Healthy Estuaries 2020: Towards Addressing Coastal Squeeze in Estuaries

Chichester and Langstone Harbour Special Protection Area (SPA)
Crouch & Roach Estuaries (Mid-Essex Coast Phase 3) SPA
Essex Estuaries Special Area of Conservation (SAC)
Foulness (Mid-Essex Coast Phase 5) SPA
Humber Estuary SAC
Humber Estuary SPA
Solent Maritime SAC

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Foreword

The **Improvement Programme for England's Natura 2000 sites (IPENS)**, supported by European Union LIFE+ funding, is a new strategic approach to managing England's Natura 2000 sites. It is enabling Natural England, the Environment Agency, and other key partners to plan what, how, where and when they will target their efforts on Natura 2000 sites and areas surrounding them.

As part of the IPENS programme, we are identifying gaps in our knowledge and, where possible, addressing these through a range of evidence projects. The project findings are being used to help develop our Theme Plans and Site Improvement Plans. This report is one of the evidence project studies we commissioned.

Coastal squeeze is an issue affecting many estuaries in England, particularly in the south and east of the country. To address coastal squeeze (the prevention by fixed sea defences of estuary 'roll-over' or migration of intertidal features in response to sea level rise) much work has been done with the Environment Agency. The evidence needs to inform this are complex and challenging, and the approach to replacing extent of lost habitat needed to be reviewed in the light of a greater focus on achieving a more sustainable estuary form. This work was needed to develop a method that will enable the evaluation of estuary morphology in Natura 2000 sites and inform future planning for habitat creation.

Addressing the impacts of coastal squeeze is largely addressed through flood risk management, and Natural England needed an evaluation of the evidence base to help give clear advice on the size, location, timing and type of habitat creation in 6 estuary complexes affected by coastal squeeze. The outcomes of the project will inform condition assessments of designated sites and enable the condition threats to be more clearly identified.

The key audience for the work, which is of a technical nature, is the staff within the Environment Agency and Natural England. The project used case studies to test the method, along with discussions with other experts in the field.

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SUMMARY

As part of the Improvement Programme for England's Natura 2000 Sites (IPENS), a range of Evidence projects were initiated. These addressed gaps in knowledge about the issues affecting Natura 2000 sites and the solutions to address them. This report forms one of these projects, focussed on estuary Natura 2000 sites and their underpinning SSSIs. It provides the background to the technical analysis of data to evaluate the morphological 'health' of an estuary and thus inform measures needed to restore and then sustain this. The morphology of an estuary is related to the amount of intertidal habitat that can be sustained. This work is needed to support Natural England's advice to the Environment Agency on intertidal habitat creation that will be needed by 2020 to restore estuaries affected by coastal squeeze to favourable condition. Intertidal habitat creation ideally needs to be in locations that will move the estuary system closer to morphological equilibrium (and achieve favourable condition). However, physical constraints can reduce opportunities.

This report presents an evidence-based methodology using GIS and Excel tools to determine the morphological condition of an estuary. In order to do this, it takes a user through a method to define the equilibrium form of an estuary using Regime Theory. This form is compared to the existing (observed) form of the estuary to determine if it is able to support additional intertidal habitat of appropriate quality in appropriate locations. The results indicate where intertidal habitat creation would promote estuary equilibrium defined by the method. The method provides consistency to whole-estuary condition assessment and is applicable to most estuaries subject to coastal squeeze.

To develop and test the method, two contrasting case study sites have been used; the Humber Estuary and Chichester Harbour. The use of 'real-life' examples provides confidence in the outcomes of the project, and has proven invaluable in the assessment of the appropriateness of elements of the method. To this end, the digital tools have been developed to allow the user to input a variety of regime relationships and other equations that support the prediction of estuary form. The results from the case studies indicate that a calculation of equilibrium form that is independent of the observed form is currently difficult to achieve. The most appropriate method is to use a 'constant evolution' relationship that uses the observed form of the estuary together with the regime relationships to predict the equilibrium form.

The method described in this report will be applied to sites as needed and those outputs will inform future actions and discussion with public and private stakeholders. Application of the method will help Natural England to update its advice as strategies are reviewed on what intertidal habitat creation would be needed to reach favourable condition, and indicate where this should ideally be provided and how it could be achieved. The audience for this report are, therefore, Natural England conservation specialists and relevant advisors responsible for carrying out site-level condition assessments, and flood risk management specialists from the Environment Agency, together with geomorphological specialists that might undertake this work in the future.

GLOSSARY

Bathymetry
Topography of the sea floor.

CD
Chart Datum – a datum or plane to which depths or heights are referred (Lowest Astronomical Tide).

Coastal squeeze
Narrowing of the intertidal zone due to the prevention of its natural landward migration in response to sea-level rise; for the purposes of this project where this is a result of defences such as sea walls preventing migration and causing intertidal erosion.

Datum
Any position or element in relation to which others are determined.

Echosounder
An instrument for determining the depth of water by measuring the time of travel of a sound-pulse from the surface of a body of water to the bottom and back.

Empirical
Based on, concerned with, or verifiable by observation or experience rather than theory or pure logic.

Estuary
A semi-enclosed body of water with freshwater input and a connection to the sea; water body where fresh water and salt water mix.

Coastal geomorphology
The study of coastal landforms, and in particular their nature, origin, processes of development, and material composition.

High water
Maximum level reached by the rising tide.

Intertidal
Area on a shore that lies between Lowest Astronomical Tide (LAT) and Highest Astronomical Tide (HAT).

LiDAR
Light Detection and Ranging.

Low water
The minimum height reached by the falling tide.

Managed realignment
The setting back of existing coastal defences in order to achieve environmental, economic and/or engineering benefits.

Morphological equilibrium
Consistent morphology observed in estuaries and inlets that reflects a state of dynamic equilibrium with the prevailing forcing conditions and constraints on the system. The dynamic state will be reached by oscillation around an 'average form' (i.e. it is not static over time).

Median particle size
Defined as the particle size where half of the population is greater than and half is less than this size. For particle size distributions the median is called the d_{50}.

Neap Tide
A tide that occurs when the tide-generating forces of the sun and moon are acting at right angles to each other, so the tidal range is lower than average.

OD
Ordnance Datum – a specific datum or plane to which depths or heights are referred to.

Planform
The outline of a body of water as seen from above.

Sea-level rise
The general term given to the upward trend in mean sea level resulting from a combination of local or regional geological movements and global climate change.

Spring tide
A tide that occurs when the tide-generating forces of the sun and moon are acting in the same directions, so the tidal range is higher than average.

Tidal prism
The amount of water that enters and exits an estuary every flood and ebb tide respectively.

CONTENTS

1 INTRODUCTION

1.1 Improvement Programme for England's Natura 2000 Sites

One of the core duties of Natural England is to ensure protection and management of Sites of Special Scientific Interest (SSSIs), which underpin England's Natura 2000 network. The Improvement Programme for England's Natura 2000 Sites (IPENS), supported by EU LIFE+, is a new strategic approach to managing England's Natura 2000 Sites. It will enable Natural England, the Environment Agency, and other key partners to plan what, how, where and when they will target their efforts on Natura 2000 sites and areas surrounding them. This project is part of the IPENS programme (LIFE11NAT/UK/000384IPENS) which is financially supported by LIFE, a financial instrument of the European Community (www.naturalengland.org.uk/ipens2000).

As part of the IPENS programme, there are a range of projects that are addressing gaps in knowledge. Healthy Estuaries 2020 is an approach that focuses on the longer-term sustainability of estuary systems to address coastal squeeze in particular and inform management decisions. In this project, Natural England is evaluating the evidence base that will enable more effective and consistent advice to the Environment Agency on intertidal habitat creation needed by 2020 to address coastal squeeze in six estuary complexes (listed in Table 1.1). The aim is to understand the requirements that will move the intertidal habitat and estuary features towards favourable condition within the Special Areas of Conservation (SACs) and Special Protection Areas (SPAs) and their underpinning SSSIs in order to meet national and international obligations for biodiversity.

Estuaries can have both SAC and SPA designations that completely or partially overlap. The rationale for selecting SACs was to include the sites with the best examples of the Annex I habitats, to form a network of sites (Natura 2000). It is recognised that Annex I habitats can occur outside of these sites, so reporting on conservation status needs to include SACs and non-SAC sites. Requirements of the Habitats Directive for SACs include establishment of conservation measures which correspond to the ecological requirements of Annex I habitats and Annex II species present on the site (Article 6.1), and to take appropriate steps to avoid deterioration of the natural habitats and habitats of species, as well as significant disturbance of species, for which the site is designated (Article 6.2). Coastal flood risk management is considered both at a strategic level and at a scheme level as a plan or project that could affect features of an SAC. Assessments of strategic Shoreline Management Plans have taken place, and identify in many estuaries the issue of coastal squeeze resulting from the maintenance of coastal defences. The Environment Agency develops Regional Habitat Creation Plans to ensure both freshwater and intertidal habitat creation is planned and delivered in a strategic manner.

Under the IPENS programme, Site Improvement Plans (SIPs) may identify coastal squeeze as an issue, and the actions required by relevant organisations to achieve and maintain the site in favourable condition, such as habitat creation by managed realignment. The Environment Agency requires advice on delivery of compensatory habitat that will maintain the coherence of the Natura 2000 network where flood and coastal erosion risk management activities are shown to be having an adverse effect on integrity. If appropriate assessments have concluded that maintaining flood defences will adversely affect the integrity of a Natura 2000 site, action is needed to provide compensatory habitat. This work also addresses remedies for estuarine and coastal SSSIs which are in unfavourable condition as a result of flood risk management, also listed in Table 1.1. Advice needs to be based on good evidence and agreed approaches, with an understanding of limitations of knowledge. This will enable effective planning for the actions needed which can be delivered to fulfil legal and policy obligations.

1.2 Sites of Special Scientific Interest and Site-level Condition Assessment

The underpinning information that is used to identify the factors that need addressing in management plans and SIPs comes from a programme of condition monitoring of SSSIs. Since 2000, there has been increased availability of information for SSSIs. Details of each site are now available via the Natural England website, showing the reasons why it was designated, the management requirements needed to maintain it, and the records of assessment of the condition of the notified features.

Natural England assesses the condition of SSSIs using standard methods developed by the Joint Nature Conservation Committee (the United Kingdom government's wildlife adviser) and the UK statutory nature conservation bodies (JNCC, 2004). In England, SSSIs are divided into smaller, more practical monitoring areas called 'units'. Each SSSI unit will have one or more notified features, which have one or more measurable characteristics that can be used to determine its condition (e.g. habitat extent and structure, species composition). A list of special features, and the targets against which they are measured on a unit, are specified in a 'favourable condition table' for each SSSI. After the assessment, the information gathered is used to determine if the unit meets all the required levels to assign it to one of the following condition categories:

- Favourable: this means that special features are in a healthy state and are being conserved for the future by appropriate management.
- Unfavourable recovering: this means that all necessary management measures are in place to address the reasons for unfavourable condition and if these measures are sustained, the site will recover over time.
- Unfavourable–no change or Unfavourable–declining: these terms are used to describe sites where the special features are not being adequately conserved, or are being lost. If appropriate management measures are not put in place, and damaging impacts are not addressed, these sites will never reach a favourable or recovering condition.
- Part destroyed or Destroyed: these terms describe a very small number of sites where there has been fundamental and lasting damage. The special features have been lost permanently and favourable condition cannot be achieved.

The assessment of SSSIs is also used in reporting on the status of features within Natura 2000 sites. Assessment of condition is a requirement in order to ensure that factors affecting condition and the remedies to achieve improvements in condition are put in place, both by individual landowners or public bodies.

Due to the dynamic nature of estuary systems, it is important to try and predict likely changes that affect long-term sustainability of designated features. These predictions need to be based on both analysis of past changes as well as understanding estuary morphology, enabling more effective management to be put in place. However there are risks in this approach, as predictions can be affected by a range of factors, and can be disputed and challenged. However, it would be ineffective to wait until negative changes occur and then aim to fix them, so this project aims to set out an evidence-based approach to understanding where there are risks, or threats to achievement of favourable condition, and the optimum locations to address these.

1.3 Background to condition targets for SSSIs

Public Service Agreements (PSAs) formed part of the obligations of public bodies up to 2010. These were used to set out the priority outcomes that Government wanted to be achieved. In 2004 a PSA target was agreed to bring into favourable or recovering condition (known as 'target condition') 95% of the area of Sites of Special Scientific Interest (SSSIs) in England by December 2010. This focused the efforts of Natural England and the Environment Agency to understand and improve the condition of protected sites where flood and erosion risk management was affecting condition. In estuary complexes, where flood risk management is a key activity for the Environment Agency in achieving its contribution to the 2010 target, minimum figures for creation of intertidal habitat through managed realignment were agreed for sites affected by coastal squeeze, to ensure progress towards ‘target condition’ was made. These initial contributions were based on an understanding of the available evidence about the scale of saltmarsh loss since designation in each estuary complex. Where action was taken to progress habitat creation all SSSI units within each estuary complex were then assessed by Natural England as ‘unfavourable recovering’ and reported as such.

As coastal squeeze is an issue requiring a long-term approach, it was also agreed that, after December 2010, these ‘unfavourable recovering’ units would only remain in this condition if there was additional intertidal habitat creation to make up for ongoing and past losses of habitat due to coastal squeeze. Therefore, to remain in ‘recovering condition’, strategic flood risk management plans had to be in place to identify what was needed in future to secure favourable condition in the longer term. Building on these targets, the Government’s objective as set out in ‘Biodiversity 2020’ (Defra, 2011) is for at least 50% of the total area of SSSIs to be in a ‘favourable’ condition by 2020, with at least 45% of the remaining area of SSSIs to be in recovery and expected to reach favourable condition (once management plans have taken effect).

Table 1.1. Estuary complexes and relevant designations

Estuary Complex	Key SSSIs within complex	Key Natura 2000 Sites within complex
Suffolk/Hamford Water Blyth Alde and Ore Deben estuary Hamford Water, Stour and Orwell	Minsmere-Walberswick Heaths and Marshes Alde-Ore Estuary Deben Estuary Hamford Water Stour Estuary Orwell Estuary	Minsmere-Walberswick Heaths and Marshes SAC Minsmere-Walberswick SPA Alde-Ore Estuary SPA Orfordness Shingle Street SAC Alde Ore and Butley Estuaries SAC Deben Estuary SPA Hamford Water SPA; Stour and Orwell Estuaries SPA
Essex estuaries	Colne Estuary Blackwater Estuary Dengie Crouch and Roach Estuaries Foulness	Essex Estuaries SAC Denge Mid-Essex coast Phase 1 SPA Foulness Mid-Essex coast Phase 5 SPA Blackwater Estuary mid-Essex coast Phase 4 SPA Colne Estuary mid-Essex coast Phase 2 SPA
Greater Thames	Benfleet and Southend marshes South Thames Estuary and Marshes Medway Estuary and Marshes The Swale	Thames Estuary and Marshes SPA Medway Estuary and Marshes SPA The Swale SPA
The Solent	Chichester Harbour Langstone Harbour Portsmouth Harbour Lee-on-Solent to Itchen Estuary Hythe to Calshot Marshes North Solent Hurst Castle and Lymington River Estuary Brading Marshes to St Helens Ledges Ryde Sands and Wooton Creek Medina Estuary Newtown Harbour Yar Estuary Christchurch Harbour	Solent Maritime SAC Solent and Southampton Water SPA Portsmouth Harbour SPA Chichester and Langstone Harbour SPA
Severn	Severn Estuary Upper Severn Estuary Bridgwater Bay	Severn Estuary SAC Severn Estuary SPA
Humber	Humber Estuary	Humber Estuary SAC Humber Estuary SPA

1.4 Objectives of the Project

In order for estuary SSSI units to be realistically assessed as being in favourable or unfavourable recovering condition following intertidal habitat creation, there must be confidence at the wider scale that the estuary can sustain adequate habitat of the appropriate quality. Hence, intertidal habitat creation will have to be carefully targeted at locations that promote estuary ‘health’ (see below). Intertidal habitat creation has to be sustainable, to clearly shift SSSI unit condition from ‘unfavourable recovering’ towards ‘favourable’ by 2020, and to maintain this condition over the longer-term. Hence, the main objectives of this project were to develop a method that will determine:

- how far an estuary SSSI is from favourable condition with regard to its morphology and amount of intertidal habitat;
- for a site in unfavourable condition, identify how much intertidal habitat creation would be needed to move it towards favourable condition; and
- potential locations for intertidal habitat creation that are morphologically beneficial for estuary form and will promote estuary equilibrium and health.

The ‘health’ of an estuary is founded on the relationship between its physical form and function, and so the estuary should be in dynamic equilibrium with natural wave, tidal and sediment transport processes. The health of an estuary can be explained by its overall morphology of which the most easily measured attribute is planform (the outline of the estuary as seen from above). This project develops a practical (as far as possible) methodology that allows a user to predict the equilibrium planform of an estuary. They will then be able to compare the equilibrium planform with the observed planform to support other assessments of where intertidal habitat creation would encourage achievement of a healthy estuary.

The method looks forward in demonstrating the amount of intertidal area that a healthy estuary can support. It moves away from just looking at past historic extents and rates of intertidal loss due to coastal squeeze, often extrapolated to set future intertidal habitat creation targets. The method is based around establishing how far an estuary is from the ‘ideal’ morphological equilibrium and determines where habitat creation would bring an estuary system towards morphological equilibrium whilst also taking account of physical limitations such as hard geology or major developments. The method can be integrated with information about the quality of intertidal habitat obtained at a unit level by ground-based surveys. The extent of past change would be reflected in the results of the analysis, but taking a system approach means that taking remedial action in the long term is not solely based on those areas of intertidal that have been lost.

1.5 Methods for Predicting how far an Estuary is from Equilibrium

There are several predictive methods that could be used to understand and interpret estuary morphology. They are categorised by considering how they deal with morphological changes in time, and how they deal with morphological changes in space. Most methods belong to one type in both the space and time categories. Short-term predictive methods (referred to as ‘bottom-up’ methods) represent detailed physical processes at local space scales over short timescales. Long-term predictive methods (referred to as ‘top-down’ methods) are based on conceptual ideas and operate at larger space and longer timescales. 'Hybrid' methods combine the best features of bottom-up and top-down methods.

In this project, the objective is to determine the equilibrium state of landscape-scale estuary systems (the sites listed in Table 1.1). The best methods to achieve this objective at this scale are top-down 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 reclamation, engineering works or dredging. Two of the most commonly used methods are Historical Trend Analysis / Expert Geomorphological Assessment and Regime Theory. It should be noted that the concept of equilibrium is one where the ideal situation involves oscillation around a particular state, not a static form of equilibrium (HR Wallingford et al., 2007).

1.5.1 Historical Trend Analysis / Expert Geomorphological Assessment

The Historical Trend Analysis method essentially involves the interrogation of time series data to identify directional trends and rates of processes and morphological change, over varying time periods. The most common dataset is historic bathymetric charts. The Expert Geomorphological Assessment method incorporates output from Historical Trend Analysis, but also takes account of information about current physical processes, geological constraints and sediment properties, and general relationships between processes and morphological responses. As long as due regard is taken of data origins and accuracy, predictions based on extrapolation of trends can provide a reliable estimate of the most probable evolution of the estuary. However, a simple linear extrapolation into the future will not take into consideration the complex nature of natural estuary systems where future conditions may differ from the past. There are many reasons for this type of departure including climatic or human-induced change, or the presence of geological controls.

1.5.2 Regime Theory

Regime Theory uses empirical relationships between estuary gross morphology and tidal prism, through simple power-law equations. Predictions of the effect of, for example, managed realignment of flood defences is made in terms of the resulting changes in estuary cross-section. Crucial to the whole philosophy of prediction using 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. The width and depth of the estuary will therefore change over time towards a state of dynamic equilibrium or 'most probable state'.

Achievement of dynamic equilibrium by any individual estuary can be affected by human interference and different parts of its form are likely to be at different stages of adjustment to natural process inputs and geological controls. Hence, the estuary will seek to reach a steady state over the long term by oscillating around theoretical equilibrium morphologies over the short- to medium-term. Regime theory provides a simple and effective (and practical) method of predicting equilibrium morphology in an estuary.

Given these attributes, Regime Theory was chosen as the most appropriate predictive method to achieve the objectives of this project. This ties in with the use of the attribute of 'morphological equilibrium' of an estuary within the Common Standards Monitoring (CSM) guidance for estuaries (JNCC, 2004). This is described as the relationship between cross-sectional area and tidal prism at the estuary mouth, and is based on previous work commissioned by English Nature (Coastal Geomorphology Partnership 1999).

The application of Regime Theory in this project uses GIS and Excel spreadsheet platforms, which allow the user to carry out step-by-step data input and calculations, which are tested using two case study estuaries; Chichester Harbour and the Humber Estuary (Figure 1.1). The method relies on bathymetry data and tidal datum data being available that can be imported into the GIS. These are the critical data upon which the analysis is based. Further details on data requirements are provided in Section 3. The Crouch-Roach Estuary system was considered as a third case study, but the bathymetry data did not provide 100% coverage, and so it was not carried forward. The implications of an incomplete bathymetry dataset are further discussed later in this report.

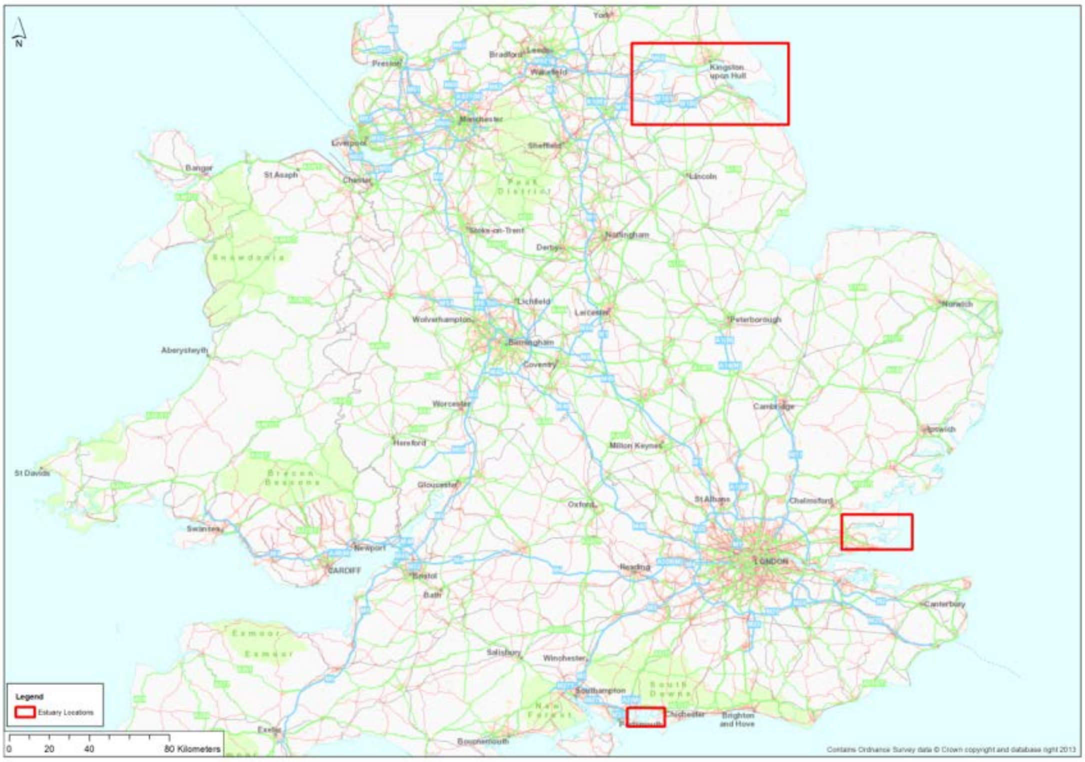

Figure 1.1. Location of the case study sites; Chichester Harbour, Humber Estuary and Crouch-Roach Estuary

2 PRINCIPLES OF REGIME THEORY

The Regime Theory used in this project 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 this project, the cross-sectional area at mean high water neap tide is used instead of mean sea level. This is because mean high water neap 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 mean high water neap tide within the tidal environment will have tidal current velocities that approach zero.

2.1 Applying Regime Theory to Inter-estuary Analysis

When the relationship is applied to a number of estuaries it is found to be linear when both data sets 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 2.1). The regression (regime) equation for the whole dataset is (All United Kingdom Estuaries regime equation):

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

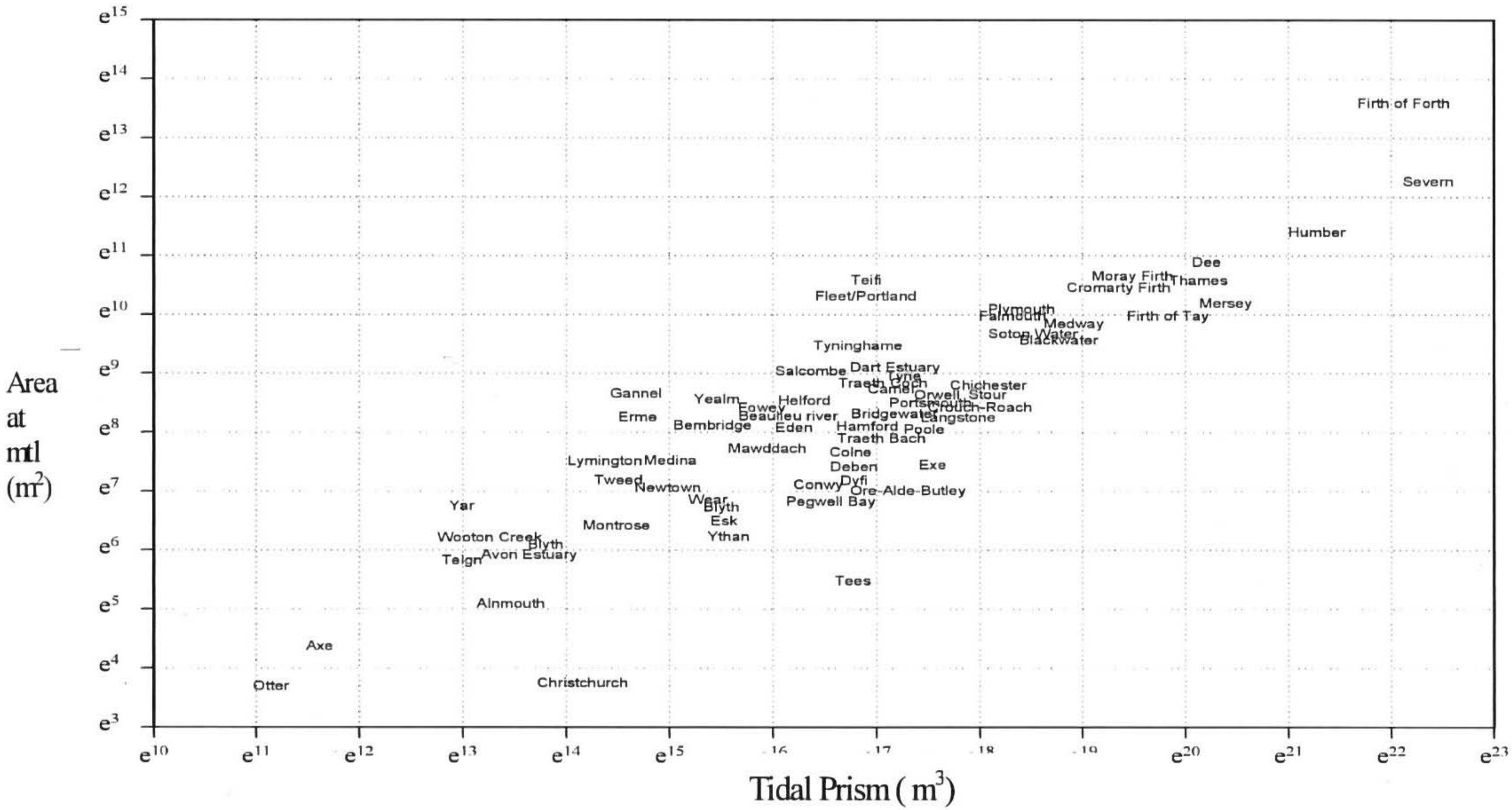

Figure 2.1. Tidal prism – cross-sectional area relationship for 66 estuaries around the United Kingdom coast (from Townend et al., 2000)

Townend et al. (2000) also divided the dataset into types of estuary, with the United Kingdom estuaries falling into three of four groups:

Group 1 - fjords (no data available).

Group 2 - rias, coastal plain estuaries of the Solent and selected complex estuaries.

$CSA = 0.0305.P^{0.747}$ ($r^2 = 0.92$);

Group 3 - all other coastal plain and complex estuaries.

$CSA = 0.0004.P^{0.911}$ ($r^2 = 0.90$); and

Group 4 - bar built estuaries.

$CSA = 0.006.P^{0.783}$ ($r^2 = 0.66$).

Townend (2005) further refined the estuaries into two overall groups based on how they have infilled with sediment during Holocene sea-level rise (Figure 2.2):

- Group B - characterised by the presence of exposed rocky shores, cliffs, or rock platforms, typically found in hard rock geology and in areas with limited sediment supply (partially responded to Holocene deposition); $CSA = 0.0058.P^{0.848}$ ($r^2 = 0.90$); and
- Group C - found in softer geology, with sand flats and flood/ebb tide deltas often present and, in some cases, barrier beaches or linear banks (mature in the context of Holocene deposition); $CSA = 0.0003.P^{0.930}$ ($r^2 = 0.91$).

Townend (2005) compared the United Kingdom data to an extensive dataset published by Hume and Herdendorf (1993) for New Zealand. Townend (2005) divided the New Zealand data into three groups, open embayments (HH-A), elongated embayments (HH-B) and inlets, estuaries and rivers (HH-C), and found a favourable comparison with the United Kingdom data (Figure 2.2).

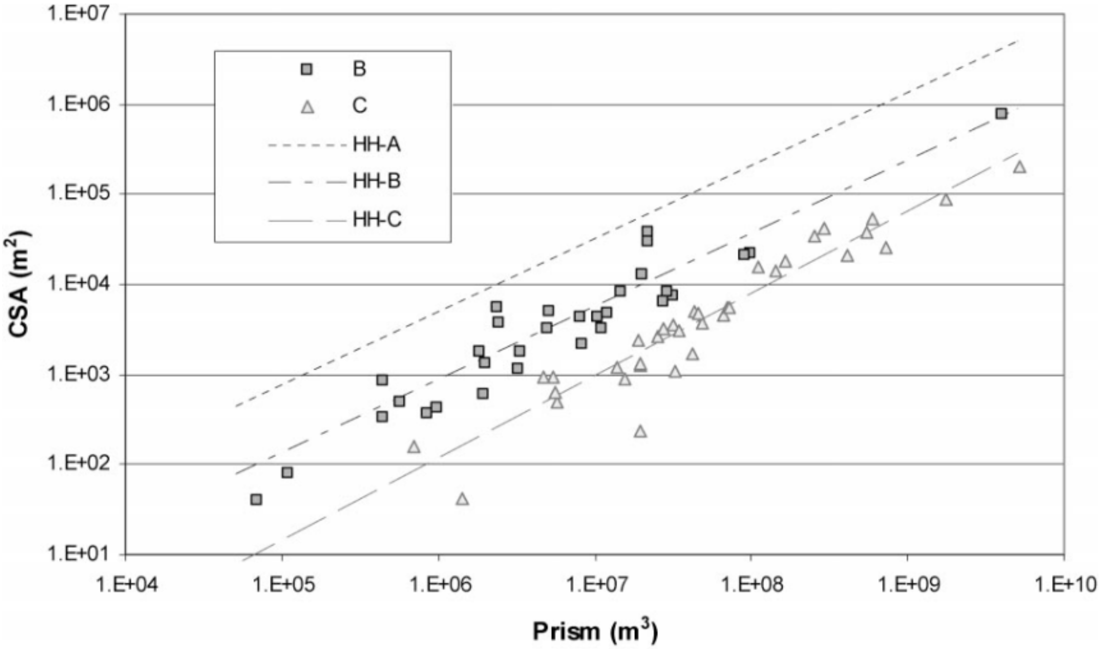

Figure 2.2. Tidal prism – cross-sectional area relationships for 66 estuaries in the United Kingdom divided into two groups by type (from Townend, 2005). The dashed lines are comparable data from New Zealand where HH-A = open embayments, HH-B = elongated embayments and HH-C = inlets, estuaries and rivers.

Figure 2.2 shows that although individual estuaries may depart from the ideal relationship between flow (tidal prism) and form (cross-section) 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 'health' of a given estuary compared to others in a regional group (but see uncertainties below in Section 2.3).

2.2 Applying Regime Theory to Intra-estuary Analysis

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

2.3 Uncertainties with Regime Theory used in this Project

The Regime Theory used in this project requires only geometric and water level information to be used as inputs. This is so the method is simple to apply by the user. 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 project to include what are more complicated mathematical formulae (which are still not fully understood and to date haven't been applied successfully) into what is essentially a practical high-level method. 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. Hence, an assessment of how a particular constraint is affecting the result from the Regime Theory used in this project will require expert judgement to be applied at the end of the step-by-step process. This is covered in the constraints section (Section 6).

Various attempts have been made to reduce the impact of these factors in the empirical method, including classifying estuaries into different geomorphological types (for United Kingdom estuaries see Townend et al., 2000 and Townend, 2005). By producing regime relationships for each separate geomorphological type, the range of scatter around the regime equation can be reduced. This is because relationships for geomorphologically and geographically similar estuaries show greater empirical adherence resulting from similar tides, waves, and sediment transport. This is exemplified by the coefficients of determination (r^2), which for all United Kingdom estuaries is 0.75, and for the various sub-sets of geomorphological classifications is generally greater than 0.90. HR Wallingford et al. (2007) argued that the remaining scatter would still be due to wave action and longshore sediment transport.

2.4 Drivers for improved understanding of estuary morphology

The various obligations of Natural England and the Environment Agency to maintain or restore the condition of estuaries affected by coastal squeeze require an objective and repeatable way to understand overall estuary morphology. The main drivers are:

- Natural England's responsibility for carrying out site-level condition assessments, and the Environment Agency responsibility for development and delivery of estuary flood risk management strategies.
- meeting targets for SSSIs set out in the Biodiversity 2020 strategy for England's wildlife and ecosystem services;
- Water Framework Directive obligations which require 'good ecological potential' to be achieved; and
- Habitats Directive obligations requiring the achievement of 'Favourable Conservation Status'.

2.4.1 Site-level Condition Assessments

An assessment of the condition of the interest features and attributes of an estuary should be built on the relationship between its broad-scale physical form and function. The process by which site-level condition assessments of protected sites are undertaken is described in Section 1.1. Local measurements of physical parameters aid the condition assessment of each feature attribute at a unit level, but they must be viewed within the context of the broader-scale natural processes that are contributing to change. This is particularly so for estuaries which are very dynamic systems and potentially subject to longer-term fluctuations in morphology.

There is also a need to understand each estuary within a wider complex, to enable comparisons and ensure that the state of each estuary is known.

Regime Theory and site-level condition assessments can be linked. A unit-level assessment will provide some information on observed changes to extent and quality (subject to information being available of previous states). If there are declines in either of these, the use of Regime Theory can provide an estuary-level analysis of the overall estuary morphology condition. If this shows that certain parts of the estuary are narrower than the predicted form, erosion may be occurring and can be checked on site. If there are areas that are wider than the predicted form, these areas may be accreting sediment. The results can inform the identification of optimal intertidal habitat creation locations that are needed to shift 'unfavourable recovering' units towards favourable condition by promoting estuary equilibrium. Hence, Natural England can apply the Regime Theory method to determine the state of the estuary morphology attribute and what action (along with other measures where relevant) is needed to move towards and sustain dynamic equilibrium in the longer term at both a site level or, where this is not possible due to physical constraints, within the same complex.

2.4.2 Water Framework Directive

European Union Water Framework Directive (WFD) monitoring is currently underway in the United Kingdom to establish the status of transitional and coastal water bodies, which need to achieve 'good ecological potential'. Managed realignment is one measure that can help meet the WFD obligations. These include the requirement to restore water bodies to good ecological status by maintaining the condition of water quality, the functioning of morphology within a coastal or estuarine system and re-establishing the ecological integrity of intertidal habitats. The use of Regime Theory to predict equilibrium form is directly linked to the Water Framework Directive obligation of functional morphology.

The Environment Agency is investigating the value of realignment sites for delivering water quality benefits under the Water Framework Directive. A European Union LIFE Environment project called 'Managed Realignment Moving Towards Water Framework Objectives' reported in 2010 (Environment Agency, 2010). The project reviewed a range of realignment sites in the United Kingdom and Europe, and used the Humber Estuary as a key location for examination.

2.4.3 Habitats Directive

Reporting on the conservation status of habitats and species in the Habitats Directive takes place every six years. The latest United Kingdom report on Favourable Conservation Status for the Habitats Directive Annex I habitats was completed in 2013 (http://jncc.defra.gov.uk/page-6563). This report used information from SSSI condition assessments on saltmarsh features. Improving the quality of SSSI feature assessments through use of the Regime Theory (see Section 2.4.1) will benefit future reporting. This is of particular importance as one aspect of Article 17 reporting is the 'future prospects' of a feature.

3 DATA REQUIREMENTS

The critical data upon which the Regime Theory method used in this project relies are recent bathymetry, tidal datum elevations and sediment particle size. The regime 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 mean high water neap tide at the mouth. Given this relationship, all the observed estuary morphological parameters (cross-sectional area, width and mean depth, Section 4) are calculated using the bathymetric data set relative to the elevation of mean high water neap tide, whereas the observed tidal prism is calculated using a combination of the mean high water spring tide datum, mean low water spring tide datum, and the bathymetry.

Although the regime equation itself does not rely on particle size as an input, a later part of the method adopted in this study does require an estimation of median particle size for the estuary of interest.

3.1 Bathymetry

Digital bathymetry can be obtained from a variety of sources (e.g. Environment Agency, Harbour Authorities and Conservancy's, Associated British Ports, Natural England) and in three main forms; single beam echosounder, multibeam echosounder and LiDAR (see collection methods described in Appendix A). The best available bathymetry should be used. If the available bathymetry is not fit for purpose then a bespoke survey would be required to support the analysis.

To be considered as the 'best available', the bathymetry data should cover all intertidal and subtidal areas up to the seaward face of the front-line defence or up to mean high water spring tide where the coastal plain rises naturally into the hinterland. The data should stretch from the upstream tidal limit(s) to the mouth of the estuary defined by the transition to an unconfined open coast (effectively a straight line between the last two constrained points in the estuary). The types and extents of bathymetry data that are potentially available, and some of the quality assurance issues are demonstrated by the case study estuaries.

3.1.1 Humber Estuary

Several data sets were available for the Humber Estuary, but the best in terms of coverage was collected in 2005 by Associated British Ports, comprising a series of single beam echosounder transects across the estuary, coupled with LiDAR data across the intertidal areas (Figure 3.1).

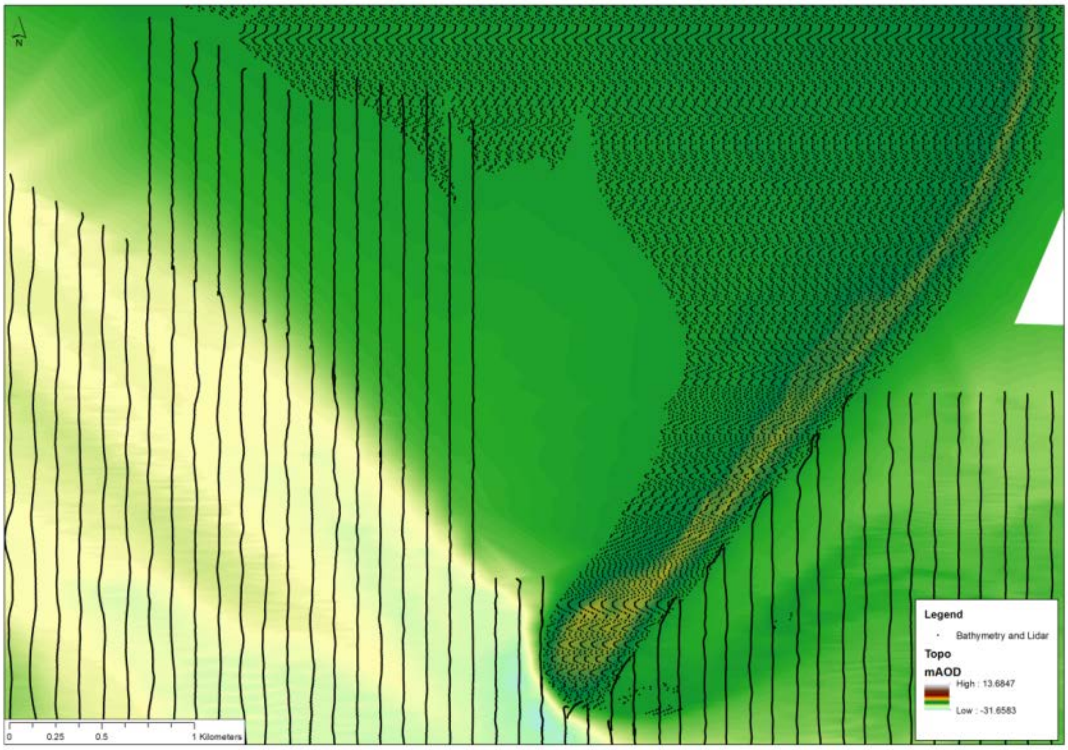

Figure 3.1. Echosounder transects and LiDAR data for the Humber Estuary collected in 2005 by Associated British Ports

3.1.2 Chichester Harbour

The best available bathymetry data set in terms of coverage for Chichester Harbour was collected in 2005 by the Chichester Harbour Conservancy and comprises a series of single beam echosounder transects across the channels, coupled with LiDAR data across the intertidal areas (Figure 3.2).

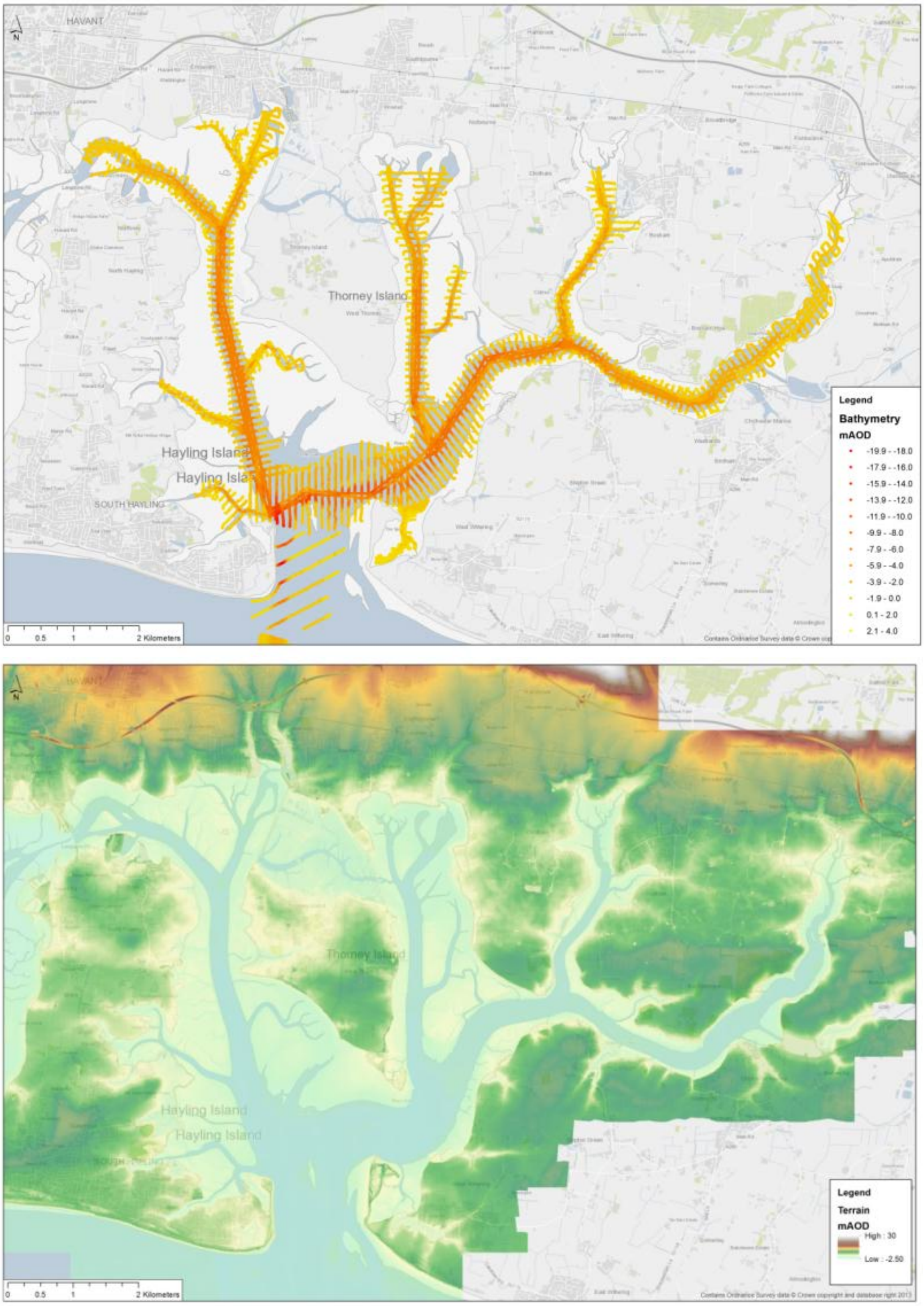

Figure 3.2. Echosounder transects (top) and LiDAR data (bottom) for Chichester Harbour collected in 2005 by Chichester Harbour Conservancy

3.1.3 Crouch-Roach Estuary

The bathymetry data for the Crouch-Roach was obtained from the Environment Agency and demonstrates one difficulty of obtaining a suitable data set, particularly for the subtidal reaches of a system. In this case, the subtidal geographical coverage of the data is limited to the main channels of the Crouch and Roach Estuaries, but data from the intricate system of connecting channels has not been collected (Figure 3.3). In addition, data from the mouth of the Crouch is also missing. Given this incomplete data set it is difficult to apply the method developed in this project and a bespoke survey would be needed to complete the bathymetric coverage.

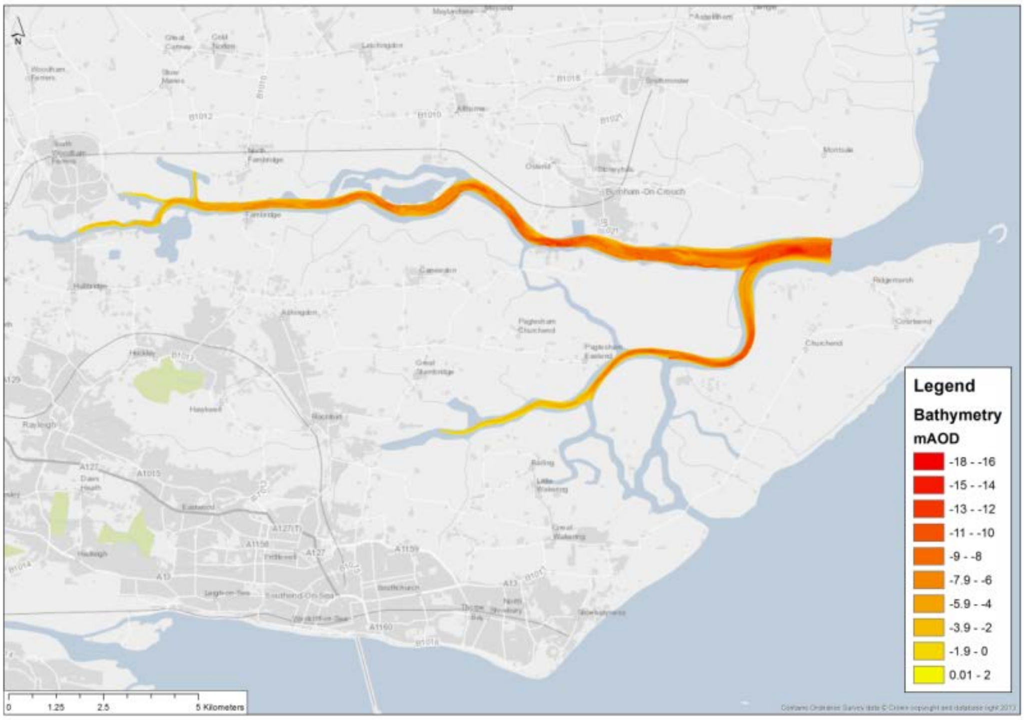

Figure 3.3. Extent of bathymetry data in the Crouch-Roach Estuary collected by the Environment Agency

3.1.4 Dealing with Gaps in the Bathymetry

There are several potential difficulties with the input and interpretation of bathymetry data. The first relates to data gaps and how they can be filled appropriately. Figure 3.4 shows a gap between the echosounder transects and LiDAR data in a shallow area near the mouth of the Humber Estuary. It is generally appropriate to perform a simple interpolation across the gap to provide a reasonable representation of the bathymetry in the gap.

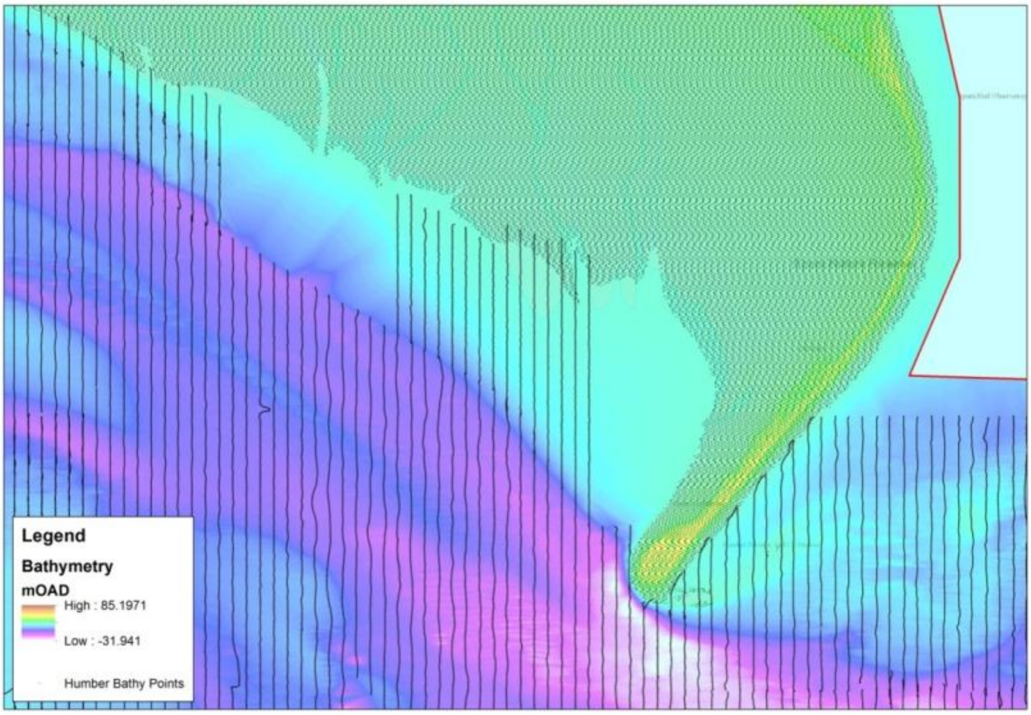

Figure 3.4. Gaps in the Humber Estuary bathymetry data

3.1.5 Dealing with Overlapping Transects

A second potential difficulty relates to multiple echosounder transects in approximately the same location. This is not a problem as long as the transects are consistent in their bathymetry values. However, there may be locations where transects overlap but their bathymetries are not consistent, which creates errors during interpolation (Figure 3.5). In this case a judgement has to be made as to which dataset is the most reliable and the poorer data removed.

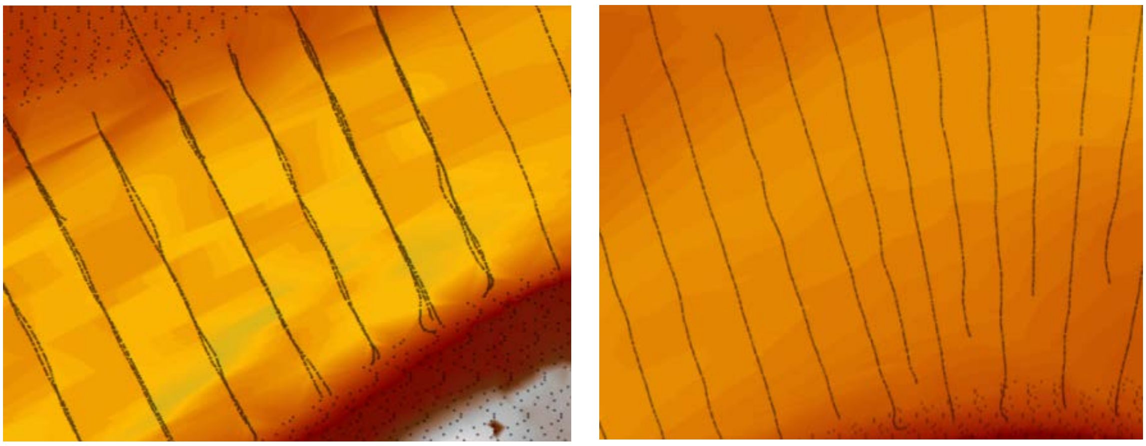

Figure 3.5. Interpolated multiple overlapping transects in the Humber Estuary (left) compared to interpolated single transects (right).

3.2 Tidal Datums

In order to calculate spring tidal prism it is necessary to know the elevations of tidal datums. In Regime Theory, the critical tidal datums are mean high water spring, mean high water neap and mean low water spring. Table 3.1 describes these tidal datum elevations for the three case study estuaries.

3.3 Particle Size

It is difficult to select a representative particle size for an estuary given the spectrum of spatially varying sizes that occur both laterally and longitudinally. Particle size across an estuary tends to be finer along the upper intertidal areas, coarsening towards the channel and being coarsest in the channel. Townend (2005) used generic median particle sizes of 0.5mm for sandy estuaries and 0.005mm for muddy estuaries but this is certainly an oversimplification.

A map of the median particle sizes for the lower Humber Estuary is shown in Figure 3.6 from which an estimation of the 'commonest' median can be made. It shows that the predominant mean particle sizes lie between 0.1mm and 0.2mm. In some cases, only a single or at best a few particle size analyses will be available.

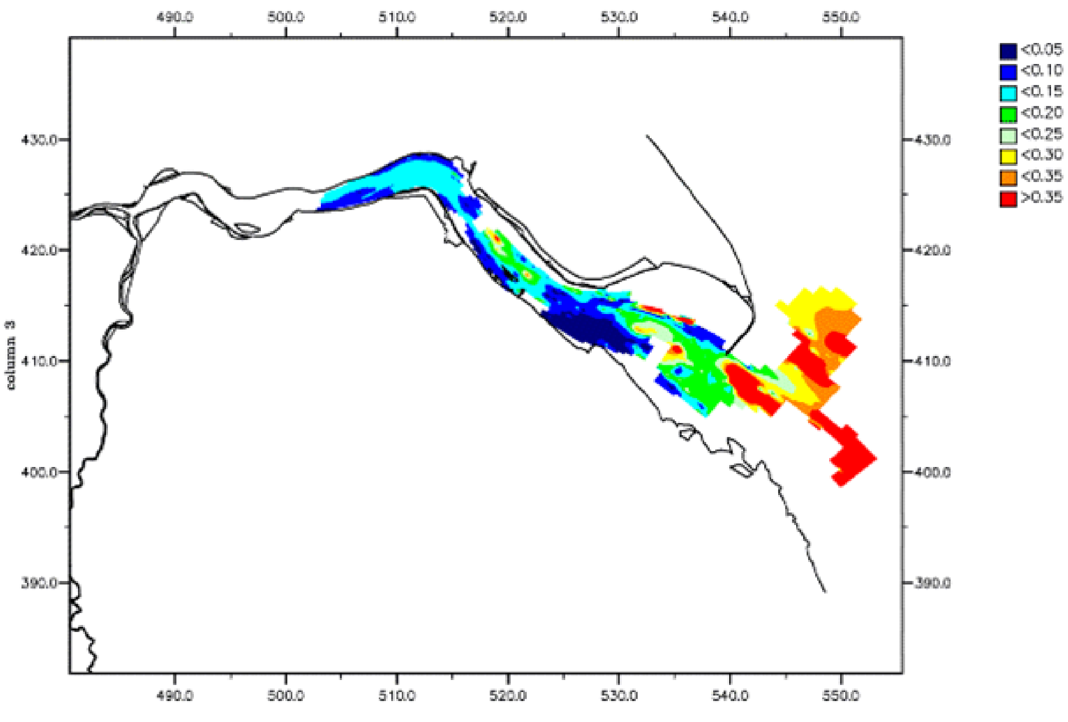

Figure 3.6. Median particle size distribution in the Humber Estuary

Table 3.1. Tidal datums in the three case study estuaries.

Tidal Station	Coordinates		Mean High Water Spring Tide (m OD)	Mean High Water Neap Tide (m OD)	Mean Low Water Spring Tide (m OD)
	Latitude	Longitude			
Humber Estuary					
• Spurn Head	53°35′N	0°07′E	3.00	1.60	-2.70
• Bull Sand Fort	53°34′N	0°04′E	3.00	1.60	-2.80
• Grimsby	53°35′N	0°04′W	3.10	1.70	-2.70
• Humber Sea Terminal	53°40′N	0°14′W	3.30	1.80	-2.80
• Immingham	53°38′N	0°11′W	3.40	1.90	-3.00
• Hull (King George Dock)	53°44′N	0°16′W	3.70	2.10	-3.20
• Hull (Albert Dock)	53°44′N	0°21′W	3.70	2.00	-3.20
• Humber Bridge	53°43′N	0°27′W	3.90	2.10	-3.00
• Burton Stather (Trent)	53°39′N	0°42′W	4.10	2.40	0.70
• Flixborough Wharf (Trent)	53°37′N	0°42′W	4.10	2.30	-0.90
• Keadby (Trent)	53°36′N	0°44′W	4.40	2.60	-0.40
• Owston Ferry (Trent)	53°29′N	0°46′W	4.30	2.40	Dry
• Blacktoft (Ouse)	53°42′N	0°43′W	4.20	2.50	-1.70
• Goole	53°42′N	0°52′W	4.30	2.30	-1.10
Chichester Harbour					
• Entrance	50°47′N	0°56′W	2.16	1.26	-1.84
• Northney	50°50′N	0°58′W	2.16	1.06	-2.24
• Itchenor	50°48′N	0°52′W	2.06	1.06	-2.14
Crouch-Roach Estuary					
• Rochford	51°35′N	0°43′E	3.00	1.90	Dry
• Burnham-on-Crouch	51°37′N	0°48′E	2.85	1.85	-2.15
• North Fambridge	51°38′N	0°41′E	2.95	1.85	-2.05
• Hullbridge	51°38′N	0°38′E	2.95	1.85	-2.05
• Battlesbridge	51°37′N	0°34′E	2.90	1.90	Dry

4 OBSERVED ESTUARY FORM

This section describes the methodology that allows a user to measure the observed form of the estuary against which the predicted equilibrium form is compared. This part of the method also sets up the structure of the GIS that allows the user to predict the estuary equilibrium at a later stage in the step-by-step process. The measurement of the observed form is carried out in four stages:

- import bathymetry into the GIS;
- overlay tidal datums on to the bathymetry;
- determine location of sections for analysis; and
- measure and compile observed estuary parameters.

More detail on how a user applies the step-by-step method in the GIS is provided in Appendix B - the Technical User Guide. The information in the Technical User Guide should be read in conjunction with this main document to fully understand the method.

4.1 Import Bathymetry into the GIS

The first step in the method is to import the bathymetry data into the GIS. The bathymetry data for the Humber Estuary and Chichester Harbour case studies are described in Sections 3.1.1 and 3.1.2, respectively. Bathymetry surfaces are created by interpolating between each echosounder survey transect and ‘stitching’ this data to the LiDAR data (Figures 4.1 and 4.2). More detail on how to import bathymetry into the GIS can be found in Sections 3, 4.1 and 4.2 of the Technical User Guide (Appendix B).

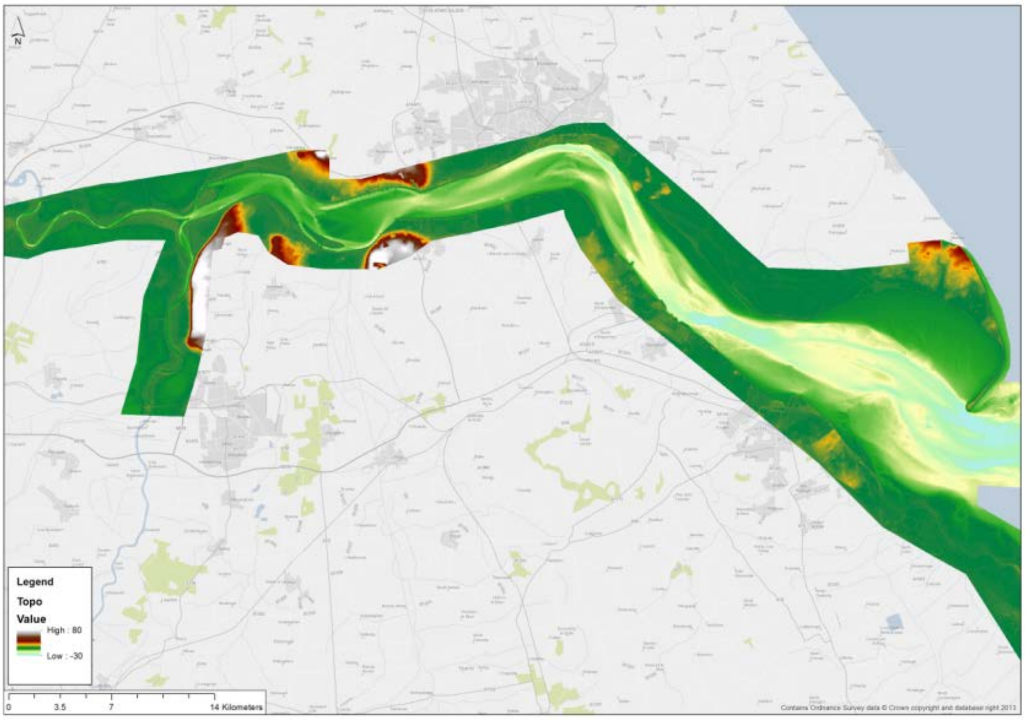

Figure 4.1. Humber Estuary bathymetry created by combining interpolated echosounder data with LiDAR data (see Figure 3.1)

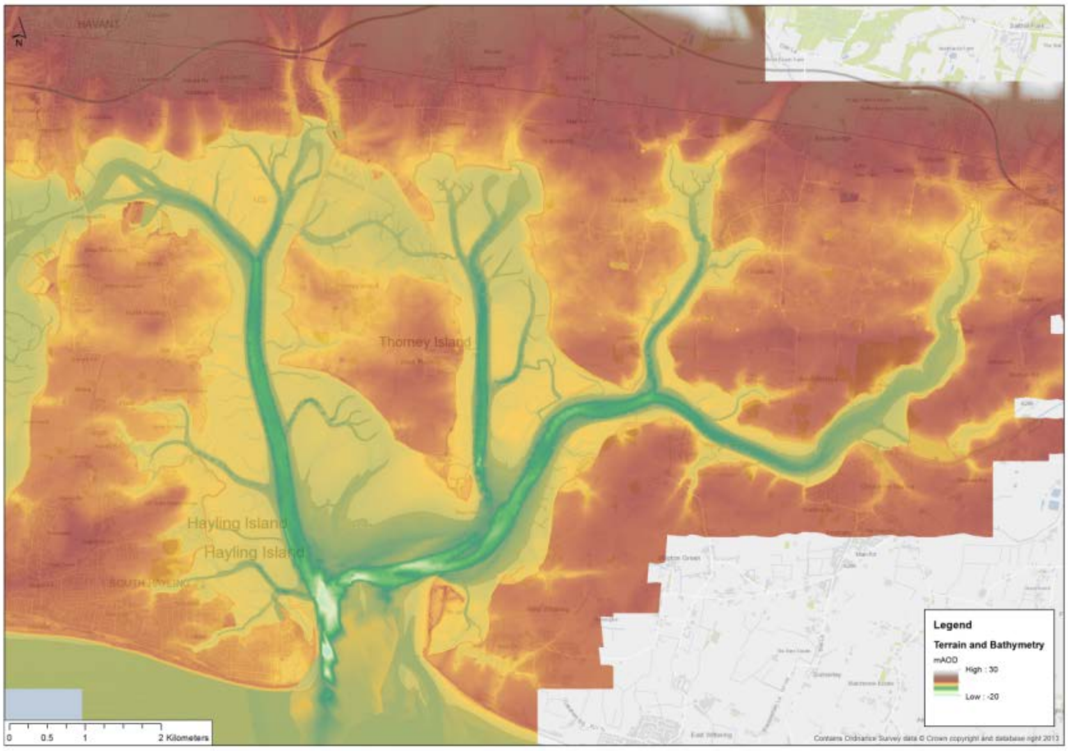

Figure 4.2. Chichester Harbour bathymetry created by combining interpolated echosounder data with LiDAR data (see Figure 3.2).

4.2 Overlay Tidal Datums on to the Bathymetry

Once the bathymetry has been uploaded into the GIS and there is confidence in the quality of the surface, the elevations of mean high water spring tide, mean high water neap tide and mean low water spring tide can be obtained from Admiralty Tide Tables and overlain on to the bathymetry. The tidal datums are published at tidal stations along an estuary (Table 3.1).

In most estuaries the elevation of a particular tidal datum will change with distance upstream. To create a surface that represents the tidal datum along the estuary will require linear interpolation between individual datum heights at each tidal station. For example, in the Humber Estuary, the elevation of each datum relative to OD is significantly different at the mouth (Spurn Head) compared to stations further upstream (Table 3.1). Figures 4.3 and 4.4 show tidal datum surfaces transposed on to the bathymetries of the Humber Estuary and Chichester Harbour case study estuaries, respectively. Section 4.3 of the Technical User Guide (Appendix B) provides information on how to create the tidal datum surfaces in the GIS.

Figure 4.3. Tidal datum surfaces in the Humber Estuary. MHWS = Mean High Water Spring. MHWN = Mean High Water Neap. MLWS = Mean Low Water Spring.

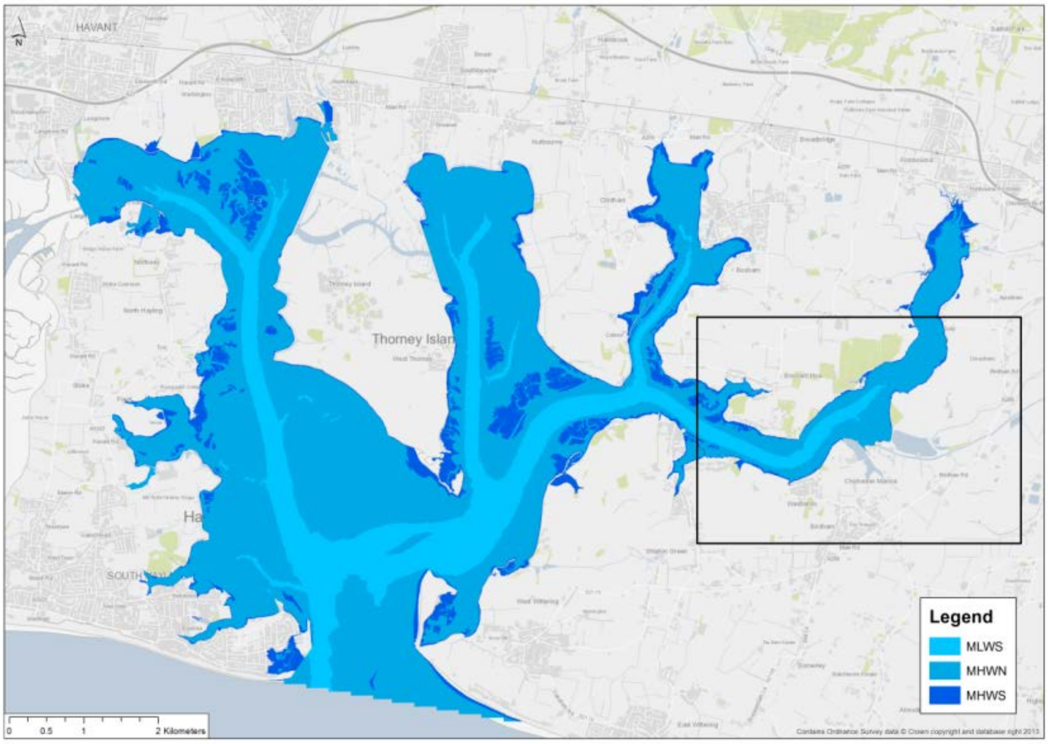

Figure 4.4. Tidal datum surfaces in Chichester Harbour. MHWS = Mean High Water Spring. MHWN = Mean High Water Neap. MLWS = Mean Low Water Spring. Box is enlarged in Figure 4.5.

In most estuary systems with multiple channels and reclaimed areas the creation of a bathymetry surface overlain with tidal datums may create unwanted datum surfaces landward of the critical surfaces in the channel (Figure 4.5). These may occur in areas cut-off or set-back from the main channel which will not be used in the analysis. These superfluous datum surfaces should be manually removed to leave only the datum surfaces in the main channel that are impinged by the rise and fall of water in the estuary.

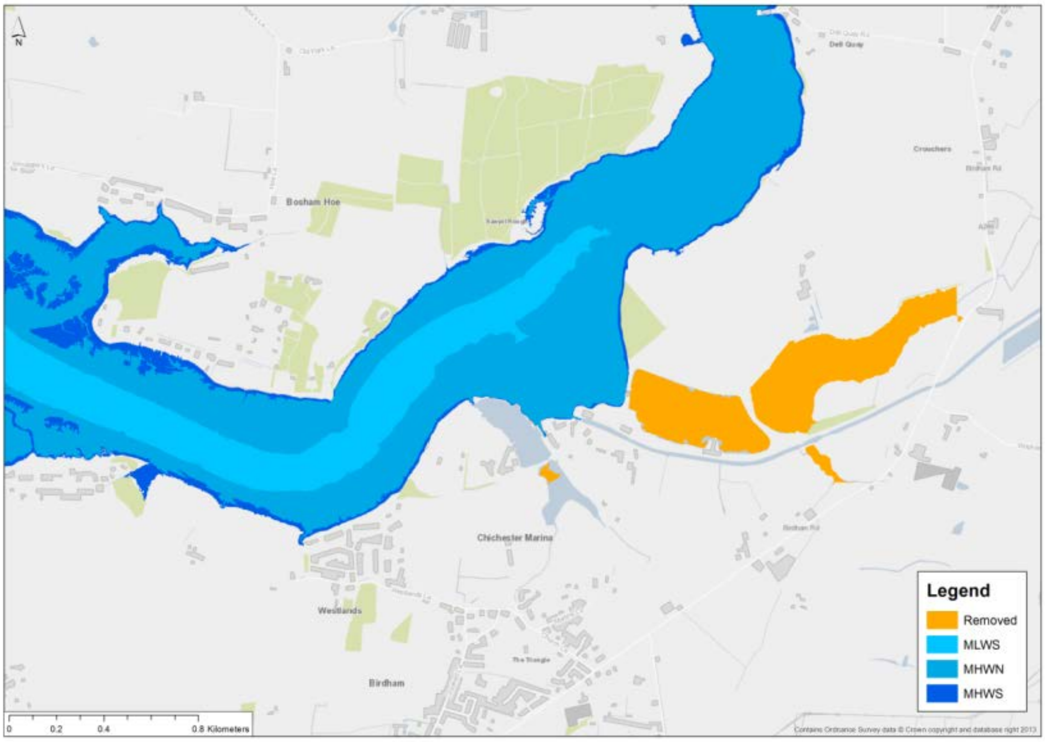

Figure 4.5. An example of superfluous datum surfaces (in orange) in Chichester Harbour. Location is shown in Figure 4.4. These surfaces were created in the GIS but are not part of the channel that is affected by the tidal prism, so they should be removed.

Section 4.3 of the Technical User Guide (Appendix B) describes a way to remove superfluous datum surfaces (using the Asset Information Management System data initially imported into the GIS). However, further manual interrogation may be required to fully complete the process.

4.3 Determine Location of Sections for Analysis

Following establishment of the tidal datum surfaces, and removal of superfluous surfaces outside the area affected by the tidal prism, the sections which will be used in Regime Theory should be defined. The number of sections will be determined by the size of the estuary. In a relatively small estuary such as Chichester Harbour where the longest channel is 10km, sections approximately 200m apart would be suitable, whereas for a large estuary such as the Humber, which is about 75km long, sections approximately 1km apart would be appropriate. The sections should stretch between mean high water spring tide on either side of the estuary and be perpendicular (as far as possible) to a line along the centre of the channel.

4.3.1 Automatic Positioning of Sections

The determination of the section locations is a critical part of the method and requires user input to define. In the first instance, a line should be drawn manually in the GIS along the approximate centre of the estuary channel(s). The GIS will then automatically draw the sections perpendicular to this line at the spacing prescribed by the user, starting this distance downstream from the tidal limit. The remaining sections will be added incrementally down-estuary until the mouth is reached (Figures 4.6 and 4.7). Further detail on the positioning of sections in the GIS is provided in Section 4.4 of the Technical User Guide (Appendix B).

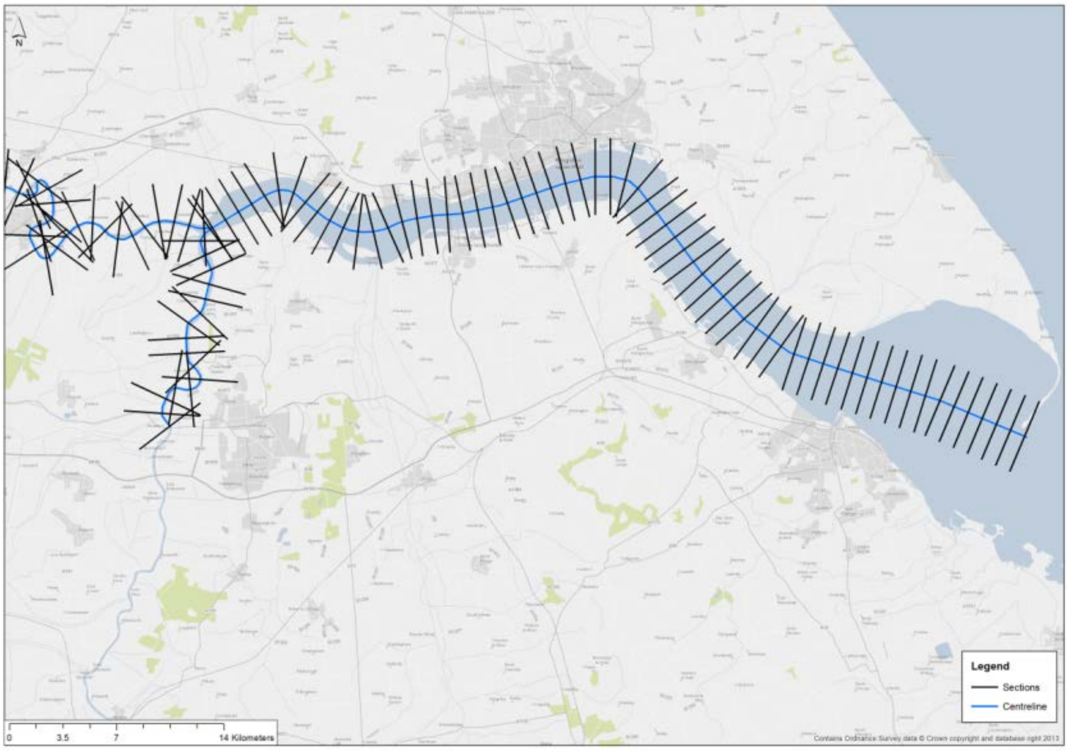

Figure 4.6. Automatic positioning of sections in the Humber Estuary at a spacing prescribed by the user (1km in this case)

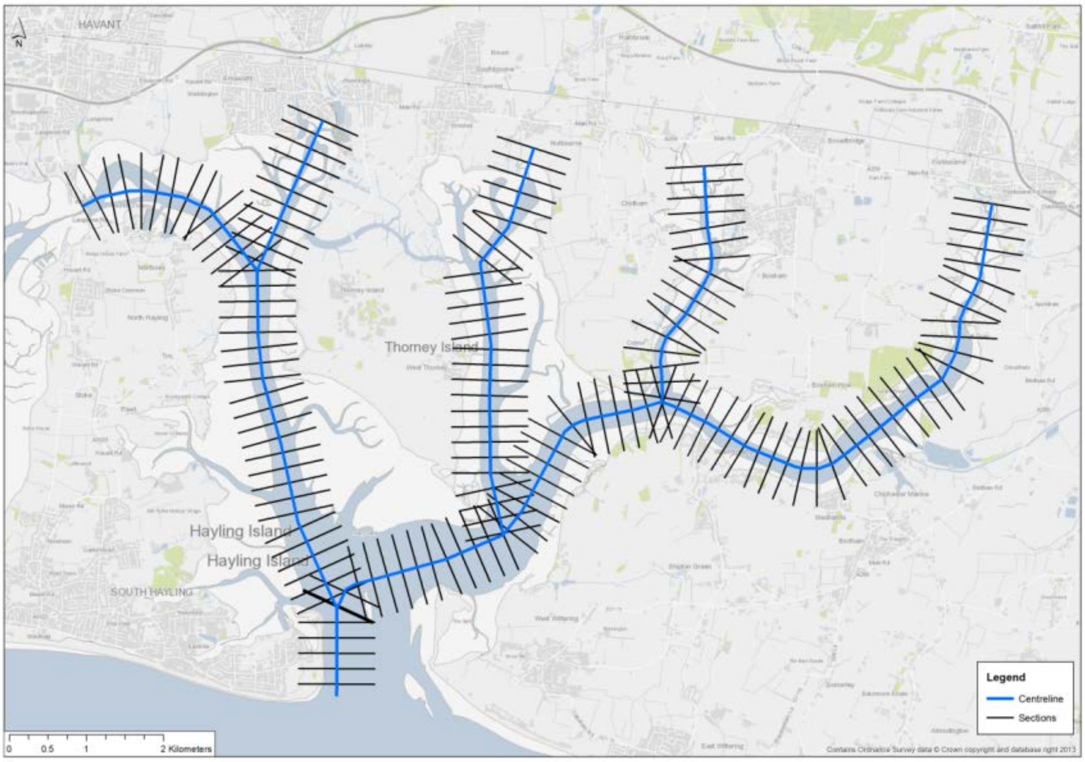

Figure 4.7. Automatic positioning of sections in Chichester Harbour at the spacing prescribed by the user (200m in this case)

4.3.2 Manual Manipulation of Sections

Although the initial locations of the sections are automated in the GIS (after the centre line has been drawn manually) some of the sections will need to be moved or removed manually to account for tributary channels, channel cut-offs and channel confluences. Tributary channels and cut-offs to the main channel should be identified by the user and then the automated sections that cut both the main channel and the tributary / cut-off should either be moved or removed. This is to ensure that the sections reflect the main channel only and do not incur anomalies caused by inclusion of tributary channels. For example, the automatically positioned Section A on Figure 4.8 (top) crosses both the tributary channel and the main channel and has been removed (Figure 4.8, bottom). In this way, Section B (which has been re-oriented slightly) now captures both the tidal prism of the upstream main channel and the tidal prism of the tributary channel. A similar procedure has been carried out further upstream along the main channel where Sections C and D have been removed (Figure 4.8).

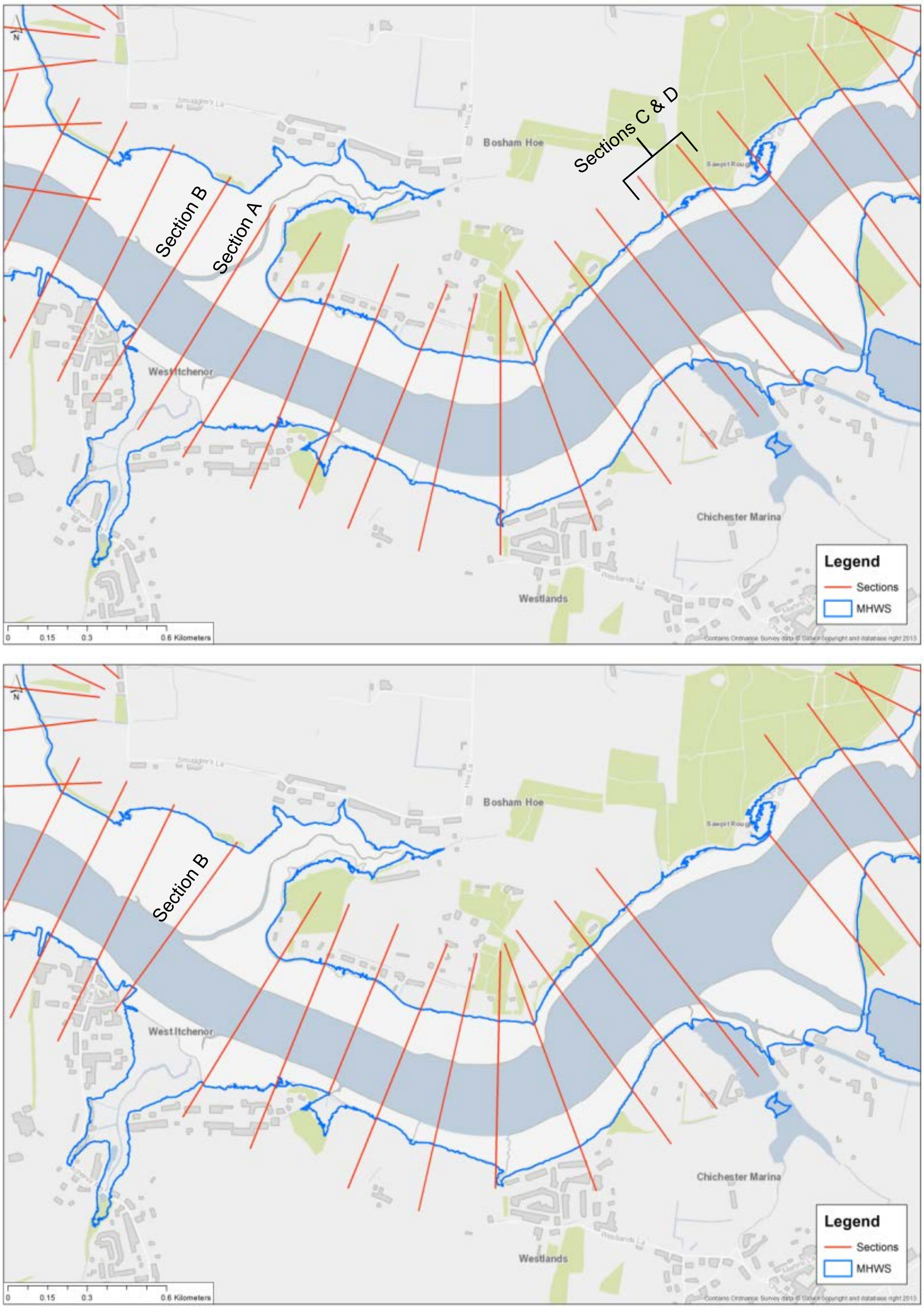

Figure 4.8. Examples of when to manually remove automated sections that cut across both the main channel and a tributary channel

In many cases, the tributary channel may only be a relatively small tidal creek meandering across an adjacent intertidal area. In this case, the anomaly would be almost imperceptible and no adjustments to the position of the section need to be made. The determination of which sections to move or remove is a user decision.

Another difficulty associated with the automation of section positions is at the confluence of two main channels in an estuary system. At these locations the channel centre lines will be at an angle to each other and the created sections may overlap (Figure 4.9, left panel). The method cannot work with sections that overlap because there will be 'double-counting' of estuary parameters. Hence, some of the sections need to be moved or removed manually so that they do not overlap at the confluence of two channels. Figure 4.9 (right panel) illustrates how this is done.

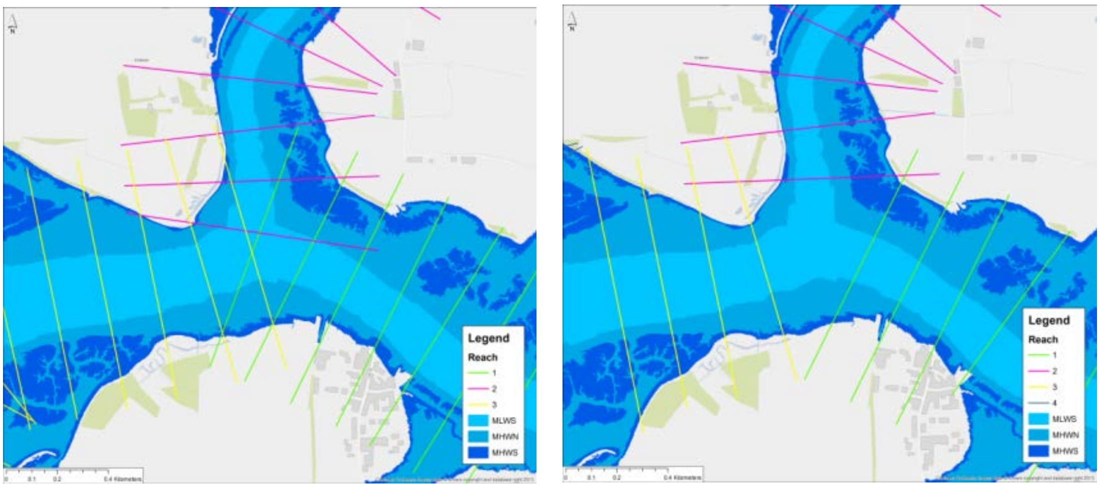

Figure 4.9. Example of when to manually move or remove automated sections that overlap at channel confluences

The locations of the sections for analysis in the two case study estuaries after manual manipulation are shown in Figures 4.10 and 4.11. Although the Humber Estuary is much larger than Chichester Harbour, it is a simpler system in terms of the number of channels. The only manual manipulation of sections that was required was at the confluence of the Ouse, Trent and Humber Estuaries (compare Figure 4.10 with Figure 4.6). Chichester is a more complex system of five channels converging at different points with progression downstream. Because a system like Chichester Harbour requires more manual manipulation, the final number of sections is significantly reduced and the spacing between some of the remaining sections are relatively large (Figure 4.11).

More detail on how to move sections or remove redundant sections in the GIS can be found in Section 4.4 of the Technical User Guide (Appendix B). Section 4 of Appendix B also describes how the sections are labelled in the GIS. The labels remain fixed throughout the remaining steps in the method and are defined by the number of channels and the spacing of the sections prescribed by the user. An example of labelled sections in the Chichester Harbour case study estuary is shown in Figure 4.12.

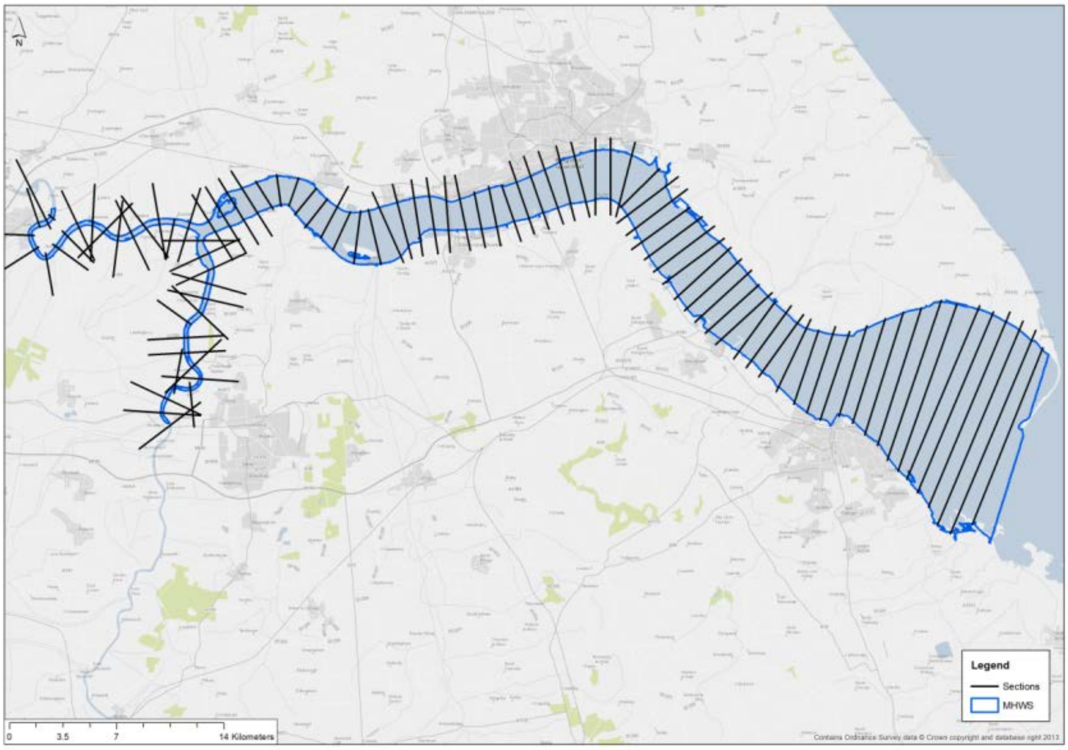

Figure 4.10. Final position of sections in the Humber Estuary after automatic positioning followed by manual manipulation

Figure 4.11. Final position of sections in Chichester Harbour after automatic positioning followed by manual manipulation

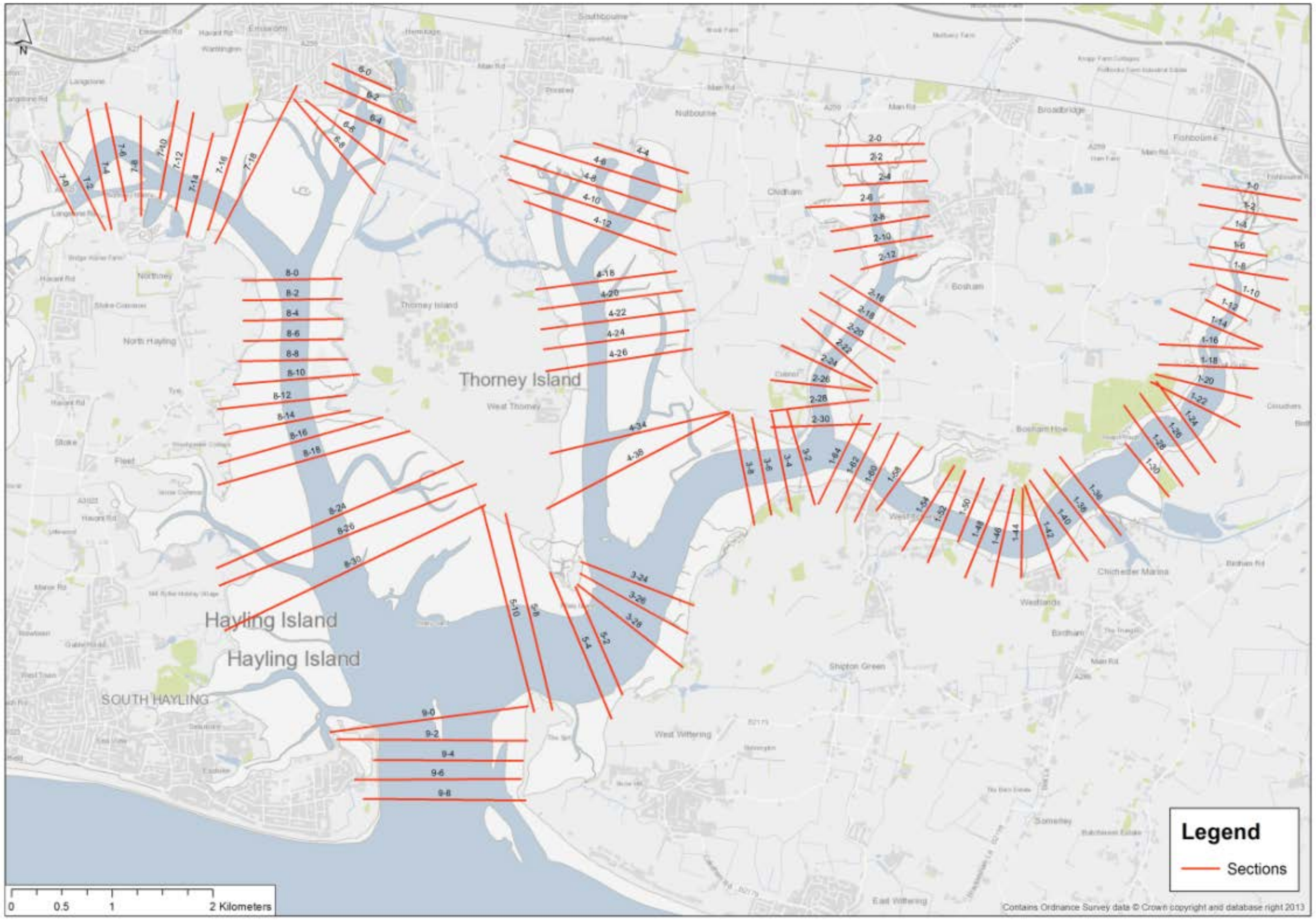

Figure 4.12. Labelled automatic and manually positioned sections in Chichester Harbour

4.4 Measure Observed Estuary Parameters

Once the sections have been finally located, the following parameters of the estuary are measured at each one, using the GIS:

- cross-sectional area beneath mean high water neap tide;
- width at mean high water neap tide;
- mean depth beneath mean high water neap tide; and
- tidal prism upstream of each section between mean high water spring and mean low water spring tides.

The methods by which the observed estuary parameters are calculated in the GIS are described in Sections 4.6 to 4.11 of the Technical User Guide (Appendix B). The calculation of cross-sectional area is automated in the GIS by measuring down from the mean high water neap tide surface to the estuary bed at 1m intervals along each section and summing the values. The width is directly measured along each section from where it crosses mean high water neap tide on one side of the estuary to where it crosses mean high water neap tide on the other side. Mean depth is calculated by dividing the cross-sectional area by the number of points that are spaced 1m apart along each section.

In the GIS, the spring tidal prism is first calculated between each section starting upstream of the first section at the head of the estuary. The second measurement is then made between the first upstream section and the next section downstream, and so on downstream, until the final section is reached at the estuary mouth. The total tidal prism at each section is then calculated by summing all the individual tidal prisms upstream of that section. Individual tidal prisms are calculated by measuring between the mean high water spring tide and mean low water spring tide surfaces (and bathymetry in the intertidal areas) from points positioned 1m apart in a square grid, and then summing the values. Where the estuary is 'dry' at mean low water spring (at the upstream ends of some channels) the measurement of tidal prism is made between the mean high water spring tide surface and the bathymetry.

The GIS creates an Excel table with values for each estuary parameter calculated at each section (Table 4.1). The data shown in Table 4.1 is defined as the observed morphology of the estuary.

Table 4.1. Observed estuary morphological parameters recorded at each section

Section	Tidal Prism (m^3)	Cross-sectional Area (m^2)	Mean Depth (m)	Width (m)
1-10	527,503	843	3.98	212
1-20	1,752,501	802	3.08	261
1-30	2,786,920	956	4.62	207
1-40	3,802,064	918	4.25	216
1-50	4,764,802	1,143	5.66	202
1-60	5,817,462	1,033	4.39	235
1-70	7,063,672	814	3.54	239
1-80	8,452,391	1,419	5.00	283
1-90	9,724,977	1,006	4.02	248
1-100	10,918,086	813	3.19	256
1-110	11,998,880	1,236	4.87	254
1-120	13,323,659	1,247	3.39	367
1-130	14,826,312	1,129	3.92	288
1-140	16,472,266	1,680	5.28	317
1-150	18,205,288	1,678	5.25	320
1-160	20,278,561	1,916	5.07	378

5 PREDICTED ESTUARY FORM

This section describes the use of a set of calculations in Excel that allow the user to predict the equilibrium morphology of an estuary at each of the sections originally defined in the measurement of observed form (Section 4). The prediction of equilibrium form is carried out in five main stages:

- 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;
- compare the predicted widths with the observed widths to determine pressure points in the estuary; and
- map pressure points against constraints.

Details on how to run the Excel tool to predict estuary equilibrium form are provided in Section 5 of the Technical User Guide (Appendix B).

5.1 Distribute Observed Tidal Prism at Mouth throughout Estuary

One result of the measurement of observed form in the 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, the Humber Estuary has the Ouse and Trent Estuaries as major channels. 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 the GIS.

5.2 Calculate Equilibrium Cross-sectional Areas

The calculation of equilibrium cross-sectional area from predicted tidal prism at each section is based on the regime equation. There are a number of regime equations that could be used including the equation for all United Kingdom estuaries and those developed for sub-sets of United Kingdom estuaries (Section 2.1). For the estuary complexes and SSSIs under scrutiny in this project (Table 1.1), most fall into the sub-sets of Groups 3 or 4 of Townend et al. (2000) and Group C of Townend (2005).

Given there are several equations that could be used for any particular estuary under consideration, the method allows input of several equations to develop a set of potential predicted equilibrium forms to see how they compare (Section 5.2 of the Technical User Guide in Appendix B). The significance of each of these potential forms relative to the observed form will then require expert interpretation towards the end of the method.

5.3 Calculate Mean Depths and Widths

Using a 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. Unfortunately, there is no definitive method for calculating mean depth in an estuary and so two alternatives are provided here (Section 5.2 of the Technical User Guide in Appendix B).

5.3.1 Using the Lacey 1930 Equation

The first method is to use the equation formulated by Lacey (1930) that relates mean depth to discharge and estuary bed particle size:

$$D_E = 0.48[(Q/1.76.\{d_{50}\}^{0.5})]^{0.33}$$

where:

D_E = equilibrium mean depth (m);
Q = discharge (m^3s^{-1}) = tidal prism / 0.5.tidal period (22,356 seconds); and
d_{50} = median particle size (mm).

If the predicted cross sectional area (Section 5.2) and channel mean depth are known, then width can be calculated by dividing the cross-sectional area by the mean depth.

The form of the equation shows that the predicted mean depth is sensitive to the input of median particle size. Hence, it is important to determine the representative

particle size to input into the equation (Section 3.3). For both the Humber Estuary and Chichester Harbour case studies, particle sizes of 0.1mm and 0.2mm were input into the Lacey equation.Using a 'Constant Evolution' Relationship
One of the main difficulties with Regime Theory, as discussed in Section 2, 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 (Figures 2.1 and 2.2). 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 understood) 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).

5.4 Compare Predicted Widths with Observed Widths

The calculations of predicted form are automated in the Excel tool and the outputs (Table 5.1) are defined as the predicted morphology of the estuary.

Table 5.1. Predicted estuary morphological parameters recorded at each section.

Section	Tidal Prism (m^3)	Cross-sectional Area (m^2)	Mean Depth (m)	Width (m)
1-10	1,217,822	502	3.07	164
1-20	1,468,974	574	2.61	220
1-30	1,771,921	656	3.82	171
1-40	2,137,345	749	3.84	195
1-50	2,578,130	856	4.90	175
1-60	3,109,818	977	4.28	229
1-70	3,751,157	1,117	4.07	275
1-80	4,524,758	1,276	4.74	269
1-90	5,457,901	1,457	4.86	300
1-100	6,583,485	1,665	4.55	366
1-110	7,941,198	1,902	6.04	315
1-120	9,578,914	2,172	4.48	485
1-130	11,554,376	2,482	5.81	427
1-140	13,937,237	2,835	6.87	413
1-150	16,811,517	3,239	7.29	445
1-160	20,278,561	3,700	7.05	525

The results obtained can now be interrogated in the GIS to compare the predicted widths with the observed widths at each section. In this way, reaches of the observed estuary which are narrower or wider than their predicted form can be mapped. The GIS allows comparison of a set of predicted widths, which have been calculated using a variety of input data generated in Excel, against the observed width. The input variables that allow prediction of different equilibrium widths are:

- different regime equations to calculate cross-sectional area (e.g. all United Kingdom estuaries; United Kingdom estuaries Group C; United Kingdom estuaries Group 3; UK estuaries Group 4 etc);
- different methods of calculating mean depth (e.g. Lacey, 1930; 'constant evolution' relationship etc); and
- different median particle size input to the Lacey (1930) equation (e.g. 0.1mm; 0.2mm etc).

The observed widths will compare with the predicted widths in one of three ways. Parts of the observed estuary will be over-sized compared to their predicted form (i.e. the observed channel is wider than predicted for the present-day tidal regime) whereas other parts of the estuary will be under-sized (i.e. the observed channel is narrower than predicted for the present-day tidal regime). A third possibility is that the observed and predicted widths are the same (or very similar), suggesting that the observed form is ‘in equilibrium’.

The reaches of the estuary that have observed widths which are narrower than the predicted widths are pressure points in the estuary. 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 and managed realignment would potentially be needed to accommodate it. The pressure points, therefore, broadly define where in the estuary there is the potential to realign the existing defences in order to allow a wider tidal channel to develop in keeping with the equilibrium form. Where channels are over-sized, no realignment will be necessary because the channels exceed their predicted equilibrium width and there may be development of intertidal habitat by natural processes.

The results of Regime Theory applied to the two case study estuaries are shown in Figures 5.1 to 5.3 (Humber Estuary) and Figures 5.4 to 5.6 (Chichester Harbour). The ability to compare a set of different equilibrium widths against the observed width in the GIS allows the user to test how sensitive the predicted width is to the different input parameters. A judgement will then need to be made at the end of the process as to where the pressure points are in the estuary. The comparison also provides a ‘reality check’ on the suitability of a particular input parameter or equation in the method.

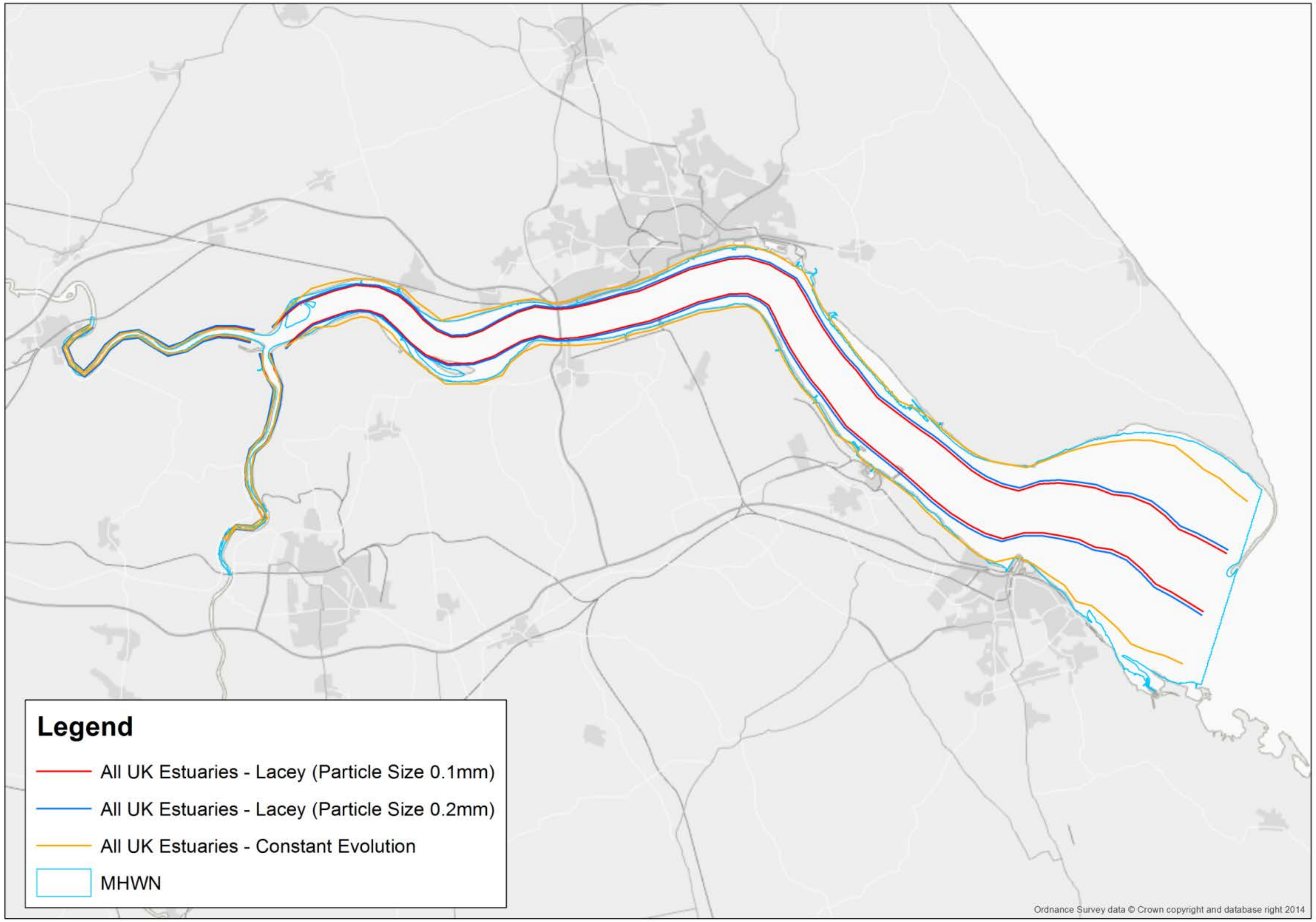

Figure 5.1. Comparison of observed and predicted widths in the Humber Estuary using the regime equation for all United Kingdom estuaries combined with 1. particle size of 0.1mm in the Lacey (1930) equation (red), 2. particle size of 0.2mm in the Lacey (1930) equation (blue), and 3. the 'constant evolution' relationship (orange)

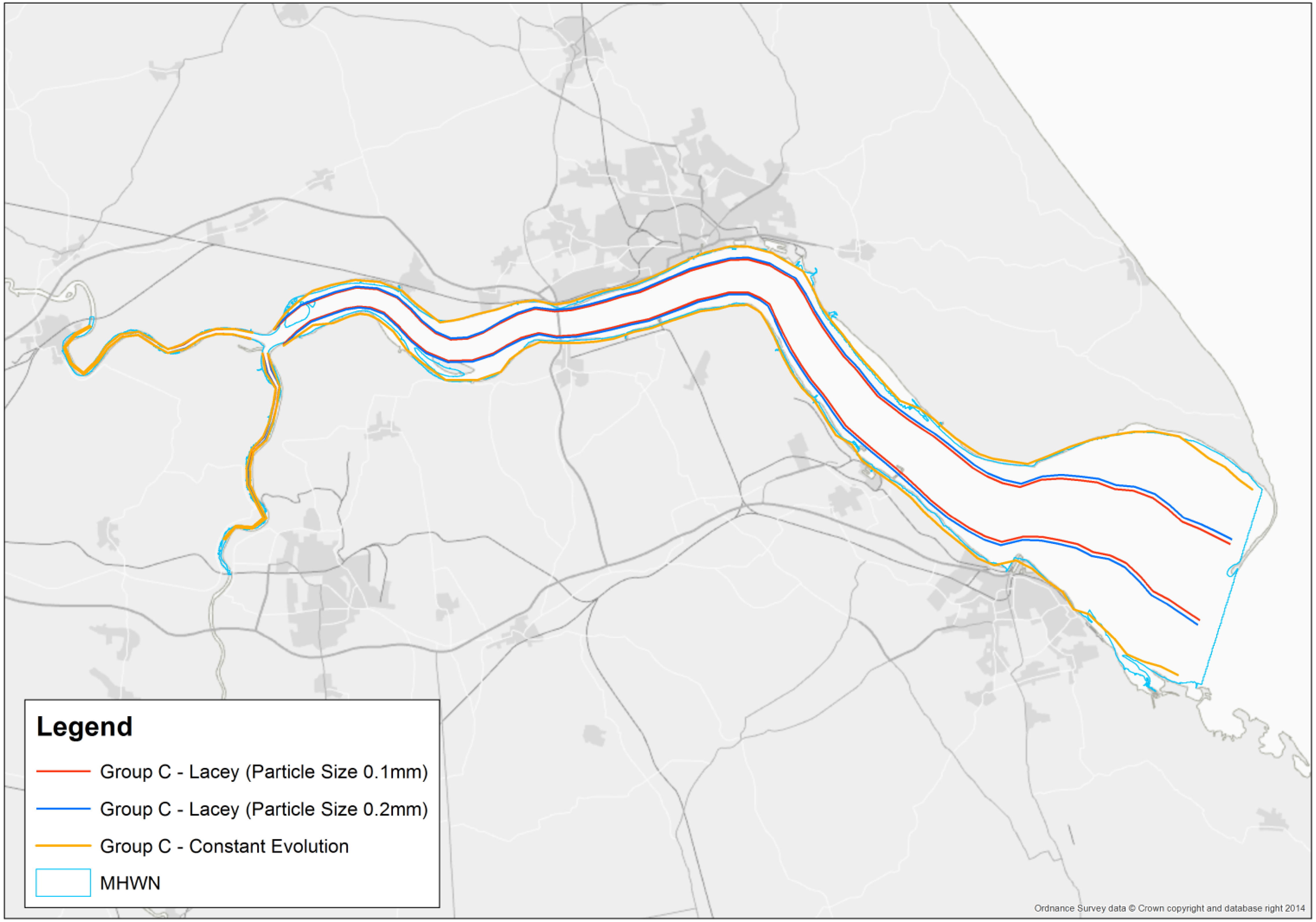

Figure 5.2. Comparison of observed and predicted widths in the Humber Estuary using the regime equation for United Kingdom estuaries Group C combined with 1. particle size of 0.1mm in the Lacey (1930) equation (red), 2. particle size of 0.2mm in the Lacey (1930) equation (blue), and 3. the 'constant evolution' relationship (orange)

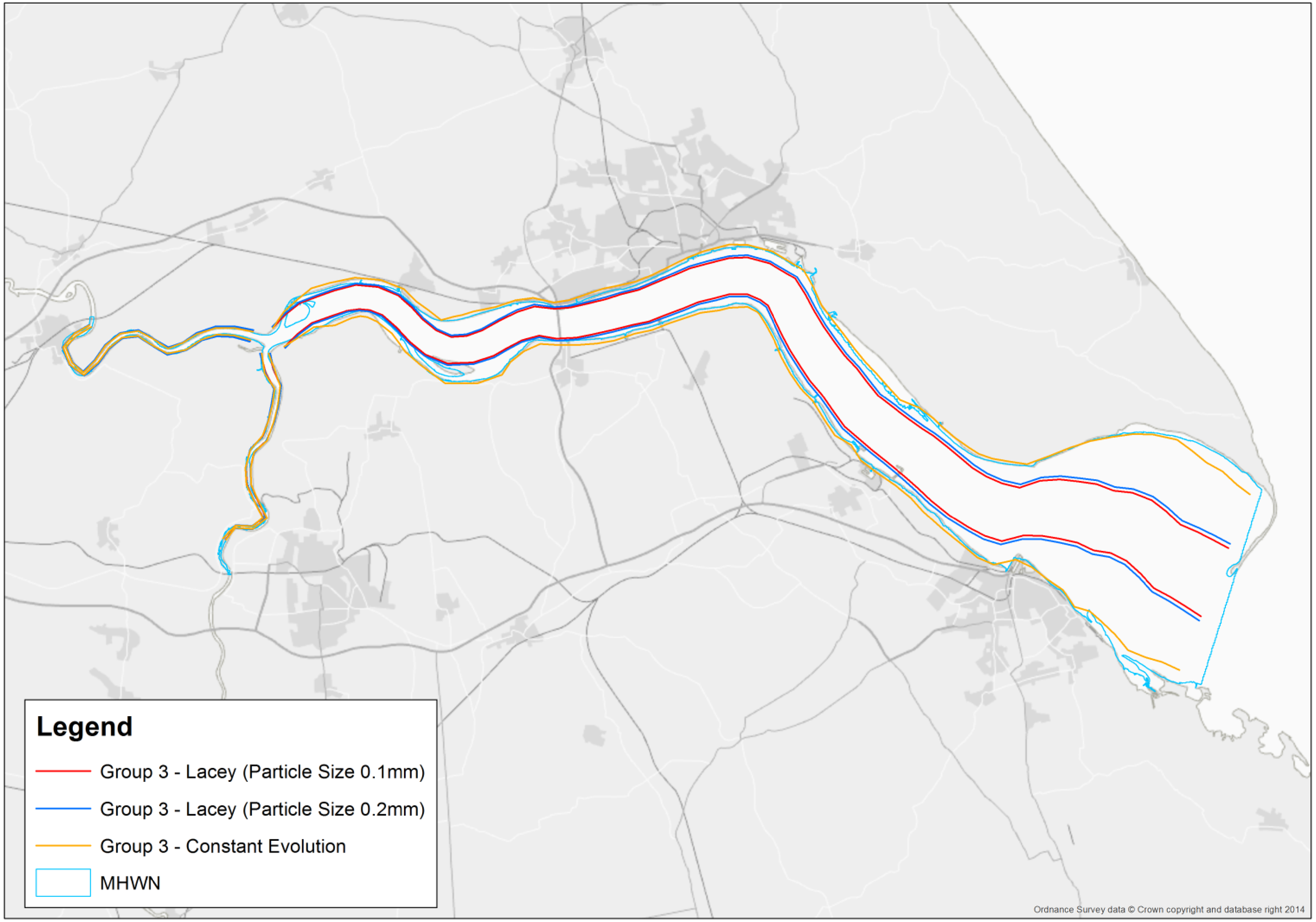

Figure 5.3. Comparison of observed and predicted widths in the Humber Estuary using the regime equation for United Kingdom estuaries Group 3 combined with 1. particle size of 0.1mm in the Lacey (1930) equation (red), 2. particle size of 0.2mm in the Lacey (1930) equation (blue), and 3. the 'constant evolution' relationship (orange)

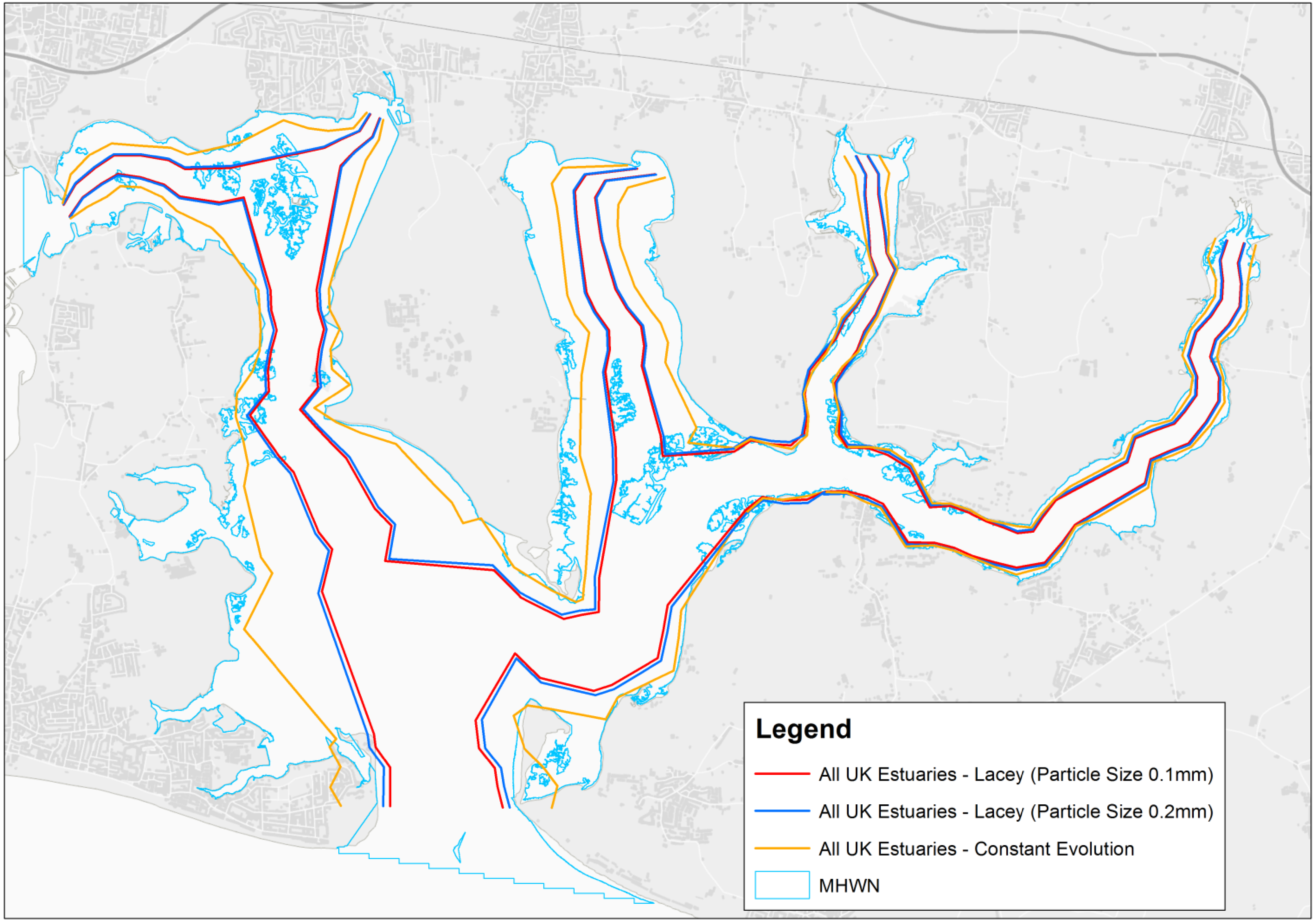

Figure 5.4. Comparison of observed and predicted widths in Chichester Harbour using the regime equation for all United Kingdom estuaries combined with 1. particle size of 0.1mm in the Lacey (1930) equation (red), 2. particle size of 0.2mm in the Lacey (1930) equation (blue) , and 3. the 'constant evolution' relationship (orange)

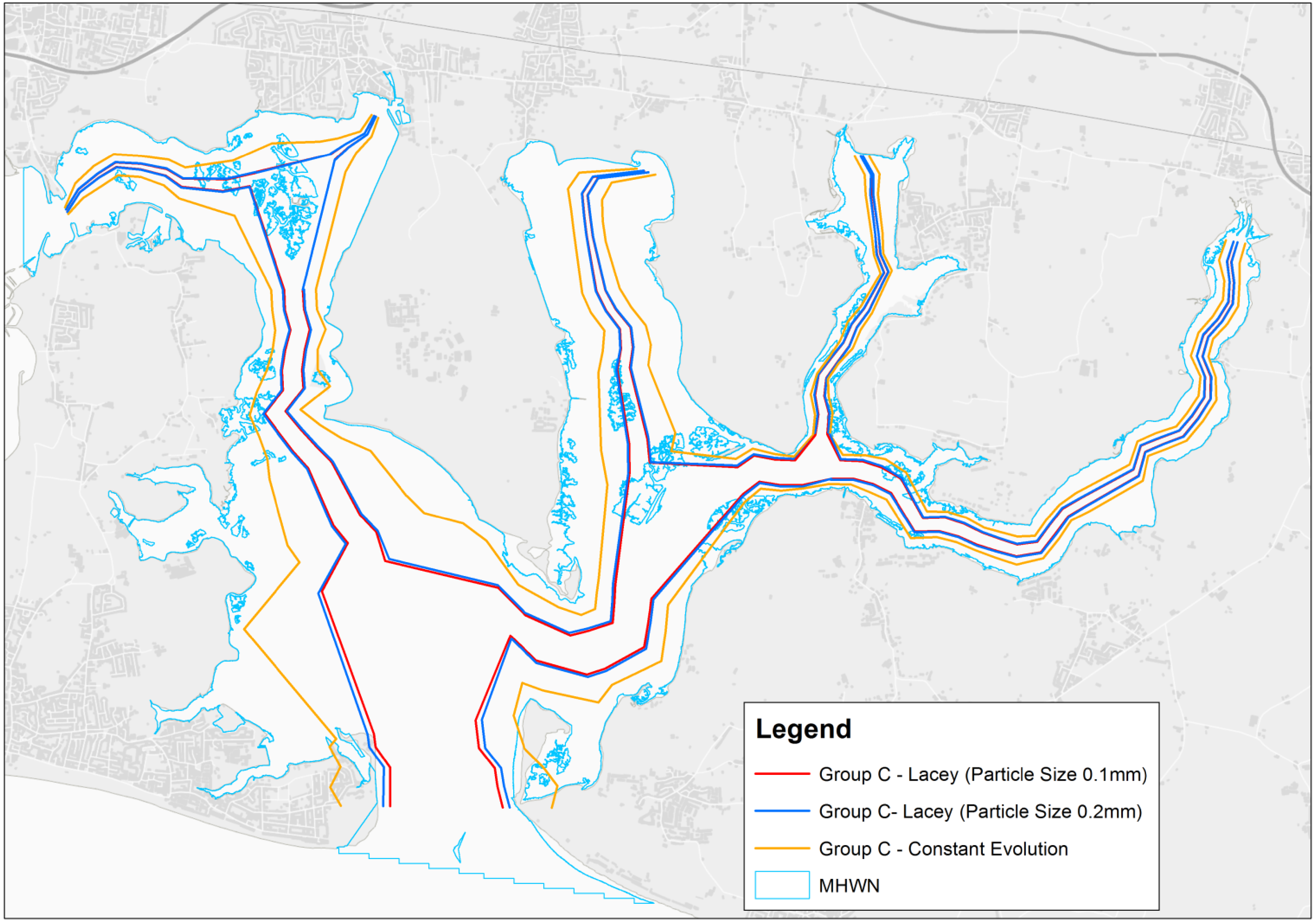

Figure 5.5. Comparison of observed and predicted widths in Chichester Harbour using the regime equation for United Kingdom estuaries Group C combined with 1. particle size of 0.1mm in the Lacey (1930) equation (red), 2. particle size of 0.2mm in the Lacey (1930) equation (blue), and 3. the 'constant evolution' relationship (orange)

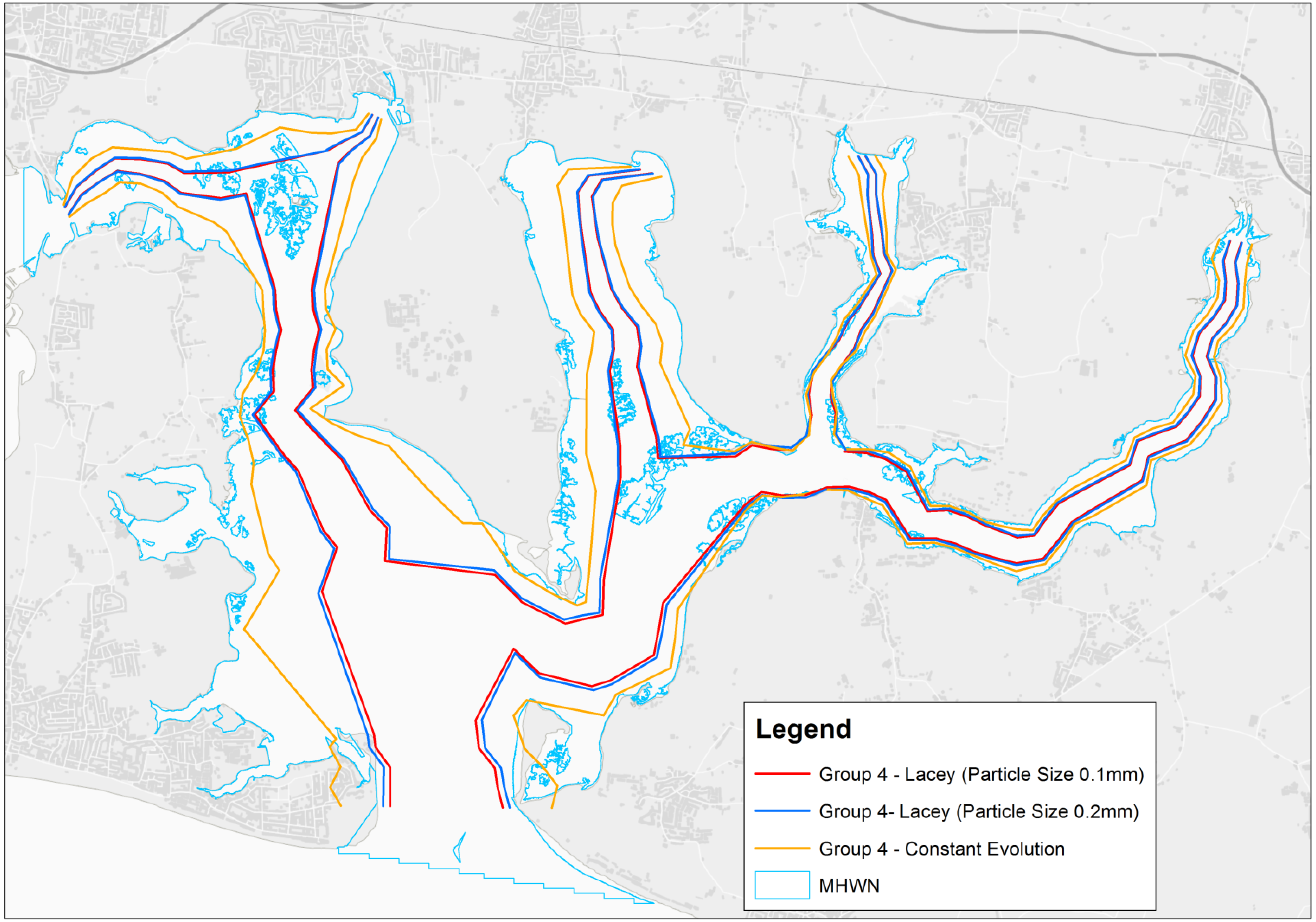

Figure 5.6. Comparison of observed and predicted widths in Chichester Harbour using the regime equation for United Kingdom estuaries Group 4 combined with 1. particle size of 0.1mm in the Lacey (1930) equation (red), 2. particle size of 0.2mm in the Lacey (1930) equation (blue), and 3. the 'constant evolution' relationship (orange)

In both case studies, the results demonstrate that regardless of which regime equation is used, the predicted width using the Lacey (1930) method (with input median particle sizes of 0.1mm and 0.2mm) is less than the observed width, at most locations. This prompts two possible conclusions. First, both the Humber Estuary and Chichester Harbour are actually over-sized throughout most of their length compared to their equilibrium form. This implies that there are no pressure points in either of these systems, which seems unlikely, given their history of development and reclamation. Second, the Lacey (1930) equation is a flawed method of calculating mean depth and hence the predicted width is in error. This implies that a different way of calculating width independently from the observed form is required.

The results show that the ‘constant evolution’ relationship provides a predicted width which is much closer to the observed width than using the Lacey (1930) equation. This is to be expected given the calculation of predicted width is derived from the relationship between observed mean depth and width.

To evaluate the ‘goodness of fit’ of the adopted methods, the observed estuary parameters can be compared and the statistics of the relationships assessed. Figures 5.7 and 5.11 show examples of these relationships in the Humber Estuary, and indicate good agreement between predicted and observed values of tidal prism and cross-sectional area (Figures 5.7 and 5.8). This indicates that the equal distribution model for predicting tidal prism and the regime equation for predicting cross-sectional area from tidal prism are appropriate.

Figures 5.9 and 5.10 show a less satisfactory relationship between observed and predicted width using the Lacey (1930) equation. This supports the view that the Lacey equation (in its existing form) is not an appropriate method of calculating estuary width, and is a potential pitfall which requires more detailed research to resolve.

Figure 5.11 shows that there is a robust relationship between observed and predicted width using the ‘constant evolution’ relationship. This suggests that in the absence of a reliable ‘independent’ method of calculating estuary equilibrium width (e.g. Lacey 1930), the ‘constant evolution’ relationship is currently the best available. However, its use should be viewed in the light of the derivation of width from a pre-existing geomorphological form of the estuary (i.e. it is not strictly an independent evaluation of equilibrium form).

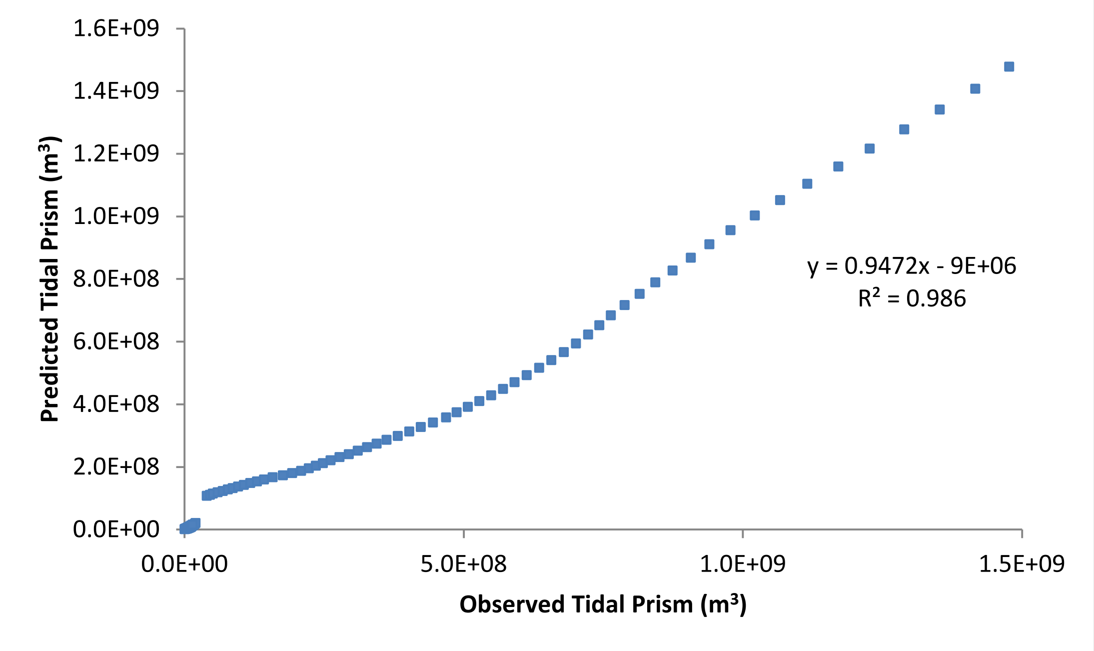

Figure 5.8. Comparison of observed and predicted tidal prisms in the Humber Estuary

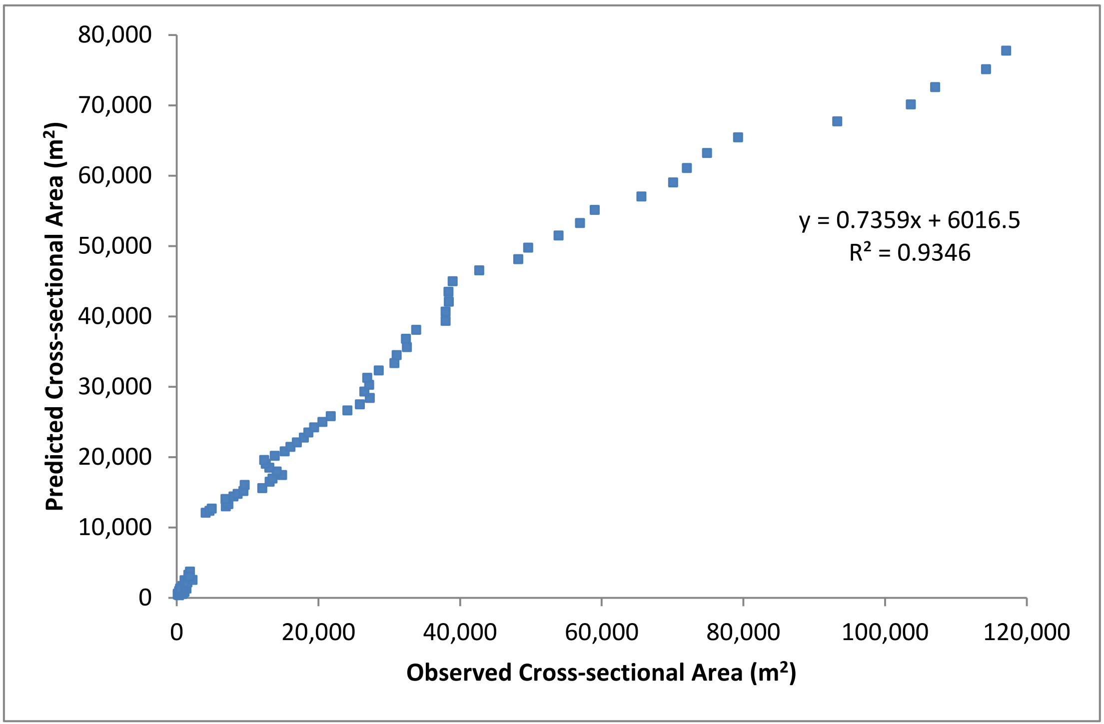

Figure 5.9. Comparison of observed and predicted cross-sectional areas in the Humber Estuary using the regime equation for Group C estuaries

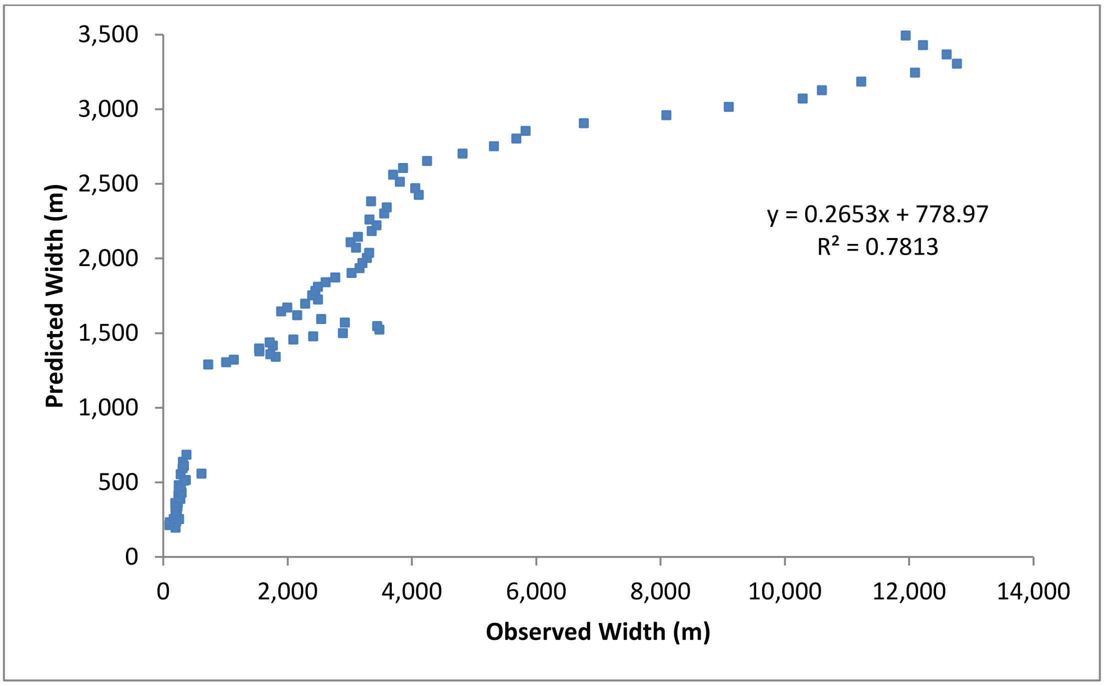

Figure 5.10. Comparison of observed and predicted widths in the Humber Estuary using the regime equation for Group C estuaries and the Lacey equation with an input particle size of 0.1mm.

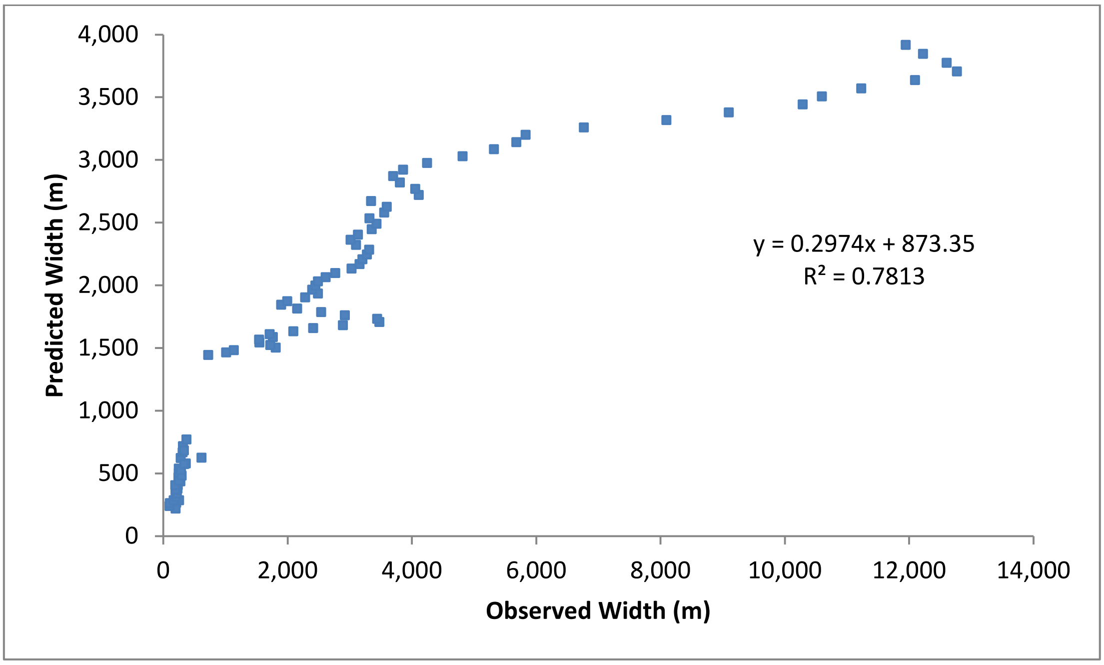

Figure 5.11. Comparison of observed and predicted widths in the Humber Estuary using the regime equation for Group C estuaries and the Lacey equation with an input particle size of 0.2mm.

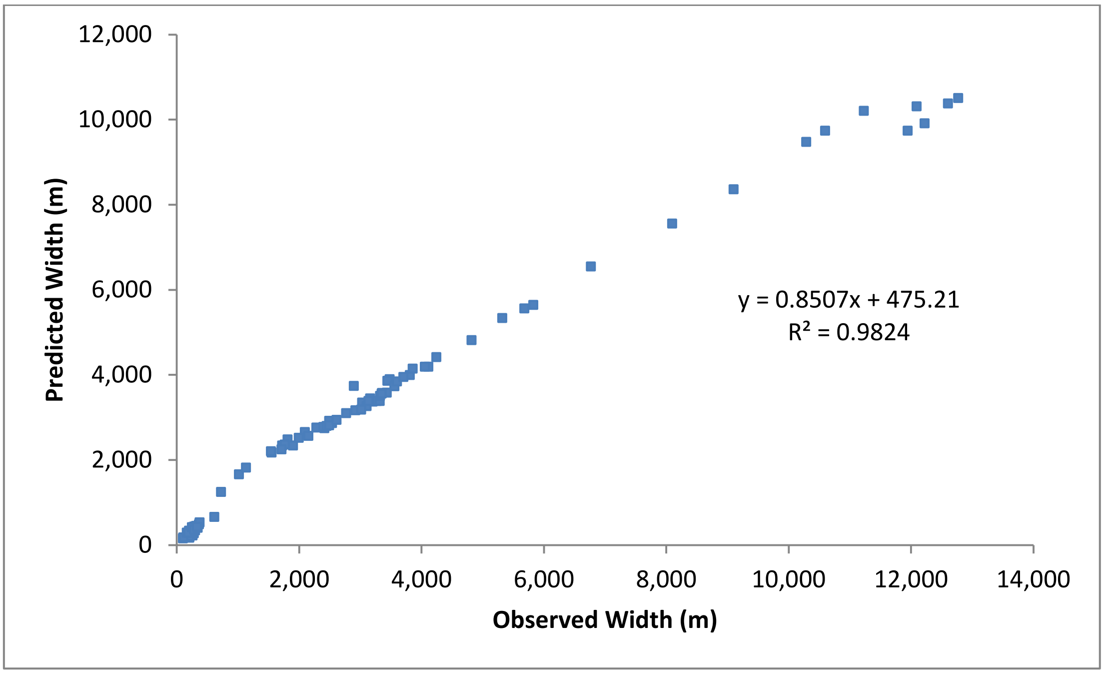

Figure 5.12. Comparison of observed and predicted widths in the Humber Estuary using the regime equation for Group C estuaries and the 'constant evolution' relationship.

5.4.1 Results of the 'Constant Evolution' Relationship for the Case Study Estuaries

It is worthwhile looking more closely at the results for the two case study estuaries of the 'constant evolution' relationship for each of the regime equations. Figures 5.1 to 5.6 show that the results are significantly different in the Humber Estuary compared to Chichester Harbour. In the Humber Estuary, the 'constant evolution' relationship predicts that from the confluence of the Ouse and Trent Estuaries downstream to approximately Immingham, the estuary is predominantly under-sized (Figures 5.1 to 5.3). There are subtle differences in the predicted scale of the disequilibrium related to the use of the three regime equations. For example, close to the Kingston upon Hull shoreline, the Group C regime equation predicts that the estuary is closer to equilibrium than the All United Kingdom Estuaries or Group 3 equations (compare Figure 5.2 with Figures 5.1 and 5.3).

At locations downstream from Immingham, the predictions change, and the estuary becomes over-sized to its mouth. The downstream transition from under-sized to over-sized varies depending on the regime equation that was used. Using the All United Kingdom Estuaries regime equation, the transition takes place between the tip of Sunk Island and Grimsby (Figure 5.1). The Group 3 and Group C equations predict a transition further downstream close to a line between Cleethorpes and the shore of Spurn Bight (the Group C transition is further downstream of these two) (Figures 5.2 and 5.3).

In Chichester Harbour, the 'constant evolution' relationship suggests a predominantly over-sized system (Figures 5.4 to 5.6). Using the Group C regime equation, the entire system is predicted as significantly over-sized, apart from an under-sized mouth (Figure 5.5). Using the Group 4 equation, the majority of the channels are predicted to be under-sized apart from the downstream reaches of the eastern two channels where the system is predicted to be close to equilibrium (Figure 5.6). The mouth of Chichester Harbour is predicted as under-sized. There is a similar result using the All United Kingdom Estuaries regime equation, but short stretches of the downstream portions of the two eastern channels are marginally under-sized (Figure 5.4).

5.5 Map Pressure Points against Physical Constraints

Figures 5.1 to 5.6 provide a view of the estuary where the observed against predicted width comparisons highlight areas where the estuary is under-sized and there is the potential to realign the existing defences in order to allow a wider tidal channel to develop in keeping with the equilibrium form. However, the reality is that it may not be possible to carry out realignment because of constraints such as geology, essential infrastructure or other land uses. Therefore, the next step in the method is to map the pressure points against physical constraints in the estuary and use their relative distributions to determine optimum locations for managed realignment.

5.5.1 Geological Constraints

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. This may be the situation at the mouth of the Humber Estuary where the bed is composed of resistant glacial deposits. In this case the width of the estuary is over-sized to compensate for the relatively shallow depths caused by the geological constraint.

A variety of different types of geological maps (drift and solid) at different scales are available from the British Geological Survey. These data can be imported into the GIS and the observed and predicted forms of the estuary compared to the outcropping and sub-cropping rock types.

5.5.2 Essential Infrastructure

One of the biggest drawbacks of managed realignment is that the option requires land to be yielded to the estuary. The location of existing essential infrastructure or buildings such as, for example, towns, ports, harbours, power stations and roads provide a major constraint to realignment. The location of infrastructure that cannot be moved reduces the availability of low-lying land that can be realigned. If important infrastructure or buildings can be relocated, it requires land elsewhere and may incur significant cost. In densely populated estuarine areas this may be very difficult.

A variety of land use maps are available from a variety of organisations including the Government's National Land Use Database. In addition, the Environment Agency Asset Information Management System (AIMS) provides data on the location of flood and coastal defence infrastructure (including man-made defences and natural defences).

6 DISCUSSION AND CONCLUSIONS

6.1 Estuary equilibrium concept and this method

The understanding of estuaries and how they function is essential to ensure sustainable human uses into the future. This work was based on the assumption that the ‘health’ or condition of an estuary is founded on the relationship between its physical form (geometry) and the forces driving its form (function/process) To support habitat in favourable condition, the estuary morphology needs to be in ‘equilibrium’ with natural wave, tidal and sediment transport processes. So the form of the bed and banks in relation to the plan form provides a set of measurable attributes which can be set against the predicted form. Over time, an estuary will have had its dynamic equilibrium morphology changed in some way by human interference and different parts of its form are likely to be at different stages of adjustment to natural process inputs. Hence, an estuary will seek to reach a steady state over the long term by oscillating around theoretical equilibrium morphologies over the short term to medium term. The width and depth of the estuary will therefore change over time towards a state of dynamic equilibrium or ‘most probable state’. Regime Theory predicts the equilibrium width of an estuary, which when compared with the observed width can be used to determine, at a high level, how far an estuary is from an equilibrium form. How close an estuary is to morphological equilibrium defines the condition of this attribute.

Estuary Regime Theory is based on the principle that tidal energy controls channel size, by promoting erosion to expand the channel if the estuary is too narrow, or accretion to make the channel smaller if it is too large. Equilibrium is an ideal state where there is a balance between erosion and accretion, so despite adjustments over time, the overall form is stable. Studies of many estuaries around the world have demonstrated a relationship between cross-sectional area and tidal prism. This study built on those established principles by looking at the relationships within estuaries and comparing the observed form with the predicted form at different points from the mouth to the upper limits.

By using real examples as case studies, a method was developed and tested to better understand how estuaries function for use in assessing the current and potential future condition across a complete system rather than at a smaller sub-set of locations within it. The method could also be used to identify natural and human constraints on estuary morphology, which can be taken account of in management measures that might be needed to improve form and function.

6.2 Results of case studies and recommendations

The methods tested demonstrated that intra-estuary assessments of morphology are possible and a step-wise process is available that can be applied to other sites. There are a number of different parameters that require further work, in particular those relating to particle size. However, the ‘constant evolution’ relationship is currently the best available, although further testing is recommended.

The method could also help to identify locations to restore intertidal habitat in such a way that a more sustainable estuary form is produced. This could reduce reliance on attempting to achieve restoration of recent past losses of intertidal habitat, although this study did not evaluate this issue in detail. The method does stress the importance of including areas with known constraints within the analysis, as it is clear that adjustment to estuary form may not be possible due to hard geology or essential infrastructure.

There is potential to use this method at a high level to support assessments of condition of designated sites. Since this project started, the estuary morphology attribute in two additional sites has been evaluated using this method. Further integration of these results with other data on habitat quality attributes will need to be done. Other data can be used to determine the likely extent of saltmarsh in relation to the tidal elevations, and compare this to known extent to identify locations which may be in poor condition.

The technical method set out in the use manual can be applied in other situations to identify opportunities to use it for reporting on the over-arching attribute of estuary morphology, linked to site-specific data on sediment budgets, physical constraints and habitat and species data. It would clearly be beneficial and cost-effective for agencies to take an integrated approach to collect, analyse and share data and findings.

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Appendix A: Bathymetry Collection Methods

Single Beam Echosounder

Single beam echo sounding is a commonly used technique for collecting bathymetric data. The technique involves using a transducer attached either to the hull of a vessel, or to a pole mounted over the side or bow of the vessel. The echo sounder calculates the water depth beneath the transducer, by transmitting a sound pulse that is returned to the vessel *via* reflection off the estuary bed. The density of soundings is dependent on the survey line spacing, vessel speed and the echo-sounder ping rate. Standard single beam echo sounders collect data for a narrow zone along the track of the vessel and hence the main limitation of the system, compared to multi beam systems, is the limited sea bed coverage. Generally, the data are presented as points (x,y,z) along the transect from which require spatial interpolation in the GIS in order to provide full bathymetry coverage.

Multibeam Echosounder

A multibeam echosounder survey provides an alternative to a single beam survey in bathymetric data collection. The main difference between a single beam echosounder and a multibeam echo-sounder is that the latter produces a number of beams forming a 'fan' of sound pulses or acoustic energy. A multi-beam system essentially consists of a receiver and transmitter that emit and detect multiple beams of sound energy in a swathe (producing swathe bathymetry). These multiple soundings are taken at right angles to vessel track, as opposed to a single sounding directly underneath a vessel with a single beam echosounder. This means that a multi-beam system can provide a greater density of soundings allowing faster coverage of a site. The main advantage of multi-beam systems is that they can provide 100% coverage of the sea bed without the need to interpolate between lines. A disadvantage of multibeam systems is that in shallow water (less than 10m), the swathe width is also significantly reduced and so in estuaries, this type of data is not common.

LiDAR

Airborne Light Detection and Ranging (LiDAR) is a remote sensing technique for the collection of bathymetry and topography data. It uses laser technology to 'scan' the ground surface, taking up to 10,000 observations per square kilometre. These observations are then converted to the local co-ordinate and elevation datum by the use of differential GPS. The system routinely achieves vertical accuracy of 11-25cm and plan accuracy of 45cm, with a very rapid speed of data capture (up to 50 km^2 per hour). This rapid data capture, coupled with the relatively automatic processing system can result in quick delivery of results. It can operate on intertidal areas but care needs to be taken in areas of water as with the normal settings the laser beam is absorbed by water rather than reflected.

Appendix B: Technical User Guide

Appendix C: Issues to Consider for Managed Realignment Projects

Following an assessment, there are a range of design methods that can be used to create intertidal habitat and restore estuary equilibrium. Numerous guidance documents and other publications are available which provide the necessary information to design a managed realignment scheme. These include:

- The Online Managed Realignment Guide (http://www.abpmer.net/omreg); and
- Coastal and Estuarine Managed Realignment: Design Issues (Leggett et al., 2004).

The details of how to design a managed realignment site are provided in the listed guidance documents. This section provides an initial summary of the methods and tools that potentially could be used to create the physical and geomorphological conditions for a successful managed realignment, as a starting point for more detailed research. The following criteria are considered critical:

- Site template;
- Creating the desired elevations (topography);
- Maximising sedimentation (sediment budgets);
- Creating an efficient drainage network;
- Establishment of vegetation;
- Design of breaches; and
- Intertidal-upland transition.

Site Template

In designing a managed realignment scheme, the intent is to restore physical processes that create and sustain the particular form or structure that supports the desired ecological functions of the intertidal habitat. This approach should not attempt to 'engineer' a predetermined replicate of an intertidal habitat, but should instead provide a setting for the natural evolution of its functions and interplay of natural ecological processes.

In order to take advantage of the physical processes that would allow the intertidal habitat to evolve, the site is typically graded before the re-introduction of tidal action. This grading is the site template and, if appropriately designed, can steer the progress of the habitat towards maturity (Figure C.1). The site template should aim to create conditions that allow the intertidal landscape to evolve through hydrodynamic and sedimentary processes, without the need for further management intervention.

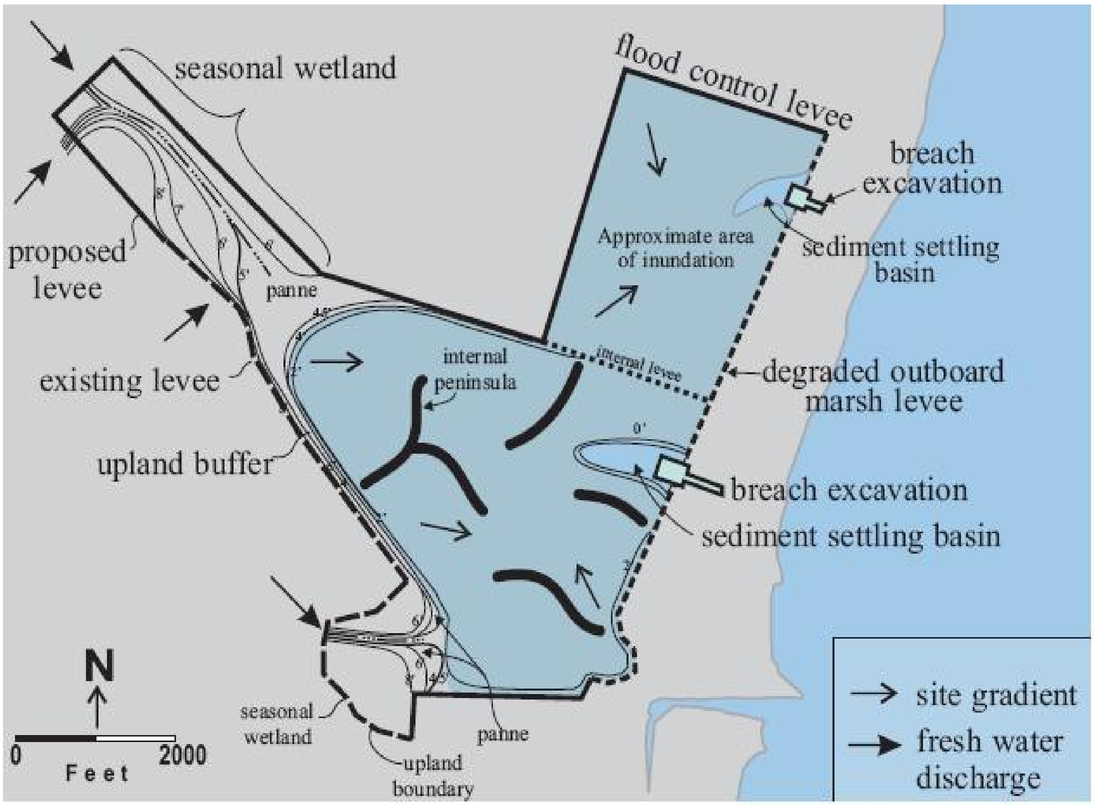

Figure C.1. Example of a site template.

Creating the Desired Elevations

The evolution of intertidal habitat will largely depend upon the achievement of appropriate elevations with respect to the tide. This is likely to require manipulation of the site prior to inundation with tidal waters. In general terms, the height of the managed realignment site relative to the varying tidal range is used as an initial indicator of the habitats which will evolve. In the UK (and elsewhere), saltmarsh colonises areas that are between mean high water neap tide and mean high water spring tide, with areas lower than this turning into mudflat (Allen, 2000). Hence, the topography of the managed realignment site and the tidal levels adjacent to it are one of the principal issues to be considered at the planning stage of a habitat creation scheme (Leggett et al., 2004). In many cases the topography of the site may not be appropriate for the type of intertidal habitats that are wanted, and actions need to be taken to either lower or raise the profile. There are two fundamental techniques for achieving the desired elevations that should be considered at the planning stage; site filling and site excavation. Land levels can be raised or lowered locally by the redistribution of material on site or by importing additional material to the site.

If the potential habitat creation site is below the elevation required for the desired habitats, then filling may be required. This is particularly so if the desired habitat is saltmarsh, but the site is not at elevations conducive to vegetation colonization. Two different strategies can be adopted to raise the elevation of a habitat creation site: take advantage of natural sedimentation or fill with imported material.

Site Filling by Taking Advantage of Natural Sedimentation
In this technique the required elevations are achieved by taking advantage of the natural deposition of suspended sediments brought into the habitat creation site on flood tides. The rate of accretion will depend on the suspended sediment concentrations carried into the site, the amount that is deposited from suspension and the amount of sediment that is eroded and carried out of the site on ebb tides. The expected rate of sedimentation at a site can be predicted from measurement of nearby suspended sediment concentrations, observed rates of sedimentation at similar realignment sites and/or local established saltmarsh areas.

Fill Site with Imported Material
If the rate of natural sedimentation is predicted to be too low to reach the target elevations, then the alternative strategy (if practical and affordable) is to fill the site with imported material. The technique could use sediment derived from various places including borrow pits on the site, nearby ponds or newly created tidal channels. Larger-volume fill could be derived from the navigational dredging of ports and harbours (or other remote areas), providing a beneficial reuse for this material.

The most suitable method to directly place material on the realignment site is by hydraulic pumping (Figure C.2). This entails pumping sediment directly on to the site through a pipe and allowing it to settle before tidal exchange is restored. With this technique, large volumes of sediment can be distributed over the site over relatively short time periods, and the volume, rate, and location of the discharged material can be controlled (Figure C.2). Consideration should be given to the sustainability of any change made. For example, if there is a possibility that the placed material could be eroded quickly from the site it will have served little purpose and might cause negative impacts elsewhere.

Figure C.2. Sediment being pumped into a realignment site.

Micro-topography

Within the broader-scale infilling or excavation of a site, there is the potential to sculpt smaller areas to achieve topography for specific purposes. This micro-topography may include construction of islands that are suitable as nesting or roosting sites for birds or borrow pit saline lagoons (Figure C.3).

Figure C.3. Borrow pit lagoon.

Maximising Sedimentation

If the desired site elevations cannot be achieved by natural sedimentation and artificial infill is too costly or impractical, then techniques can be adopted to accelerate sedimentation rates. This means maximizing the amount of sediment that is deposited on the flood tide and/or minimizing the amount that is eroded and leaves on the ebb tide.

Wave Breaks

A significant factor inhibiting deposition of sediment across a site is wave energy, which slows deposition rates and induces re-suspension of deposited mud (Burd, 1995; French et al., 2000). The amount of wave energy affecting a site is dependent on the wind climate, which cannot be controlled, and the fetch length, which can be controlled, by the construction of internal wind-wave breaks (Figure C.4). The need for the installation of wave breaks will depend on the desired habitat. If a given wind-wave climate dictates an equilibrium mudflat elevation and this is the desired habitat then breaks need not be installed. However, if the desired habitat is saltmarsh then wind-wave effects may need to be reduced.

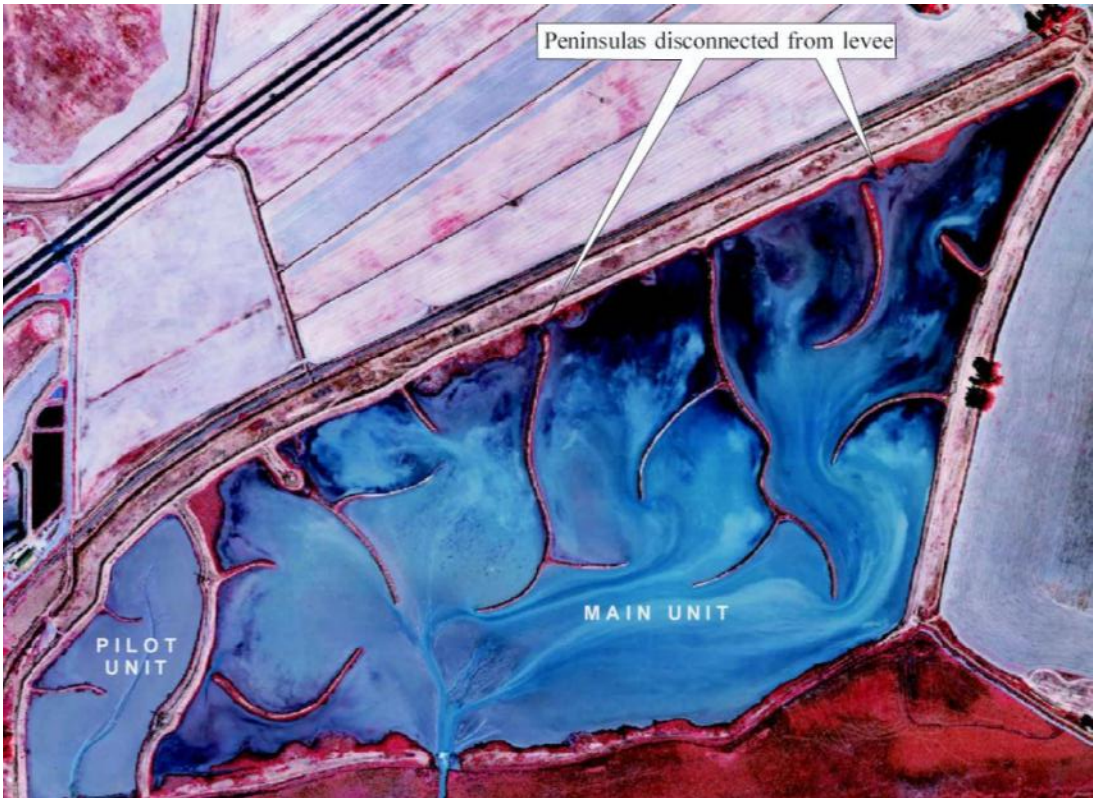

Figure C.4. Wave breaks (peninsulas).

Sedimentation Fields

Tidal currents also inhibit deposition of sediment and their velocities can be reduced to enable fine sediments to settle out of suspension. 'Sedimentation fields' can be created by constructing permeable brushwood fences or groynes (shore normal or boxed) on existing mudflats or shallow subtidal areas (Figure C.5). These structures result in increased sediment deposition due to the build-up of relatively stagnant water behind the structure on a flood tide, followed by slow draining on the ebb tide through the permeable sides.

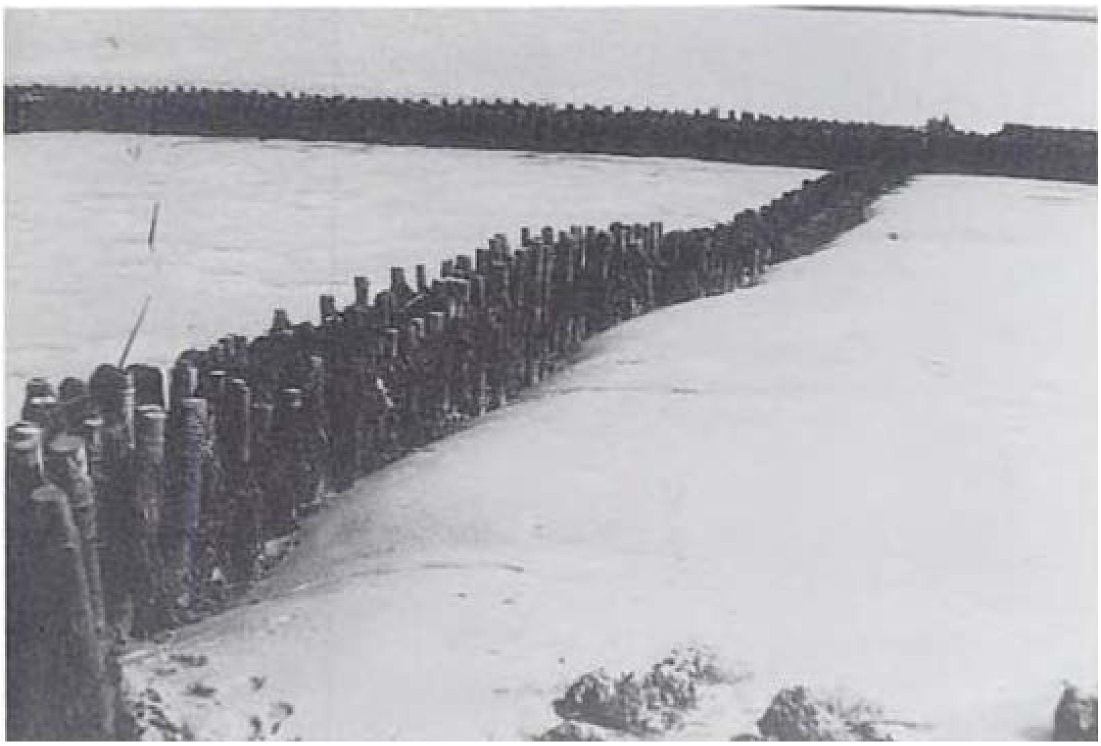
Figure C.5. Sedimentation field

Re-introducing River Sediment Inputs
Intertidal habitats can be starved of sediment because the supply from inland rivers has been reduced due to damming upstream or by diversion. Removal of dams or re-introduction of the original course of a river into a degraded intertidal area or realignment site would introduce extra sediment and deposition. Careful consideration would need to be given to all the local and regional environmental effects of releasing potentially large amounts of sediment back into the system.

Creating an Efficient Drainage Network
When a managed realignment site is freshly inundated by the tides, the tidal flows will tend to focus in existing ditches or depressions that can fix the location and geometry of the drainage system. As the site develops through sedimentation, mudflats accrete and develop into saltmarshes in which the pre-existing drainage system can persist and control the nature of the tidal channel system. Often, in agricultural land, the existing drainage consists of straight field drains or ditches (Figure 6.6). It is generally thought that sinuous channel systems provide a more complex habitat and support a wider range of intertidal habitat functions than linear channels. Hence, with suitable grading prior to reintroduction of tidal action, a different channel system template can be created.

Figure C.6. Straight drains and buried channels

Modification of Pre-existing Drainage

Across some managed realignment sites the original ‘natural’ channel system may still be expressed in the land surface, even though it has been partially or wholly filled in (Figure 6.6). Concentrating tidal flows into the old channels could scour out the loose sediment infills and restore the original tidal drainage system. This can be achieved by appropriate selection of breach location(s), removal of obstructions, and blocking borrow ditch channels. The decision whether to modify the pre-existing drainage system would be based on a trade-off between the costs of grading the system versus the potential benefits of (or adverse impacts avoided by) a modified system.

Excavation of New Tidal Channels

The excavation of a new set of tidal channels within a realignment site will assist in the effective functioning of the habitat (Leggett et al., 2004). If possible, the artificial cuts should tie in with relict natural creek systems (which may be observed on aerial photographs). Early establishment of a tidal channel system enables tidal water and its sediment load to disperse into the site and the tide to drain off the site. Construction of tidal channels is likely to be needed if a site was previously filled or where the sediments are compacted and resistant to erosion.

The appropriate size of tidal channels in the created habitat can be calculated using a technique known as hydraulic geometry. This term refers to empirical relationships between the shape of natural channels and the channel-forming flow, which in mature marshes is largely a function of the tidal prism. In order to use this technique, a regional empirical relationship between channel parameters (depth, top width, cross-sectional area) and tidal prism (or habitat area) should be established from existing data. This relationship can then be applied to the potential managed realignment area to calculate geometries for the tidal channels.

Establishment of Vegetation

Natural Colonisation, Seeding or Planting

In situations where saltmarsh habitat is the creation objective, natural vegetation colonisation is generally preferred over seeding or planting (Leggett et al., 2004). This is because natural colonisation will reflect the existing species and allow the vegetation community to change over time from initial colonisation to site maturity. This will provide a range of plant species that can adapt to future change and are suited to the niche environment offered by the realignment site. However, there may be some situations where natural colonization will not take place and seeding or planting is necessary (Brooke et al., 2000). In these cases, the plant source should be from an existing saltmarsh close to the site so adaptation to local conditions can take place.

Mossman et al. (2012) compared plant communities and environmental characteristics of managed realignment sites (between one and 14 years old) with those on natural reference saltmarshes in the United Kingdom. They found that the community composition of managed realignment sites was significantly different from the reference sites, with early-successional species remaining dominant, even on the high marsh. They suggested that marshes created by managed realignment do not satisfy the requirements of the Habitats Directive, and that adherence might be improved by additional management interventions, such as manipulation of topographic heterogeneity or planting of mid- and upper-marsh species.

Soil Treatment

Vegetation colonization to create saltmarsh requires a suitable substrate in the rooting zone in terms of its soil chemistry, particle size and bulk properties. Saltmarsh plants are adapted to take advantage of and thrive in naturally deposited sediments. Filled sites may have unsuitable substrates, perhaps due to high acidity, low nutrients or excessive compaction. A potential strategy for dealing with this problem (in addition to fill removal) is to modify the soil substrate, by artificial addition of sediment. In general, saltmarsh plants prefer to grow in sediment finer than sand (which is not compacted or polluted).

Design of Breaches

Tidal inundation of a previously drained area is likely to require breaching of the seaward embankment or defence (Figure C.7). Once a cut is made in an embankment, natural scouring will erode the breach and a channel across any outboard fringing intertidal areas to reconnect the site to full tidal influence. An advantage of leaving defences in place either side of the breach is that they limit the realignment sites exposure to wave action and encourage sedimentation. This has been the most commonly used breaching technique and, over time, the connecting channel should reach equilibrium with the tidal prism of the site (hydraulic geometry) (Burd, 1995; Leggett et al., 2004). It may be possible to position a breach coincident with existing channels that cross the outboard profile (or crossed it historically), thus reducing the impact on the outboard area.


Figure C.7. Breach at flood tide.

Consideration should also be given to the number and positions of the breach or breaches to control the distribution of tidal water over the site. Inundation is typically carried out by simply breaching the embankment although more elaborate schemes may be considered including regulated tidal exchange, or even complete removal of the defence. The position, width and sill height of the breach will determine the degree of exchange of tidal water, and thereby potentially affect the habitat that is created.

Intertidal to Upland Transition

The intertidal to upland transition zone provides critical feeding, resting and refuge for a number of animals and plants, and can also serve as part of a buffer to protect the saltmarsh from disturbance and predators. In a heavily reclaimed area, the transition zone is generally narrow, greatly decreased by embankments and the placement of fill for development along the margin of the intertidal area. In addition to a intertidal-upland transition zone, buffer areas that extend beyond the transition zone are important for various habitat functions, such as sediment filtration or retention, pollution retention, habitat and food web support, and flood protection.

The feasibility and creation of a transition zone should be important components in the planning and design of habitat creation. Ideally, a transition could be achieved by grading the edge of the intertidal area to create a gently shelving bench between mean high water and future extreme high water (allowing for sea-level rise). Typically, this shelving bench will have a maximum slope of 1 in 10 and a minimum width of 30 m to provide