphological equilibrium. The upper reaches are narrower than their predicted equilibrium form and the lower reaches are wider than their predicted equilibrium form.

A combination of flood embankments and geological constraints control the upstream disequilibrium. In order to allow a wider channel to develop in keeping with the equilibrium form may necessitate realignment of the flood embankments to restore former land-claimed intertidal areas to tidal processes. The geological constraints are permanent and cannot be changed. Currently, the Shoreline Management Plan (Atkins, 2010) contains several managed realignment policies for the reaches of the estuary upstream of the M4 road bridge that could act as drivers to move this part of the estuary towards morphological equilibrium (Figure 3.10 and Table 3.3).

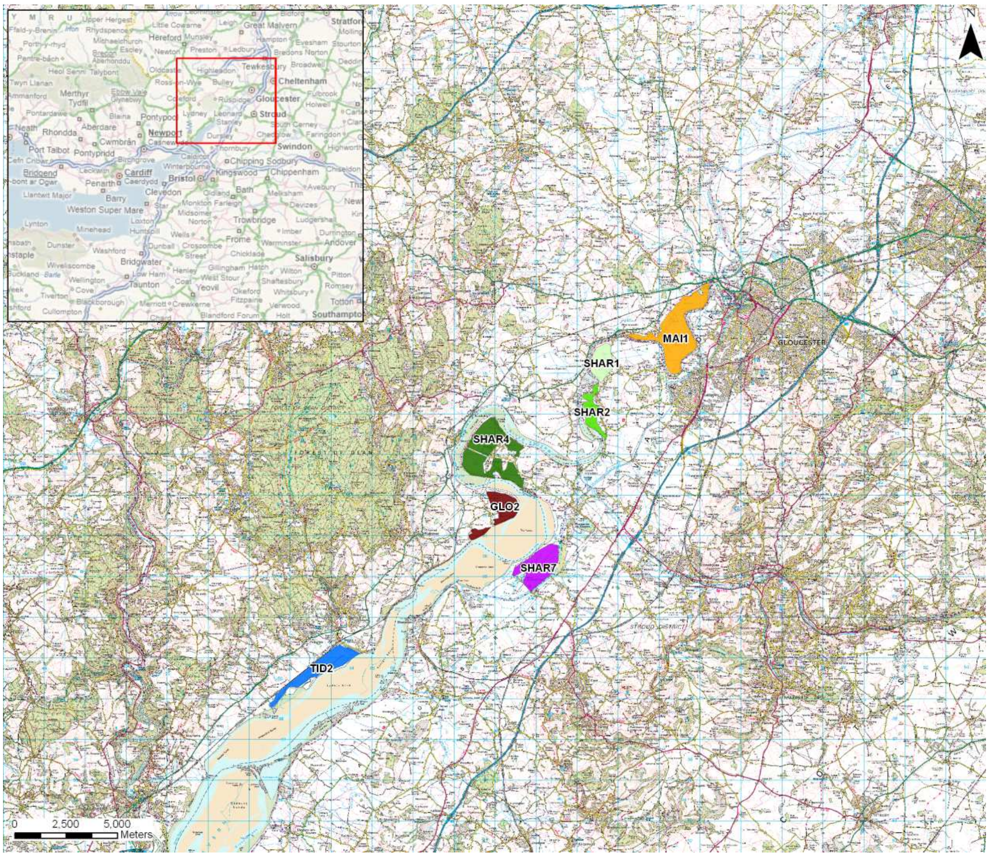

Figure 3.10. Location of seven potential managed realignment sites in the inner Severn Estuary (Atkins, 2010)

Table 3.3. Potential managed realignment sites in the inner Severn Estuary (Atkins, 2010)

Coastal Stretch	Management Unit	Epoch 1	Epoch 2	Epoch 3
Tidenham and other villages – Guscar Rocks to Lydney Harbour	TID 2	HTL	HTL	**MR**
Gloucester to Sharpness – Frampton Pill to Royal Drift outfall	SHAR 7	**MR**	HTL	HTL
Lydney to Gloucester – Brims Pill to Northington Farm	GLO 2	**MR**	HTL	HTL
Gloucester to Sharpness – Overton Lane to upstream of Hock Cliff	SHAR 4	HTL	**MR**	MR
Gloucester to Sharpness – Wicks Green to Longley Green	SHAR 2	HTL	**MR**	HTL
Gloucester to Sharpness – Severn Farm to Wicks Green	SHAR 1	HTL	**MR**	**MR**
Gloucester to Maisemore – West bank at Drain from Long Brook to west bank at railway / A40 bridge	MAI 1	**MR**	HTL	HTL

4 RESULTS FOR THE SOLWAY FIRTH

4.1 Bathymetry

The best available bathymetry for the Solway Firth was obtained in three different formats; two from the Environment Agency Geomatics Group and one from Natural England. These were LiDAR at 2m resolution and Admiralty Chart data in vector format from Geomatics and multibeam data from Natural England. All three datasets required processing and manipulation before being ‘stitched’ together to create the final bathymetry. These were the only three datasets used in the analysis (a list of all bathymetry data that was received is provided in Appendix B). The following procedure was followed:

- The LiDAR data, in OD, was processed from single ASCII files into a mosaicked dataset covering the shallow parts of the upper estuary and southern shore of the Solway Firth (Figure 4.1)

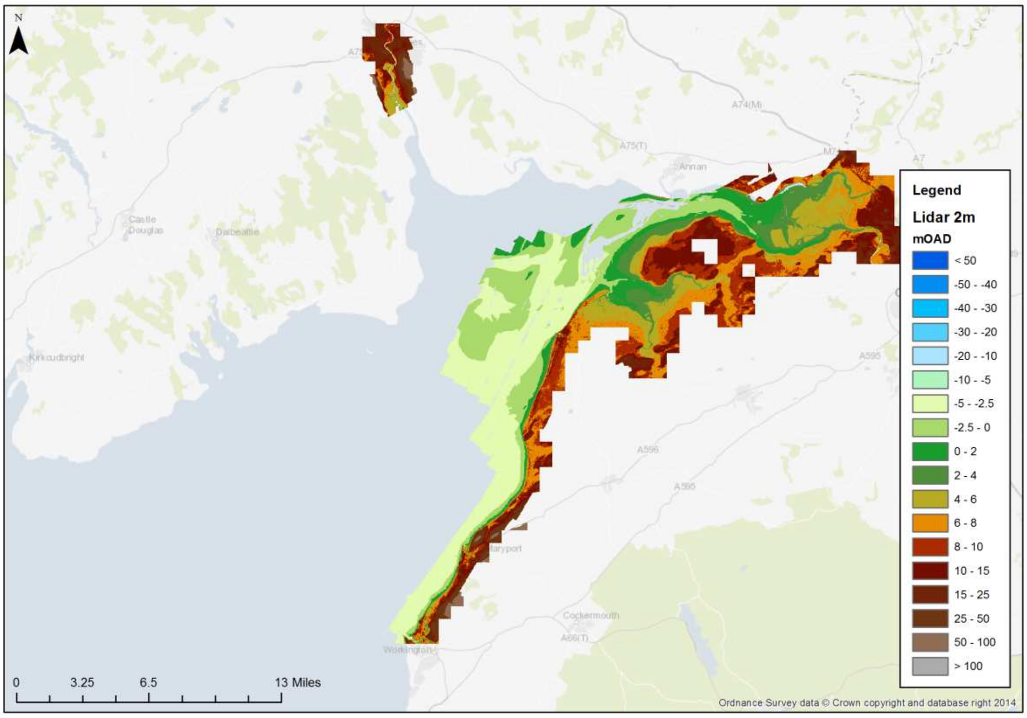

Figure 4.1. LiDAR data in the upper Solway Firth

- The Admiralty Chart data was converted into a raster (Figure 4.2) and clipped to the study area extent. These data were converted from CD to OD using the conversion factors in the 2015 Admiralty Tide Tables.

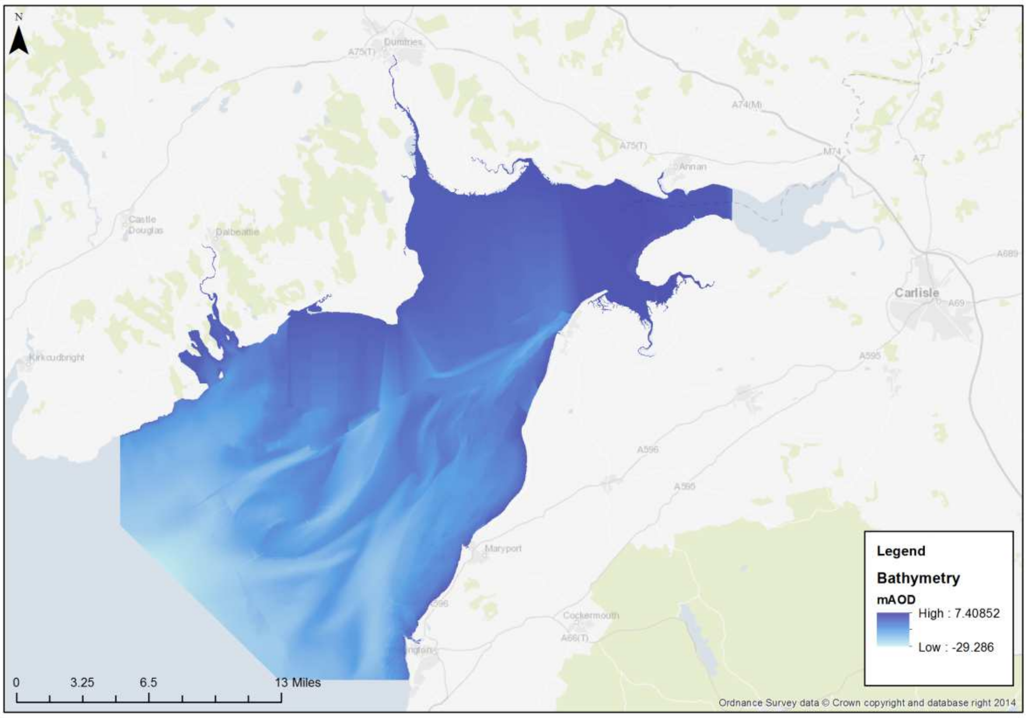

Figure 4.2. Admiralty Chart bathymetry data in the Solway Firth

- The multibeam survey (in OD) was processed and added into the GIS (Figure 4.3).

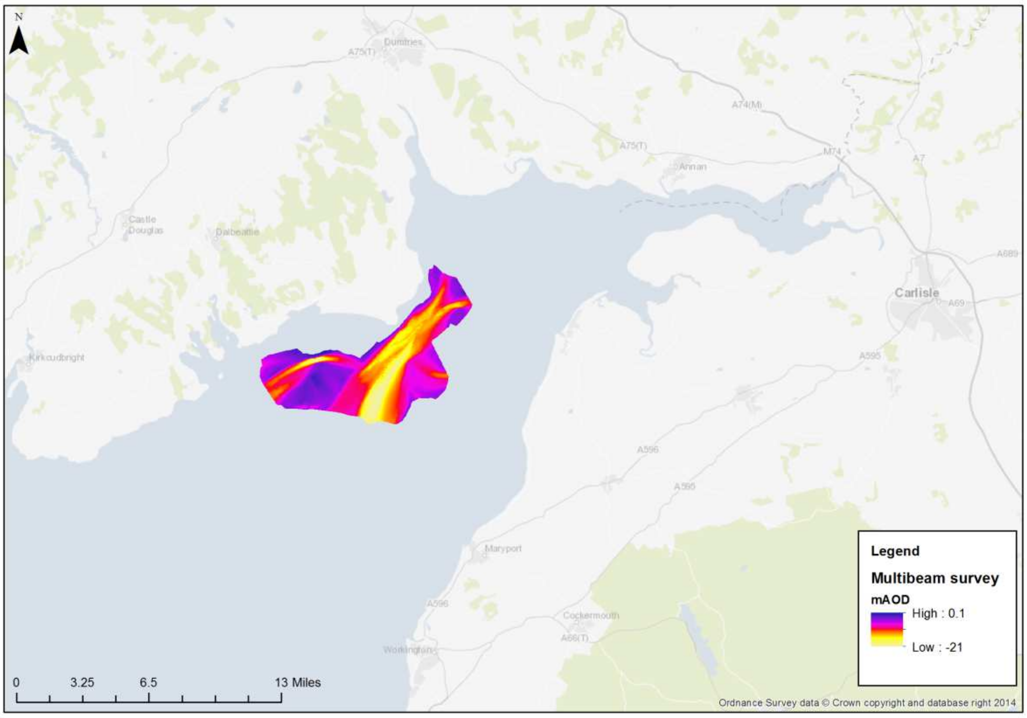

Figure 4.3. Multibeam bathymetry data in part of the Solway Firth

* The Admiralty Chart bathymetry data was very poor along the north and northwest sides of the estuary and was considered to be erroneous (Figure 4.2). Unfortunately, no LiDAR or multibeam data was available to fill this gap. Therefore, the gap was filled by creating an artificial bathymetry by interpolating between the level of MHWS at the coast and the LiDAR data and multibeam data combined in the offshore (Figure 4.4). This is the 'best' that could achieve with the data available.

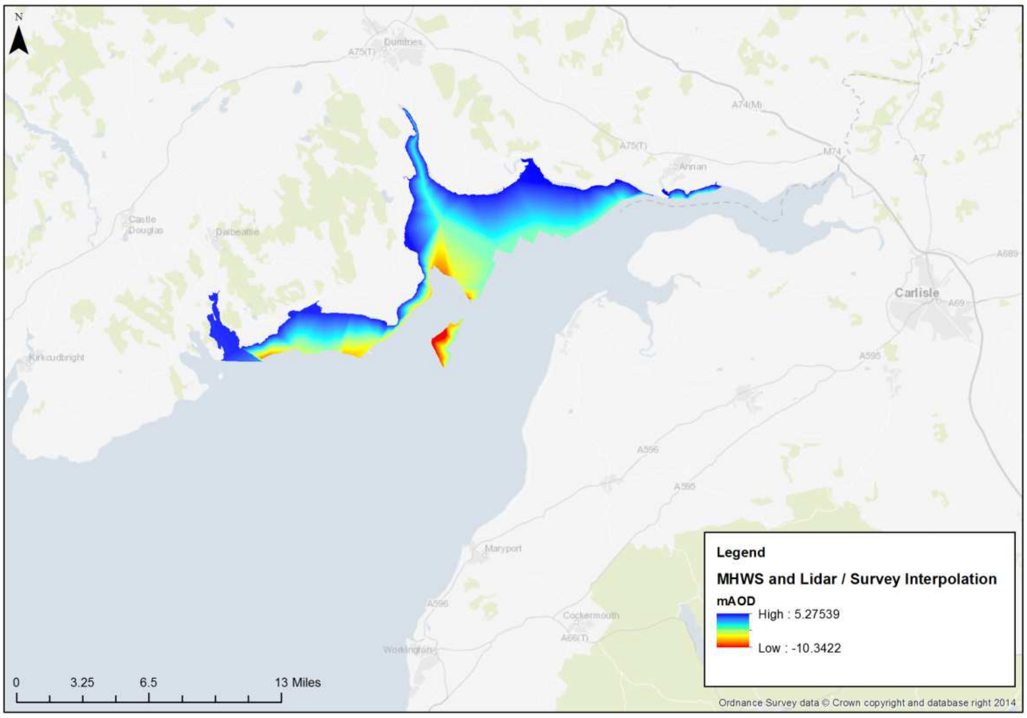

Figure 4.4. Artificially created bathymetry data in part of the Solway Firth

* The LiDAR data also contained gaps in some of the deeper channels of the upper estuary. Linear interpolation using data either side of the channels was carried out across these gaps.
* All the data were merged together (Figure 4.5) to create the overall bathymetry for the Solway Firth used in our analysis (Figure 4.6) with LiDAR data taking precedent, then the multibeam survey, the interpolated grid and finally the Admiralty Chart bathymetry. This is a different approach to the Severn Estuary as each site required a bespoke analysis to determine the 'best available' bathymetry.

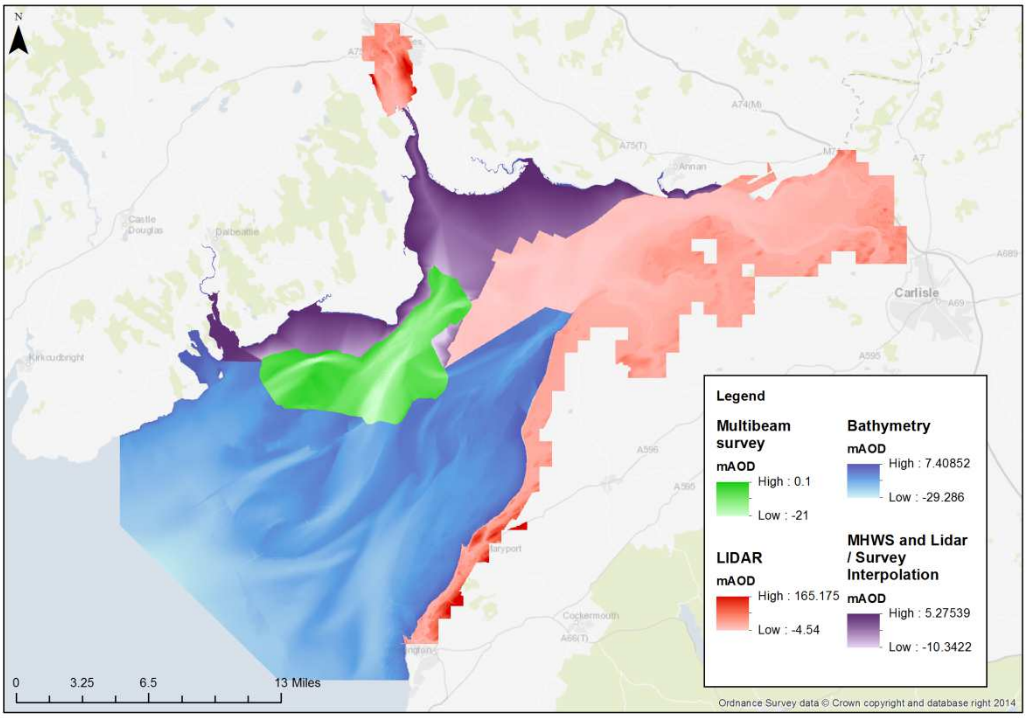

Figure 4.5. Datasets used to create the final bathymetry in the Solway Firth

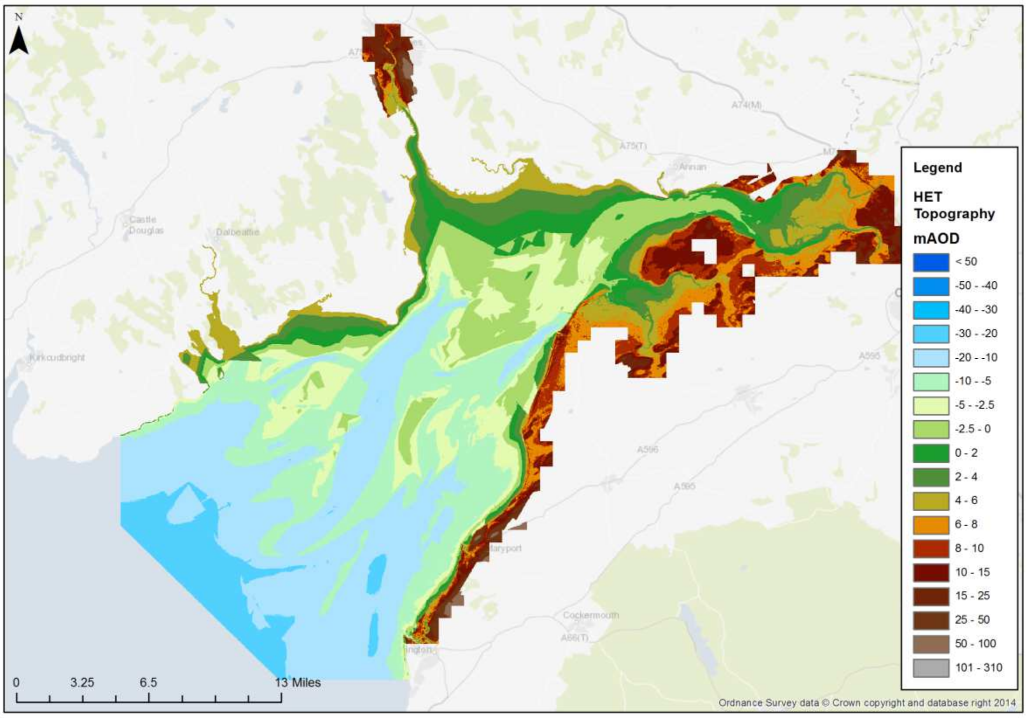

Figure 4.6. Solway Firth bathymetry created by combining all datasets (in OD)

4.2 Tidal Regime

In order to calculate the spring tidal prism and cross-sectional area of the Solway Firth it is necessary to know the elevations of tidal datums. Table 4.1 presents the MHWS, MHWN and MLWS tidal datum elevations at tidal stations along the Solway Firth. Figure 4.7 shows the tidal datum surfaces transposed on to the bathymetry of the Solway Firth.

Table 4.1. Tidal datums in the Solway Firth (2015 Admiralty Tide Tables)

Tidal Station	Coordinates		Mean High Water Spring Tide (m OD)	Mean High Water Neap Tide (m OD)	Mean Low Water Neap Tide (m OD)	Mean Low Water Spring Tide (m OD)
	Easting	Northing				
Kirkcudbright Bay	267033.62	546975.90	3.80	2.20	-1.30	-2.90
Hestan Islet	284473.49	549834.54	4.29	2.29	-1.61	-3.11
Annan Waterfoot	318798.71	564666.47	5.00	2.70	-1.90	Tide doesn’t normally fall below CD
Torduff Point	326480.14	564533.62	5.44	2.74	Tide doesn’t normally fall below CD	Tide doesn’t normally fall below CD
Redkirk	329698.27	565594.88	5.51	2.91	Tide doesn’t normally fall below CD	Tide doesn’t normally fall below CD
Silloth	310254.75	553698.54	4.80	2.70	-2.10	-3.60
Maryport	303480.78	537141.87	4.30	2.30	-1.80	-3.40
Workington	298798.16	529452.26	4.10	2.20	-1.50	-3.20
Whitehaven	296609.35	518370.11	3.80	2.10	-1.80	-3.20

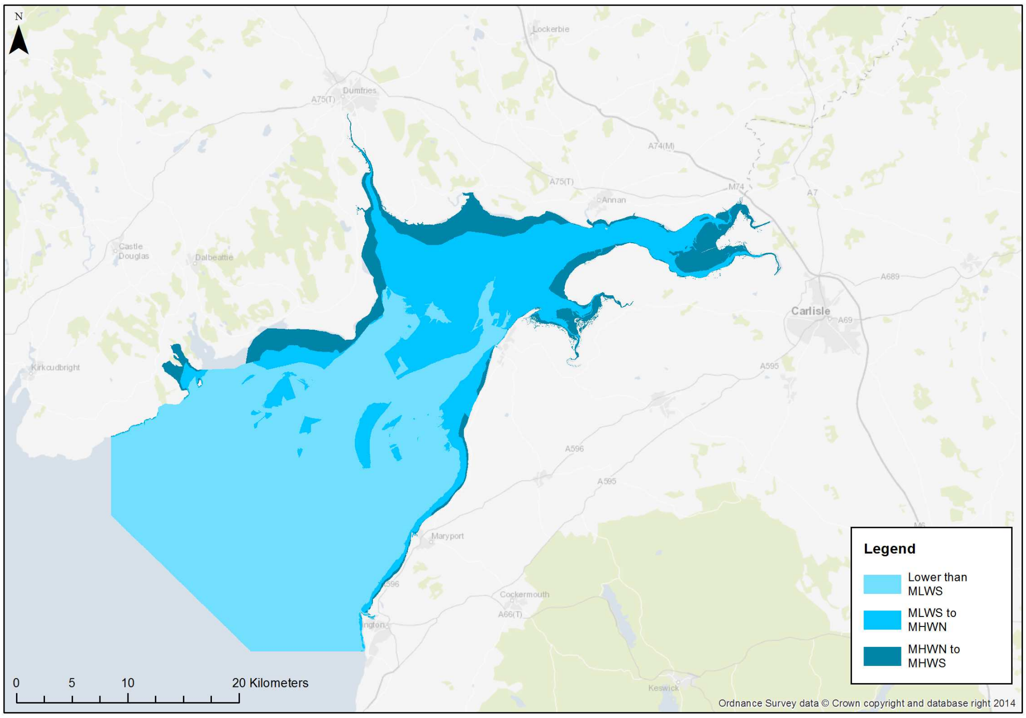

Figure 4.7. Tidal datums in the Solway Firth

4.3 Extent of Estuary and Area of Intertidal Habitat

The areas of intertidal habitat (between MHWS and MLWS) and potential saltmarsh (between MHWS and MHWN) in the Solway Firth are shown in Figures 4.8 and 4.9, respectively. The plan extents of the estuary parameters, which apply to the entire study area chosen (not the SAC specifically), are presented in Table 4.2.

Table 4.2. Planform extent of the Solway Firth and its intertidal and subtidal areas. Note these extents are for the entire study area, not just the SAC.

Parameter	Area (km^2)
Estuary extent below MHWS	860
Intertidal area between MHWS and MLWS	330
Subtidal area below MLWS	530
Potential saltmarsh area between MHWS and MHWN	90

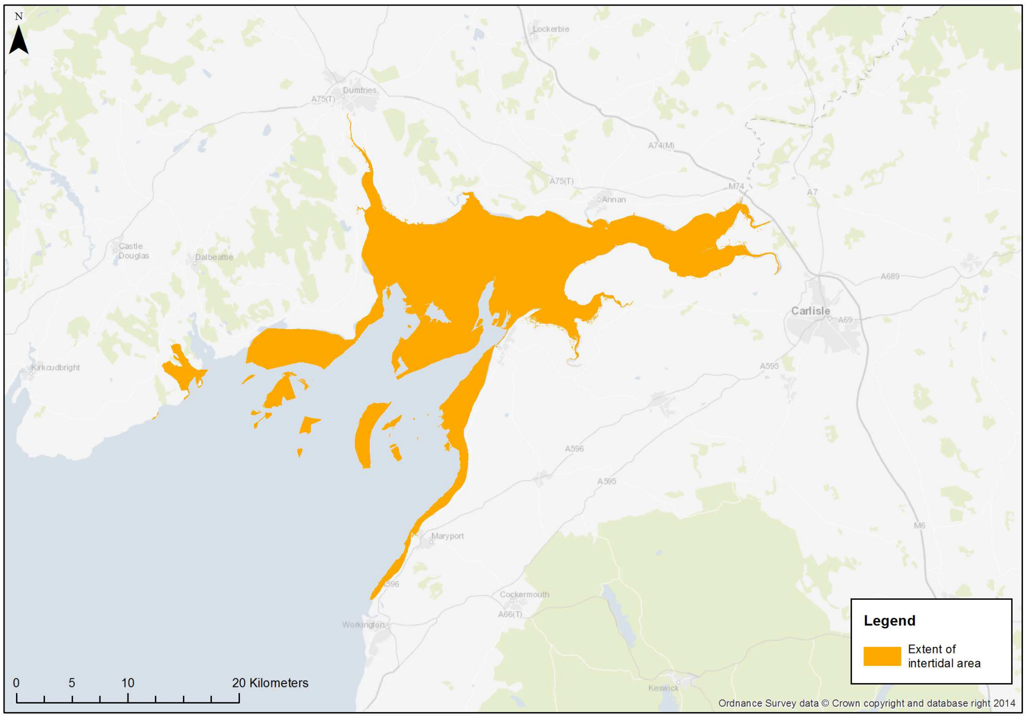

Figure 4.8. Area of intertidal habitat in the Solway Firth (area between MHWS and MLWS datums)

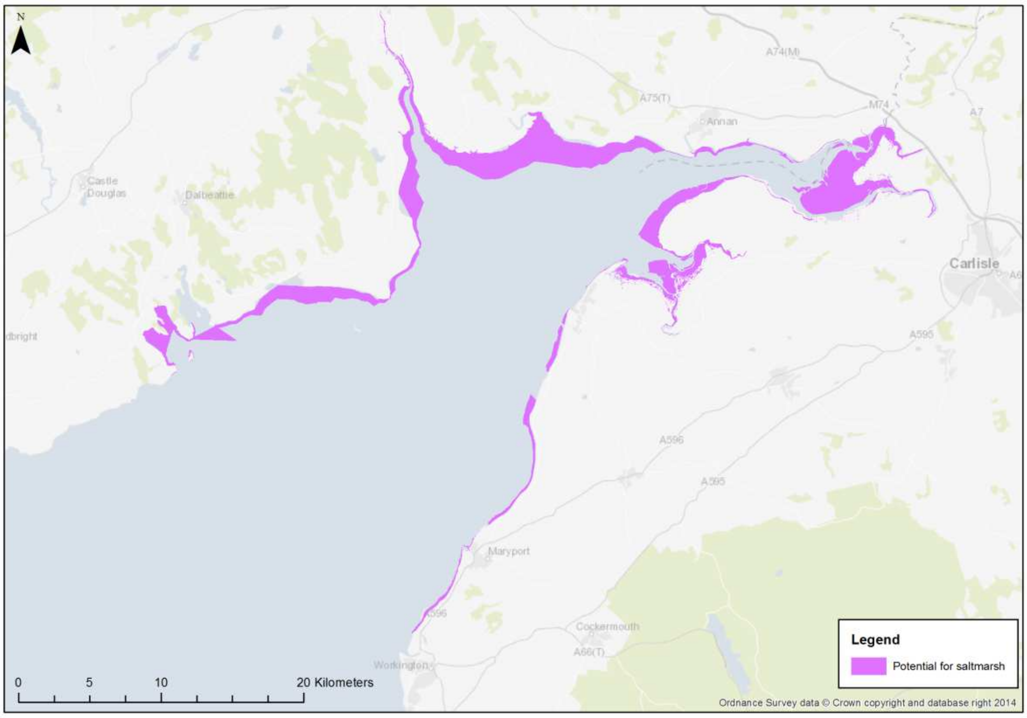

Figure 4.9. Intertidal area in the Solway Firth where saltmarsh could potentially develop if the substrate was suitable for development of this type of habitat (area between MHWS and MHWN datums)

The actual area of saltmarsh in the Solway Firth was calculated using the saltmarsh polygons of the Land Classification Mapping (LCM) carried out in 2007. The LCM estimated area of intertidal saltmarsh is 30km^2 (Figure 4.10). However, it should be noted that the LCM data does not cover the Scottish coast west of the River Nith and so the area is likely to be an underestimate.

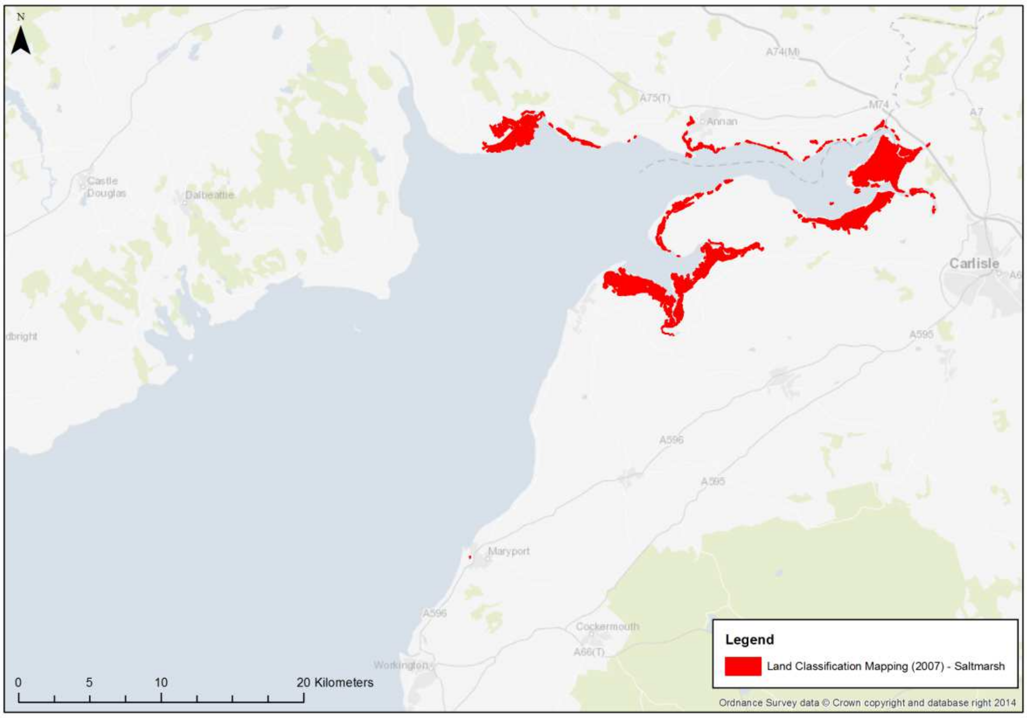

Figure 4.10. Saltmarsh in the Solway Firth (2007 Land Classification Mapping)

4.4 Morphological Equilibrium

4.4.1 Observed Estuary Form

Using the bathymetry and tidal datums in a GIS, the observed estuary parameters at sections spaced 1km apart were measured along the estuary in a similar way to the Severn Estuary analysis (Section 3.4.1). The locations of the sections in the Solway Firth where the observed form is measured are shown in Figure 4.11 and the data at each section is presented in Appendix E. The Solway Firth is broken down into several constituent water courses. These include the River Esk and River Eden at the head of the estuary, the Rivers Wampool and Waver entering on the south shore in Moricambe Bay and the River Nith entering on the north shore.

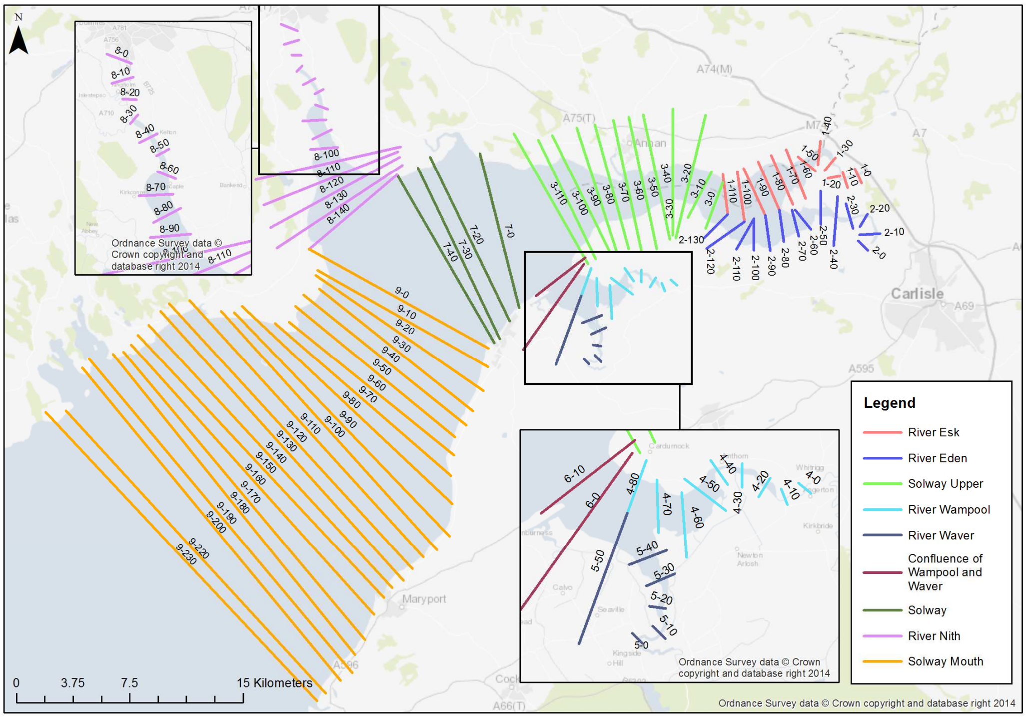

Figure 4.11. Position of the sections in the Solway Firth where the observed form is measured

4.4.2 Predicted Estuary Form

The same method used to predict estuary form in the Severn Estuary (Section 3.4.2) is used in the Solway Firth and is not repeated here. Using this method, the predicted form of the Solway Firth at each section is presented in Appendix F.

4.4.3 Comparison of Predicted Equilibrium Widths with Observed Widths

The results were interrogated using GIS to compare the predicted equilibrium widths (Appendix F) with the observed widths (Appendix E) at each section. In this way, reaches of the observed estuary which are narrower or wider than their predicted form were mapped. The comparison for the Solway Firth is shown in Figure 4.12.

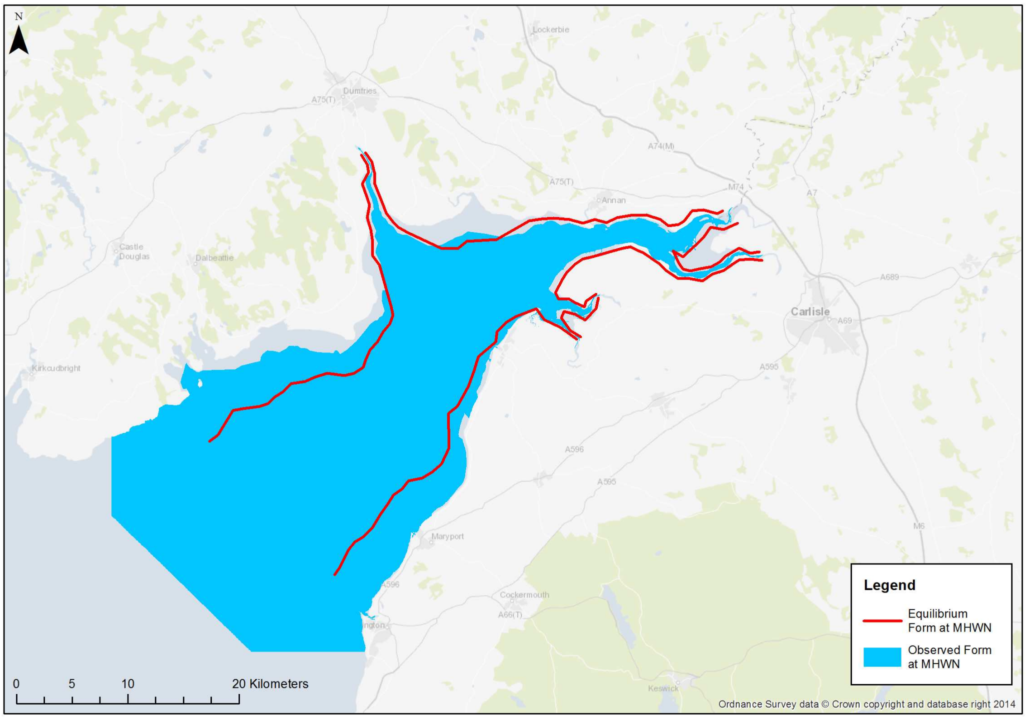

Figure 4.12. Observed and predicted forms of the Solway Firth using the regime equation for all United Kingdom estuaries and the 'constant evolution' method

The observed widths compare with the predicted equilibrium widths in the Solway Firth in one of three ways. The Rivers Esk, Eden and Nith, and the upper Solway Firth (upstream of the River Wampool on the south shore) is under-sized compared to its predicted form (i.e. the observed channel is narrower than predicted for the present-day tidal regime) (Figure 4.12). However, the results of the River Nith and the north shore of the Solway Firth to the east of the River Nith may be spurious, given the artificial nature of the created bathymetry.

The Rivers Wampool and Waver (Moricambe Bay) have observed and predicted widths which are similar, suggesting that their observed forms are close to equilibrium. Downstream of the Rivers Waver and Nith there is a rapid transition to an estuary that is over-sized compared to its predicted form (i.e. the observed channel is wider than predicted for the present-day tidal regime). However, it is difficult to judge in this segment of the water course where the open coast might begin in a seaward direction. It is possible that seaward of a line between Southerness and Allonby, the impact of estuary processes is negligible and this area is subject to open coast processes only. This would mean that Regime Theory could not be applied.

It appears that the majority of the Solway Firth is either under-sized or over-sized with only a small proportion nearing an equilibrium form (Moricambe Bay). The upper reaches of the Solway Firth and the confluencing Rivers Esk and Eden are pressure points in the estuary. This means that here the estuary form should be wider than it actually is and to obtain equilibrium the estuary has to widen from its current form (i.e. it should erode resulting in loss of intertidal habitat if the high water mark is unable to migrate landwards). Future sea-level rise will exacerbate this trend for erosion. The outer Solway Firth is over-sized, and so it exceeds its predicted equilibrium width and over the long term there may be development of intertidal habitat by natural processes.

4.5 Physical Constraints to Morphological Equilibrium

4.5.1 Under-sized Reaches

The shores of the upper Solway Firth including the Rivers Esk and Eden are dominated by intertidal flats and saltmarsh backed by shoreline defences, which protect adjacent low-lying land from flooding. The estuary here is predicted as under-sized and estuarine processes should be attempting to widen the channel to establish an equilibrium form. In the upper estuary the fringing saltmarshes are eroding due to coastal squeeze against the shoreline defences (Halcrow, 2010) confirming the view that the estuary is trying to widen here. The defences are currently constraining its natural widening. Indeed the shoreline management policy along the English side of the upper Solway Firth is managed realignment to allow a return to a more natural shoreline, with insufficient economic justification to maintain defences (Halcrow, 2010).

4.5.2 Reaches in Near-equilibrium

At the confluence of the Rivers Wampool and Waver (Moricambe Bay), the coast is sheltered from higher energy conditions, which has resulted in the development of extensive areas of saltmarsh, which is generally stable. This stability is in keeping with the predicted near-equilibrium form of the Solway Firth in this area. However, Grune Point spit which protects the saltmarsh in Moricambe Bay is an exception to this stability because it is currently eroding. This erosion is likely to be related to direct wave action and not tidal processes

4.5.3 Over-sized Reaches

It is difficult to make judgements regarding the over-sized part of the estuary downstream of the Rivers Waver and Nith, because it is unclear where estuarine processes end and open coast processes begin. The sea bed is sandy in this area and there is no indication that bedrock is near the surface that would constrain the depth, forcing the estuary to be over-wide. On the English side, between Moricambe Bay and Silloth (north of where the water course widens significantly to the south), the coastline is defended by sea walls and rock armour revetments, and so a constrained coastline would be expected. Periodic beach re-nourishment has been required along this coastline indicting erosion not accretion. It is possible that this over-sized reach is too far seaward to be influenced by estuarine processes which would make the results of the Regime Theory invalid.

4.5.4 Overall Condition of the Morphological Equilibrium Attribute

The overall condition of the Solway Firth SAC that is driven mainly by tidal processes is morphological disequilibrium, whereby the estuary is narrower than its predicted equilibrium form. The most likely cause for the disequilibrium is coastal squeeze caused by the inability of the intertidal system to migrate landwards due to flood defences. Currently, the Shoreline Management Plan policy for almost the entire English coastline of the Solway Firth, east of Moricambe Bay is managed realignment (Halcrow, 2010)

(Figure 4.13 and Table 4.3). Future actions to implement this policy could act as a driver to move the estuary containing the SAC towards morphological equilibrium. The main environmental rationale for managed realignment in the SMP is continued natural shoreline evolution which will help maintain the condition of the SAC and provide opportunities for future habitat creation to be included within the Environment Agency's Regional Habitat creation Programme.

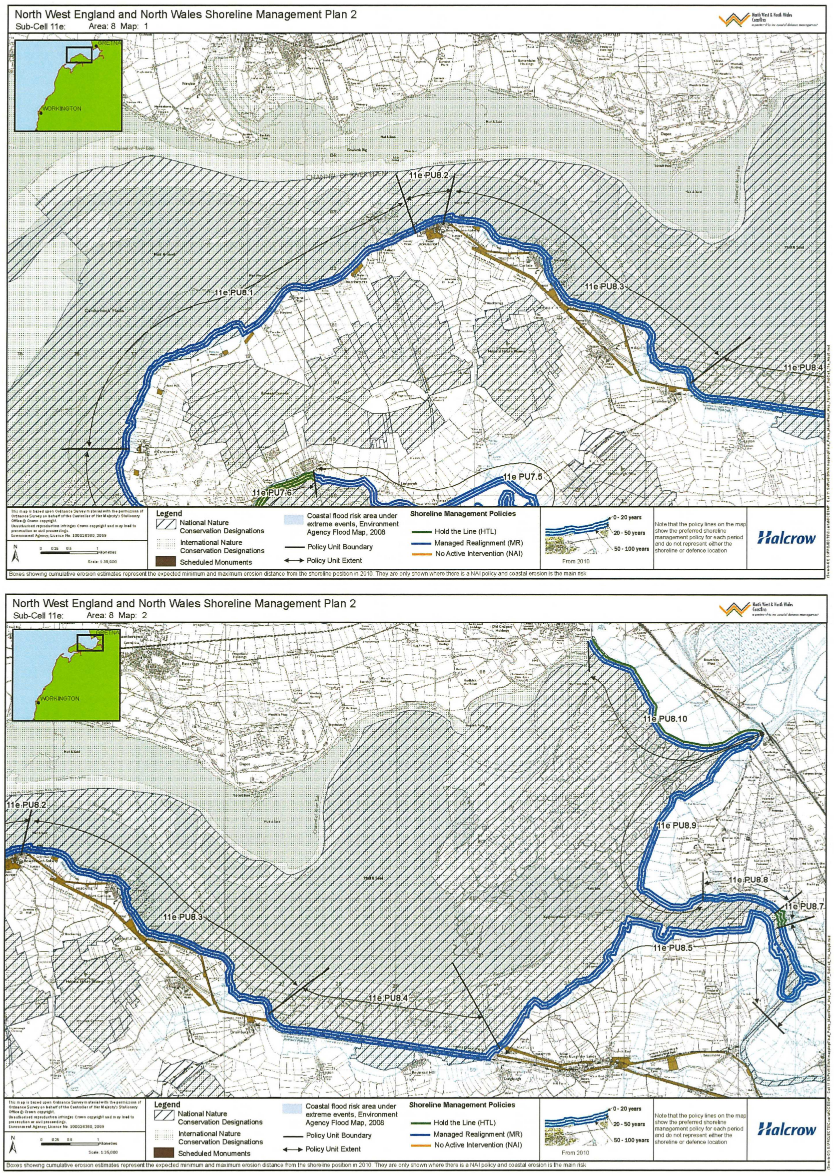

Figure 4.13. Location of potential managed realignment (blue lines) along the inner Solway Firth (English side) (Halcrow, 2010)

Table 4.3. Potential managed realignment sites in the inner Solway Firth (Halcrow, 2010)

Coastal Stretch	Policy Unit	Epoch 1	Epoch 2	Epoch 3
Cardurnock to Bowness-on-Solway	8:1	**MR**	**MR**	**MR**
Bowness-on-Solway	8:2	**MR**	**MR**	**MR**
Bowness-on-Solway to Drumburgh	8:3	**MR**	**MR**	**MR**
Drumburgh to Dykesfield	8:4	**MR**	**MR**	**MR**
Dykesfield to Kingsmoor (Eden Normal Tidal Limit)	8:5	**MR**	**MR**	**MR**
Kingsmoor (Eden Normal Tidal Limit) to Rockcliffe	8:6	**MR**	**MR**	**MR**
Rockcliffe to Demesne Farm	8:8	**MR**	**MR**	**MR**
Demesne Farm to Metal Bridge (Esk)	8:9	**MR**	**MR**	**MR**
Metal Bridge (Esk) to the River Sark	8:10	**MR**	**MR**	HTL

5 MORPHOLOGICAL MONITORING STRATEGY

Monitoring is continuous or repeated data collection over a period of time. The term monitoring covers a range of activities and types of data collection usually designed to detect changes from which a suitable coastal management strategy can be applied. The Severn Estuary and Solway Firth are dynamic environments and their processes are variable and in many ways unpredictable. Condition assessments must recognise this and must be reviewed, and changed if necessary, in light of changing circumstances. This process of review can only sensibly be carried out if the response of the estuary to both natural and human-induced forces is monitored.

Morphological monitoring can combine a wide range of techniques of varying sophistication including ground surveys, repeat bathymetric surveys, LiDAR and aerial photography. The monitoring strategies for the Severn Estuary and Solway Firth should be designed to measure attributes that contribute to an understanding of morphological equilibrium, which can be used as a measure of estuary condition in the future. As part of the monitoring strategy, the best way to monitor these two estuaries and some of the advantages and disadvantages of the various data collection methods that could be used are higlighted.

5.1 Bathymetry in the Severn Estuary and Solway Firth

The critical data upon which the Regime Theory method relies is bathymetry from which all the resulting characterisation parameters (cross-sectional area, width and tidal prism) can be derived. A time series of bathymetric data can provide an indication of how these parameters are changing, which can be used to determine if the estuary (or parts of the estuary) is moving towards or away from a more equilibrium form. There are a number of potential techniques available for the collection of bathymetric data in the Severn Estuary and Solway Firth including single beam echo-sounding, multibeam echo-sounding and LiDAR (http://www.channelcoast.org/southwest/survey_techniques/).

5.1.1 Single Beam Echo Sounding

Single beam echo sounding involves using a transducer attached either to the hull of a vessel, or to a pole mounted over the side or bow of the vessel. The echo sounder calculates the water depth beneath the transducer, by transmitting a sound pulse that is returned to the vessel *via* reflection off the sea bed. The density of soundings is dependent on the survey line spacing, vessel speed and the echo-sounder ping rate.

Standard single beam echo sounders collect data for a narrow zone along the track of the vessel and hence the main limitation of the system, compared to multibeam systems, is the limited sea bed coverage. Generally the data are presented either in a line form, or spatial interpolation is undertaken in order to provide full bathymetry coverage. This technique has been used widely to generate marine (Admiralty) charts. Single beam echo sounding can be combined with LiDAR and/or ground survey for a more complete view of the whole estuary.

5.1.2 Multibeam Echo Sounding

A multibeam echo-sounder survey provides an alternative to a single beam survey in bathymetric data collection. The main difference between a single beam echo-sounder and a multibeam echo-sounder is that the latter produces a number of beams forming a 'fan' of sound pulses or acoustic energy. A multibeam system essentially consists of a receiver and transmitter that emit and detect multiple beams of sound energy in a swathe (producing swathe bathymetry). These multiple soundings are taken at right angles to vessel track, as opposed to a single sounding directly underneath a vessel with a single beam echo sounder. This means that a multibeam system can provide a greater density of soundings allowing faster coverage of a site.

The main advantage of multibeam systems is that they can provide 100% coverage of the sea bed without the need to interpolate between lines. A disadvantage of multibeam systems is the high cost compared to single beam surveys. In shallow water (less than 10m), the swathe width is also significantly reduced.

5.1.3 LiDAR

Airborne Laser Induced Direction and Range (LiDAR) is a remote sensing technique for the collection of bathymetric and topographic data. It uses laser technology to 'scan' the ground surface (or estuary bed at low tide), taking up to 10,000 observations per square kilometre. These observations are then converted to the local co-ordinate and elevation datum by the use of differential GPS. The system routinely achieves vertical accuracy of +/-11-25cm and plan accuracy of +/-45cm, with a very rapid speed of data capture (up to 50km^2 per hour). It can operate on mudflats but care needs to be taken in areas of standing water as with the normal settings the laser beam is absorbed by water rather than reflected. The resulting data can be presented as a contour plot of bathymetry or used to create a digital terrain model.

5.1.4 Bathymetry Monitoring Strategy for the Severn Estuary and Solway Firth

A combined echosounder and LiDAR survey is recommended for both the Severn Estuary and Solway Firth. A survey is recommended every ten years in order to capture estuary-scale changes in morphology as the system evolves into the future. However, if the saltmarsh boundary measurements (see Section 5.2) indicate a deviation away from standard limits of natural variation, then a survey should be completed to support that observation. This is in line with the CSM guidance for estuaries and coastal saltmarsh (JNCC, 2004) (Table 1.1).

The LiDAR survey should be undertaken at low tide along the shallower parts of each estuary supplemented by an echosounder survey (preferably multibeam) in deeper water where LiDAR is unable to penetrate. Care should be taken to ensure that the LiDAR and multibeam data overlap to provide a seamless bathymetry across the estuaries. Difficulties in overlapping the data may occur in the inner Solway Firth where the water at low tide may be too deep for penetration of LiDAR and too shallow at high tide for a boat to operate safely. In this case the 'best available' dataset should be created by interpolation through the ensuing gaps in combination with expert geomorphological assessment as to what the gaps should look like. The same principle should apply to the Severn Estuary, although the locations where gaps could occur may be fewer.

5.2 Saltmarsh and Mudflat

There is great diversity in the morphology of saltmarshes and mudflats and the boundary between them that relates to the changing balance of physical, sedimentological and biological forces on the sediment. In general terms, the width of a mudflat will be greater in areas of high tidal range (c.f. the Severn Estuary and Solway Firth) than in areas of low tidal range, but there are considerable deviations that indicate there are other controls. Generally mudflats undergoing erosion have low and concave-upward profiles and those experiencing deposition have high and convex-upward profiles.

Any changes in the fronting mudflat profile causes change in the duration of wave attack, altering the rates of erosion and deposition, so there may be a gradual progression to a new equilibrium. A high convex mudflat shape is desirable because waves are progressively attenuated as they approach the shore, protecting the marsh edge from erosion. Low concave mudflats result in steadily increasing wave height and energy at the marsh edge, exacerbating its erosion.

The boundary between saltmarsh and mudflat in the Severn Estuary and Solway Firth can be monitored using aerial photography supported by land-based ground-truthing (and in combination with the LiDAR collection). It is recommended that, to understand changes to the morphological equilibrium attribute, these types of monitoring should take place every five years, with every other survey timed to coincide with the bathymetric surveys. This is a deviation from the CSM guidance, as Regime Theory is typically applied to understand the long-term changes to an estuary.

5.2.1 Aerial Photography

Vertical aerial surveys of a shoreline can provide quantitative data on large-scale changes of the coast, such as movement of the saltmarsh edge. The process of reviewing and assessing geomorphology from aerial photography generally requires registration of the data into digital systems such as GIS that allow the data to be correctly spatially located and allow accurate location and measurement to be achieved.

5.2.2 Ground-based Survey

A common form of field morphological monitoring is topographic survey. Saltmarsh and mudflat morphology can be monitored using topographic data to assess changes in height, width and slope. Topographic survey information can usefully be combined with the aerial photographs and bathymetric surveys in order to gain an overall representation of the intertidal area.

Several techniques of varying sophistication are available for collecting topographic survey data. The least sophisticated method (although not necessarily the least accurate) is survey using a quick set level, staff and chain. More advanced methods include using a total station with electronic distance measurement to a survey reflector prism and computer logging of data points. Current best practice involves the use of

GPS (Global Positioning System). The use of Real Time Kinematic (RTK) GPS can be very fast and efficient, entailing the establishment of a base station at a control point and surveying the profile using a separate GPS rover unit. A survey of this kind enables vertical accuracies of +/-30mm on hard surfaces and +/-50mm on soft surfaces, and horizontal accuracies of +/-20mm.

5.2.3 Saltmarsh / Mudflat Monitoring Strategy for the Severn Estuary and Solway Firth

A combined aerial photograph capture along with ground survey is recommended for both estuaries every five years. The data collection should be synchronous with the bathymetric data capture, to obtain a specific time-slice of estuary morphology. The ground surveys are likely to be limited in there extent given the large size of the estuaries. However, initial analysis of the remotely sensed data should provide an indication as to the critical areas for further investigation on the ground. The ground survey work should tie in with the timing of SSSI condition assessments.

5.3 Data Management

Data and its collection, in all the various forms, is usually relatively costly. The return on the investment of gathering and collating the data should be maximised through the means by which the data is stored, maintained and accessed. In this regard, a data governance strategy should be set up between Natural England and Scottish Natural Heritage for the Solway Firth and Natural England and Natural Resources Wales for the Severn Estuary to provide frameworks for the data to be stored, updated and shared. Each of these organisations would have joint coordinating roles over the way the data is captured, stored and used in their relevant estuary. Partners in each of these enterprises would include the Environment Agency (both estuaries) and the Scottish Environment Protection Agency (Solway Firth). These partners would work closely with the lead organisations to ensure the data is managed for the good of all interested parties. Also, the coordination of data management across organisations and geographical boundaries would allow resources to be shared and any ongoing data collection programmes to be efficiently streamlined into the process. For example, the Environment Agency already monitors saltmarshes in Water Framework Directive surveillance bodies.

5.3.1 Metadata

Data gathering should include meticulous recording of metadata. Metadata is information about the data rather than the data itself. It should include detail regarding the quality of the data, the parameters that have been gathered, the units/format/datums that have been used, the scale, any geographical referencing, and the appropriateness of the data and its intended application. In addition, information such as the spatial extent of the data and keywords will provide means by which efficient search and retrieval routines can interrogate the metadata. Establishing a metadata management system to administer project datasets allows easy review of existing information and potential cost savings through data re-use. Metadata should provide potential users with sufficient information to make an informed decision about the quality and potential for use of the data for any given requirement.

It is recommended that data collected to support morphological analysis of the Severn Estuary and Solway Firth complies with the metadata standards defined by MEDIN (Marine Environmental Data and Information Network). Information regarding what these standards are can be found at:

http://www.oceannet.org/submit_metadata/creating.html

5.3.2 Digital Format

Ideally, data should be collected, stored and used in digital formats. The volume of data generally generated from survey is such that it precludes any format other than digital. Having data in digital format can also allow the integration of datasets. As far as possible, greatest benefit will be achieved if it can be stored in industry standard digital formats. This will facilitate its use on a wider range of applications and increase the longevity of the data. Digital data in standard formats also makes data transfer and exchange more economical and less labour intensive.

5.3.3 Information Management

Information management is the capacity to efficiently store and retrieve relevant information. A key area is the use of GIS as a management and analysis tool. A GIS is a software package for the acquisition, storage, retrieval, manipulation and analysis of spatially referenced data. The most sophisticated GISs are expensive and require considerable processing power and storage capacity, whilst basic systems are also available for use on desk-top PCs at a modest cost. All systems are based on two components:

- a database capable of storing and retrieving information about the data, which is mapped by geographical position
- a visualisation system capable of displaying spatially-referenced data and interrogating the mapped data for co-ordinate information.

5.3.4 Monitoring Plan

Table 5.1 summarises a potential morphological monitoring plan for determination of morphological equilibrium in the future.

Data	**Frequency**	**Methods**
Bathymetry	Every 10 years	Single beam echo sounder Multibeam echosounder LiDAR
Saltmarsh-mudflat boundary	Every 5 years	Aerial Photographs Ground survey

6 CONCLUSION

An understanding of how the Severn Estuary and Solway Firth function is essential to ensure sustainable human uses of them into the future. This work was based on the assumption that the ‘health’ or condition of these estuaries is founded on the relationship between their physical forms (geometry) and the forces driving their forms (function/process) in line with the Regime Theory concepts and approaches developed by the Healthy Estuaries 2020 project (Natural England 2015).

To support habitat in favourable condition, the estuary morphologies need to be in ‘equilibrium’ with natural wave, tidal and sediment transport processes. Over time, these two estuaries have had their dynamic equilibrium morphologies changed in some way by human interference and different parts of their forms are at different stages of adjustment to natural process inputs. Hence, into the future both estuaries will seek to reach a steady state over the long term and their widths and depths will change over time towards a state of dynamic equilibrium or ‘most probable state’.

Regime Theory has been used in the Severn Estuary and Solway Firth to predict their equilibrium widths, which have been compared with their observed widths to determine, at a high level, how far they are from equilibrium forms. How close each estuary is to morphological equilibrium defines the condition of this attribute. The method has been combined with known natural and human constraints on morphology, where adjustment of the estuary form may not be possible due to hard geology or essential infrastructure. The method also supports identification of potential locations to restore intertidal habitat in such a way that a more sustainable estuary form is produced.

7 REFERENCES

ABPmer. 2006. Severn Estuary CHaMP Morphological Assessments. Part E: Historical Trends Analysis. Report to Jacobs Babtie (on behalf of the Environment Agency), June 2007.

ABPmer. 2009. Severn Estuary SMP2: Baseline Understanding of Coastal Behaviour and Dynamics. Report to Atkins, May 2009.

Atkins. 2010. Severn Estuary Shoreline Management Plan Review (SMP2). Available at: http://www.severnestuary.net/secg/smpr.html

Dargie, T. 1998. NVC Survey of saltmarsh habitat in the Severn Estuary 1998. Countryside Council for Wales Science Report 341.

Halcrow. 2010. North West England and North Wales Shoreline Management Plan SMP2. Available at: http://www.allerdale.gov.uk/downloads/nw_shoreline_management_plan_2.pdf

HR Wallingford, ABPmer and Pethick, J. 2007. Review and formalisation of geomorphological concepts and approaches for estuaries. Defra/Environment Agency R&D Technical Report FD2116/TR2.

JNCC. 2004. Common Standards Monitoring Guidance for Estuaries. Version August 2004.

Natural England. 2006. Coastal Squeeze, Saltmarsh Loss and Special Protection Areas. English Nature Research Report 710.

Natural England. 2015. Healthy Estuaries 2020: Towards Addressing Coastal Squeeze in Estuaries. Improvement Programme for England's Natura 2000 Sites. IPENS002. Natural England.

O'Brien, M.P. 1931. Estuary tidal prism related to entrance areas. Civil Engineering, 1, 738-739.

Spearman, J. R. 1995. Estuary regimes and methods for prediction of long-term changes. PhD Thesis, Oxford Brookes University.

Spearman, J. R. 2001. A simulation of tidal creek response to managed retreat using a hybrid regime model. HR Wallingford Report TR 118.

Townend, I., Wright, A. and Price, D. 2000. An investigation of the gross properties of UK estuaries. In EMPHASYS Consortium. 2000. Modelling Estuary Morphology and Process, 73-81.

Appendix A: Regime Theory and its Application to the Severn Estuary and Solway Firth

A.1. General Principles of Regime Theory

Regime Theory is based on empirical relationships between estuary properties that reflect their size and shape. The most widely used of these regime relationships is between channel cross-sectional area and upstream tidal prism (or discharge). This relationship, first proposed by O'Brien (1931), is between the spring tidal prism (the volume of water that enters and leaves the estuary during a spring tide) and the cross-sectional area at mean sea (tide) level at the mouth. This equation takes the form:

$$CSA = a.P^{b}$$

where:

CSA = cross-sectional area (mean sea level);
P = upstream spring tidal prism;
a = constant coefficient; and
b = constant exponent.

In the regime equation adopted in the Severn Estuary and Solway Firth, the cross-sectional area at MHWN tide is used instead of mean sea level. This is because MHWN tide is deemed to be the boundary of the active estuarine channel geomorphology, because when the water level is at this datum, maximum discharge takes place (immediately before inundation of the saltmarsh). Areas higher than MHWN tide within the tidal environment will have tidal current velocities that approach zero.

A.1.1. Applying Regime Theory to Inter-estuary Analysis

When the regime relationship is applied to a number of estuaries it is found to be linear when both datasets are transformed into their log values. The best-fit regression line that is constructed through a log-log plot represents the theoretical equilibrium morphology for those estuaries in general. This theoretical equilibrium has been applied successfully across a range of estuaries in the United Kingdom. Townend et al. (2000) described an empirical regime relationship for 66 estuaries around the United Kingdom coast (Figure A.1). The regression (regime) equation for the whole dataset is:

$$CSA = 0.024.P^{0.71} \quad (r^2 = 0.75)$$

This is the regression equation that was used in the Severn Estuary and Solway Firth.

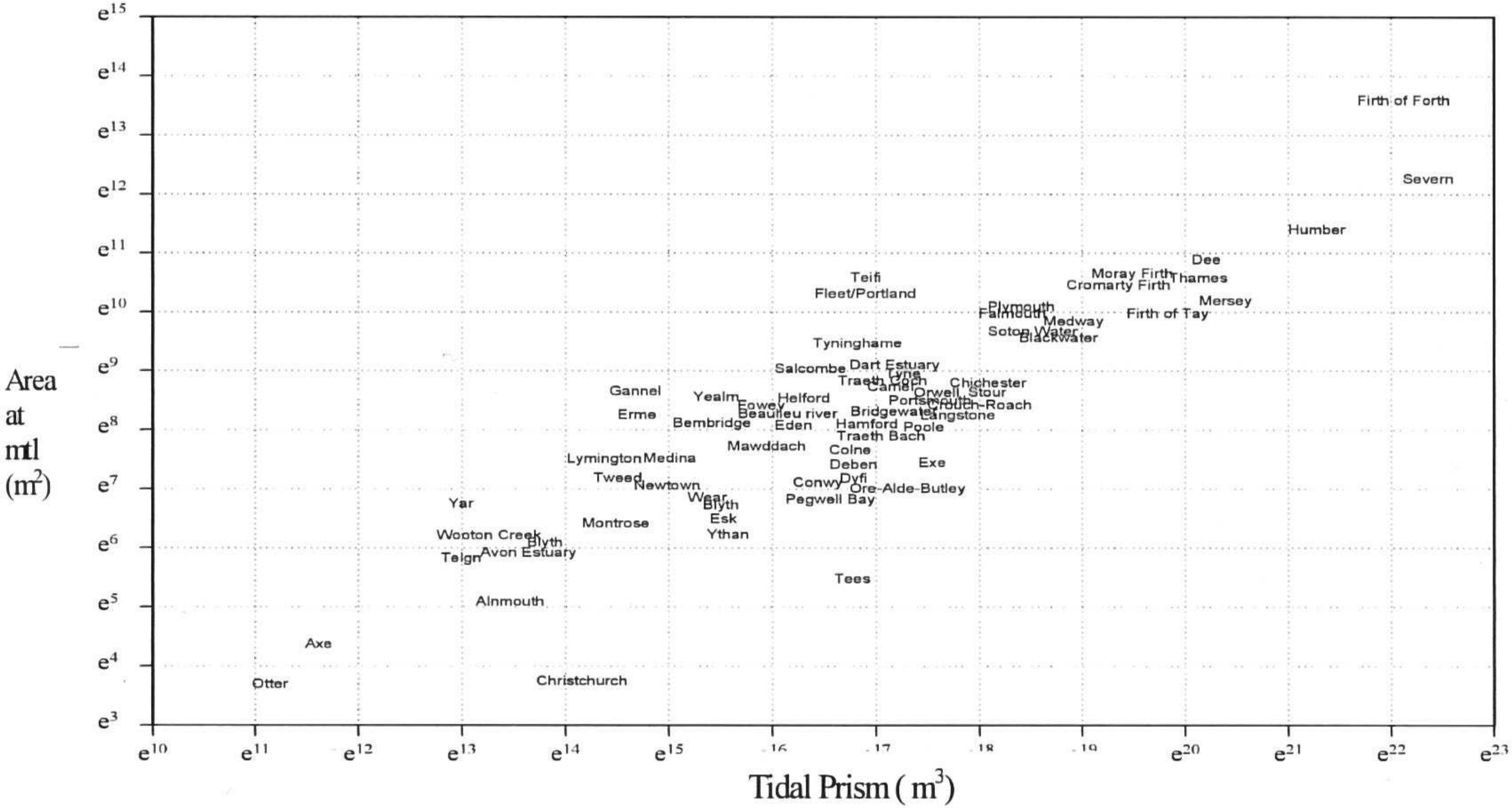

Figure A.1. Tidal prism – cross-sectional area relationship for 66 estuaries around the United Kingdom coast (from Townend et al., 2000)

Figure A.1 shows that although individual estuaries may depart from the ideal relationship between flow (tidal prism) and form (cross-section) (i.e. a linear regression line through the data) due to, for example human intervention or natural constraints such as geology, these departures will form a random scatter around the fundamental relationship that can be expressed as the best-fit regression to the data. The relationship is in this way, a useful tool to describe the overall condition of a given estuary compared to others in a regional group (but see uncertainties below).

A.1.2. Applying Regime Theory to Intra-estuary Analysis
As well as being applicable between estuaries, the relationship can equally be applied within a single estuary. Thus a downstream increase in tidal prism in a given estuary will be matched by an increase in the cross-sectional area of successive channel profiles. This provides a measure of the equilibrium morphology of an estuary along its length and a tool to assess condition by determining how the tidal prism / channel cross-sectional area relationship changes with distance along the estuary.

A.1.3. Uncertainties with Regime Theory
The Regime Theory only requires geometric and water level information to be used as inputs. This is so the method is simple to apply. HR Wallingford et al. (2007) showed that the use of only bathymetry as input to the method is an oversimplification because it does not take into account other important mechanisms controlling estuary evolution. These may include the effects of waves, fluvial discharge, longshore sediment transport and geology.

The potential weakness of the method related to these parameters is acknowledged, but it is beyond the scope of this study to include what are more complicated mathematical formulae (which are still not fully understood and to date haven't been applied successfully). It is understood that the level of uncertainty in the regime equation is important for understanding the uncertainty in the corresponding equilibrium predictions arising from its use.

A.2. Methods used to Predict Estuary Equilibrium Form in the Severn Estuary and Solway Firth
The two main parts to the analysis in the Severn Estuary and Solway Firth are:

1. Measure the observed forms; and
2. Predict the equilibrium forms.

These two forms are then compared to see how close the estuaries are to morphological equilibrium.

A.2.1. Development of Sections and Observed Estuary Form
The observed (present-day) cross-sectional area and tidal prism have been calculated in each estuary using the bathymetric datasets relative to the tidal elevations at specific sections along each of the estuaries. The number of sections is typically determined by the size of the estuary. Given the relatively large-scales of the two estuaries, the spacings of the sections are approximately 2km in the Severn Estuary and 1km in the Solway Firth. The sections stretch between MHWS tide on either side of the estuary and

are perpendicular (as far as possible) to a line along the centre of the channel. It is then possible to create a table in GIS with values for each estuary parameter calculated at each section. This data is defined as the observed morphology of the estuary (Appendices C to F).

A.2.2. Morphological Equilibrium based on the Predicted Estuary Form

In order to provide a preliminary assessment of the condition of the morphological equilibrium attribute, the observed forms of the estuaries are compared to the equilibrium forms predicted using a set of calculations at each of the sections originally defined in the measurement of observed form. The prediction of the equilibrium forms was carried out in three main stages using the methodology developed for Healthy Estuaries 2020 (Natural England, 2015):

- distribute throughout the estuary the total observed tidal prism at the mouth to predict the tidal prism upstream of each section;
- calculate equilibrium cross-sectional areas from the upstream tidal prisms at each section; and
- calculate mean depths and equilibrium widths at each section.

The calculations of predicted form are automated in the Excel tool and the outputs defined as the predicted morphology of the estuary. The results obtained are then interrogated using GIS to compare the predicted form with the observed form at each section to gauge how far from equilibrium the estuary is.

A.2.3. Distributing the Observed Tidal Prism at the Mouth throughout the Estuary

One result of the measurement of observed form using GIS is the spring tidal prism of the entire estuary (i.e. the tidal prism observed at the estuary mouth). In order to predict the equilibrium form of the estuary at each section this total tidal prism has to be distributed throughout the estuary from its mouth to its head. The tidal prism at each section is calculated using an equal distribution model with the following equation:

$$P_x = e^{[-3.(x/l)]}.P_{tot}$$

where:

P_x = tidal prism at each section (m^3);
x = distance to section from estuary mouth (m);
l = total estuary length from mouth to head (m); and
P_{tot} = total tidal prism (observed) (m^3).

This equation distributes the total tidal prism along the estuary according to distance from the mouth. The calculation of tidal prism upstream of a particular section from the mouth is based on a cubic exponent, which is multiplied by the ratio of the distance to the section from the mouth (x) and the total length of the estuary (l). The ratio x/l is a non-dimensional distance along the estuary axis; i.e. it varies from 0 at the mouth to 1 at the head. The use of an exponential set at 3 has been verified by empirical calibration using United Kingdom estuaries (unpublished).

The calculation of P_x is straightforward in an estuary with a single channel. However, an estuary typically has a main channel with one or more smaller channels joining it, which makes the designation of x and l in the equation complicated. For example, both the Severn Estuary and Solway Firth have major channels with smaller channels joining at points along their lengths. In this situation, the equal distribution equation is first applied to each joining channel; the tidal prism is apportioned based on the observed tidal prism at the channel mouths with l as the total channel length. The equation is then applied to the main channel only, but the observed tidal prism at the mouth is reduced by the sum of the observed tidal prisms at the mouths of the joining channels. The sum of the tidal prisms of the joining channels is then added back on to the predicted tidal prism at each section of the main channel. The calculation of tidal prism at each section is automated in the Excel tool from files imported directly from GIS.

A.2.4. Calculating Equilibrium Cross-sectional Areas

The calculation of equilibrium cross-sectional area from predicted tidal prism at each section is based on the regime equation for all United Kingdom estuaries:

$$CSA = 0.024.P^{0.71} \ (r^2 = 0.75)$$

A.2.5. Predicting Estuary Width using the 'Constant Evolution' Method

Using the regime equation the equilibrium cross-sectional area at each section is predicted. However, the crucial parameter in the assessment is regime width (planform). In order to predict the regime width from the equilibrium cross-sectional area, it is necessary to predict the equilibrium mean depth. In this study, the 'constant evolution' method is used as described in Healthy Estuaries 2020 (Natural England, 2015).

One of the main difficulties with Regime Theory is that in most cases, an estuary system does not conform to a smooth relationship of the type:

$$CSA = a.P^b$$

Instead an estuary presents considerable scatter around a best fit relationship of that form. Adopting the best fit relationship and implementing the regime equation to derive the equilibrium cross-sectional area of an estuary may provide results that are driven mainly by the scatter in the data and the uncertainty inherent in the method (Spearman, 1995, 2001; HR Wallingford et al., 2007).

To overcome this problem, Spearman (2001) suggested that the discrepancies between the observed estuary cross-sectional area and the equilibrium cross-sectional area given by the regime equation at each section are held to be constant throughout the evolution. In this way the observed cross-sectional area at each section is assumed to be in regime (for reasons that are not fully understand) and is adjusted in proportion to the relative change between its form and the equilibrium form (HR Wallingford et al., 2007).

Using this methodology it is possible to predict mean depths and equilibrium widths based on the relationship between the observed and predicted cross-sectional areas at each section. Equilibrium width is predicted using the observed mean depth to width ratio at each section and applying the same ratio to the predicted cross-sectional area:

$W_E = (CSA_E.W_O/D_O)^{0.5}$

where:

W_E = equilibrium width (m);
CSA_E = equilibrium cross-sectional area (m^2);
W_O = observed width (m); and
D_O = observed mean depth (m).

The same principle can be applied to calculate equilibrium mean depth:

$D_E = (CSA_E/[W_O/D_O])^{0.5}$

where:

D_E = equilibrium mean depth (m).

Appendix B: List of datasets received and used in this study

Severn and Solway	Healthy Estuary 2020 toolbox	Healthy Estuaries 2020 Toolbox.tbx	ESRI Toolbox	Python toolbox used to produce the Healthy Estuaries 2020 output	Royal HaskoningDHV	Yes
Severn and Solway	Admiralty Charts	Charts_Astrium.gdb	Raster	Geodatabase of all UK admiralty charts	Environment Agency - Geostore	No
Severn and Solway	Admiralty Charts	UKHO_Vector_Defra.gdb	Vector	Geodatabase containing vector admiralty datasets	Environment Agency - Geostore	Yes
Severn and Solway	DiGMapGB-50 - Artificial	dgm_50_artificial	Vector	1:50,000 map representing artificial geology (Study extent)	Environment Agency - Geostore	Yes
Severn and Solway	DiGMapGB-50 - Bedrock	dgm_50_bedrock	Vector	1:50,000 map representing bedrock geology	Environment Agency - Geostore	Yes
Severn and Solway	DiGMapGB-50 - Superficial	dgm_50_superficial	Vector	1:50,000 map representing superficial geology	Environment Agency - Geostore	Yes
Severn and Solway	Landcover Map 2007	lcm2007_25m_gb	Raster	CEH Land classification Mapping	Environment Agency - Geostore	No
Severn and Solway	Landcover Map 2007	lmap_2007_ceh	Vector	CEH Land classification Mapping	Environment Agency - Geostore	Yes
Severn and Solway	2m Lidar Grids	multiple types	Text	ASCI LIDAR tiles	Natural England (EA Geomatics)	Yes
Severn and Solway	Port locations and tidal datum's	Tidal Datum	Text	Location of Tidal datum's from Admiralty Tide Tables (2015)	UKHO	Yes
Severn	2012_EACCWNE Grab Sample data	multiple types	Vector	Severn Sabellaria Samples_i	Natural England	No
Severn	CCW data	multiple types	Vector	Subtidal reef GIS layers	Natural England	No
Severn	Channel Coast observatory Single Beam	multiple types	Vector	Single beam	Natural England	No
Severn	Seastar Survey Severn Estuary SAC Sandbanks Bathymetry	Severn Estuary SAC Final SBES_RTK and Manual Tides 2D Fill All Lines 24_09_2013 2m Sort 225 min leg 1 step	Vector (dxf)	Bathymetry Survey	Natural England	No
Severn	Sidescan Mosaics UTM	multiple types	Raster	Bathymetry Survey	Natural England	No
Solway	Allonby Bay Survey	CS0286_SolwayFirth_XYZ_2011	Text	Solway Firth Bathymetric Survey	Natural England	No
Solway	Multibeam Survey	Solway_MBES_Coverage_061110	Text	Solway Firth Bathymetric Survey	Natural England	Yes
Solway	Single Beam Survey	SBES Summary 061110-V2	Text	Solway Firth Bathymetric Survey	Natural England	No
Solway	Single Beam Survey	SBES_Bathy_upto_4_October_All_vessels	Text	Solway Firth Bathymetric Survey	Natural England	No
Solway	Single Beam Survey Summary	SBES Summary 061110-V2a	Text	Solway Firth Bathymetric Survey	Natural England	No

Appendix C: Observed form of the Severn Estuary at each section

Section	Tidal Prism (m^3)	Cross-Sectional Area (m^2)	Width (m)	Mean Depth (m)
1-0	24	#N/A	#N/A	#N/A
1-20	514,509	#N/A	#N/A	#N/A
1-40	2,128,563	#N/A	#N/A	#N/A
1-60	3,437,534	#N/A	#N/A	#N/A
1-80	5,661,526	#N/A	#N/A	#N/A
1-100	8,648,420	#N/A	#N/A	#N/A
1-120	12,551,041	#N/A	#N/A	#N/A
1-140	16,125,550	#N/A	#N/A	#N/A
1-160	20,673,766	#N/A	#N/A	#N/A
1-180	26,185,575	#N/A	#N/A	#N/A
1-200	41,022,826	#N/A	#N/A	#N/A
1-220	61,377,463	#N/A	#N/A	#N/A
1-240	82,477,399	#N/A	#N/A	#N/A
1-260	100,034,068	#N/A	#N/A	#N/A
1-280	114,360,065	3,715	1,087	3.42
1-300	135,090,011	6,375	1,601	3.98
1-320	165,517,582	8,623	2,338	3.69
1-340	202,145,941	11,864	2,626	4.52
1-360	245,153,384	13,651	2,603	5.24
1-380	296,992,047	15,646	3,166	4.94
1-400	362,477,783	17,409	3,672	4.74
1-420	427,693,696	21,056	3,598	5.85
1-440	492,189,289	16,572	2,487	6.67
1-460	537,184,802	21,506	2,828	7.60
1-480	611,002,813	27,019	3,566	7.57
1-500	684,307,775	23,865	3,835	6.22
1-520	791,173,724	61,768	6,029	10.25
1-540	932,978,751	68,064	7,644	8.90

Section	Tidal Prism (m^3)	Cross-Sectional Area (m^2)	Width (m)	Mean Depth (m)
1-560	1,102,314,394	69,797	8,383	8.33
1-580	1,277,145,257	79,573	8,362	9.52
1-600	1,437,647,740	79,229	7,623	10.39
1-620	1,598,117,050	84,079	7,765	10.83
1-640	1,782,203,269	97,944	8,838	11.08
1-660	1,985,397,190	117,827	10,295	11.45
1-680	2,227,141,284	138,337	12,328	11.22
2-0	2,826	96	42	2.23
2-20	3,982,063	1,375	226	6.08
2-40	9,638,829	2,457	334	7.36
2-60	22,139,618	5,662	1,213	4.66
3-0	2,539,670,055	162,648	13,968	11.64
3-20	2,850,424,644	181,508	15,033	12.08
3-40	3,174,234,615	192,819	15,815	12.19
3-60	3,484,324,230	210,382	16,319	12.89
3-80	3,830,102,749	223,768	15,864	14.10
3-100	4,173,990,465	225,205	14,732	15.29
3-120	4,503,723,010	244,598	16,374	14.94
3-140	4,839,280,618	253,991	14,621	17.37
3-160	5,157,305,369	257,806	15,025	17.16
3-180	5,478,310,850	274,198	14,578	18.81
3-200	5,795,814,600	352,370	18,560	18.98
3-220	6,105,707,924	362,128	20,518	17.65
4-0	2,969	44	31	1.47
4-20	355,186	97	55	1.76
4-40	885,454	341	158	2.16
4-60	3,100,397	341	119	2.89
4-80	4,929,500	611	170	3.60
4-100	7,134,166	958	230	4.18
4-120	10,484,613	924	216	4.26

Section	Tidal Prism (m^3)	Cross-Sectional Area (m^2)	Width (m)	Mean Depth (m)
4-140	15,926,627	1,618	364	4.44
4-160	23,250,990	3,294	803	4.11
4-180	36,177,218	6,134	1,296	4.73
5-0	6,910,239,269	400,175	24,433	16.38
5-20	7,474,225,354	415,746	22,803	18.23
5-40	7,993,902,903	427,495	22,357	19.12
5-60	8,500,979,236	431,380	21,957	19.65
5-80	9,002,299,746	440,544	22,222	19.83
5-100	9,507,896,229	461,863	23,271	19.85
5-120	9,977,818,279	459,835	22,188	20.72
5-140	10,434,857,355	484,283	22,383	21.64
5-160	10,852,156,317	509,093	21,903	23.24
5-180	11,269,484,005	536,617	22,143	24.24
5-200	11,650,165,858	536,861	20,102	26.71

Appendix D: Predicted equilibrium form of the Severn Estuary at each section

Section	Tidal Prism (m^3)	Cross-Sectional Area (m^2)	Width (m)	Mean Depth (m)
1-0	110,882,835	12,361	#N/A	#N/A
1-20	121,111,233	13,160	#N/A	#N/A
1-40	132,283,149	14,011	#N/A	#N/A
1-60	144,485,620	14,917	#N/A	#N/A
1-80	157,813,709	15,882	#N/A	#N/A
1-100	172,371,249	16,908	#N/A	#N/A
1-120	188,271,651	18,001	#N/A	#N/A
1-140	205,638,786	19,165	#N/A	#N/A
1-160	224,607,955	20,404	#N/A	#N/A
1-180	245,326,936	21,724	#N/A	#N/A
1-200	267,957,141	23,128	#N/A	#N/A
1-220	292,674,872	24,623	#N/A	#N/A
1-240	319,672,692	26,215	#N/A	#N/A
1-260	349,160,929	27,910	#N/A	#N/A
1-280	381,369,310	29,714	3,074	9.67
1-300	416,548,757	31,635	3,566	8.87
1-320	454,973,335	33,681	4,622	7.29
1-340	496,942,391	35,858	4,565	7.85
1-360	542,782,887	38,176	4,353	8.77
1-380	592,851,944	40,645	5,103	7.97
1-400	647,539,625	43,272	5,790	7.47
1-420	707,271,977	46,070	5,321	8.66
1-440	772,514,344	49,048	4,278	11.47
1-460	843,775,000	52,219	4,408	11.85
1-480	921,609,101	55,595	5,116	10.87
1-500	1,006,623,016	59,190	6,039	9.80
1-520	1,099,479,048	63,016	6,089	10.35
1-540	1,200,900,592	67,091	7,589	8.84

Section	Tidal Prism (m³)	Cross-Sectional Area (m²)	Width (m)	Mean Depth (m)
1-560	1,311,677,776	71,428	8,481	8.42
1-580	1,432,673,611	76,046	8,174	9.30
1-600	1,564,830,719	80,962	7,706	10.51
1-620	1,709,178,670	86,197	7,862	10.96
1-640	1,866,842,011	91,769	8,555	10.73
1-660	2,039,049,022	97,702	9,374	10.42
1-680	2,227,141,284	104,019	10,689	9.73
2-0	1,102,267	468	94	4.96
2-20	2,996,271	952	188	5.07
2-40	8,144,710	1,936	296	6.53
2-60	22,139,618	3,938	1,012	3.89
3-0	2,441,281,097	111,025	11,541	9.62
3-20	2,501,481,214	112,962	11,857	9.53
3-40	2,580,556,594	115,486	12,240	9.44
3-60	2,684,425,423	118,767	12,261	9.69
3-80	2,820,861,488	123,022	11,763	10.46
3-100	3,000,075,984	128,521	11,129	11.55
3-120	3,235,481,744	135,603	12,192	11.12
3-140	3,544,697,087	144,681	11,035	13.11
3-160	3,950,864,413	156,265	11,698	13.36
3-180	4,484,382,238	170,970	11,511	14.85
3-200	5,185,180,285	189,537	13,613	13.92
3-220	6,105,707,924	212,855	15,731	13.53
4-0	1,801,158	663	118	5.61
4-20	2,513,718	840	162	5.17
4-40	3,508,176	1,065	279	3.81
4-60	4,896,054	1,349	235	5.73
4-80	6,832,994	1,709	284	6.01
4-100	9,536,211	2,166	345	6.28
4-120	13,308,855	2,744	373	7.35

Section	Tidal Prism (m³)	Cross-Sectional Area (m²)	Width (m)	Mean Depth (m)
4-140	18,574,003	3,476	534	6.52
4-160	25,922,110	4,405	928	4.75
4-180	36,177,218	5,581	1,236	4.51
5-0	6,416,126,291	220,483	18,135	12.16
5-20	6,512,071,972	222,819	16,693	13.35
5-40	6,641,585,095	225,956	16,254	13.90
5-60	6,816,409,525	230,163	16,038	14.35
5-80	7,052,397,821	235,793	16,257	14.50
5-100	7,370,948,701	243,306	16,890	14.41
5-120	7,800,947,412	253,300	16,468	15.38
5-140	8,381,384,959	266,542	16,606	16.05
5-160	9,164,893,694	284,002	16,359	17.36
5-180	10,222,519,861	306,900	16,745	18.33
5-200	11,650,165,858	336,750	15,921	21.15

Appendix E: Observed form of the Solway Firth at each section

Section	Tidal Prism (m^3)	Cross-Sectional Area (m^2)	Width (m)	Mean Depth (m)
1-0	63,063	N/A	N/A	N/A
1-10	266,685	N/A	N/A	N/A
1-20	485,522	N/A	N/A	N/A
1-30	1,067,330	N/A	N/A	N/A
1-40	2,026,106	N/A	N/A	N/A
1-50	3,851,452	43	261	0.17
1-60	6,777,733	237	489	0.48
1-70	11,033,457	322	560	0.58
1-80	16,423,915	767	1,226	0.63
1-90	24,136,788	1,881	1,614	1.17
1-100	33,219,289	2,259	1,952	1.16
1-110	41,620,242	2,943	1,772	1.66
2-0	151,090	N/A	N/A	N/A
2-10	423,202	N/A	N/A	N/A
2-20	751,639	14	101	0.14
2-30	1,241,623	42	108	0.38
2-40	2,543,218	130	336	0.39
2-50	4,797,631	307	456	0.68
2-60	6,499,155	400	415	0.97
2-70	9,391,532	422	307	1.37
2-80	12,897,515	707	628	1.13
2-90	16,781,705	590	310	1.90
2-100	19,011,324	745	453	1.64
2-110	22,529,570	1,067	692	1.54
2-120	26,722,310	1,403	938	1.50
2-130	76,244,371	4,578	2,631	1.74
3-0	89,767,688	4,833	2,348	2.06
3-10	100,410,968	5,437	2,391	2.27

Section	Tidal Prism (m^3)	Cross-Sectional Area (m^2)	Width (m)	Mean Depth (m)
3-20	112,410,464	5,771	2,086	2.77
3-30	123,001,782	5,644	2,000	2.82
3-40	133,386,869	5,387	1,754	3.07
3-50	146,011,719	6,696	2,327	2.88
3-60	158,521,301	6,784	2,228	3.05
3-70	173,201,685	8,976	2,918	3.08
3-80	191,649,797	11,163	3,739	2.99
3-90	215,123,211	12,540	4,327	2.90
3-100	237,000,243	13,288	4,792	2.77
3-110	10,984	N/A	N/A	N/A
4-0	76,031	N/A	N/A	N/A
4-10	215,619	N/A	N/A	N/A
4-20	473,130	N/A	N/A	N/A
4-30	850,924	36	76	0.48
4-40	1,805,162	38	215	0.18
4-50	4,332,898	275	536	0.51
4-60	7,262,659	935	758	1.23
4-70	10,488,338	997	800	1.24
4-80	19,463	N/A	N/A	N/A
5-0	68,623	N/A	N/A	N/A
5-10	212,527	N/A	N/A	N/A
5-20	569,889	50	140	0.36
5-30	1,411,858	101	121	0.83
5-40	4,209,194	472	494	0.96
5-50	23,321,897	4,084	2,585	1.58
6-0	32,761,428	3,946	1,927	2.05
6-10	431,276,886	29,308	7,754	3.78
7-0	529,088,915	38,433	9,395	4.09
7-20	599,087,474	50,495	10,111	4.99
7-30	655,154,255	50,499	10,364	4.87

Section	Tidal Prism (m³)	Cross-Sectional Area (m²)	Width (m)	Mean Depth (m)
7-40	2,327	N/A	N/A	N/A
8-0	76,391	N/A	N/A	N/A
8-10	169,399	N/A	N/A	N/A
8-20	353,305	N/A	N/A	N/A
8-30	630,283	33	66	0.49
8-40	967,018	48	81	0.59
8-50	1,366,900	69	118	0.59
8-70	2,792,424	311	421	0.74
8-80	4,559,781	358	424	0.85
8-90	6,412,587	439	462	0.95
8-100	9,314,849	970	945	1.03
8-110	14,094,387	1,425	1,272	1.12
8-120	20,592,683	2,328	1,928	1.21
8-130	30,381,840	3,495	3,065	1.14
8-140	41,461,121	4,877	3,600	1.35
9-0	927,149,475	67,029	11,037	6.07
9-10	1,009,604,877	78,823	10,884	7.24
9-20	1,084,020,595	80,923	10,744	7.53
9-30	1,167,480,801	83,660	11,031	7.60
9-40	1,248,293,251	89,257	11,792	7.94
9-50	1,334,019,963	96,098	12,192	8.42
9-60	1,416,161,492	99,855	11,979	8.88
9-70	1,502,400,975	116,410	13,237	8.79
9-80	1,612,682,340	131,423	14,967	8.78
9-90	1,766,625,739	146,520	16,546	8.86
9-100	1,889,689,818	155,312	17,305	8.97
9-110	2,025,265,448	164,095	18,877	8.69
9-120	2,174,879,126	193,954	19,811	9.79
9-130	2,304,759,172	197,374	20,139	9.80
9-140	2,458,273,677	206,124	20,974	9.83

Section	Tidal Prism (m³)	Cross-Sectional Area (m²)	Width (m)	Mean Depth (m)
9-150	2,599,041,306	212,218	20,965	10.12
9-160	2,762,558,069	232,452	21,913	10.61
9-170	2,956,034,451	256,631	22,953	11.18
9-180	3,111,588,665	271,023	23,461	11.55
9-190	3,315,116,368	291,857	24,609	11.86
9-200	3,470,719,956	306,250	25,413	12.05
9-220	3,848,737,666	347,267	24,923	13.93
9-230	4,012,429,385	372,723	25,335	14.71

Appendix F: Predicted equilibrium form of the Solway Firth at each section

Section	Tidal Prism (m^3)	Cross-Sectional Area (m^2)	Width (m)	Mean Depth (m)
1-0	2,072,150	733	N/A	N/A
1-10	2,721,856	889	N/A	N/A
1-20	3,575,272	1,079	N/A	N/A
1-30	4,696,269	1,310	N/A	N/A
1-40	6,168,747	1,589	N/A	N/A
1-50	8,102,908	1,929	1,739	1.11
1-60	10,643,510	2,341	1,537	1.52
1-70	13,980,696	2,841	1,663	1.71
1-80	18,364,231	3,449	2,598	1.33
1-90	24,122,188	4,185	2,399	1.74
1-100	31,685,506	5,080	2,926	1.74
1-110	41,620,242	6,165	2,563	2.40
2-0	1,675,762	630	N/A	N/A
2-10	2,110,737	742	N/A	N/A
2-20	2,658,618	874	809	1.08
2-30	3,348,712	1,030	539	1.91
2-40	4,217,932	1,213	1,028	1.18
2-50	5,312,774	1,430	982	1.46
2-60	6,691,803	1,684	851	1.98
2-70	8,428,785	1,984	666	2.98
2-80	10,616,633	2,337	1,142	2.05
2-90	13,372,376	2,753	670	4.11
2-100	16,843,424	3,243	945	3.43
2-110	21,215,448	3,821	1,309	2.92
2-120	26,722,310	4,501	1,676	2.69
2-130	76,739,524	9,519	3,792	2.51
3-0	79,372,327	9,749	3,333	2.93
3-10	82,830,624	10,049	3,251	3.09

Section	Tidal Prism (m³)	Cross-Sectional Area (m²)	Width (m)	Mean Depth (m)
3-20	87,373,243	10,437	2,805	3.72
3-30	93,340,163	10,939	2,784	3.93
3-40	101,177,963	11,583	2,572	4.50
3-50	111,473,242	12,408	3,166	3.92
3-60	124,996,522	13,459	3,135	4.29
3-70	142,759,919	14,790	3,745	3.95
3-80	166,092,886	16,469	4,541	3.63
3-90	196,741,717	18,573	5,265	3.53
3-100	237,000,243	21,197	6,051	3.50
3-110	522,184	275	N/A	N/A
4-0	759,773	359	N/A	N/A
4-10	1,105,463	469	N/A	N/A
4-20	1,608,439	612	N/A	N/A
4-30	2,340,264	799	357	2.24
4-40	3,405,065	1,042	1,124	0.93
4-50	4,954,340	1,360	1,192	1.14
4-60	7,208,522	1,775	1,045	1.70
4-70	10,488,338	2,317	1,220	1.90
4-80	209,563	144	N/A	N/A
5-0	381,850	220	N/A	N/A
5-10	695,775	338	N/A	N/A
5-20	1,267,785	517	450	1.15
5-30	2,310,055	791	340	2.33
5-40	4,209,194	1,212	792	1.53
5-50	15,596,881	3,071	2,242	1.37
6-0	32,761,428	5,201	2,212	2.35
6-10	288,949,237	24,400	7,074	3.45
7-0	355,754,380	28,283	8,060	3.51
7-20	451,808,237	33,514	8,237	4.07
7-30	655,154,255	43,633	9,634	4.53

Section	Tidal Prism (m³)	Cross-Sectional Area (m²)	Width (m)	Mean Depth (m)
7-40	2,064,228	731	N/A	N/A
8-0	2,557,530	851	N/A	N/A
8-10	3,168,720	990	N/A	N/A
8-20	3,925,969	1,153	N/A	N/A
8-30	4,864,184	1,343	424	3.17
8-40	6,026,610	1,563	465	3.36
8-50	7,466,829	1,820	602	3.02
8-70	9,251,227	2,119	1,098	1.93
8-80	11,462,053	2,468	1,112	2.22
8-90	14,201,216	2,873	1,181	2.43
8-100	17,594,974	3,345	1,755	1.91
8-110	21,799,761	3,895	2,102	1.85
8-120	27,009,394	4,535	2,690	1.69
8-130	33,464,007	5,280	3,767	1.40
8-140	41,461,121	6,148	4,042	1.52
9-0	861,700,035	53,005	9,814	5.40
9-10	884,700,230	54,005	9,009	5.99
9-20	910,904,895	55,136	8,868	6.22
9-30	940,760,489	56,413	9,046	6.24
9-40	974,775,674	57,854	9,269	6.24
9-50	1,013,529,977	59,478	9,280	6.41
9-60	1,057,683,671	61,306	9,093	6.74
9-70	1,107,989,018	63,362	9,766	6.49
9-80	1,165,303,088	65,672	10,580	6.21
9-90	1,230,602,363	68,264	11,294	6.04
9-100	1,304,999,371	71,170	11,714	6.08
9-110	1,389,761,639	74,422	12,713	5.85
9-120	1,486,333,295	78,057	12,568	6.21
9-130	1,596,359,666	82,117	12,990	6.32
9-140	1,721,715,309	86,645	13,598	6.37

Section	Tidal Prism (m³)	Cross-Sectional Area (m²)	Width (m)	Mean Depth (m)
9-150	1,864,535,957	91,689	13,780	6.65
9-160	2,027,254,896	97,301	14,177	6.86
9-170	2,212,644,429	103,538	14,579	7.10
9-180	2,423,863,106	110,462	14,978	7.38
9-190	2,664,509,536	118,141	15,657	7.55
9-200	2,938,683,701	126,648	16,342	7.75
9-220	3,606,950,869	146,481	16,187	9.05
9-230	4,012,429,385	157,990	16,495	9.58

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