Using Healthy Estuaries to Provide a Morphological Characterisation of the Dee Estuary and the Estuaries in and Adjacent to Morecambe Bay

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Using Healthy Estuaries to Provide a Morphological Characterisation of the Dee Estuary and the Estuaries in and Adjacent to Morecambe Bay

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REPORT

A1 Morphological Characterisation of the Dee Estuary and the Estuaries in and adjacent to Morecambe Bay

1.1

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Executive Summary

The Dee Estuary and the estuaries within and immediately outside Morecambe Bay support a variety of habitats designated within Sites of Special Scientific Interest (SSSI). These SSSIs 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 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.

Of the five estuaries within and immediately outside Morecambe Bay, only two (Duddon Estuary and Wyre Estuary) were deemed suitable for the application of Regime Theory. The other three were not analysed due to being dominated by open coast processes rather than estuarine processes (Leven Estuary and Kent Estuary) or lack of suitable bathymetric data (Lune Estuary).

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 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 each of the estuaries are different. The whole of the Wyre Estuary is under-sized compared to its predicted form; the observed channel is narrower than predicted for the present-day tidal regime. In the Dee Estuary, the stretch upstream from where the main channel divides is under-sized, whereas the downstream reaches in the Mostyn Channel and Hilbre Channel are tending towards equilibrium, whereby the observed and predicted widths are similar. A similar situation occurs in the Duddon Estuary, where the stretch upstream from Millom is under-sized and the downstream reach is tending towards equilibrium.

Under-sizing means that to obtain an equilibrium form the estuaries have to widen from their current forms. They should erode by loss of intertidal habitat because the high water mark is constrained by flood defences which do not allow it to migrate landwards. None of the three estuaries have reaches which are over-sized, where the observed channels are wider than predicted for the present-day tidal regimes.

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.

The Dee Estuary is a large and dynamic system located between the north Wales coast and Wirral Peninsula. Further north, four smaller estuaries enter Morecambe Bay (Leven, Kent, Lune and Wyre), which is a large open water tidal embayment rather than an estuary. A further estuary (Duddon) enters the Irish Sea to the north of Morecambe Bay. Both the Dee Estuary and the estuaries within and immediately outside Morecambe Bay support a variety of habitats including intertidal sandflats, mudflats, dune systems and reefs, which are designated within Sites of Special Scientific Interest (SSSI). All these estuaries are potentially subject to longer-term fluctuations in morphology, reflecting estuary evolution processes as well as responses to past or present human interventions.

This study uses existing data to characterise the functioning of the Dee Estuary and the estuaries within and immediately outside Morecambe Bay under four headline parameters to support condition assessment judgements. These are estuary extent (including intertidal area), tidal regime, bathymetry/topography, and (whole-estuary) morphological equilibrium (*Table 0.1*).

Regime Theory

The best way to determine how far an estuary system is from its 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 which uses empirical relationships between estuary gross morphology and tidal prism, through simple power-law equations (O'Brien, 1931; Coastal Geomorphology Partnership, 1999; Natural England, 2015). 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 (*Table 0.1*).

Crucial to the philosophy of Regime Theory is that the morphology will evolve to achieve equilibrium between the forcing of the waves and currents transporting sediment and the resulting form of the estuary created by that transport. 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 its observed width can be used to determine how far an estuary is from an equilibrium form, which can then be used to define the condition of this attribute.

Table 0.1.Factors involved in condition of morphological equilibrium attributes

Feature	Attribute	Measure	Target	Comment	Method
• Estuaries	• xtent	• 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 2.3). This ties in with the use of spring tidal datums to establish tidal prism in Regime Theory (Appendix A)
	• orphological Equilibrium	• Intra- and inter-estuarine tidal prism/cross-sectional area (Tp/Cs) relationship	• No significant deviation from the intra- and inter- estuarine Tp/Cs relationship from the established baseline	• 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 horizontal 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
• Intertidal Mudflats and Sandflats (mudflats and sandflats not covered by seawater at low tide)	• xtent	• Area measured once every reporting cycle	• No decrease in extent from an established baseline	• The extent of the feature is a reporting requirement of the Habitats Directive • • For dynamic coastlines, fluctuations in extent may be great, but are attributable to natural coastal processes	• Extent should be assessed periodically against a baseline map showing the distribution of littoral sediment, or through the review of any known activities that may have caused an alteration in extent
	• opography	• Tidal elevation and shore slope, measured periodically (frequency to be determined).	• Shore profile measured in the summer months should not deviate significantly from an established baseline, subject to natural change • • Environment Agency LIDAR survey 2003 may provide a baseline	• In the intertidal, topography reflects the energy conditions and stability of the sediment, which is key to the structure of the feature • • Topography is a major influence on the distribution of communities throughout the feature. Obvious changes in topography in terms of an overall lowering (shallowing) of the shore slope may act as a trigger for further investigation. Scouring adjacent to sea defences, which lowers the shore slope, should be considered unfavourable. A suitable period over which to ascertain trends resulting in a net lowering of shore profiles is 5 years	• Comparison of LIDAR data
• Pioneer Saltmarsh (*Salicornia* and other annuals colonising mud and sand)	• xtent	• Area measured once every reporting cycle	• No decrease in extent of pioneer saltmarsh communities from established baseline level	• The extent of the feature is a reporting requirement of the Habitats Directive. For dynamic coastlines fluctuations in extent may be great, but are attributable to natural coastal processes	• Combination of remote sensing and GPS (frequency to be determined)

Methods

Existing data is used to characterise the key baseline geomorphological parameters of the Dee Estuary SSSI, estuarine parts of the Morecambe Bay SSSI, Duddon Estuary SSSI, Lune Estuary SSSI, and Wyre Estuary SSSI. Regime Theory was applied to the Dee Estuary and the estuaries around Morecambe Bay 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 main stages of this study in support of an assessment of morphological equilibrium in the Dee Estuary and estuaries in and around Morecambe Bay are:

collate the essential bathymetry data up to the foot of flood defences or mean high water spring (MHWS) if no defences are present;

define the mean high water spring, mean high water neap (MHWN) and mean low water spring (MLWS) tidal datums;

validation of data to check for gaps and inconsistencies;

develop a series of cross sections from the tidal limit(s) to the estuary mouth and measure the current form and predict the equilibrium form of the estuary 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 (relationship between tidal prism and channel cross-sectional area), in accordance with Common Standards Monitoring (CSM) guidance (JNCC, 2004).

The critical data upon which the Healthy Estuaries 2020 tool relies are recent bathymetry and tidal datum elevations as inputs into the GIS. The Regime Theory relationship is between spring tidal prism (the volume of water that enters and leaves the estuary during a spring tide) and the cross-sectional area at MHWN tide at the mouth. Given this relationship, all the observed estuary morphological parameters were calculated using the bathymetric data set relative to the elevation of MHWN tide, whereas the observed tidal prism is calculated using a combination of the MHWS tide datum, MLWS tide datum, and the bathymetry. Details of the principles of Regime Theory and the specifics of how the methodology is used here are provided in Appendix A.

Bathymetry

Digital bathymetries for each estuary were compiled from various sources (e.g. Environment Agency, UK Hydrographic Office) collected using several different methods (mainly LiDAR and multibeam echosounder). The best available bathymetry data for each estuary was compiled, as far as possible. 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. It stretches from as close to the upstream tidal limit(s) as possible to the downstream boundary, which is defined by the transition to an unconfined open coast (effectively a straight line between the last two constrained points in the estuary). The bathymetries in all the systems are a single survey or 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.

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 2018 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. The critical tidal datums for the estuary equilibrium analysis are MHWS, MHWN and MLWS.

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 (2018 UK 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.

Where possible, 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 (e.g. 1996 for Morecambe Bay and 2009 for the Dee 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.

Development of Sections and Observed and Predicted Forms

The basis of Regime Theory is that a downstream increase in tidal prism 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 is a tool to assess equilibrium by determining how the tidal prism / channel cross-sectional area relationship changes with distance along the estuary. Given this relationship, the observed cross-sectional area (at MHWN) and tidal prism (at MHWS) were calculated using the bathymetric datasets relative to the tidal elevations at specific sections along each of the estuaries. The sections stretch between MHWS tide on either side of the estuary and were perpendicular (as far as possible) to a line along the centre of the low-water channel. They transect the SSSI boundary where it is within the area affected by water movements.

Preliminary Assessment of the Morphological Equilibrium Attribute

In order to provide a preliminary assessment of the condition of the morphological equilibrium attribute, the observed planforms of the estuaries were compared to the equilibrium planforms 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 four 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;

calculate mean depths and equilibrium widths at each section; and

compare the predicted widths with the observed widths.

The predicted forms and observed forms at each section were compared to gauge how far from equilibrium the estuary is. In this way, reaches of the observed estuary which are narrower or wider than their predicted form were mapped.

The results of the morphological equilibrium analysis in combination with the results of the constraints analysis were used to determine how far each estuary is from favourable condition with regard to its morphological equilibrium attribute. The observed forms of the estuaries compare with the predicted equilibrium forms in one of three ways:

observed form is under-sized compared to predicted form (i.e. the observed channel is narrower than predicted for the present-day tidal regime). The most likely cause for this type of disequilibrium is coastal squeeze caused by the inability of the intertidal system to migrate landwards due to flood defences;

observed and predicted forms are similar, suggesting that their observed forms are close to equilibrium; and

observed form is over-sized compared to its predicted form (i.e. the observed channel is wider than predicted for the present-day tidal regime). In these cases, the estuary exceeds its predicted equilibrium width and over the long term there may be development of intertidal habitat by natural processes.

Constraints to Estuary Equilibrium Form

The reaches of the estuary that have observed widths which are narrower than the predicted widths are considered to be pressure points in the estuary (and may be subject to coastal squeeze). This means that at these locations 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. However, it may not be possible for the estuary to widen because of constraints such as geology, essential infrastructure or other land uses. Therefore, the pressure points were mapped against physical constraints in the estuary.

The underlying geology of the estuary is important because it potentially constrains the channel from widening and/or deepening. If the geology is sufficiently hard so that the bed and banks are resistant to physical processes then it is likely that the estuary will not conform to the regime relationship. Also, the location of existing essential infrastructure or buildings such as flood and coastal defences, towns and harbours provide major constraints in estuaries.

Dee Estuary SSSI

The estuary of the Dee stretches from its normal tidal limit at Chester Weir to its mouth between Point of Ayr spit and Hilbre Point. The mouth is wide with two low water channels (Mostyn Channel to the west and Hilbre Channel to the east) divided by a central sand bank, entering Liverpool Bay between wide intertidal sandflats. The eastern side of the mouth is composed of a sandstone outcrop at Hilbre Point with detached outcrops (the Hilbre Islands) within the estuary. Upstream, a single low-water channel flows along the western side of the estuary with extensive intertidal flats and saltmarshes exposed at low tide on its eastern side. Most of the estuary is lined by flood defences behind the intertidal areas, apart from glacial till cliffs along the east shore near Thurstaston.

Upstream of Connah's Quay, the estuary is canalised within the New Cut, built in the 18th century to improve navigation up to Chester. This canalisation and its extension through training walls downstream of Connah's Quay have shifted the low water channel to the western shore, after previously being further east. The change in the position of the channel has led to rapid sedimentation along the eastern shore, creating the extensive intertidal flats and saltmarsh seen today (CH2MHill, 2013a). Later planting of *Spartina* has further encouraged the development of saltmarsh. As of December 2015, the area of saltmarsh in the Dee Estuary was 2,188ha (0.22km^2) (Natura 2000, 2015), comprising:

108ha of *Salicornia* and other annuals colonising mud and sand;

35ha of *Spartina* swards (*Spartinion maritimae*); and

2,045ha of Atlantic salt meadows (*Glauco-Puccinellietalia maritimae*).

The saltmarsh edge along the western side of the estuary is generally eroding where not protected. Approximately 5,000ha of the estuary has been land-claimed since 1732 including large areas either side of the New Cut. This represents a loss of habitat of almost 25% of the original area of the estuary.

There are several docks located along the western shore of the estuary including Mostyn Docks. The channel fronting Mostyn Docks requires regular maintenance dredging. Approximately 800,000m^3 of sediment was capital dredged from Mostyn Channel in 2001-2002, with the sediment disposed in Liverpool Bay. Maintenance dredging has subsequently been undertaken since that time. The regular dredging activities at Mostyn Docks and elsewhere have artificially increased the depth of the low water channels in these areas.

Extent of Study Area

The Dee Estuary SSSI on the English side has an area of 63.20km^2 (6,320ha) (*Figure 0.1*) and supports internationally important numbers of wintering waterfowl and passage terns, and a nationally important assemblage of breeding birds. It also supports extensive areas of saltmarsh vegetation and exhibits a complete succession from early pioneer vegetation colonising intertidal flats through lower, middle and upper saltmarsh to brackish and freshwater transitions at the top of the shore. The extensive intertidal mudflats and sandflats form the fifth largest area within an estuary in the UK. The sandstone cliffs of the Hilbre Islands contain cliff vegetation and maritime heathland and grassland with assemblages of nationally scarce plants.

Although the Dee Estuary SSSI is located along the English side of the estuary, the entire estuary is analysed using the Healthy Estuaries 2020 tool to characterise its equilibrium status.

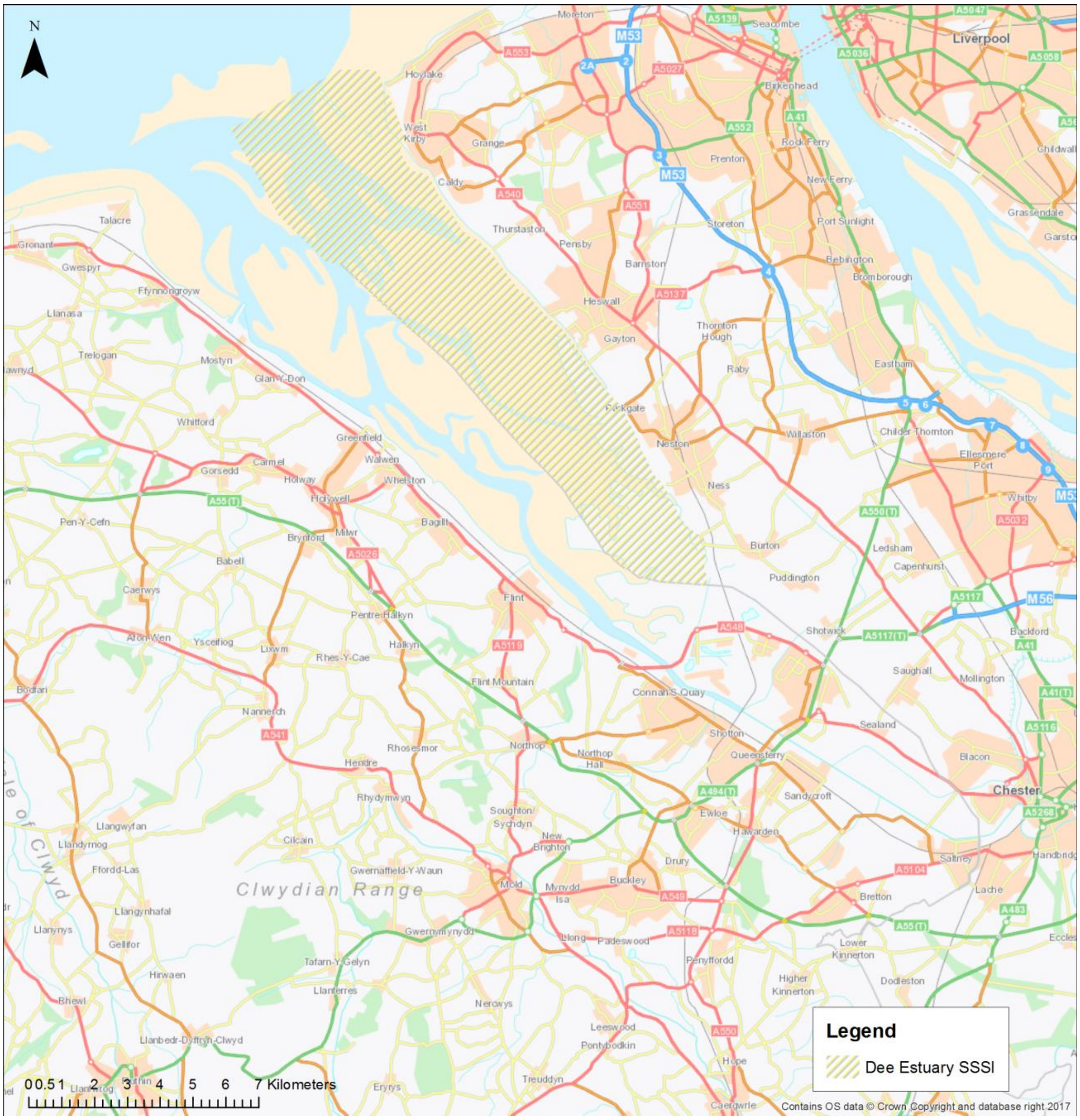

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Figure 0.1. Extent of the Dee Estuary SSSI (English side)

Bathymetry

The best available bathymetry for the Dee Estuary was obtained in two different formats and uploaded to the GIS. These were:

LiDAR at 2m resolution captured in various years (combined dataset which uses the best data from a range of years) for areas not covered by water at that time (*Figure 0.2*) downloaded from the Environment Agency’s Survey Open Data site (http://environment.data.gov.uk/ds/survey/index.jsp#/survey); and

Multibeam echosounder captured in 2012 and 2015 for areas covered by water at that time (*Figure 0.3*) downloaded from the UK Hydrographic Office Inspire Portal (http://aws2.caris.com/ukho/mapViewer/map.action). For these areas, the LiDAR data did not record the bed of the estuary because it was covered by water. The LiDAR therefore recorded the water surface.

Both datasets required processing and manipulation before being ‘stitched’ together to create the final bathymetry. The LiDAR data, in Ordnance Datum (OD), was processed from single ASCII files into a mosaicked dataset covering the shallower parts of the Dee Estuary (*Figure 0.2*). The multibeam echosounder data was processed and added into the GIS (*Figure 0.3*). If the landward part of the multibeam echosounder data overlapped the seaward part of the LiDAR data, then the echosounder data was used to avoid errors associated with the water surface. Where there was a gap between the LiDAR data and the echosounder data, a linear interpolation was completed to stitch the LiDAR data to the shallowest parts of the echosounder data.

The two datasets were merged together to create the overall bathymetry for the Dee Estuary used in this analysis (*Figure 0.4*). The bathymetry data covers all intertidal and subtidal areas up to the seaward face of the front-line defences, and stretches from the upstream tidal limit to the defined downstream boundary.

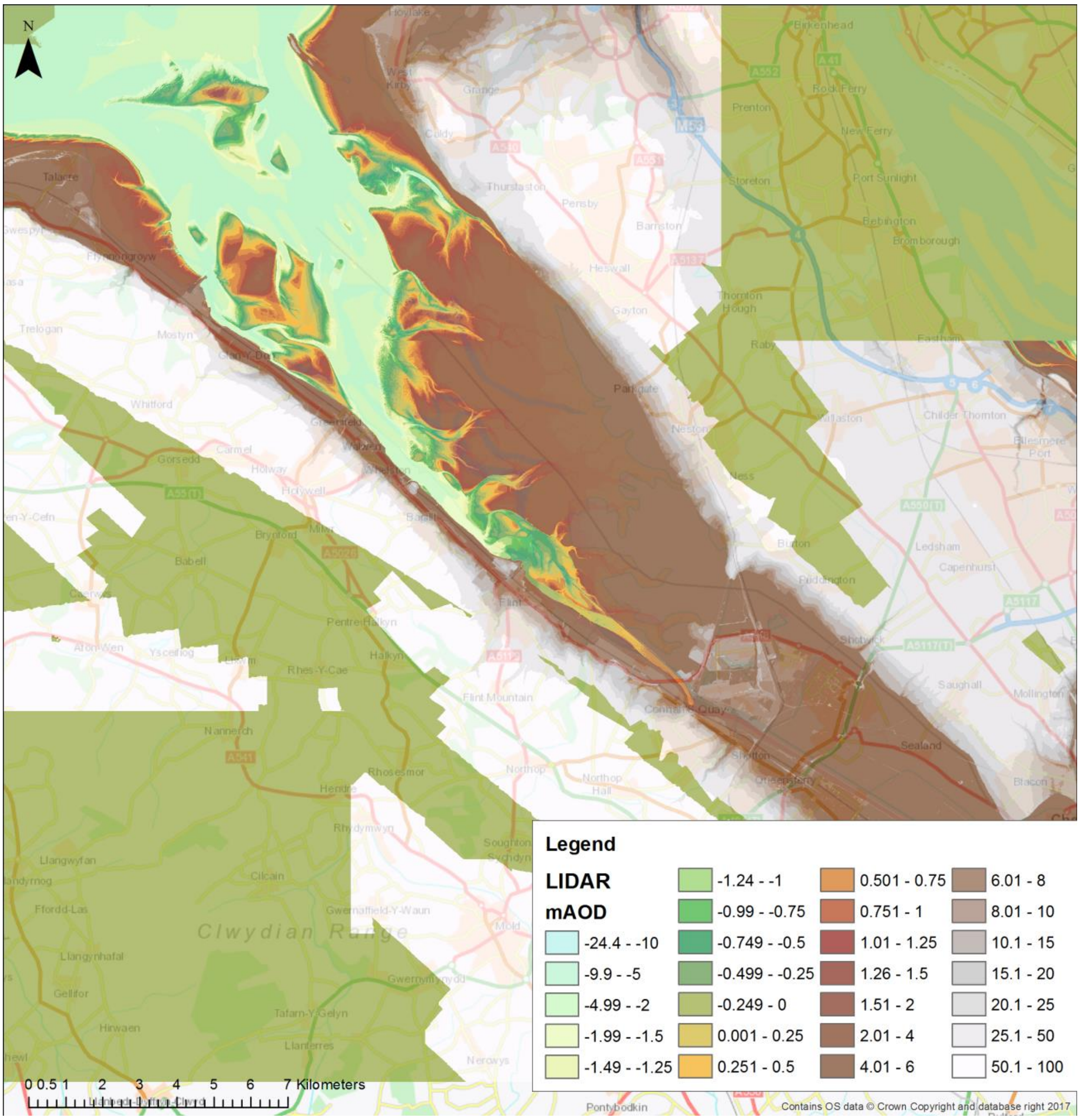

Figure 0.2. Environment Agency LiDAR data in the Dee Estuary

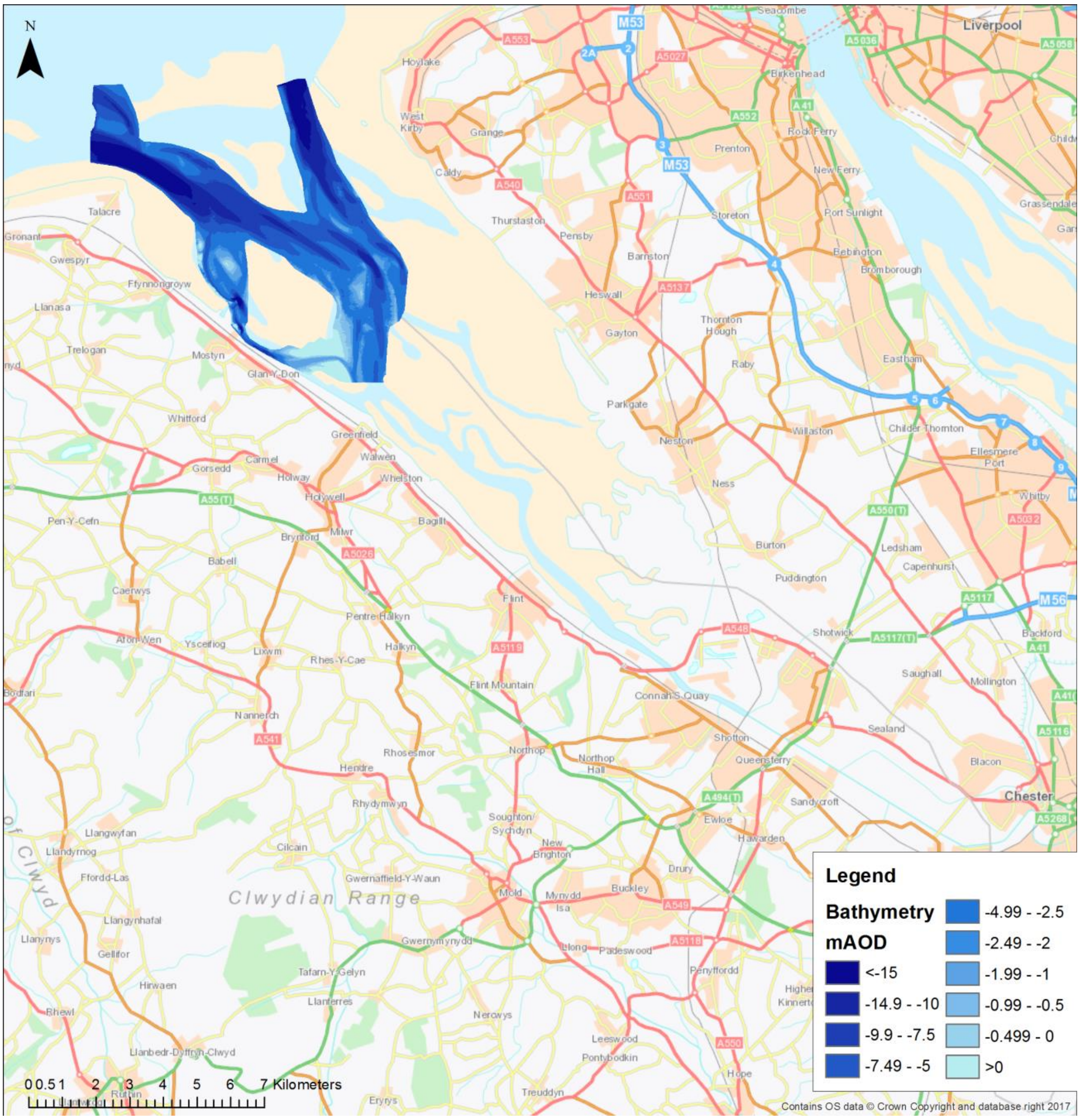

Figure 0.3. UK Hydrographic Office multibeam bathymetry data in the Dee Estuary

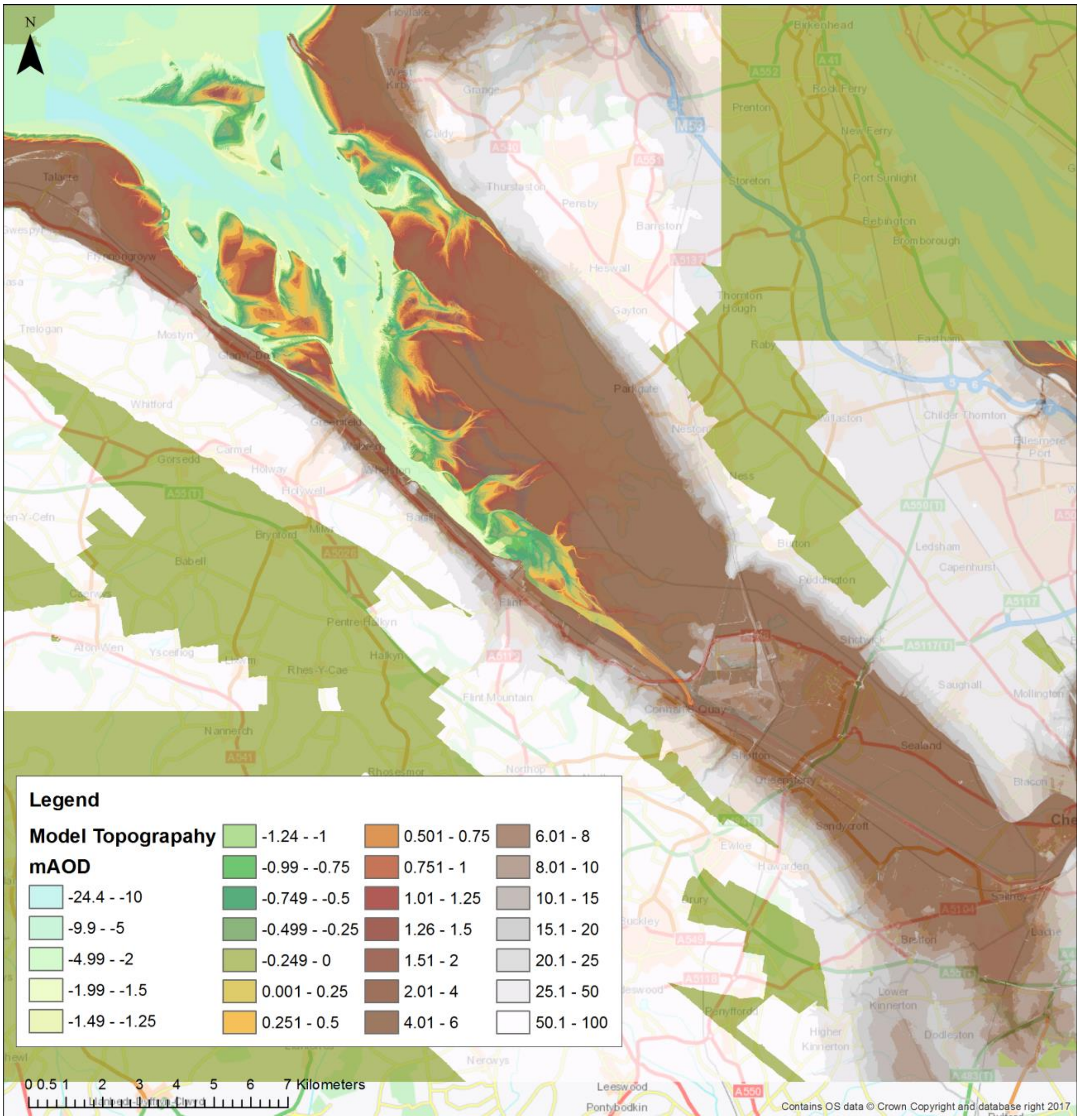

Figure 0.4. Combined LiDAR and multibeam echosounder data in the Dee Estuary

Tidal Regime

In order to calculate the spring tidal prism and cross-sectional area of the Dee Estuary it is necessary to know the elevations of tidal datums. *Table 0.2* presents the MHWS, MHWN and MLWS elevations at tidal stations along the Dee Estuary.

Table 0.2. Tidal datums in the Dee Estuary relative to Ordnance Datum (OD) (2018 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)**
	Long	Lat				
• ilbre Island	• 3.2333	• 3.3833	• 4 .07	• 2 .27	• - 1.83	• - 3.63
• hester	• 2.9000	• 3.2000	• 4 .60	• 2 .60	• D ries out	• D ries out
• onnah's Quay	• 3.0500	• 3.2167	• 3 .95	• 2 .25	• D ries out	• D ries out
• ostyn Docks	• 3.2667	• 3.3167	• 4 .00	• 2 .20	• N o data	• N o data

In order to delineate the plan positions of these datums, their elevations were overlain on to the Dee Estuary bathymetry. The elevations of the datums change with distance upstream (*Table 0.2*) and to create a surface that represents them along the estuary, the individual datum heights at each tidal station were linearly interpolated. *Figure 0.5* shows the tidal datum surfaces after they have been transposed on to the bathymetry of the Dee Estuary. Note that upstream of Connah’s Quay in the upper estuary, there is no data in the Admiralty Tide Tables for datums lower than MHWN.

Figure 0.5. Tidal datums in the Dee Estuary

Extent of the 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 (*Table 0.3* and *Figure 0.6*).

Table 0.3. Planform extent of the Dee Estuary and its intertidal and subtidal areas. Note these extents are for the entire estuary (Figure 0.6) from the tidal limit to the mouth

Parameter	Approximate Area (km^2)
• Estuary extent below MHWS	• 12.9
• Intertidal area between MHWS and MLWS	• 10.5
• Subtidal area below MLWS	• 2.4

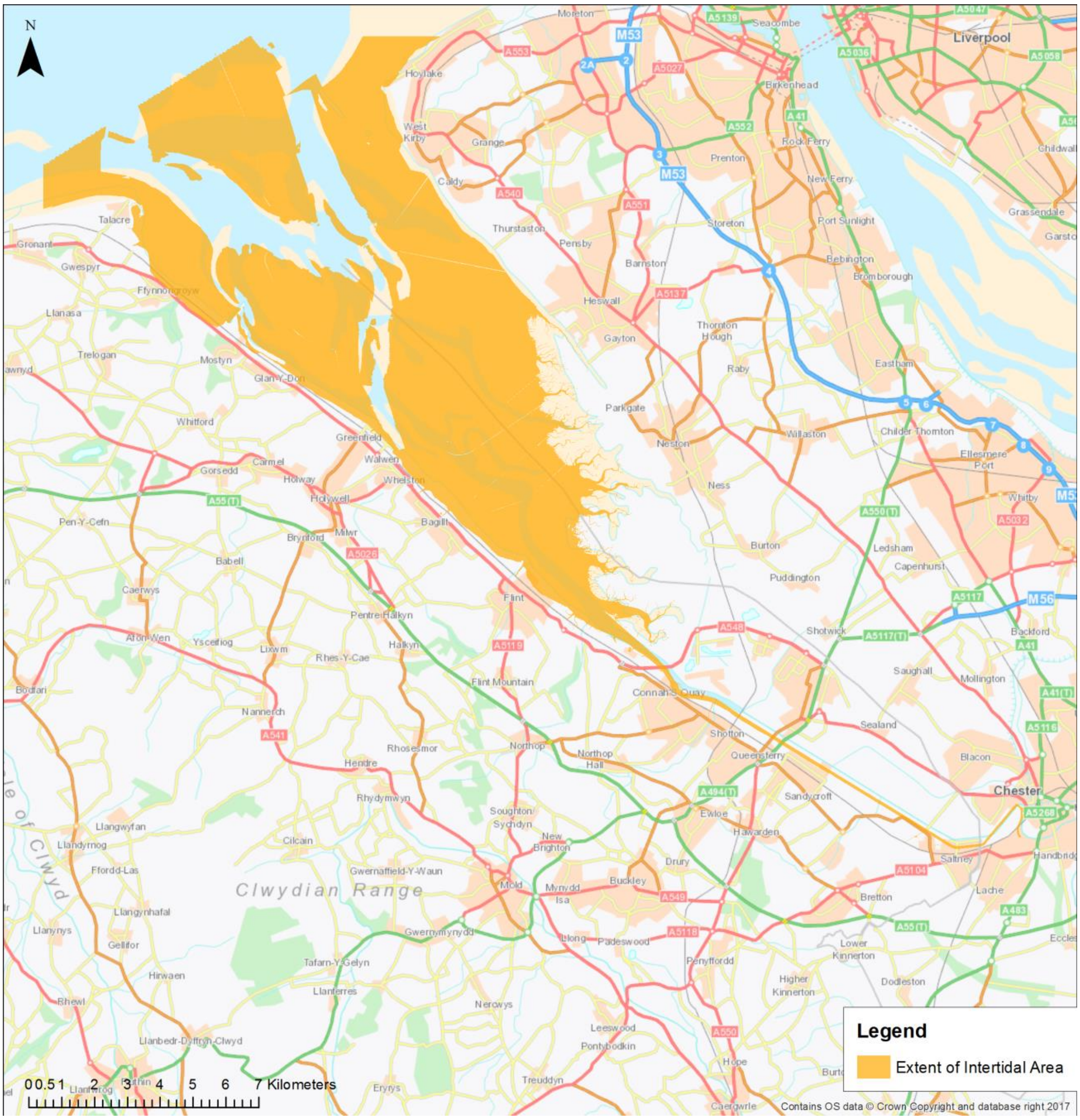

Figure 0.6. Intertidal area in the Dee Estuary (area between the MHWS and MLWS datums)

Morphological Equilibrium

Observed Estuary Form

Using the bathymetry and tidal datums in a GIS, each of the following parameters was measured at sections spaced about 200m 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 0.7* and the observed data at each section is presented in Appendix B.

An issue that had to be resolved in the Dee Estuary was the downstream division of the channel into Mostyn Channel and Hilbre Channel and their separation by sand banks at or below the elevation of MHWS. This presents difficulties in compartmentalisation of the estuary in order for the spring tidal prism to be split logically to drive the equilibrium profiles of the two neap channels. The difficulty was that between the channels, the sand banks are flooded on spring tides, and so the tidal prism that floods and drains these areas has to be attributed to both of the tidal channels to either side of it. The key was to place the 'tidal watershed' at a location across the sand banks so that the tidal prism is shared appropriately between each channel. The location of the tidal watershed is shown in *Figure 0.7*.

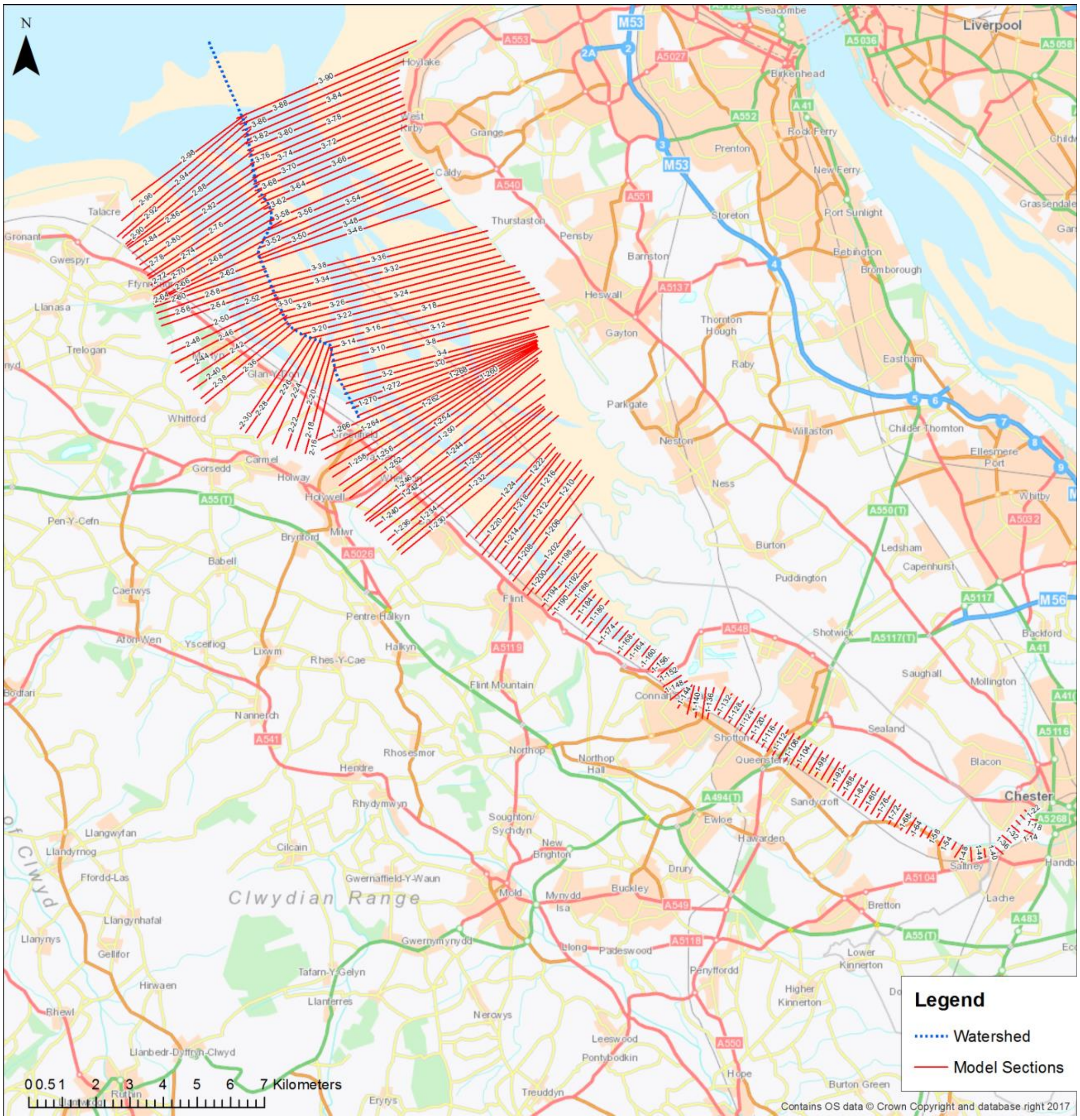

Figure 0.7. Position of the sections in the Dee Estuary where the observed form was measured. The dotted line is the location of the 'tidal watershed' driving the tidal prism along the adjacent Mostyn and Hilbre Channels

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). 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. The regime equation that encapsulates all United Kingdom estuaries was used (Townend *et al*., 2000).

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

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), and this was adopted here. Using these two steps, the equilibrium form of the Dee Estuary was predicted at each section; the predicted data is presented in Appendix C.

Comparison of Predicted Equilibrium Widths with Observed Widths

The results were interrogated using the GIS to compare the predicted equilibrium widths (Appendix C) with the observed widths (Appendix B) at each section. The comparison for the Dee Estuary is shown in Figure 0.8 and Figure 0.9. *Figure 0.9* also highlights the locations of potential constraints on estuary evolution. The observed widths compare with the predicted equilibrium widths in the Dee Estuary in one of two ways:

The downstream part of the estuary where the main channel splits around several sand banks into Mostyn Channel (west) and Hilbre Channel (east) has observed and predicted widths which are largely similar, suggesting that here the observed form is close to equilibrium.

The upstream reaches of the estuary where there is a single low-water channel is under-sized compared to its predicted form (i.e. the observed channel is narrower than predicted for the present-day tidal regime). A larger scale map showing the under-sized portion of the Dee Estuary is presented in Appendix D.

Figure 0.8. Comparison of predicted equilibrium widths with observed widths in the Dee Estuary (map background)

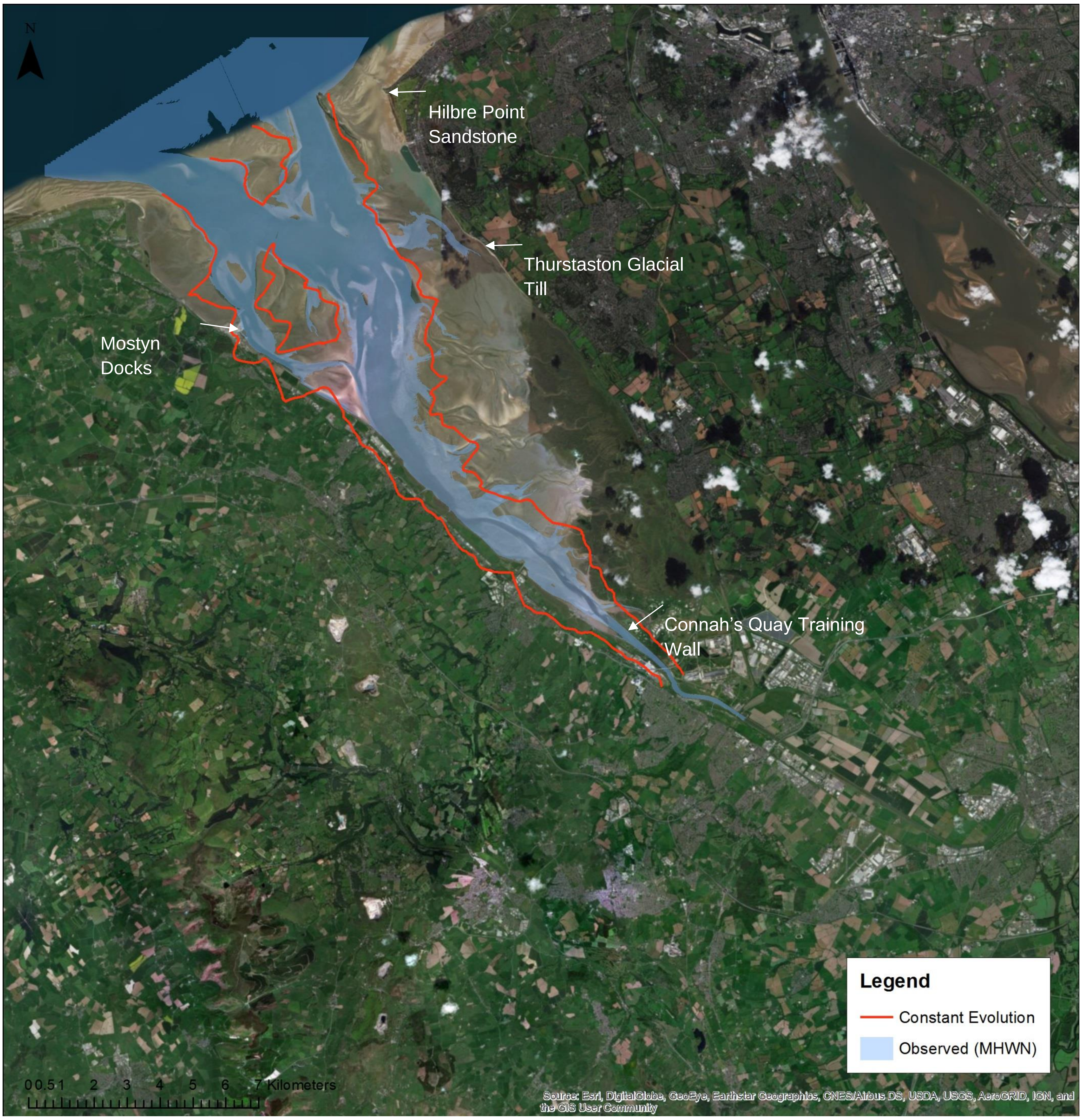

Figure 0.9. Comparison of predicted equilibrium widths with observed widths in the Dee Estuary (aerial photograph background)

Physical Constraints to Morphological Equilibrium

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

Under-sized Reaches

Upstream from the division of the channel into Mostyn and Hilbre Channels, the estuary is predicted as under-sized and processes will be attempting to widen the channel to establish an equilibrium form. However, it is not possible for the estuary to widen here on its western shore because of coastal defence and land use (mainly dock areas) constraints. There is also a partial constraint on the eastern side of the channel created by the training wall downstream of Connah's Quay. Downstream of the training wall, the eastern side of the estuary is less constrained, where it contains a wide expanse of intertidal flats and saltmarsh.

It would appear that the estuary is continuing to respond to the effects of the upstream canalisation, training walls and extensive land-claim that have taken place in the past. Indeed, the saltmarsh areas on its western side are eroding. CH2MHill (2013a) argued that the Dee Estuary training wall plays a major role in determining the stability of the estuary. If it was removed or fell into disrepair the main channel would revert to a much more dynamic pattern of behaviour, with the potential for erosion on the east side of the estuary and navigation problems on the west side.

Reaches in Near-equilibrium

Downstream of the point where the main channel splits into Mostyn Channel (west) and Hilbre Channel (east) appears to be largely in a state of near-equilibrium. Although the whole estuary is bounded by coastal defences on the western side and by both high ground (till cliffs and rock outcrops) and coastal defences to the east, it appears to have enough space to adapt and equilibrate to the driving processes. It may also be responding to the flood dominance of the Dee Estuary (CH2MHill, 2013a), which implies stronger flood-tide currents and net mud and sand movement into the estuary. The transport of sand has led to the formation of the sand banks and relatively wide sandflats at the mouth of the estuary, through which the low-water channels flow. It is possible that the deposition of this sand may be offsetting the potential widening of the channel that is being forced by the tidal prism.

The results along Mostyn Channel, describe variability in the width of the predicted channel form (*Figure 0.8* and *Figure 0.9*). This variability is caused by the locations of the dredged and non-dredged parts of the channel, where the narrow predictions are associated with the dredged portions and the wider predictions with the non-dredged portions. This is because the constant evolution method relies on the relationship between the observed cross-sectional area and the predicted cross-sectional area, and if the observed cross-sectional area is large due mainly to depth rather than width, then the tool will predict a narrower width (and *vice versa*).

Overall Condition of the Morphological Equilibrium Attribute

The results of Regime Theory in the Dee Estuary show that only the downstream third to the mouth is close to morphological equilibrium. The upstream two thirds to Chester Weir have developed into a more confined shape than would be expected if it was in morphological equilibrium. Hence, the estuary has developed into a slightly more exaggerated 'trumpet' shape than would be expected if it was in morphological equilibrium. The upper reaches are narrower than their predicted equilibrium form and the lower reaches are closer to their predicted equilibrium form.

In order to allow a wider channel to develop in keeping with the equilibrium form may necessitate realignment of the coastal defences to restore former land-claimed intertidal areas to tidal processes. Currently, the Shoreline Management Plan (Halcrow, 2010) advocates maintenance of protection to assets where necessary but to provide more accommodation space where practical to do so (*Figure 0.10*). Along the eastern shore, the policy is for undefended cliffs to be allowed to erode naturally with roll back of saltmarsh to be allowed where possible (No Active Intervention – orange lines on *Figure 0.10*). In the trained sections of the estuary and along the New Cut, the policy is to continue to manage flood risks by holding the coastal defences in place.

Limited opportunities for managed realignment are recognised in the plan (blue lines), but even limited implementation of the policy would mean that the estuary could resume a more natural form in some locations. *Table 0.4* describes the locations of the proposed managed realignment policy. According to Halcrow (2010), the Hold The Line policy in the first epoch allows for the investigation of opportunities to set back defences to create space for estuary roll back and potential future habitat creation or the creation of Biodiversity Action Plan habitat, which may be needed to compensate for future coastal squeeze. Future actions to implement this policy could act as a driver to move the SSSI towards morphological equilibrium.

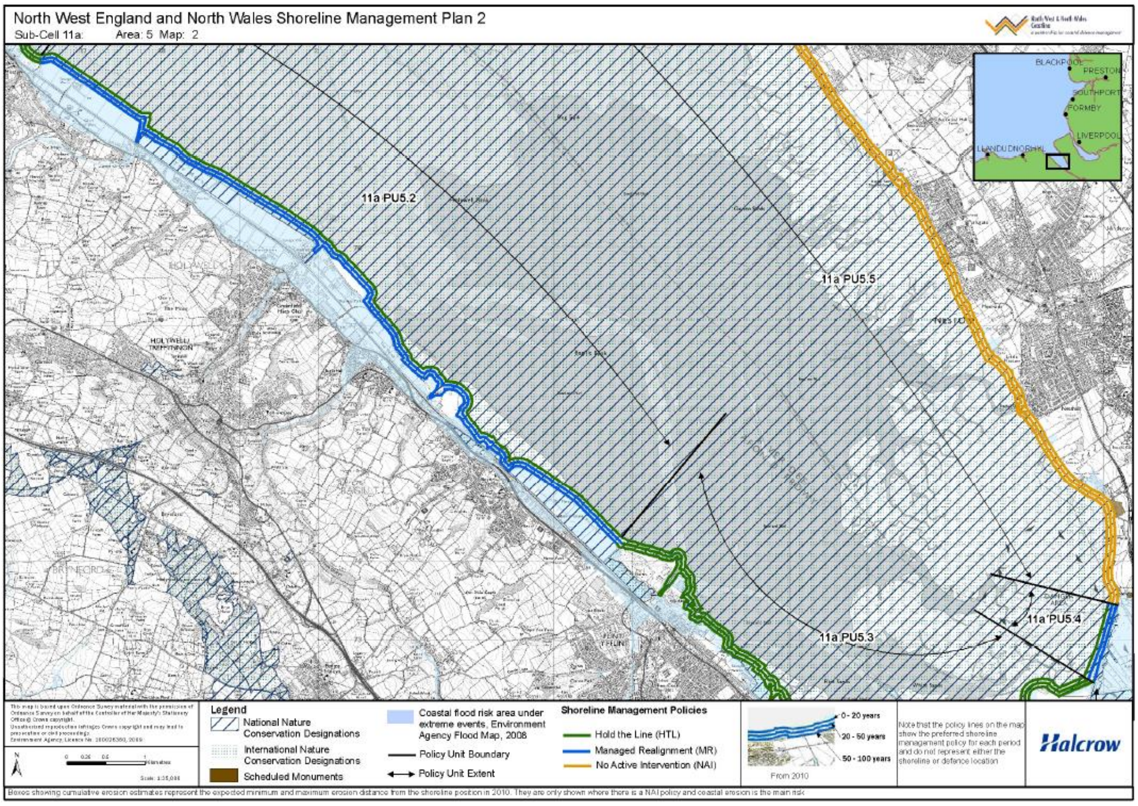

Figure 0.10. Location of potential managed realignment sites (blue lines) in the Dee Estuary (Halcrow, 2010)

Table 0.4. Potential managed realignment sites in the Dee Estuary (Halcrow, 2010). HTL = Hold The Line, MR = Managed Realignment

Coastal Stretch	Policy Unit	Epoch 1	Epoch 2	Epoch 3
• Mostyn to Flint Marsh	• .2	• TL	• R	• R
• Sealand Rifle Range to Burton Point	• .4	• TL	• R	• R

Morecambe Bay

The Morecambe Bay, Duddon Estuary, Lune Estuary and Wyre Estuary SSSIs have a combined area of 455.68km^2 (45,568ha) (*Figure 0.11*). Morecambe Bay and its surrounding estuaries contain the largest continuous area of intertidal mudflats and sandflats in the UK which attract internationally important numbers of migratory birds, arriving to overwinter in the bay. The area is designated for a variety of habitat features including intertidal mudflat and sandflat, reef and saltmarsh.

Application of the Tool to Estuaries around Morecambe Bay

Five main estuaries enter the Irish Sea either within Morecambe Bay itself (Leven, Kent, Lune and Wyre Estuaries) or immediately outside its confines (Duddon Estuary to the north). Each of these estuaries has different characteristics and data quality that determine whether application of Regime Theory using the Healthy Estuaries 2020 tool is possible, or not.

Leven Estuary and Kent Estuary

The Leven Estuary and Kent Estuary enter north Morecambe Bay. They have relatively wide mouths with low-water channels that meander between active intertidal sandflats. Bathymetric data is available for a small proportion of the estuaries at their mouths, so the depth and extent of the channel can be determined along with LiDAR data for the adjacent intertidal areas. Further upstream, data is restricted to LiDAR only and the low water channels are not resolved. Across the channels, the location of tidal datums and the tidal prism associated with them would not be accounted for in the tool. However, the channels upstream of the mouths are narrow and shallow, and hence their omission from the tool in terms of tidal prism is unlikely to affect the outcome greatly.

The main problem associated with both these estuaries is the presence of large areas of intertidal sandflat at their mouths and indeed further upstream, which are connected to the wider and larger areas of sandflat around Morecambe Bay. These sandflats are more likely to be driven predominantly by marine sedimentary processes rather than by estuarine processes; the mouths of the Leven and Kent Estuaries are sub-embayment’s of the larger Morecambe Bay. Hence, the application of Regime Theory is fraught with problems and the outputs of the Healthy Estuary tool would not be reliable, because the sandflat accretion and channel migration driven by marine processes obscures the estuarine processes driven by changes in tidal prism. Analyses of the Leven Estuary and Kent Estuary are therefore excluded for these reasons.

Lune Estuary

Reliable bathymetry data was not available for the Lune Estuary and hence this is also not analysed.

Duddon Estuary and Wyre Estuary

The Duddon Estuary and Wyre Estuary are different from the Leven Estuary and Kent Estuary, as their mouths are constrained, and there is likely to be smaller interaction with marine processes. The Duddon and Wyre Estuaries can therefore be characterised using the Healthy Estuary tool, because Regime Theory applies (there is a relationship between tidal prism and cross-sectional area).

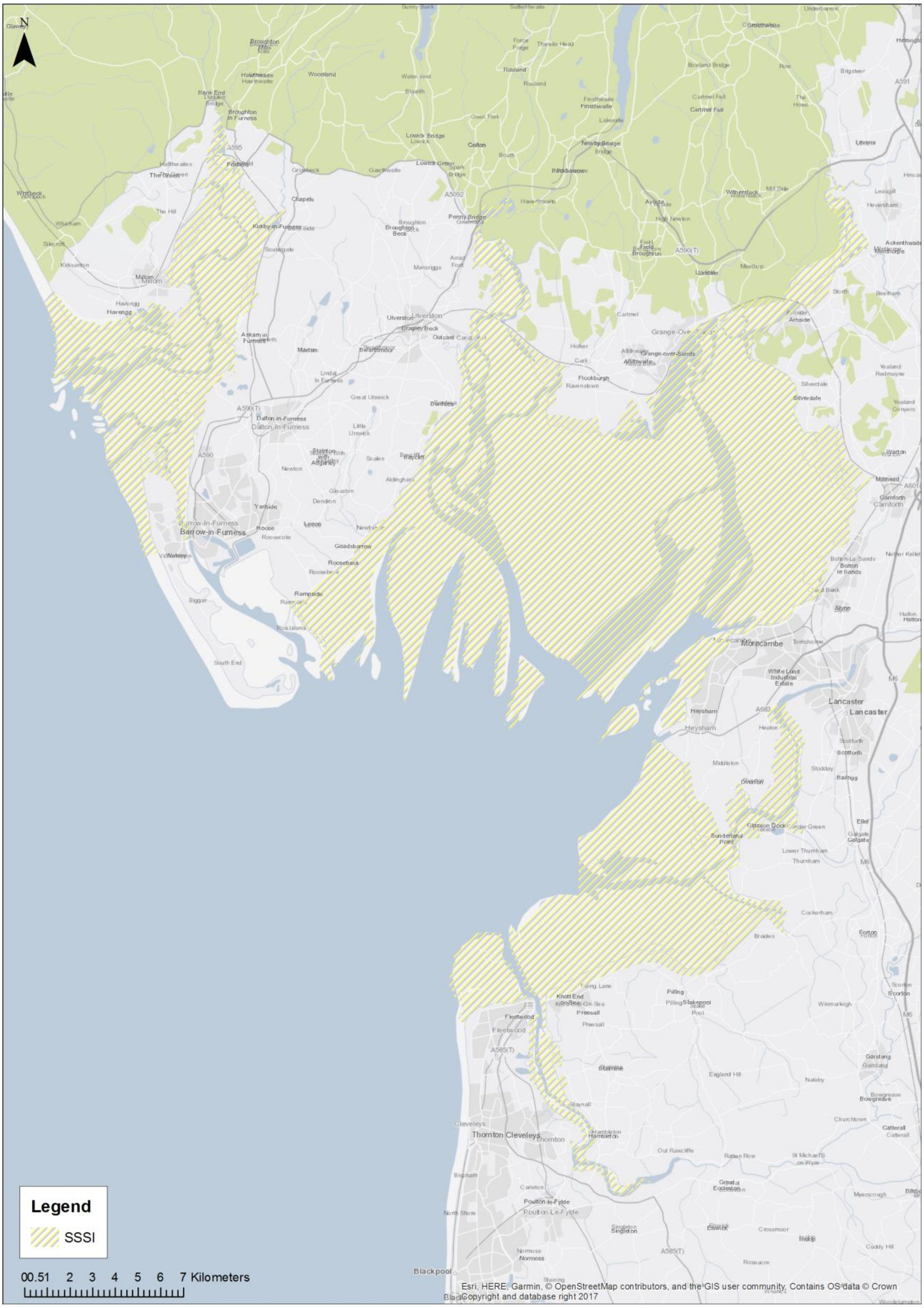

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Figure 0.11. Extent of the Morecambe Bay, Duddon Estuary, Lune Estuary and Wyre Estuary SSSIs

Duddon Estuary SSSI

The Duddon Estuary stretches from a line between the northern end of Walney Island and Haverigg Point to the normal tidal limit at Duddon Bridge. It is dominated by intertidal sandflats through which a low-water channel meanders. The channel is largely unconfined, free to migrate, and changes rapidly in position and size. The upstream parts of the estuary are flanked by areas of saltmarsh. CH2MHill (2013b) indicated a general trend for saltmarsh erosion in the early 20th century, followed by saltmarsh advance in the mid 20th century with a return to slow saltmarsh erosion in the late 20th century. The current trend is for erosion of the saltmarsh edge. The present-day area of saltmarsh in the Duddon Estuary is difficult to ascertain as it is generally combined with and not differentiated from the area of saltmarsh within Morecambe Bay.

Land-claim and enclosure of saltmarsh for agriculture from the 16th century onwards and the construction of coastal defences have influenced the morphological evolution of the estuary. Land-claim has removed approximately 1,500ha of the intertidal area, although there has been little land-claim within the estuary since 1900. Other constraints include a low glacial till cliff at Askam-in-Furness which fronts a shore platform, and the dune systems of Haverigg Haws (northern shore) and Sandscale Haws (southern shore) which occur at the mouth of the estuary.

Bathymetry

The bathymetric surface in the Duddon Estuary was created using only LiDAR data from the Environment Agency (http://environment.data.gov.uk/ds/survey/index.jsp#/survey) (*Figure 0.12*). Hence, the deeper thalweg at the mouth of the estuary has not been recorded because even at low tide, the LiDAR would have only recorded the water surface. Hence, the tidal prism calculated in the tool may be underestimated towards the mouth of the estuary. Although an ‘artificial’ channel could have been created here, based on expert judgement of channel depth, this approach was not adopted, given the shallow nature of the whole system dominated by migrating sandflats. The inclusion of an artificial channel would be unlikely to increase the tidal prism significantly, and so the results using LiDAR only are considered robust.

Tidal Regime

Table 0.5 presents the MHWS, MHWN and MLWS elevations at the Duddon Bar tidal station in Morecambe Bay and *Figure 0.13* shows the tidal datum surfaces transposed on to the bathymetry of the Duddon Estuary. Note that there is no slicing at MLWS because its elevation could not be extracted from the LiDAR data.

Table 0.5. Tidal datums in the Duddon Estuary relative to Ordnance Datum (OD) (2018 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)**
	Long	Lat				
• Duddon Bar	-3.3333	54.1500	4.15	2.25	-1.75	-3.45

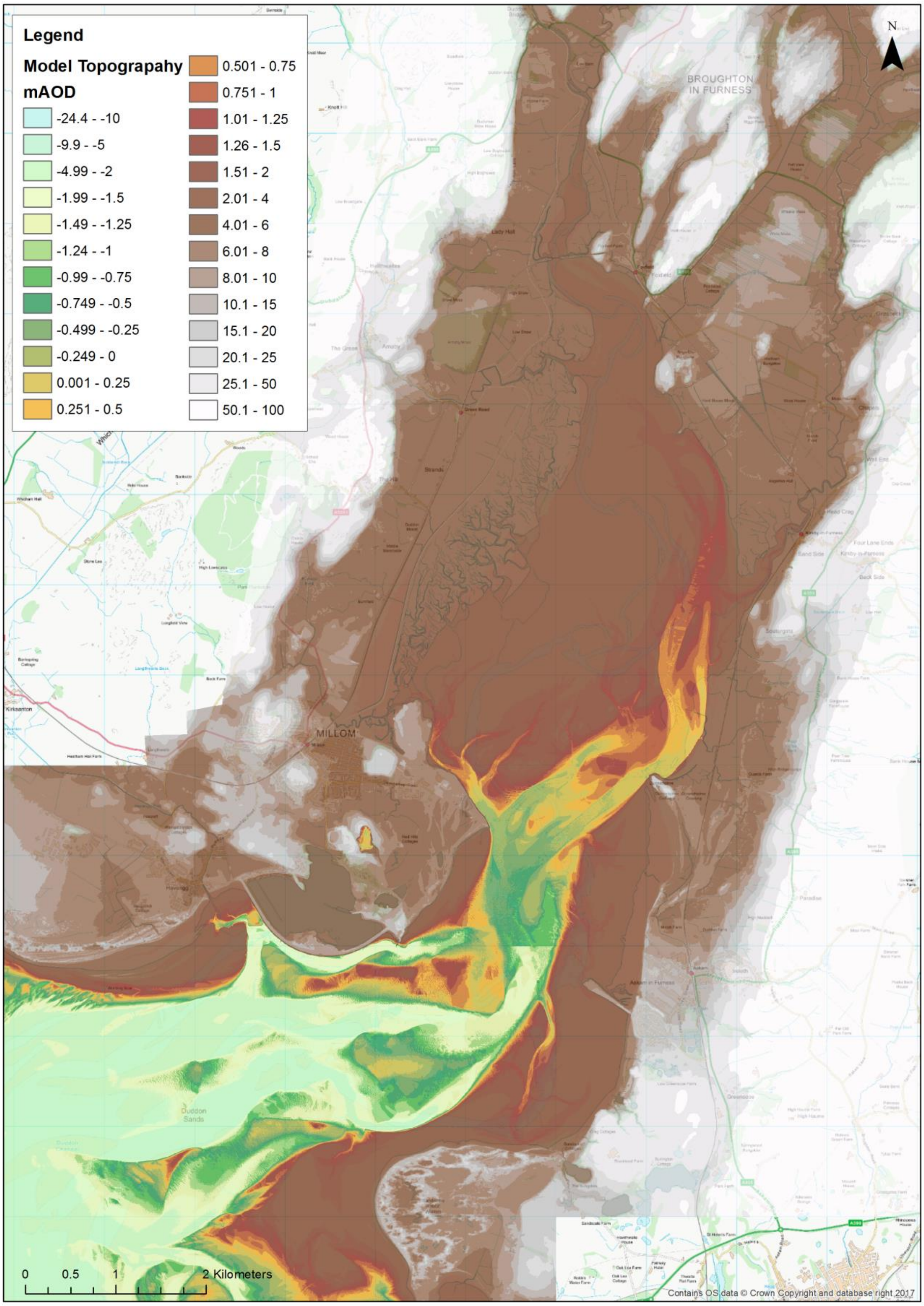

Figure 0.12. Environment Agency LiDAR data in the Duddon Estuary

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Figure 0.13. Tidal datums in the Duddon Estuary. Note that there is no slicing at MLWS because its elevation could not be extracted from the LiDAR data

Extent of the Estuary and Area of Intertidal Habitat

The extent of the estuary (total area of estuary feature) was mapped using MHWS and is estimated to be approximately 3.2km^2. The intertidal area could not be calculated because a reliable MLWS datum could not be extracted from the LiDAR data (Section 5.1).

Morphological Equilibrium

Observed Estuary Form

Using the bathymetry and tidal datums in the GIS, the observed estuary parameters at sections spaced 200m apart were measured along the estuary in a similar way to the Dee Estuary analysis. The locations of the sections in the Duddon Estuary where the observed form is measured are shown in *Figure 0.14* and the observed data at each section is presented in Appendix E.

Predicted Estuary Form

The same method used to predict estuary form in the Dee Estuary (Section 3.5.2) was used in the Duddon Estuary and is not repeated here. Using this method, the equilibrium form of the Duddon Estuary at each section was predicted; the data is presented in Appendix F.

Comparison of Predicted Equilibrium Widths with Observed Widths

The results were interrogated using the GIS to compare the predicted equilibrium widths (Appendix F) with the observed widths (Appendix E) at each section. The comparison for the Duddon Estuary is shown in *Figure 0.15* and *Figure 0.16*. *Figure 0.16* also highlights the locations of potential constraints on estuary evolution. The observed widths compare with the predicted equilibrium widths in the Duddon Estuary in one of two ways:

The estuary downstream of Millom has observed and predicted widths which are similar, suggesting that along the downstream half of the estuary the observed form is close to equilibrium.

The estuary upstream of Millom to the normal tidal limit is under-sized compared to its predicted form (i.e. the observed channel is narrower than predicted for the present-day tidal regime). A larger scale map showing the under-sized portion of the Duddon Estuary is presented in Appendix G.

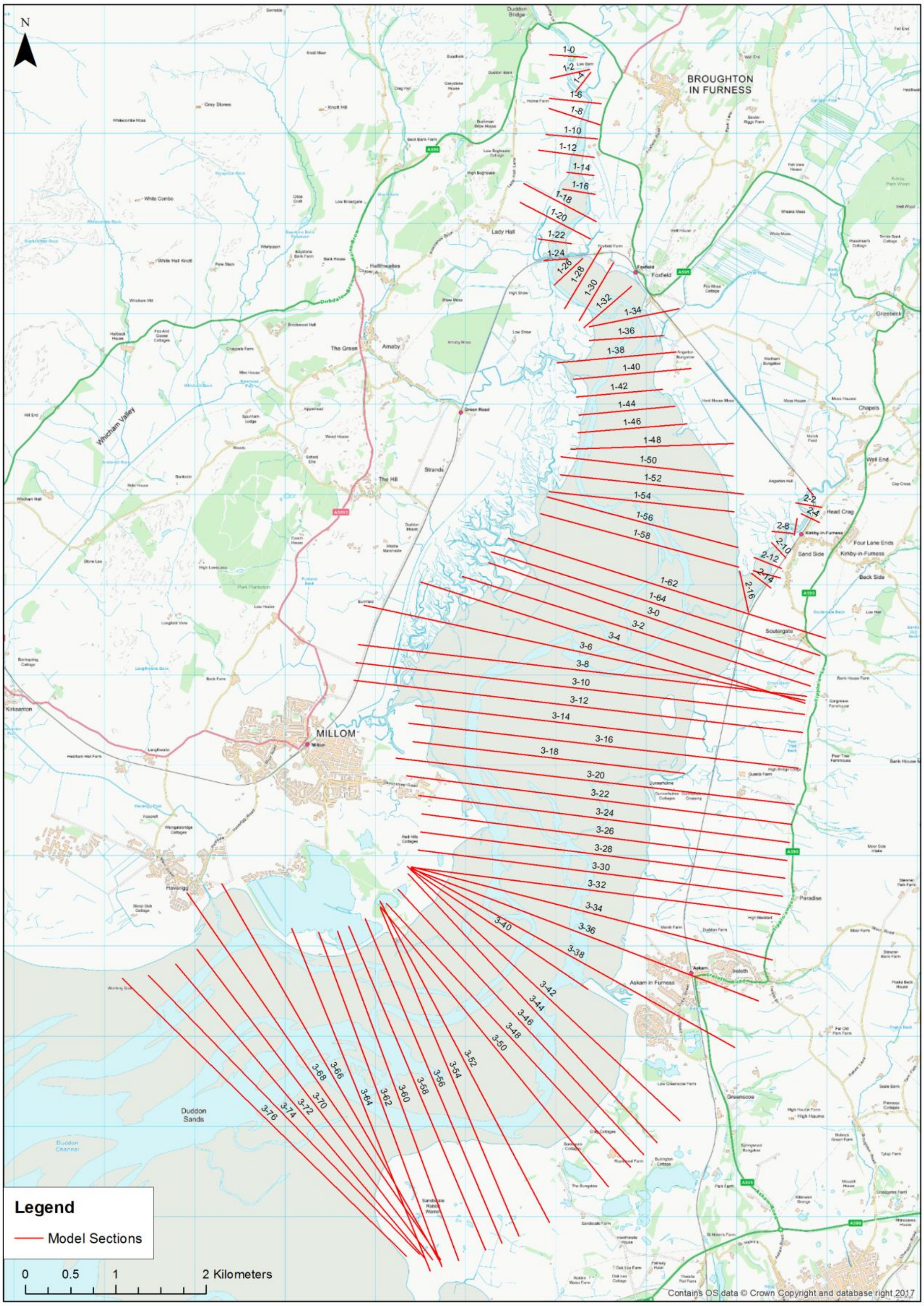

Figure 0.14. Position of the sections in the Duddon Estuary where the observed form was measured

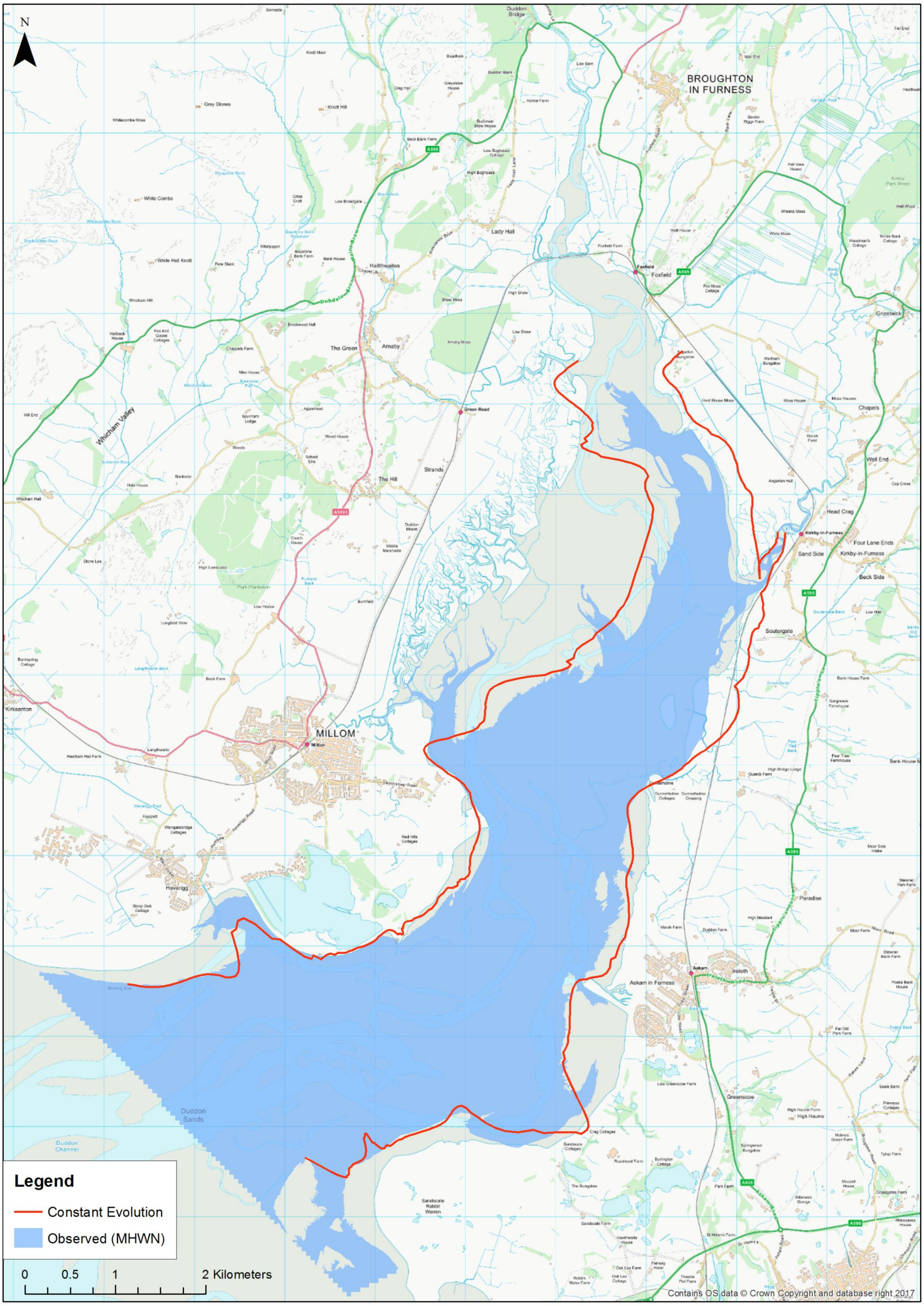

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Figure 0.15. Comparison of predicted equilibrium widths with observed widths in the Duddon Estuary (map background)

Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Figure 0.16. Comparison of predicted equilibrium widths with observed widths in the Duddon Estuary (aerial photograph background)

Physical Constraints to Morphological Equilibrium

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

Under-sized Reaches

Upstream from Millom, the estuary is predicted as under-sized and processes will be attempting to widen the channel to establish an equilibrium form. However, it is not possible for the estuary to widen here because of flood defence constraints. The fringing saltmarshes upstream of Millom are eroding due to coastal squeeze against the defences confirming the view that the estuary is trying to widen here. Indeed, the Shoreline Management Plan policy along the western side of the upper Duddon Estuary is managed realignment to allow a return to a more natural shoreline (Halcrow, 2010) (*Figure 0.17*).

Reaches in Near-equilibrium

Downstream of Millom, the estuary appears to be largely in a state of near-equilibrium. Although the estuary is bounded by coastal defences and dunes on the western side and by both high ground (till cliffs and dunes) and coastal defences to the east, it appears to have been able to equilibrate to the natural processes since land-claim ceased in the early 20th century.

Overall Condition of the Morphological Equilibrium Attribute

Currently, the Shoreline Management Plan (Halcrow, 2010) describes opportunities to allow parts of the western side of the estuary upstream of Millom to return to a more natural shoreline, allowing future expansion of the intertidal flats and saltmarshes (*Figure 0.17* and *Table 0.6*). The long-term plan is to seek to realign or withdraw from defending frontages where opportunities exist. The potential managed realignment locations upstream of Millom are supported by this analysis of morphological equilibrium, as they are located along the under-sized part of the estuary with the greatest difference between the observed and predicted widths.

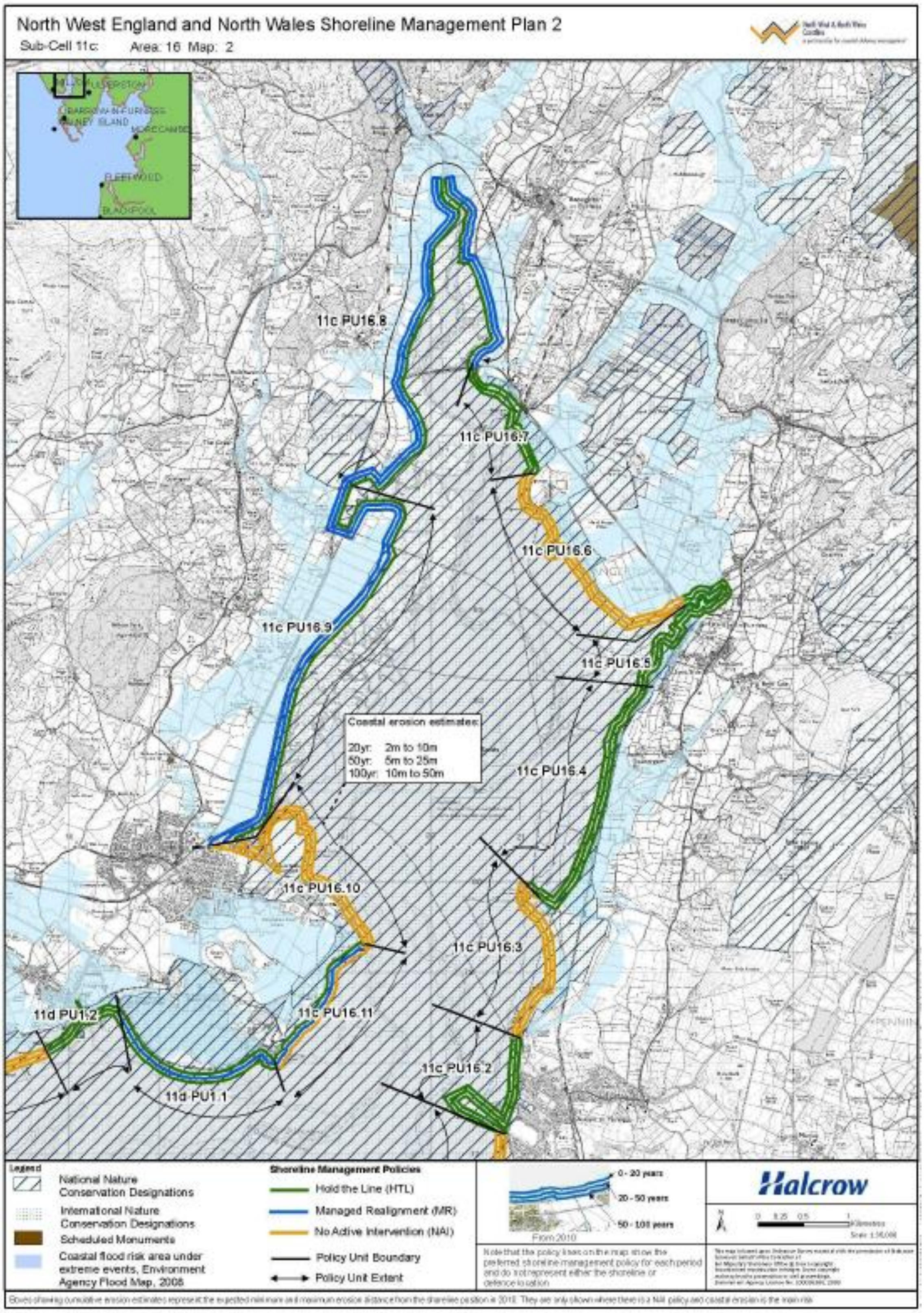

Figure 0.17. Location of potential managed realignment sites (blue lines) in the Duddon Estuary (Halcrow, 2010)

Table 0.6. Potential managed realignment sites in the Duddon Estuary (Halcrow, 2010). NAI = No Active Intervention, HTL = Hold The Line, MR = Managed Realignment

Coastal Stretch	**Policy Unit**	**Epoch 1**	**Epoch 2**	**Epoch 3**
• Duddon estuary (both banks upstream of Viaduct and right bank south to Green Road Station)	• 6.8	• TL	• R	• R
• Millom Marshes	• 6.9	• TL	• R	• R
• Hodbarrow Mains	• 6.11	• AI	• R	• TL

Wyre Estuary SSSI

The Wyre Estuary extends from its mouth between Fleetwood and Knott End-on-Sea to its normal tidal limit at St. Michael's on Wyre. The estuary is sinuous and is considered to be 'bottle' shaped in plan, with the mouth representing the neck, upstream of which it first widens and then narrows again. The northerly orientation and narrow mouth means that wave energy inside the estuary is low and sediment transport is driven by tidal currents in the low water channel. Developments have included land-claim and the construction of flood defences along both sides of the estuary. Since the 19th century the intertidal area has decreased by approximately 50% from 1,000ha in 1840s to 500ha in 2000 (CH2MHill, 2013c). The flood defences are interspersed with natural high ground.

Bathymetry

The bathymetric surface in the Wyre Estuary was created using only LiDAR data from the Environment Agency (http://environment.data.gov.uk/ds/survey/index.jsp#/survey) (*Figure 0.18*). It is possible that the deeper thalweg at the mouth of the estuary has not been recorded because even at low tide, the LiDAR would have only recorded the water surface. Hence, the tidal prism may be underestimated because there is no MLWS input into the Healthy Estuaries 2020 tool.

Tidal Regime

Table 0.7 presents the MHWS, MHWN and MLWS tidal datum elevations at Fleetwood and *Figure 0.19* shows the tidal datum surfaces transposed on to the bathymetry of the Wyre Estuary. Note that there is no slicing at MLWS because its elevation could not be extracted from the LiDAR data.

Table 0.7. Tidal datums in the Wyre Estuary relative to Ordnance Datum (OD) (2018 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)**
	Long	Lat				
• Fleetwood	-3.0000	53.9333	4.50	2.40	-1.80	-3.70

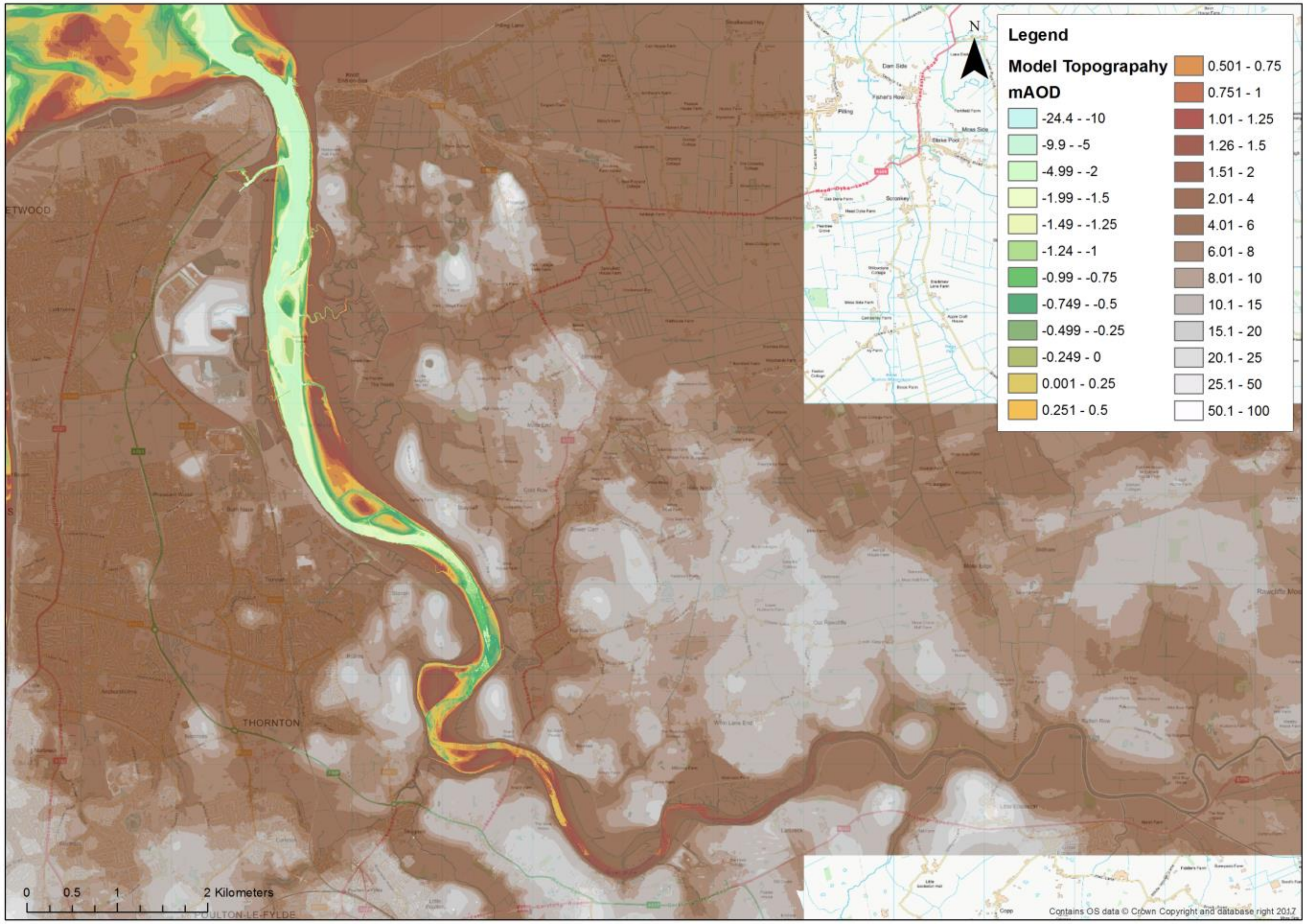

Figure 0.18. Environment Agency LiDAR data in the Wyre Estuary

Figure 0.19. Tidal datums in the Wyre Estuary. Note that there is no slicing at MLWS because its elevation could not be extracted from the LiDAR data

Extent of the Estuary and Area of Intertidal Habitat

The extent of the estuary (total area of estuary feature) was mapped using MHWS and is estimated to be approximately 1.0km^2. The intertidal area could not be calculated because a reliable MLWS datum could not be extracted from the LiDAR data (Section 6.1).

Morphological Equilibrium

Observed Estuary Form

Using the bathymetry and tidal datums in the GIS, the observed estuary parameters at sections spaced 200m apart were measured along the estuary in a similar way to the Dee Estuary and Duddon Estuary analyses. The locations of the sections in the Wyre Estuary where the observed form is measured are shown in *Figure 0.20* and the observed data at each section is presented in Appendix H.

Predicted Estuary Form

The same method used to predict estuary form in the Dee Estuary and Duddon Estuary is used in the Wyre Estuary and is not repeated here. Using this method, the equilibrium form of the Wyre Estuary at each section was predicted; the data is presented in Appendix I.

Comparison of Predicted Equilibrium Widths with Observed Widths

The results were interrogated using the GIS to compare the predicted equilibrium widths (Appendix I) with the observed widths (Appendix H) at each section. The comparison for the Wyre Estuary is shown in *Figure 0.21* and *Figure 0.22*. *Figure 0.22* also highlights the locations of potential constraints on estuary evolution. The whole estuary is under-sized compared to its predicted form (i.e. the observed channel is narrower than predicted for the present-day tidal regime). The magnitude of the disequilibrium decreases in a downstream direction. Where the estuary widens downstream of Thornton, the under-sizing is relatively small compared to upstream of Thornton.

It should be noted that even if a MLWS was available for input to the tool, it would not change the overall under-sized result. The input of MLWS into the tool would potentially increase the overall disequilibrium, because the spring tidal prism would be increased.

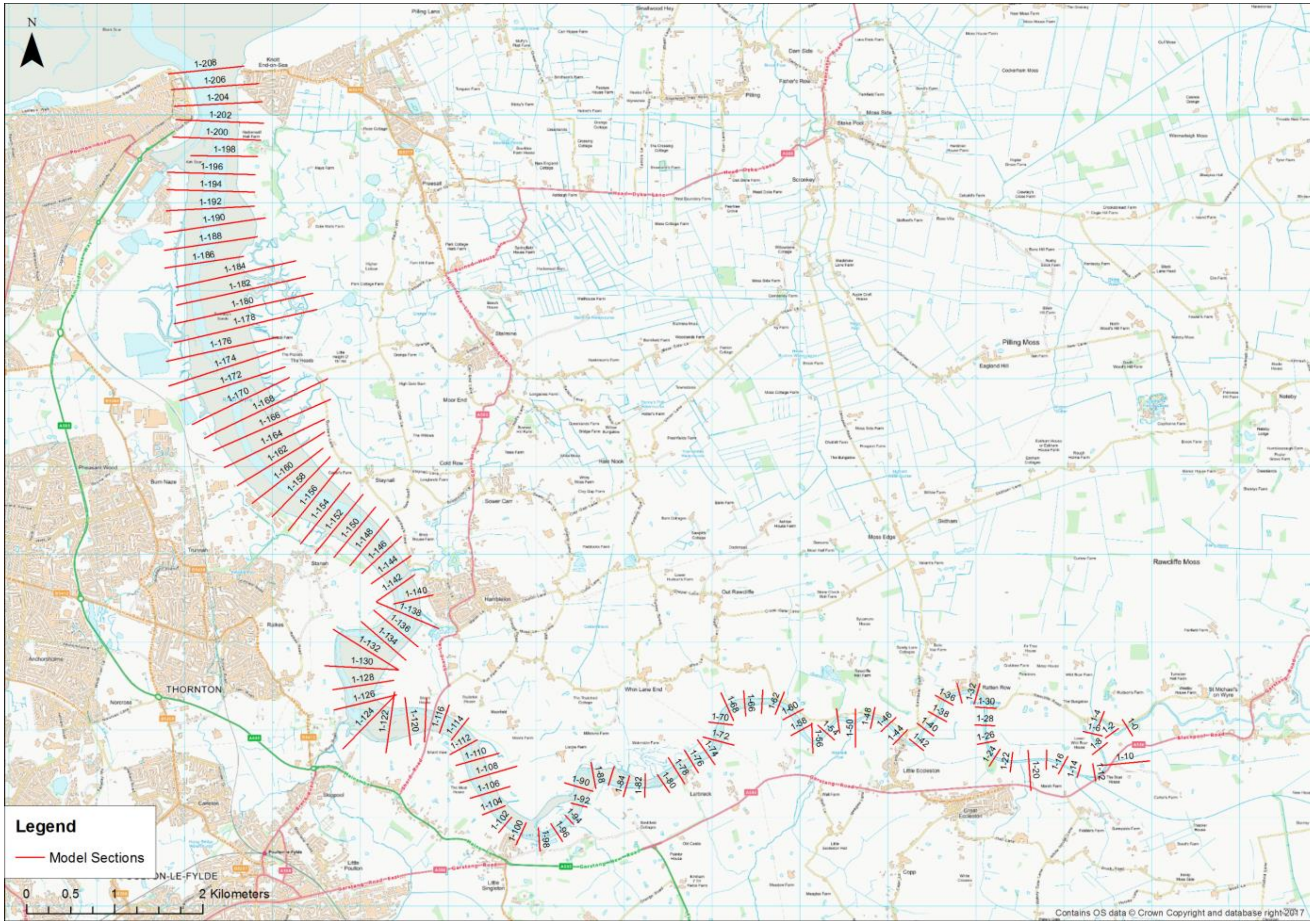

Figure 0.20. Location of sections in the Wyre Estuary where the observed form was measured

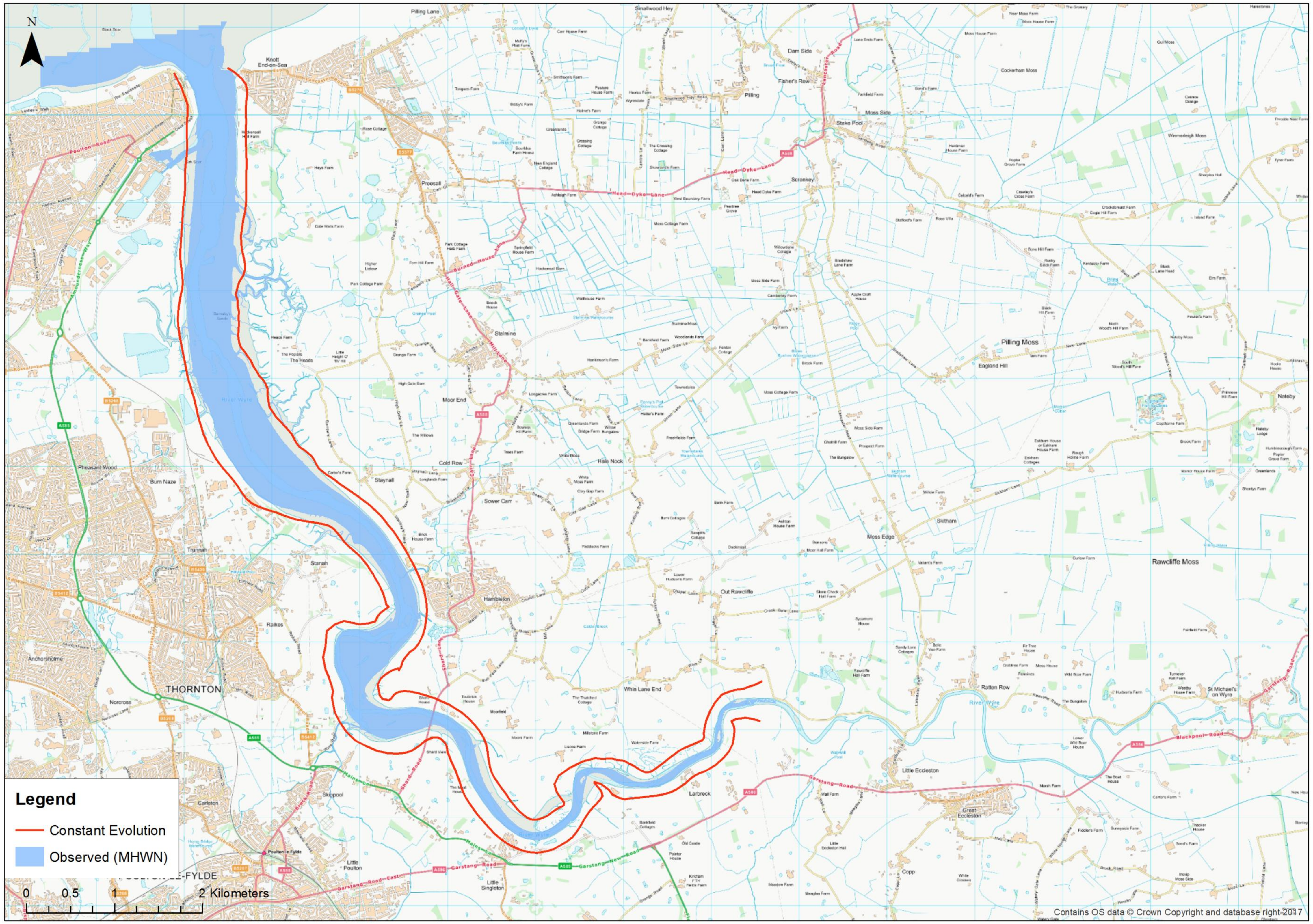

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Figure 0.21. Comparison of predicted equilibrium widths with observed widths in the Wyre Estuary (map background)

Figure 0.22. Comparison of predicted equilibrium widths with observed widths in the Wyre Estuary (aerial photograph background)

Physical Constraints to Morphological Equilibrium

The single distinct equilibrium state of the Wyre Estuary suggests that the entire system is at a similar stage of adjustment to natural process inputs. The entire estuary is predicted as under-sized and processes will be attempting to widen it to establish an equilibrium width. However, it is not possible for the channels to widen because of flood defence constraints.

Overall Condition of the Morphological Equilibrium Attribute

The long-term policy in the Shoreline Management Plan for the downstream reaches of the Wyre Estuary is to continue to provide protection, even though this will constrain its natural development (Halcrow, 2010). This Hold The Line policy (green lines on *Figure 0.23*) is to protect large areas of development at risk of flooding. In the upper reaches of the estuary, the longer-term policy is to allow a more naturally functioning system through managed realignment to create additional intertidal habitat (blue lines on *Figure 0.23* and *Table 0.8*). Although the equilibrium form of the lower reaches of the estuary would benefit from managed realignment, the greater benefit would be for realignment upstream, in keeping with the policy. This is because potential managed realignment locations would be better placed along the under-sized part of the estuary with the greatest difference between the observed and predicted widths (although any realignment will have knock-on effects further downstream too).

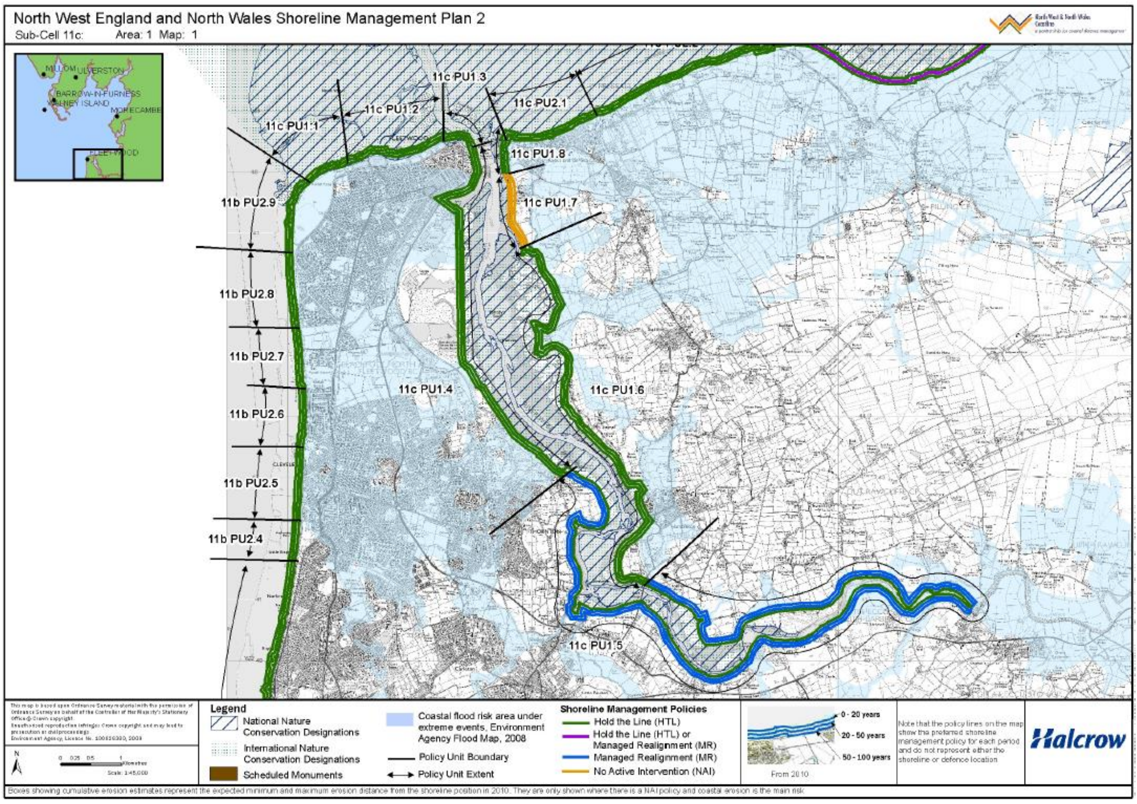

Figure 0.23. Location of potential managed realignment site (blue line) in the Wyre Estuary (Halcrow, 2010)

Table 0.8. Potential managed realignment site in the Wyre Estuary (Halcrow, 2010). HTL = Hold The Line, MR = Managed Realignment

Coastal Stretch	Policy Unit	Epoch 1	Epoch 2	Epoch 3
• Stanah to Cartford Bridge (south bank) and Cartford Bridge to Shard Bridge (north bank)	• .5	• TL	• R	• R

Conclusions

An understanding of how the Dee Estuary and the estuaries within and adjacent to Morecambe Bay 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 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 all the 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 Dee Estuary and the estuaries within and adjacent to Morecambe Bay 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.

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Appendix A: Regime Theory and its Application

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 Dee Estuary and Morecambe Bay SSSIs, 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.

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:

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

This is the regression equation that was used in the Dee Estuary and Morecambe Bay estuaries.

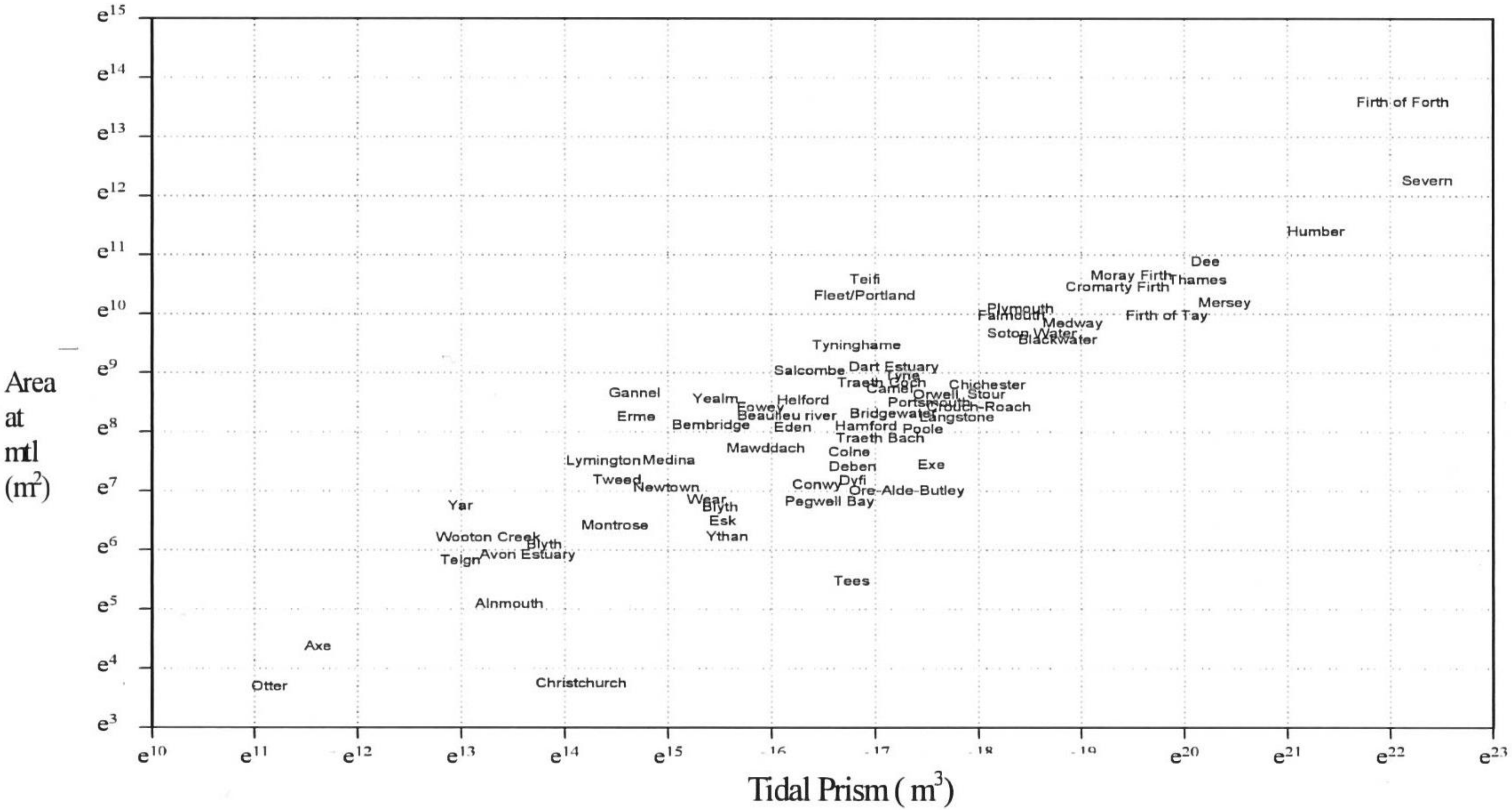

Figure A.1. Tidal prism – cross-sectional area relationship for 66 estuaries around the United Kingdom coast (from Townend et al., 2000)

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).

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.

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.

Methods used to Predict Estuary Equilibrium Form in the Dee Estuary and Morecambe Bay estuaries

The two main parts to the analysis in the Dee Estuary and Morecambe Bay estuaries are:

Measure the observed forms; and

Predict the equilibrium forms.

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

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 small scales of the three estuaries, the spacing’s of the sections are approximately 200m in each. 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 B, E and H).

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 (Appendices C, F and I). 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.

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, all the estuaries 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.

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:

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

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: Observed Form of the Dee Estuary at each Section

Section	Tidal Prism (m³)	Cross-Sectional Area (m²)	Width (m)	Mean Depth (m)
1-14	19,068	#N/A	#N/A	#N/A
1-16	42,331	#N/A	#N/A	#N/A
1-18	70,473	#N/A	#N/A	#N/A
1-20	99,749	#N/A	#N/A	#N/A
1-22	130,615	#N/A	#N/A	#N/A
1-24	156,594	#N/A	#N/A	#N/A
1-26	188,994	#N/A	#N/A	#N/A
1-28	222,842	#N/A	#N/A	#N/A
1-30	257,903	#N/A	#N/A	#N/A
1-32	294,417	#N/A	#N/A	#N/A
1-34	330,964	#N/A	#N/A	#N/A
1-36	368,495	#N/A	#N/A	#N/A
1-38	407,744	#N/A	#N/A	#N/A
1-40	445,985	#N/A	#N/A	#N/A
1-42	485,513	#N/A	#N/A	#N/A
1-44	526,335	#N/A	#N/A	#N/A
1-46	568,754	#N/A	#N/A	#N/A
1-48	615,820	#N/A	#N/A	#N/A
1-50	661,806	#N/A	#N/A	#N/A
1-52	712,271	#N/A	#N/A	#N/A
1-54	759,054	#N/A	#N/A	#N/A
1-56	807,142	#N/A	#N/A	#N/A
1-58	855,814	#N/A	#N/A	#N/A
1-60	914,782	#N/A	#N/A	#N/A
1-62	965,857	#N/A	#N/A	#N/A
1-64	1,017,867	#N/A	#N/A	#N/A
1-66	1,069,743	#N/A	#N/A	#N/A
1-68	1,123,374	#N/A	#N/A	#N/A
1-70	1,176,411	#N/A	#N/A	#N/A
1-72	1,231,816	#N/A	#N/A	#N/A
1-74	1,287,588	#N/A	#N/A	#N/A
1-76	1,343,661	#N/A	#N/A	#N/A
1-78	1,399,205	#N/A	#N/A	#N/A

Section	Tidal Prism (m³)	Cross-Sectional Area (m²)	Width (m)	Mean Depth (m)
1-80	1,455,220	#N/A	#N/A	#N/A
1-82	1,500,105	#N/A	#N/A	#N/A
1-84	1,529,146	#N/A	#N/A	#N/A
1-86	1,558,727	#N/A	#N/A	#N/A
1-88	1,588,233	#N/A	#N/A	#N/A
1-90	1,617,610	#N/A	#N/A	#N/A
1-92	1,647,201	#N/A	#N/A	#N/A
1-94	1,680,469	#N/A	#N/A	#N/A
1-96	1,713,910	#N/A	#N/A	#N/A
1-98	1,747,882	#N/A	#N/A	#N/A
1-100	1,782,687	#N/A	#N/A	#N/A
1-102	1,817,737	#N/A	#N/A	#N/A
1-104	1,851,987	#N/A	#N/A	#N/A
1-106	1,885,104	#N/A	#N/A	#N/A
1-108	1,918,873	#N/A	#N/A	#N/A
1-110	1,952,036	#N/A	#N/A	#N/A
1-112	1,985,886	#N/A	#N/A	#N/A
1-114	2,018,925	#N/A	#N/A	#N/A
1-116	2,052,511	#N/A	#N/A	#N/A
1-118	2,089,989	#N/A	#N/A	#N/A
1-120	2,127,353	#N/A	#N/A	#N/A
1-122	2,164,854	#N/A	#N/A	#N/A
1-124	2,207,029	19	107	0.19
1-126	2,251,639	28	97	0.29
1-128	2,298,537	38	104	0.36
1-130	2,346,848	46	128	0.36
1-132	2,401,176	46	134	0.35
1-134	2,477,310	45	143	0.32
1-136	2,535,306	43	137	0.32
1-138	2,594,724	39	127	0.31
1-140	2,651,620	37	127	0.29
1-142	2,706,508	35	122	0.29
1-144	2,771,170	35	132	0.27
1-146	2,838,190	75	156	0.48
1-148	2,953,177	193	162	1.19

Section	Tidal Prism (m³)	Cross-Sectional Area (m²)	Width (m)	Mean Depth (m)
1-150	3,039,319	132	132	1.04
1-152	3,123,182	140	120	1.17
1-154	3,217,390	145	135	1.07
1-156	3,307,472	137	143	0.97
1-158	3,405,599	162	153	1.07
1-160	3,516,346	185	170	1.10
1-162	3,646,553	222	190	1.17
1-164	3,793,151	262	241	1.09
1-166	3,959,772	261	235	1.12
1-168	4,133,342	267	249	1.08
1-170	4,330,011	254	257	1.00
1-172	4,557,173	259	248	1.05
1-174	4,793,357	291	268	1.09
1-176	5,068,984	347	299	1.16
1-178	5,368,918	424	343	1.24
1-180	6,407,856	492	479	1.03
1-182	6,848,245	528	499	1.06
1-184	7,288,338	493	540	0.92
1-186	7,771,909	571	617	0.93
1-188	8,323,136	587	661	0.89
1-190	9,018,682	728	709	1.03
1-192	9,885,455	899	824	1.10
1-194	10,833,342	1,086	1,054	1.03
1-196	11,801,257	1,064	1,075	0.99
1-198	12,907,877	1,275	1,235	1.03
1-200	14,069,974	1,515	1,375	1.10
1-202	15,378,809	#N/A	#N/A	#N/A
1-206	19,039,699	1,693	1,119	1.53
1-208	20,554,646	1,648	980	1.68
1-210	22,036,472	1,818	1,094	1.66
1-212	23,838,016	1,918	1,205	1.59
1-214	25,642,698	1,976	1,268	1.56
1-216	27,538,810	1,785	1,264	1.41
1-218	29,466,506	1,657	1,187	1.40
1-220	33,258,687	1,763	1,073	1.64

Section	Tidal Prism (m³)	Cross-Sectional Area (m²)	Width (m)	Mean Depth (m)
1-224	35,285,871	1,198	842	1.42
1-230	41,689,763	1,700	731	2.33
1-232	43,766,586	1,757	788	2.23
1-234	45,931,448	1,785	821	2.17
1-236	47,925,344	1,756	833	2.11
1-238	49,847,557	1,740	755	2.30
1-240	51,689,760	1,688	762	2.22
1-242	54,020,308	2,245	1,348	1.67
1-244	57,045,606	2,224	1,356	1.64
1-246	59,427,823	2,268	1,332	1.70
1-250	63,822,622	2,775	1,353	2.05
1-252	66,602,912	2,713	1,279	2.12
1-254	69,177,975	2,725	1,153	2.36
1-256	71,448,582	2,708	1,169	2.32
1-258	74,186,285	2,467	1,173	2.18
1-260	76,310,074	2,394	1,051	2.41
1-262	79,066,271	2,736	1,271	2.26
1-264	81,711,068	3,255	1,485	2.34
1-266	85,004,614	3,493	1,537	2.29
1-268	87,480,070	3,658	1,605	2.36
1-270	91,090,883	4,010	2,046	2.01
1-272	94,211,434	4,186	1,936	2.18
2-16	33,114,891	92	136	0.68
2-18	33,904,461	215	293	0.74
2-20	34,691,211	214	276	0.78
2-22	36,955,059	234	318	0.74
2-26	38,156,154	511	560	0.91
2-28	40,063,735	366	458	0.80
2-36	42,661,915	1,256	212	5.93
2-38	43,686,093	1,020	346	2.96
2-40	44,753,797	1,102	629	1.75
2-42	46,087,042	1,101	772	1.43
2-44	47,506,785	1,256	746	1.68
2-46	48,815,577	2,336	712	3.28
2-48	50,247,567	1,953	674	2.90

Section	Tidal Prism (m³)	Cross-Sectional Area (m²)	Width (m)	Mean Depth (m)
2-50	51,660,172	1,940	608	3.20
2-52	53,018,184	3,654	533	6.87
2-54	54,867,511	5,023	542	9.28
2-56	56,725,251	2,453	751	3.27
2-58	58,808,806	2,182	950	2.30
2-60	61,047,575	1,986	1,121	1.77
2-62	63,328,982	1,820	994	1.83
2-64	65,611,642	1,813	1,069	1.70
2-66	68,064,870	2,479	1,444	1.74
2-68	71,458,571	5,844	2,199	2.66
2-70	75,372,159	8,788	2,377	3.70
2-72	79,621,869	11,668	2,401	4.86
2-74	83,950,767	12,129	2,237	5.42
2-76	88,383,160	12,324	2,206	5.59
2-78	92,638,994	12,413	2,139	5.81
2-80	96,866,371	12,851	2,011	6.39
2-82	101,127,482	13,424	1,935	6.94
2-84	105,442,928	14,178	2,068	6.86
2-86	109,867,830	14,737	2,136	6.90
2-88	114,778,753	14,888	2,401	6.20
2-90	119,954,390	14,816	2,389	6.20
2-92	124,936,468	14,330	2,238	6.41
2-94	129,147,292	13,842	1,975	7.01
2-96	133,678,844	13,911	1,871	7.43
2-98	137,847,401	14,686	1,810	8.11
3-0	35,495,996	4,465	1,874	2.40
3-2	70,226,490	4,325	1,954	2.21
3-4	74,085,765	4,238	1,967	2.22
3-8	83,040,193	4,355	2,054	2.13
3-10	87,564,558	4,615	1,857	2.49
3-12	92,293,322	5,014	1,900	2.66
3-14	96,927,559	5,192	1,966	2.65
3-16	101,596,473	5,064	2,030	2.50
3-18	106,763,102	5,375	2,197	2.45
3-20	111,758,911	5,654	2,187	2.59

Section	Tidal Prism (m^3)	Cross-Sectional Area (m^2)	Width (m)	Mean Depth (m)
3-22	117,192,021	5,815	2,349	2.48
3-24	122,812,217	5,821	2,068	2.81
3-26	128,547,952	5,988	1,962	3.05
3-28	134,033,271	6,895	1,992	3.46
3-30	140,279,157	7,294	2,412	3.02
3-32	146,058,157	7,492	2,548	2.94
3-34	152,319,430	8,243	2,605	3.17
3-36	158,687,752	10,176	3,045	3.34
3-38	165,393,471	12,330	2,960	4.17
3-46	192,633,885	13,564	3,343	4.06
3-48	201,436,317	14,510	3,318	4.38
3-50	207,640,737	14,921	3,437	4.35
3-52	214,331,329	15,589	3,493	4.46
3-54	220,457,013	15,517	3,192	4.86
3-56	226,655,520	13,206	2,885	4.58
3-58	232,138,122	10,150	2,913	3.54
3-62	241,646,767	8,136	2,273	3.58
3-64	245,973,043	8,210	2,148	3.83
3-66	250,316,869	8,320	2,400	3.47
3-68	254,594,471	8,787	2,207	3.98
3-70	258,818,020	9,287	1,826	5.09
3-72	262,870,092	9,873	1,650	5.99
3-74	266,885,150	10,234	1,567	6.54
3-76	270,849,533	10,729	1,541	6.96
3-78	274,729,950	10,371	1,180	8.80
3-80	278,287,458	10,022	1,091	9.19
3-82	281,667,514	10,820	1,117	9.70
3-84	285,089,020	11,083	1,328	8.37
3-86	288,672,665	11,166	1,493	7.52
3-88	292,455,777	11,461	1,549	7.40
3-90	296,659,552	12,636	1,799	7.03

Appendix C: Predicted Equilibrium Form of the Dee Estuary at each Section

Section	Tidal Prism (m³)	Cross-Sectional Area (m²)	Width (m)	Mean Depth (m)
1-14	5,473,692	1,460	#N/A	#N/A
1-16	5,595,777	1,483	#N/A	#N/A
1-18	5,720,584	1,507	#N/A	#N/A
1-20	5,848,176	1,530	#N/A	#N/A
1-22	5,978,613	1,555	#N/A	#N/A
1-24	6,111,960	1,579	#N/A	#N/A
1-26	6,248,280	1,604	#N/A	#N/A
1-28	6,387,641	1,629	#N/A	#N/A
1-30	6,530,111	1,655	#N/A	#N/A
1-32	6,675,758	1,681	#N/A	#N/A
1-34	6,824,653	1,708	#N/A	#N/A
1-36	6,976,870	1,735	#N/A	#N/A
1-38	7,132,481	1,762	#N/A	#N/A
1-40	7,291,564	1,790	#N/A	#N/A
1-42	7,454,194	1,818	#N/A	#N/A
1-44	7,620,452	1,847	#N/A	#N/A
1-46	7,790,418	1,876	#N/A	#N/A
1-48	7,964,175	1,906	#N/A	#N/A
1-50	8,141,807	1,936	#N/A	#N/A
1-52	8,323,401	1,966	#N/A	#N/A
1-54	8,509,046	1,997	#N/A	#N/A
1-56	8,698,831	2,029	#N/A	#N/A
1-58	8,892,849	2,061	#N/A	#N/A
1-60	9,091,194	2,093	#N/A	#N/A
1-62	9,293,963	2,126	#N/A	#N/A
1-64	9,501,255	2,160	#N/A	#N/A
1-66	9,713,170	2,194	#N/A	#N/A
1-68	9,929,812	2,229	#N/A	#N/A
1-70	10,151,286	2,264	#N/A	#N/A
1-72	10,377,699	2,300	#N/A	#N/A
1-74	10,609,163	2,336	#N/A	#N/A
1-76	10,845,789	2,373	#N/A	#N/A
1-78	11,087,692	2,410	#N/A	#N/A

Section	Tidal Prism (m³)	Cross-Sectional Area (m²)	Width (m)	Mean Depth (m)
1-80	11,334,991	2,448	#N/A	#N/A
1-82	11,587,806	2,487	#N/A	#N/A
1-84	11,846,259	2,526	#N/A	#N/A
1-86	12,110,477	2,566	#N/A	#N/A
1-88	12,380,588	2,606	#N/A	#N/A
1-90	12,656,724	2,648	#N/A	#N/A
1-92	12,939,019	2,689	#N/A	#N/A
1-94	13,227,609	2,732	#N/A	#N/A
1-96	13,522,637	2,775	#N/A	#N/A
1-98	13,824,245	2,819	#N/A	#N/A
1-100	14,132,579	2,863	#N/A	#N/A
1-102	14,447,791	2,909	#N/A	#N/A
1-104	14,770,034	2,954	#N/A	#N/A
1-106	15,099,463	3,001	#N/A	#N/A
1-108	15,436,241	3,048	#N/A	#N/A
1-110	15,780,529	3,097	#N/A	#N/A
1-112	16,132,497	3,145	#N/A	#N/A
1-114	16,492,315	3,195	#N/A	#N/A
1-116	16,860,158	3,246	#N/A	#N/A
1-118	17,236,206	3,297	#N/A	#N/A
1-120	17,620,640	3,349	#N/A	#N/A
1-122	18,013,650	3,402	#N/A	#N/A
1-124	18,415,425	3,455	1,391.82	2.48
1-126	18,826,161	3,510	1,079.00	3.25
1-128	19,246,058	3,565	1,013.82	3.52
1-130	19,675,321	3,622	1,133.11	3.20
1-132	20,114,157	3,679	1,192.83	3.08
1-134	20,562,782	3,737	1,292.68	2.89
1-136	21,021,412	3,796	1,282.01	2.96
1-138	21,490,272	3,856	1,254.04	3.07
1-140	21,969,590	3,917	1,301.04	3.01
1-142	22,459,597	3,978	1,291.28	3.08
1-144	22,960,535	4,041	1,414.61	2.86
1-146	23,472,644	4,105	1,157.85	3.55
1-148	23,996,176	4,170	753.38	5.53

Section	Tidal Prism (m³)	Cross-Sectional Area (m²)	Width (m)	Mean Depth (m)
1-150	24,531,385	4,236	733.29	5.78
1-152	25,078,531	4,302	665.67	6.46
1-154	25,637,881	4,370	741.63	5.89
1-156	26,209,706	4,439	810.20	5.48
1-158	26,794,285	4,509	800.90	5.63
1-160	27,391,902	4,581	842.66	5.44
1-162	28,002,849	4,653	869.43	5.35
1-164	28,627,422	4,726	1,024.23	4.61
1-166	29,265,926	4,801	1,005.17	4.78
1-168	29,918,671	4,877	1,061.20	4.60
1-170	30,585,975	4,954	1,129.61	4.39
1-172	31,268,162	5,032	1,091.51	4.61
1-174	31,965,564	5,111	1,120.52	4.56
1-176	32,678,522	5,192	1,154.31	4.50
1-178	33,407,381	5,274	1,210.15	4.36
1-180	34,152,496	5,357	1,579.83	3.39
1-182	34,914,231	5,442	1,599.08	3.40
1-184	35,692,955	5,528	1,806.46	3.06
1-186	36,489,047	5,615	1,933.89	2.90
1-188	37,302,896	5,704	2,059.26	2.77
1-190	38,134,897	5,794	1,993.39	2.91
1-192	38,985,455	5,885	2,100.20	2.80
1-194	39,854,983	5,978	2,473.25	2.42
1-196	40,743,905	6,072	2,566.64	2.37
1-198	41,652,654	6,168	2,716.43	2.27
1-200	42,581,671	6,266	2,796.45	2.24
1-202	43,531,409	6,364	#N/A	#N/A
1-206	45,494,907	6,567	2,188.22	3.00
1-208	46,509,621	6,671	1,970.20	3.39
1-210	47,546,968	6,776	2,110.71	3.21
1-212	48,607,452	6,883	2,282.80	3.02
1-214	49,691,589	6,992	2,384.10	2.93
1-216	50,799,906	7,102	2,519.93	2.82
1-218	51,932,943	7,214	2,476.85	2.91
1-220	53,091,251	7,328	2,187.82	3.35

Section	Tidal Prism (m^3)	Cross-Sectional Area (m^2)	Width (m)	Mean Depth (m)
1-224	55,485,948	7,561	2,115.90	3.57
1-230	59,282,032	7,925	1,578.50	5.02
1-232	60,604,254	8,050	1,685.23	4.78
1-234	61,955,966	8,177	1,757.46	4.65
1-236	63,337,827	8,306	1,811.98	4.58
1-238	64,750,509	8,437	1,662.77	5.07
1-240	66,194,699	8,570	1,717.27	4.99
1-242	67,671,100	8,706	2,655.01	3.28
1-244	69,180,431	8,843	2,704.13	3.27
1-246	70,723,425	8,983	2,650.02	3.39
1-250	73,913,427	9,268	2,472.67	3.75
1-252	75,561,986	9,415	2,382.83	3.95
1-254	77,247,314	9,563	2,160.22	4.43
1-256	78,970,232	9,714	2,213.19	4.39
1-258	80,731,577	9,868	2,307.07	4.28
1-260	82,532,208	10,023	2,090.71	4.79
1-262	84,373,000	10,182	2,391.05	4.26
1-264	86,254,848	10,342	2,563.07	4.04
1-266	88,178,669	10,506	2,656.56	3.95
1-268	90,145,399	10,671	2,692.32	3.96
1-270	92,155,995	10,840	3,321.06	3.26
1-272	94,211,434	11,011	3,128.68	3.52
2-16	40,052,529	5,999	1,096.67	5.47
2-18	40,598,588	6,057	1,550.99	3.91
2-20	41,179,124	6,118	1,472.62	4.15
2-22	41,796,313	6,183	1,632.62	3.79
2-26	43,150,055	6,325	1,970.64	3.21
2-28	43,891,685	6,402	1,915.83	3.34
2-36	47,356,956	6,757	492.18	13.73
2-38	48,364,199	6,858	895.24	7.66
2-40	49,435,036	6,966	1,579.74	4.41
2-42	50,573,484	7,079	1,956.40	3.62
2-44	51,783,810	7,199	1,786.03	4.03
2-46	53,070,553	7,326	1,261.13	5.81
2-48	54,438,538	7,459	1,316.24	5.67

Section	Tidal Prism (m^3)	Cross-Sectional Area (m^2)	Width (m)	Mean Depth (m)
2-50	55,892,894	7,600	1,201.21	6.33
2-52	57,439,075	7,749	775.41	9.99
2-54	59,082,878	7,906	679.22	11.64
2-56	60,830,466	8,071	1,362.51	5.92
2-58	62,688,393	8,245	1,847.08	4.46
2-60	64,663,625	8,429	2,308.44	3.65
2-62	66,763,568	8,623	2,164.14	3.98
2-64	68,996,096	8,826	2,357.23	3.74
2-66	71,369,581	9,041	2,742.84	3.30
2-68	73,892,922	9,267	2,768.40	3.35
2-70	76,575,580	9,504	2,472.13	3.84
2-72	79,427,615	9,754	2,195.42	4.44
2-74	82,459,721	10,017	2,033.03	4.93
2-76	85,683,266	10,294	2,015.59	5.11
2-78	89,110,337	10,584	1,974.50	5.36
2-80	92,753,786	10,890	1,850.50	5.88
2-82	96,627,273	11,211	1,768.51	6.34
2-84	100,745,323	11,548	1,866.53	6.19
2-86	105,123,376	11,902	1,919.13	6.20
2-88	109,777,849	12,274	2,179.37	5.63
2-90	114,726,194	12,664	2,208.86	5.73
2-92	119,986,965	13,074	2,137.08	6.12
2-94	125,579,888	13,503	1,950.00	6.92
2-96	131,525,935	13,954	1,873.93	7.45
2-98	137,847,401	14,427	1,794.23	8.04
3-0	43,046,613	6,314	2,220.83	2.84
3-2	75,253,069	9,387	2,878.19	3.26
3-4	76,111,047	9,463	2,895.71	3.27
3-8	78,008,525	9,630	3,048.13	3.16
3-10	79,056,462	9,722	2,695.41	3.61
3-12	80,176,642	9,819	2,646.88	3.71
3-14	81,374,047	9,923	2,713.41	3.66
3-16	82,654,000	10,034	2,851.73	3.52
3-18	84,022,191	10,152	3,015.52	3.37
3-20	85,484,705	10,277	2,947.65	3.49

Section	Tidal Prism (m³)	Cross-Sectional Area (m²)	Width (m)	Mean Depth (m)
3-22	87,048,042	10,410	3,143.08	3.31
3-24	88,719,155	10,551	2,784.42	3.79
3-26	90,505,473	10,702	2,622.59	4.08
3-28	92,414,938	10,861	2,499.40	4.35
3-30	94,456,040	11,031	2,966.52	3.72
3-32	96,637,853	11,212	3,116.29	3.60
3-34	98,970,079	11,403	3,063.29	3.72
3-36	101,463,087	11,606	3,251.94	3.57
3-38	104,127,960	11,822	2,897.72	4.08
3-46	116,755,669	12,823	3,248.90	3.95
3-48	120,474,799	13,111	3,152.09	4.16
3-50	124,450,322	13,417	3,256.56	4.12
3-52	128,699,915	13,741	3,279.62	4.19
3-54	133,242,470	14,083	3,040.83	4.63
3-56	138,098,186	14,446	3,017.09	4.79
3-58	143,288,650	14,829	3,494.48	4.24
3-62	154,767,724	15,663	3,153.83	4.97
3-64	161,107,371	16,116	3,007.77	5.36
3-66	167,884,068	16,595	3,389.54	4.90
3-68	175,127,944	17,100	3,078.97	5.55
3-70	182,871,206	17,633	2,515.75	7.01
3-72	191,148,283	18,196	2,239.44	8.13
3-74	199,995,973	18,790	2,122.89	8.85
3-76	209,453,615	19,417	2,073.24	9.37
3-78	219,563,259	20,078	1,641.07	12.23
3-80	230,369,852	20,775	1,569.81	13.23
3-82	241,921,442	21,509	1,573.17	13.67
3-84	254,269,389	22,283	1,880.30	11.85
3-86	267,468,592	23,098	2,141.15	10.79
3-88	281,577,736	23,957	2,238.85	10.70
3-90	296,659,552	24,861	2,522.79	9.85

Appendix D: Under-sized Reach of the Dee Estuary

Map background

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Aerial photograph background

Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Appendix E: Observed Form of the Duddon Estuary at each Section

Section	Tidal Prism (m³)	Cross-Sectional Area (m²)	Width (m)	Mean Depth (m)
1-0	165	#N/A	#N/A	#N/A
1-2	2,187	#N/A	#N/A	#N/A
1-4	7,534	#N/A	#N/A	#N/A
1-6	19,943	#N/A	#N/A	#N/A
1-8	30,837	#N/A	#N/A	#N/A
1-10	45,245	#N/A	#N/A	#N/A
1-12	62,786	#N/A	#N/A	#N/A
1-14	84,249	#N/A	#N/A	#N/A
1-16	119,533	#N/A	#N/A	#N/A
1-18	167,017	#N/A	#N/A	#N/A
1-20	210,626	#N/A	#N/A	#N/A
1-22	257,577	#N/A	#N/A	#N/A
1-24	310,566	#N/A	#N/A	#N/A
1-26	354,255	#N/A	#N/A	#N/A
1-28	412,664	#N/A	#N/A	#N/A
1-30	491,610	#N/A	#N/A	#N/A
1-32	578,700	#N/A	#N/A	#N/A
1-34	710,715	#N/A	#N/A	#N/A
1-36	881,777	#N/A	#N/A	#N/A
1-38	1,133,309	4	80	0.05
1-40	1,388,975	2	54	0.03
1-42	1,622,211	17	167	0.11
1-44	1,876,722	52	251	0.21
1-46	2,168,582	93	343	0.27
1-48	2,633,201	319	842	0.38
1-50	3,189,664	201	461	0.44
1-52	3,654,567	286	557	0.51
1-54	4,183,319	331	545	0.61
1-56	4,930,221	390	629	0.63
1-58	5,618,059	470	715	0.66
1-62	7,308,357	764	971	0.79
1-64	8,186,472	758	892	0.85

Section	Tidal Prism (m³)	Cross-Sectional Area (m²)	Width (m)	Mean Depth (m)
2-2	9,301	#N/A	#N/A	#N/A
2-4	19,465	#N/A	#N/A	#N/A
2-6	34,408	#N/A	#N/A	#N/A
2-8	59,019	5	24	0.20
2-10	95,456	25	79	0.38
2-12	142,503	29	81	0.35
2-14	159,274	30	48	0.63
2-16	258,930	69	219	0.32
3-0	9,183,896	870	889	0.98
3-2	11,109,627	965	977	0.99
3-6	11,982,143	1,184	1,199	0.99
3-8	13,047,289	1,253	1,283	0.98
3-10	14,390,019	1,498	1,865	0.80
3-12	15,858,412	1,820	2,171	0.84
3-14	17,547,894	2,418	2,350	1.03
3-16	19,216,131	2,883	2,430	1.19
3-18	20,930,586	3,113	2,768	1.12
3-20	22,501,678	3,067	2,339	1.31
3-22	24,005,956	3,429	1,905	1.80
3-24	25,439,660	3,281	1,736	1.89
3-26	26,756,415	2,768	1,520	1.82
3-28	28,007,293	2,627	1,490	1.76
3-30	29,310,517	2,572	1,462	1.77
3-32	30,634,217	2,821	1,528	1.85
3-34	31,828,499	2,999	1,677	1.79
3-36	33,081,205	3,167	1,702	1.88
3-38	34,488,322	3,342	1,762	1.90
3-40	35,519,409	3,415	1,563	2.19
3-42	37,569,185	3,776	1,808	2.11
3-44	39,184,382	4,189	2,014	2.08
3-46	41,124,809	4,237	2,153	1.97
3-48	43,081,433	4,340	2,754	1.58
3-50	44,882,134	4,982	2,723	1.83
3-52	48,080,499	5,565	2,143	2.62
3-54	49,826,636	5,737	2,102	2.73

Section	Tidal Prism (m³)	Cross-Sectional Area (m²)	Width (m)	Mean Depth (m)
3-56	51,959,063	6,133	2,121	2.89
3-58	54,029,467	6,048	2,106	2.87
3-60	56,081,294	6,377	2,099	3.04
3-62	58,217,678	6,727	2,163	3.11
3-64	60,761,411	7,841	2,379	3.30
3-66	64,548,074	10,874	3,270	3.33
3-68	68,093,699	9,277	2,649	3.50
3-70	71,067,246	8,844	2,661	3.32
3-72	74,004,982	8,840	2,748	3.22
3-74	77,102,797	9,703	2,995	3.25
3-76	80,201,884	9,959	2,771	3.60

Appendix F: Predicted Equilibrium Form of the Duddon Estuary at each Section

Section	Tidal Prism (m³)	Cross-Sectional Area (m²)	Width (m)	Mean Depth (m)
1-0	407,580	231	#N/A	#N/A
1-2	447,640	247	#N/A	#N/A
1-4	491,636	264	#N/A	#N/A
1-6	539,956	282	#N/A	#N/A
1-8	593,026	301	#N/A	#N/A
1-10	651,312	322	#N/A	#N/A
1-12	715,326	344	#N/A	#N/A
1-14	785,632	368	#N/A	#N/A
1-16	862,848	393	#N/A	#N/A
1-18	947,653	420	#N/A	#N/A
1-20	1,040,793	449	#N/A	#N/A
1-22	1,143,088	480	#N/A	#N/A
1-24	1,255,436	513	#N/A	#N/A
1-26	1,378,827	549	#N/A	#N/A
1-28	1,514,345	586	#N/A	#N/A
1-30	1,663,183	627	#N/A	#N/A
1-32	1,826,649	670	#N/A	#N/A
1-34	2,006,181	716	#N/A	#N/A
1-36	2,203,359	765	#N/A	#N/A
1-38	2,419,916	818	1,161	0.70
1-40	2,657,758	874	1,205	0.73
1-42	2,918,976	934	1,220	0.77
1-44	3,205,868	999	1,099	0.91
1-46	3,520,958	1,067	1,160	0.92
1-48	3,867,015	1,141	1,593	0.72
1-50	4,247,086	1,219	1,134	1.08
1-52	4,664,511	1,303	1,188	1.10
1-54	5,122,963	1,393	1,119	1.25
1-56	5,626,474	1,489	1,221	1.22
1-58	6,179,473	1,591	1,314	1.21
1-62	7,453,867	1,818	1,497	1.21
1-64	8,186,472	1,943	1,429	1.36

Section	Tidal Prism (m³)	Cross-Sectional Area (m²)	Width (m)	Mean Depth (m)
2-2	18,757	26	#N/A	#N/A
2-4	27,291	34	#N/A	#N/A
2-6	39,708	44	#N/A	#N/A
2-8	57,775	58	83	0.69
2-10	84,062	75	125	0.60
2-12	122,310	98	150	0.65
2-14	177,960	128	99	1.30
2-16	258,930	167	340	0.49
3-0	12,017,947	2,552	1,522	1.68
3-2	12,311,422	2,596	1,603	1.62
3-6	12,972,678	2,694	1,809	1.49
3-8	13,344,581	2,749	1,899	1.45
3-10	13,747,036	2,808	2,553	1.10
3-12	14,182,551	2,870	2,727	1.05
3-14	14,653,843	2,938	2,588	1.14
3-16	15,163,850	3,010	2,482	1.21
3-18	15,715,753	3,088	2,756	1.12
3-20	16,312,993	3,170	2,377	1.33
3-22	16,959,295	3,259	1,857	1.75
3-24	17,658,689	3,354	1,755	1.91
3-26	18,415,536	3,455	1,698	2.03
3-28	19,234,556	3,564	1,736	2.05
3-30	20,120,857	3,680	1,741	2.11
3-32	21,079,964	3,803	1,773	2.15
3-34	22,117,860	3,935	1,920	2.05
3-36	23,241,017	4,076	1,919	2.12
3-38	24,456,437	4,226	1,982	2.13
3-40	25,771,702	4,387	1,771	2.48
3-42	27,195,012	4,557	1,976	2.31
3-44	28,735,243	4,739	2,142	2.21
3-46	30,402,000	4,933	2,322	2.12
3-48	32,205,676	5,139	2,996	1.72
3-50	34,157,520	5,358	2,823	1.90
3-52	36,269,703	5,591	2,140	2.61
3-54	38,555,396	5,839	2,120	2.75

Section	Tidal Prism (m³)	Cross-Sectional Area (m²)	Width (m)	Mean Depth (m)
3-56	41,028,853	6,102	2,116	2.88
3-58	43,705,497	6,383	2,164	2.95
3-60	46,602,021	6,680	2,148	3.11
3-62	49,736,487	6,996	2,206	3.17
3-64	53,128,441	7,332	2,300	3.19
3-66	56,799,034	7,688	2,749	2.80
3-68	60,771,158	8,066	2,470	3.27
3-70	65,069,581	8,467	2,604	3.25
3-72	69,721,108	8,892	2,756	3.23
3-74	74,754,746	9,343	2,936	3.18
3-76	80,201,884	9,822	2,751	3.57

Appendix G: Under-sized Reach of the Duddon Estuary

Map background

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Aerial photograph background

Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Appendix H: Observed Form of the Wyre Estuary at each Section

Section	Tidal Prism (m³)	Cross-Sectional Area (m²)	Width (m)	Mean Depth (m)
1-0	27	#N/A	#N/A	#N/A
1-2	3,137	#N/A	#N/A	#N/A
1-4	6,293	#N/A	#N/A	#N/A
1-6	9,102	#N/A	#N/A	#N/A
1-8	11,898	#N/A	#N/A	#N/A
1-10	15,080	#N/A	#N/A	#N/A
1-12	17,417	#N/A	#N/A	#N/A
1-14	21,531	#N/A	#N/A	#N/A
1-16	26,536	#N/A	#N/A	#N/A
1-18	30,396	#N/A	#N/A	#N/A
1-20	33,729	#N/A	#N/A	#N/A
1-22	38,081	#N/A	#N/A	#N/A
1-24	43,982	#N/A	#N/A	#N/A
1-26	49,583	#N/A	#N/A	#N/A
1-28	55,709	#N/A	#N/A	#N/A
1-30	62,306	#N/A	#N/A	#N/A
1-32	69,478	#N/A	#N/A	#N/A
1-34	76,579	#N/A	#N/A	#N/A
1-36	84,111	#N/A	#N/A	#N/A
1-38	91,952	#N/A	#N/A	#N/A
1-40	101,728	#N/A	#N/A	#N/A
1-42	111,491	#N/A	#N/A	#N/A
1-44	121,530	#N/A	#N/A	#N/A
1-46	131,293	#N/A	#N/A	#N/A
1-48	142,906	#N/A	#N/A	#N/A
1-50	160,152	#N/A	#N/A	#N/A
1-52	179,772	#N/A	#N/A	#N/A
1-54	194,212	#N/A	#N/A	#N/A
1-56	209,894	#N/A	#N/A	#N/A
1-58	227,324	#N/A	#N/A	#N/A
1-60	251,197	#N/A	#N/A	#N/A
1-62	270,492	#N/A	#N/A	#N/A
1-64	293,488	4	30	0.14

Section	Tidal Prism (m³)	Cross-Sectional Area (m²)	Width (m)	Mean Depth (m)
1-66	324,267	31	58	0.54
1-68	362,507	32	57	0.58
1-70	392,830	29	52	0.55
1-72	435,817	36	63	0.60
1-74	480,631	43	66	0.67
1-76	525,565	66	81	0.82
1-78	575,872	66	81	0.81
1-80	629,617	80	82	0.97
1-82	678,499	54	60	0.89
1-84	729,474	68	96	0.71
1-86	809,642	115	104	1.10
1-88	883,958	82	67	1.23
1-90	984,457	71	131	0.54
1-92	1,061,264	122	102	1.21
1-94	1,131,031	72	78	0.94
1-96	1,184,138	70	82	0.84
1-98	1,238,706	80	91	0.88
1-100	1,301,458	90	92	0.99
1-102	1,370,532	100	100	1.00
1-104	1,443,712	134	122	1.10
1-106	1,536,795	142	129	1.10
1-108	1,640,896	206	140	1.48
1-110	1,760,327	205	148	1.39
1-112	1,878,817	229	167	1.37
1-114	1,997,737	249	154	1.63
1-116	2,112,814	211	140	1.52
1-118	2,247,311	265	210	1.27
1-120	2,423,807	300	286	1.05
1-122	2,643,205	473	339	1.39
1-124	2,935,668	581	345	1.68
1-126	3,275,985	405	261	1.55
1-128	3,501,139	537	279	1.94
1-130	3,855,869	912	543	1.68
1-132	4,320,005	943	643	1.47
1-134	4,743,565	817	384	2.13
1-136	5,036,327	634	313	2.05

Section	Tidal Prism (m³)	Cross-Sectional Area (m²)	Width (m)	Mean Depth (m)
1-138	5,323,612	734	276	2.66
1-140	5,553,288	679	254	2.67
1-142	5,803,068	676	257	2.63
1-144	6,062,611	644	245	2.64
1-146	6,317,554	690	258	2.68
1-148	6,599,182	741	276	2.70
1-150	6,891,652	780	290	2.69
1-152	7,218,611	864	275	3.14
1-154	7,592,225	1,034	332	3.12
1-156	8,011,125	1,197	427	2.81
1-158	8,522,508	1,534	539	2.85
1-160	9,124,076	1,377	629	2.19
1-162	9,764,765	1,580	638	2.48
1-164	10,403,210	1,405	624	2.25
1-166	11,067,417	1,446	609	2.37
1-168	11,691,102	1,515	593	2.56
1-170	12,329,006	1,473	611	2.42
1-172	13,065,694	1,707	590	2.89
1-174	13,764,816	1,919	584	3.29
1-176	14,548,914	1,718	483	3.56
1-178	15,221,820	1,618	485	3.34
1-180	15,959,887	1,724	514	3.35
1-182	16,736,176	2,033	520	3.91
1-184	17,502,906	1,929	545	3.55
1-186	18,216,249	2,139	566	3.78
1-188	18,949,699	1,928	515	3.74
1-190	19,656,197	1,939	518	3.75
1-192	20,331,306	1,944	529	3.77
1-194	20,947,500	1,878	492	3.82
1-196	21,526,722	1,738	470	3.70
1-198	22,096,555	1,764	456	3.87
1-200	22,973,218	1,761	446	3.95
1-202	23,527,497	1,737	440	3.95
1-204	24,058,568	1,771	447	4.16
1-206	24,623,982	1,891	490	3.87
1-208	25,237,362	2,062	422	4.89

Appendix I: Predicted Equilibrium Form of the Wyre Estuary at each Section

Section	Tidal Prism (m³)	Cross-Sectional Area (m²)	Width (m)	Mean Depth (m)
1-0	1,256,494	514	#N/A	#N/A
1-2	1,293,267	524	#N/A	#N/A
1-4	1,331,116	535	#N/A	#N/A
1-6	1,370,073	546	#N/A	#N/A
1-8	1,410,170	557	#N/A	#N/A
1-10	1,451,440	569	#N/A	#N/A
1-12	1,493,918	581	#N/A	#N/A
1-14	1,537,640	593	#N/A	#N/A
1-16	1,582,641	605	#N/A	#N/A
1-18	1,628,959	618	#N/A	#N/A
1-20	1,676,632	630	#N/A	#N/A
1-22	1,725,701	643	#N/A	#N/A
1-24	1,776,206	657	#N/A	#N/A
1-26	1,828,188	670	#N/A	#N/A
1-28	1,881,693	684	#N/A	#N/A
1-30	1,936,763	698	#N/A	#N/A
1-32	1,993,444	713	#N/A	#N/A
1-34	2,051,785	727	#N/A	#N/A
1-36	2,111,833	743	#N/A	#N/A
1-38	2,173,638	758	#N/A	#N/A
1-40	2,237,253	774	#N/A	#N/A
1-42	2,302,729	790	#N/A	#N/A
1-44	2,370,121	806	#N/A	#N/A
1-46	2,439,485	823	#N/A	#N/A
1-48	2,510,880	840	#N/A	#N/A
1-50	2,584,364	857	#N/A	#N/A
1-52	2,659,998	875	#N/A	#N/A
1-54	2,737,846	893	#N/A	#N/A
1-56	2,817,973	911	#N/A	#N/A
1-58	2,900,444	930	#N/A	#N/A
1-60	2,985,329	949	#N/A	#N/A
1-62	3,072,699	969	#N/A	#N/A
1-64	3,162,625	989	456	2.17

Section	Tidal Prism (m³)	Cross-Sectional Area (m²)	Width (m)	Mean Depth (m)
1-66	3,255,183	1,010	330	3.06
1-68	3,350,450	1,030	319	3.23
1-70	3,448,505	1,052	315	3.34
1-72	3,549,430	1,074	336	3.20
1-74	3,653,308	1,096	328	3.34
1-76	3,760,227	1,118	332	3.37
1-78	3,870,275	1,142	337	3.39
1-80	3,983,543	1,165	314	3.71
1-82	4,100,126	1,189	283	4.20
1-84	4,220,122	1,214	406	2.99
1-86	4,343,629	1,239	343	3.62
1-88	4,470,750	1,265	263	4.81
1-90	4,601,592	1,291	560	2.30
1-92	4,736,264	1,318	334	3.94
1-94	4,874,876	1,345	334	4.03
1-96	5,017,546	1,373	367	3.74
1-98	5,164,390	1,401	381	3.68
1-100	5,315,533	1,430	365	3.91
1-102	5,471,098	1,460	383	3.81
1-104	5,631,217	1,490	407	3.66
1-106	5,796,021	1,521	422	3.60
1-108	5,965,649	1,552	383	4.05
1-110	6,140,241	1,584	410	3.87
1-112	6,319,943	1,617	444	3.64
1-114	6,504,903	1,650	395	4.18
1-116	6,695,277	1,685	394	4.28
1-118	6,891,223	1,719	533	3.23
1-120	7,092,903	1,755	691	2.54
1-122	7,300,486	1,791	660	2.71
1-124	7,514,143	1,828	612	2.99
1-126	7,734,054	1,866	560	3.33
1-128	7,960,401	1,905	523	3.64
1-130	8,193,372	1,944	792	2.45
1-132	8,433,161	1,985	932	2.13
1-134	8,679,968	2,026	604	3.35
1-136	8,933,998	2,068	562	3.68

Section	Tidal Prism (m³)	Cross-Sectional Area (m²)	Width (m)	Mean Depth (m)
1-138	9,195,462	2,110	468	4.51
1-140	9,464,579	2,154	453	4.76
1-142	9,741,571	2,199	464	4.74
1-144	10,026,670	2,244	456	4.92
1-146	10,320,113	2,290	470	4.87
1-148	10,622,144	2,338	489	4.78
1-150	10,933,014	2,386	507	4.70
1-152	11,252,982	2,436	462	5.27
1-154	11,582,315	2,486	514	4.84
1-156	11,921,286	2,537	621	4.09
1-158	12,270,177	2,590	700	3.70
1-160	12,629,279	2,644	871	3.04
1-162	12,998,890	2,698	834	3.24
1-164	13,379,318	2,754	874	3.15
1-166	13,770,881	2,811	849	3.31
1-168	14,173,903	2,869	816	3.52
1-170	14,588,719	2,929	860	3.40
1-172	15,015,676	2,989	781	3.83
1-174	15,455,128	3,051	736	4.14
1-176	15,907,442	3,114	651	4.79
1-178	16,372,993	3,179	679	4.68
1-180	16,852,169	3,244	705	4.60
1-182	17,345,368	3,312	664	4.99
1-184	17,853,002	3,380	721	4.69
1-186	18,375,492	3,450	719	4.80
1-188	18,913,273	3,521	696	5.06
1-190	19,466,794	3,594	704	5.10
1-192	20,036,513	3,669	718	5.11
1-194	20,622,907	3,745	695	5.39
1-196	21,226,461	3,822	697	5.48
1-198	21,847,680	3,901	678	5.75
1-200	22,487,079	3,982	671	5.94
1-202	23,145,191	4,064	673	6.04
1-204	23,822,564	4,148	668	6.21
1-206	24,519,761	4,234	732	5.78
1-208	25,237,362	4,322	611	7.07

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