UNIVERSITY OF SOUTHAMPTON

FACULTY OF ENGINEERING, SCIENCE AND MATHEMATICS

School of Civil Engineering and the Environment

Modelling Large-Scale Estuarine Morphodynamics Using Equilibrium Concepts: Responses to Anthropogenic Disturbance and Climatic Change

by

Sara Kate Rossington

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ABSTRACT

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MODELLING LARGE-SCALE ESTUARINE MORPHODYNAMICS USING EQUILIBRIUM CONCEPTS: RESPONSES TO ANTHROPOGENIC DISTURBANCE AND CLIMATIC CHANGE

Sara Kate Rossington

This thesis explores the application of equilibrium concepts in the modelling of large-scale estuarine morphodynamics. Empirical relationships have been observed between a number of morphological measures and forcing parameters in estuaries and this suggests that estuaries tend towards a morphology that is in equilibrium with forcing.

A geographical information system was used to analyse historical bathymetry charts for eight English estuaries and to construct a time series of morphological change for each estuary. Equilibrium relationships in this data set, and for a larger selection of English and Welsh estuaries, were analysed. A behaviour-oriented numerical model based on equilibrium concepts, ASMITA (Stive et al., 1997), was used to further investigate the nature of equilibrium in the study estuaries.

ASMITA represents estuaries schematically, as aggregate systems containing a number of distinct morphological elements. These estuary schematisations provide a useful structure for analysing the large scale changes in morphology and also allow the equilibrium state of each element to be examined. New schematisations were used where necessary to represent the wide range of estuary morphologies found in the study sample, and in UK estuaries as a whole.

The study estuaries show a variety of morphological behaviours: those showing the largest changes were the Ribble Estuary, Southampton Water and Portsmouth Harbour. In all these cases, the morphological evolution of the estuaries was driven by human disturbances to the natural regime.

In general, ASMITA was able to reproduce the evolution of the estuaries studied in line with observed data. Analysis of the data and application of ASMITA indicated that the equilibrium volume of the channel (water volume below mean low water) could be defined as a linear function of the tidal prism. Equilibrium volume of the flats (sediment volume above mean low water) could also be defined, but was sensitive to changes in basin area, such as those caused by land reclamation, making it less useful for modelling application.

Generic equilibrium relationships, based on a larger sample of estuaries, were found to be poor predictors of equilibrium in the eight study estuaries and it was concluded that estuary specific relationships are much better for for modelling applications. Equilibrium theory is useful in modelling the large-scale behaviour of estuaries and has the potential to be a useful tool for long-term estuary management, especially if improved relationships can be found to define flat equilibrium volume.

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LIST OF SYMBOLS

α_c Channel equilibrium coefficient

α_d Ebb-tidal delta equilibrium coefficient

α_f Flat equilibrium coefficient

δ_{cd} Horizontal exchange coefficient between the channel and ebb-tidal delta elements

δ_{do} Horizontal exchange coefficient between the ebb-tidal delta and the outside world

δ_{fc} Horizontal exchange coefficient between the flat and channel elements

$\frac{d\zeta}{dt}$ Rate of sea-level rise

A Area available for sediment exchange

A_b Basin area

A_{change} Area change caused by a disturbance (positive for managed realignment and negative for land reclamation)

A_c Channel area

A_d Ebb-tidal delta area

A_f Flat area

A_{MHW} Surface area at mean high water (also called basin area (A_b))

A_{MLW} Surface area at mean low water (also called flat area (A_f))

b_c Non-linear channel equilibrium coefficient

b_d Non-linear ebb-tidal delta equilibrium coefficient

c Channel

c_{ce} Local equilibrium concentration for channel element

c_c Concentration in channel element

c_{de} Local equilibrium concentration for ebb-tidal delta element

c_d	Concentration above ebb-tidal delta element
C_E	Global equilibrium concentration
c_{fe}	Local equilibrium concentration for flat element
c_f	Concentration above flat element
D	Diffusion coefficient
d	Ebb-tidal delta
f	Flat
H	Tidal range
h	Average water depth
H_c	Average channel depth
H_f	Average flat height
L	Length scale of exchange
P	Tidal Prism (the volume of water flowing through an inlet on a single tide)
r	Coefficient
u	Peak flow velocity
V_c	Channel volume, defined as water volume below mean low water
V_d	Ebb-tidal delta volume, defined as excess sediment volume above a hypothetical non-inlet shoreface
V_{ce}	Channel equilibrium volume
V_{de}	Ebb-tidal delta equilibrium volume
V_{fe}	Flat equilibrium volume
V_f	Flat volume, defined as sediment volume above mean low water
V_{MLW}	Water volume below mean low water (also called channel volume (V_c))
w_{s_c}	Vertical sediment exchange coefficient for channel element
w_{s_d}	Vertical sediment exchange coefficient for ebb-tidal delta element
w_{s_f}	Vertical sediment exchange coefficient for flat element

DEFINITIONS AND ABBREVIATIONS

ABPmer	Associated British Ports Marine Environmental Research
ASMITA	Aggregated Scale Morphological Interaction between Tidal inlets and the Adjacent coast
BNG	British National Grid
BSS	Brier's Skill Score
CD	Chart Datum
DEFRA	Department for Environment, Food and Rural Affairs
DINAS-COAST	Dynamic and INteractive ASsessment of National, Regional and Global Vulnerability of COASTal Zones to Climate Change and Sea-Level Rise
DIVA	Dynamic and Interactive Vulnerability Assessment
ENSO	El Niño Southern Oscillation
eSMP	Estuary Shoreline Management Plan
GIS	Geographical Information System
IHO	International Hydrographic Organisation
JNCC	Joint Nature Conservation Committee
LAT	Lowest Astronomical Tide
MAFF	Ministry of Agriculture, Fisheries and Food
MHW	Mean High Water
MLW	Mean Low Water
MLWS	Mean Low Water Springs
MSE	Mean Square Error
ODL	Ordnance Datum Liverpool
ODN	Ordnance Datum Newlyn
OS	Ordnance Survey
SAC	Special Area for Conservation

SLR	Sea-level Rise
SMP	Shoreline Management Plan
SPA	Special Protected Area
SSSI	Site of Special Scientific Interest
WPRL	Water Pollution Research Laboratory

1. INTRODUCTION

1.1 Background and Justification

Equilibrium is a concept the has been applied to geomorphic systems for over a century and, if valid, provides a basis for a range of useful predictions about future states of morphological features. This thesis explores the modelling of large-scale estuarine morphodynamics using equilibrium concepts.

1.1.1 Estuaries

Estuaries are found along coastlines throughout the world. They form distinct environments where freshwater meets saltwater leading to complex interactions between physics, biology and chemistry. Most estuaries and tidal inlets found on the world's coasts today formed when river valleys and low lying land were inundated during a period of rapid postglacial sea-level rise between 15,000 and 6000 years ago (Kench, 1999). Since inundation, the rates of sea-level rise have slowed, to approximately still stand (Church et al., 2001) and the estuaries have, to various degrees, accumulated marine and fluvial sediments. These create the intertidal flats, sand bodies and other morphological features that we see today.

Estuary morphology evolves over a range of interacting time and space scales (Cowell et al., 2003a). The subject of this thesis is large-scale estuarine morphodynamics, refering to changes in morphology happening over time-scales of tens to hundreds of years and space scales of tens of metres to several kilometres (Stive et al., 2002). This time and space scale may be referred to as historic or engineering timescale as it is the time span over which coastal morphology and processes adjust to human interventions, such as coastal structures, reclamations and resource extraction. Large scale morphodynamics describes changes to large scale features such as channels, intertidal flats and ebb-tidal deltas observable over these timescales, including the response to sea-level rise. Geological time and space scales, including factors such as the long-term inundation of estuaries can be considered as boundary conditions for large scale morphodynamics. Smaller scale events, such as seasonal variations in tides and waves, are regarded as noise, but are important in determining large-scale behaviour as they may accumulate over may years to an observable change on the timescale of interest.

The coastline of the United Kingdom is dissected by more than 170 estuaries with a variety of physical characteristics, spatial areas and management issues (Pontee and Cooper, 2005). Estuaries are highly productive ecosystems and have an important role in coastal food chains. 76 % of estuarine area in the UK is covered by European nature conservation designations and intertidal areas are particularly important for numerous species including migrating birds (Townend, 2004). Intertidal flats and saltmarshes, often contained within estuaries, provide valuable natural coastal defences, dissipating wave energy as it approaches the shore (Houwing, 2000; Widdows and Brinsley, 2002; Moller, 2006).

Many UK estuaries are located on low-lying coastal plains. Historically, estuaries have been sites of human activity and settlements, with some of the UK's major cities located on estuaries, including London, Liverpool and Southampton. The Environment Agency (1999) estimated that 11.5 million people lived within 1 km of an estuary shoreline.

Estuaries are economically important, with 400 million tonnes (95%) of UK international trade passing through ports located in estuaries (Townend, 2004). Other heavy industry and infrastructure is also commonly found in estuaries due to their proximity to port facilities and water supply (Doody, 2007). Less developed land surrounding estuaries is often of high agricultural value (Pontee and Cooper, 2005), including areas that have been reclaimed from the estuary flood plain. Many estuaries are also important recreational sites, both for local people and for tourists, and may be used for activities such as sailing, walking, fishing and bird watching.

The desirability of estuaries as sites for industry, ports, places to live and relax and the obligations to protect estuarine habitats and ecology lead to a variety of pressures on estuarine systems. Urban and industrial developments require protection from flooding and coastal erosion. Ports need to maintain shipping channels and may wish to expand, requiring more land for ports activities and possibly capital dredging to create larger navigation channels. In addition, we are obliged under the Habitats Directive (EEC, 1992) to maintain designated sites in a favourable conservation status.

Responding to the pressures on estuaries inevitably has consequences. Providing flood defences and coastal protection to developed areas deceases the sediment supply to the estuary via bank erosion and fixes the estuary boundaries in place (French, 1997; Townend and Pethick, 2002). Port and industrial developments are also likely to introduce hard, immovable structures, locking up sediment and fixing the coastline. Maintenance dredging for ports removes sediment from the estuarine sediment budget and may cause erosion elsewhere in the estuary; capital dredging also removes sediment and may alter tidal propagation in the estuary (Pethick, 2002; Morris, 2007).

In addition to the direct human-induced pressures, the rate of sea-level rise is predicted to accelerate over the next century. As sea levels rise, the natural response of an estuary is to retreat upwards and landwards in a process known as "rollover" (Allen, 1990; Townend and Pethick, 2002). Townend and Pethick (2002) suggest that rollover is achieved by horizontal erosion of the seaward edges of saltmarshes and mud flats which is balanced by vertical accretion at the landward edge of the intertidal zone. Seawalls and embankments, protecting urban developments, industry and agricultural land from flooding and erosion, constrain the ability of the estuary to respond to changes in sea level. Erosion still occurs at landward edges, but sea defences prevent landward accretion and the estuary's morphology and tidal regime cannot be maintained (Townend and Pethick, 2002). Sea-level rise is likely to be a major force driving change within estuaries, possibly resulting in loss of intertidal areas, erosion of shorelines and increased flood risk of low lying areas around estuaries.

The variety of pressures facing estuarine systems mean that in order to manage estuaries effectively, we require an understanding of the morphology and processes happening at large scales, upon which all human-induced changes are superimposed. In particular, we need to understand how estuaries will respond to management interventions such as new port developments, flood defences or managed realignment schemes. We also need to know what effect accelerated sea-level rise may have on estuaries. We can improve our understanding by looking at how an estuary has behaved in the past and using models to predict how this may change in the future.

1.1.2 Equilibrium

The concept of equilibrium has been used by coastal engineers for several decades to predict how coasts will change in the future. Various definitions of equilibrium have been proposed, including "the profile of equilibrium which the water would ultimately impart, if allowed to carry its work to completion" (Fenneman, 1902); "a long-term profile produced by a particular wave climate and type of coastal sediment" (Schwartz, 1982) and "the state where no net [sediment] transport occurs, when considered over a suitably long period" (Roberts et al., 2000). The equilibrium concept suggests that, if forcing, including waves and tides, remains constant over long time periods, coastal morphologies, including beaches, inlets and estuaries, will evolve towards an average, steady state, form that is in balance with the forcing.

In this thesis, equilibrium is defined in terms of mass flux equilibrium, where some measure of the mass of the feature of interest is in equilibrium with forcing (Thorn and Welford, 1994). Dynamic equilibrium is defined as the functional relationship describing the balance between the output (form) and inputs (forcing) (Ahnert, 1967; Howard, 1988). This definition allows equilibrium to be applied to non-static systems, where input forcing is not constant through time. Steady state equilibrium, as described by Fenneman (1902); Schwartz (1982); Roberts et al. (2000) is thus defined as the form the morphology would achieve if forcing were constant over sufficiently long periods of time. Equilibrium definitions and possible equilibrium behaviours are described in more detail in Chapter 2.3.2

In estuaries, the most commonly reported dynamic equilibrium relationship is between the cross-section area of the estuary mouth and the tidal prism. Strong correlations between cross-section area and tidal prism have been found from tidal inlets in the USA and the Netherlands (O'Brien, 1931; 1969; Jarret, 1976) and from estuaries in New Zealand (Hume and Herdendorf, 1988) and the United Kingdom (Townend, 2005). The physical explanation for this relationship is based on feedback between tidal prism, flow area and flow velocity. If the cross section area were to decrease, the same volume of water would have to pass through a smaller flow area and current velocities would increase. Higher current velocities lead to increased erosion, thus increasing the flow area. If the flow area of the inlet mouth was larger than equilibrium, current velocities would decrease, allowing deposition to occur.

Relationships between tidal prism and cross-section area have been found to describe upstream sections of estuaries as well as the mouth (Spearman et al., 1998). Similar relationships have been extended to predict the water volume contained in the estuarine channels and the volume of sediment in the intertidal zone. Changes to the forcing parameters (e.g. tidal prism) cause changes to the morphology of the estuary and so equilibrium theory can be used to model large-scale morphological change.

Traditionally, coastal modelling has involved process-based models, based on physical understanding of small scale coastal behaviour over relatively short timescales (De Vriend et al., 1993). Running these models over longer time periods does not necessarily accurately predict long-term coastal evolution, because process-based models do not accurately describe small residual sediment fluxes and non-linear behaviours that become important at larger scales (De Vriend et al., 1993; Niedoroda et al., 1995). Models using equilibrium concepts belong to a larger class of models know as behaviour-oriented models, which overcome scaling up issues associated with process-based models by representing the observed behaviour of a coastal system with a simple mathematical model that may or may not be related to underlying physical processes (Capobianco et al., 1999). This results in relatively simple models that can be used to predict large scale estuary behaviour from limited data input, making them potentially attractive tools for coastal management.

One example of a behaviour-oriented model based on equilibrium concepts is ASMITA[1] (Stive et al., 1998). ASMITA has been applied to tidal basins and ebb-tidal deltas of the Dutch Wadden Sea and the Po Delta (Italy) to model the effects of sea-level rise (van Goor et al., 2003) and human disturbances (Buijsman, 1997; Stive et al., 1997; Kragtwijk et al., 2004). A reduced version of ASMITA (Bijsterbosch, 2003) has also been applied to predict indirect erosion at tidal inlets due to sea-level rise, on a worldwide scale, in the DIVA tool[2] (DINAS-COAST Consortium, 2006)[3].

[1] Aggregated Scale Morphological Interaction between Tidal basin and the Adjacent coast
[2] Dynamic and Interactive Vulnerability Assessment
[3] Dynamic and INteractive ASsessment of National, Regional and Global Vulnerability of

In the DIVA tool, estuary equilibrium state is based on relationships for the Dutch Wadden Sea (Bijsterbosch, 2003), but the assumption that these relationships are suitable for all estuaries has not been tested.

It is generally assumed that equilibrium relationships can be used to describe estuarine responses to climatic and human disturbances, and that following a disturbance an estuary will evolve towards a new equilibrium that fulfills the characteristic equilibrium relationship. However, this idea has not been extensively tested for UK estuaries, which have a wide variety of morphological types due to the range of tidal ranges and geological settings. Townend (2005) found strong correlations between cross-section area at the mouth of UK estuaries and their tidal prisms, but did not examine how well these relationships described individual estuaries. Estuary specific equilibrium relationships have been investigated for the Lune Estuary, UK (Spearman et al., 1998), where it was found that the relationship between peak discharge and cross section area was the same before and after a major human interference at this site, suggesting that the estuary rapidly adjusted to equilibrium following the disturbance.

Whilst equilibrium relationships are useful for describing aspects of estuarine morphology and predicting possible future changes, their limits have not been systematically tested. This includes whether equilibrium relationships can be used to describe estuaries with a wide range of morphological types and whether disturbances of a certain magnitude can disrupt a system to such an extent that the estuary cannot evolve towards a new equilibrium or that the characteristic equilibrium relationship is changed.

1.2 Aims and Objectives

The aim of this research is to investigate the validity and appropriateness of equilibrium concepts in describing the large-scale morphodynamics of UK estuaries.

The specific objectives of this research are:

1. To explore estuary specific equilibrium relationships to describe a sample of English estuaries.

   Method: Carry out historical analysis looking at natural- and human-induced morphological changes in a sample of eight estuaries. In addition to morphological changes, equilibrium relationships were investigated and the equilibrium status of each study estuary is assessed (Chapter 4).

2. To test whether the implementation of equilibrium theory in a numerical model can predict the evolution and behaviour of the study estuaries at engineering timescales.

COASTal Zones to Climate Change and Sea-Level Rise

3. To examine whether equilibrium theory can be used to model response to gradual changes, such as sea-level rise, and sudden changes, such as large scale land reclamation or managed realignment

   Method: Apply ASMITA(Stive et al., 1998) to the study estuaries as a specific example of how equilibrium concepts can be implemented in numerical models. Applying ASMITA allows the equilibrium relationships derived from the data to be investigated further, particularly in relation to which relationships are the best predictors of estuary behaviour. This allows strengths and weaknesses of the estuary specific equilibrium relationships to be identified, along with potential short comings of ASMITA itself (Chapter 5).

4. To investigate generic relationships, based on morphological type, to describe equilibrium in specific estuaries (Chapter 6).

   Method: To modify ASMITA to better represent estuary morphologies found in England and Wales and to overcome any shortcomings identified in Chapter 5 (Chapter 6).

5. Assess the usefulness of numerical models based on equilibrium concepts to help estuary managers to predict and understand the likely responses of estuaries to sea-level rise and human interventions

   Method: Carry out ASMITA simulations of possible future sea-level rise and management scenarios to demonstrate how equilibrium relationships may be applied within a numerical model as a tool for estuary management (Chapter 7).

1.3 Structure

This thesis contains nine chapters. Chapter Two contains a review of literature relevant to equilibrium theory, both in estuaries and the open coast, and a discussion of previous models of large scale estuarine morphodynamics. This chapter also introduces the processes that are important in shaping estuaries at the time-scale of interest and the pressures faced by modern estuaries, including anthropogenic disturbances and climate change.

Chapter Three describes the methodologies used, including data sources, collection and analysis. Potential error, arising from the data and from data processing are discussed and quantifies. Details of ASMITA, the numerical model used to investigate the application of equilibrium theory, are also given in Chapter Three.

A historical analysis of morphological changes in eight English estuaries is presented in Chapter Four. This includes a review of relevant literature for each estuary and analysis of historical morphology data derived from bathymetry charts. The likely equilibrium status of each estuary is also discussed.

Chapter Five presents the initial application of ASMITA to the study estuaries and evaluates the ability of ASMITA to reproduce the observed behaviour. The application of ASMITA gives further insight into the equilibrium status of each estuary.

Chapter Six investigates the potential for generic equilibrium relationships based on a larger sample of English and Welsh estuaries. Generic relationships are compared with the estuary specific relationships used in Chapter Five.

In Chapter Seven ASMITA is applied to predict the likely future evolution of the eight study estuaries under accelerated sea-level rise. This includes predictions for the evolution of the estuary under the DEFRA (2006a) sea-level rise scenario and predictions of the critical rate of sea-level rise (van Goor et al., 2003; Rossington et al., 2007), for each estuary.

In Chapter Eight the objectives listed in section 1.2 are returned to and discussed in relation to the data presented. Recommendations for future work are made. The overall conclusions are stated in Chapter Nine.

In addition to these chapters, which form the main body of this thesis, three appendices are included. Appendix A presents the FutureCoast estuary classification (Dyer, 1980). Appendix B contains data on disturbances such as dredging and land reclamations occurring in the study estuaries. This data set was applied to include these disturbances in ASMITA modelling by correcting the predicted volumes in years where a disturbance occurred. Appendix C contains data from the Estuaries Database (EMPHASYS, 2000) used to investigate generic equilibrium relationships in Chapter Six.

2. LITERATURE REVIEW

2.1 Introduction

2.1.1 What are estuaries?

Estuaries are commonly defined as "a semi-enclosed body of water having a free connection with the open sea and within which sea water is measurably diluted with fresh water derived from land drainage" (Cameron and Pritchard, 1963). This broad definition encompasses a wide range of morphologies. Dalrymple et al. (1992) defined estuaries in geological terms as "the seaward portion of a drowned valley system which receives sediment from both fluvial and marine sources and which contains facies influenced by tide, wave and fluvial processes. The estuary is considered to extend from the landward limit of tidal facies at its head to the seaward limit of coastal facies at its mouth" . The limitations of these definitions, and of commonly used estuary classification systems, were reviewed by Perillo (1995) in an attempt to find an all encompassing estuary definition that is acceptable for all disciplines.

Perillo (1995) proposed estuaries should be defined as "a semi-enclosed body of water that extends to the effective limit of tidal influence, within which sea water entering from one or more free connections with the open sea, or any other saline body of water, is significantly diluted with fresh water derived from land drainage, and can sustain euryhaline biological species from either part or the whole of their life cycle."

The majority of estuary definitions cited above suggest that sea water must be significantly diluted with fresh water in estuaries. This excludes systems, such as tidal inlets and lagoons, where fluvial influence may be negligible. Tidal inlets are formed where sea level has risen over extremely low relief coastal plains and are characterised by narrow mouth areas linking the sea with a tidal lagoon behind a barrier beach (Dyer, 2002). Tidal inlet and lagoon systems have similar tidal and wave influenced morphologies to estuaries and have similar management issues, and have been included as a distinct morphological type in some estuary classification systems (e.g. Dyer (2002)) (Table 2.1). Tidal inlets are considered estuaries for purposes of the current study due to similarities in their morphological behaviour, management issues and the likelihood that the morphological behaviour of tidal inlets and estuaries can be described by a single conceptual model.

Most estuaries and tidal inlets found on the world's coasts today formed when river valleys and low lying land were inundated during a period of rapid postglacial

Tab. 2.1: Estuary classification used in FutureCoast (Dyer, 2002)

Behavioural Type	Sub-type	Origin
1. Fjord	a. With spits b. Without spits	Glaciated valley
2. Fjard	a. With spits b. Without spits	
3. Ria	a. With spits b. Without spits	Drowned river valley
4. Spit-enclosed	a. Single spit b. Double spit c. Filled Valley	
5. Funnel shaped		
6. Embayment		
7. Tidal inlet	a. Symmetrical b. Asymmetrical	Drowned coastal plain

sea-level rise between 15,000 and 6000 years ago (Kench, 1999). Over the last 6000 years, rates of sea-level rise slowed to approximately still stand (Church et al., 2001). During this period, estuaries and tidal inlets have undergone various degrees of infilling with marine and fluvial sediment to give the morphologies we see today. Estuaries can be classified based on their mode of origin, physical process and morphological characteristics. Many classification systems have been used to describe estuaries (Hayes, 1975; Dalrymple et al., 1992; Perillo, 1995). Most useful for UK estuaries is the classification used in FutureCoast (Dyer, 2002), which modifies Hume and Herdendorf (1988)'s classification and is based on estuary origin and morphological behaviour type (Table 2.1).

Glacial estuaries are found in high latitudes where glacial processes have deepened and widened river valleys, which were then flooded when the glacier retreated and sea level rose (Perillo, 1995). Glaciated estuaries are characterised by a u-shaped basin, usually with a sill at the mouth. Fjords occur in hard rock landscapes, fjards are present where the rock is softer. Scottish Lochs may be classified as fjords, but none of the estuary sample used in the present study are of glacial origin.

Drowned river valleys are the most common types of estuary and occur where sea-level rise has inundated a valley cut by fluvial processes. They can be divided into several behavioural types including rias, spit-enclosed estuaries, funnel shaped estuaries and embayments (Dyer, 2002).

Rias are found on hard rock coasts and have steep relief (e.g. Dart Estuary). The sediment bodies found varydepending on sediment supply. Rias with relatively high sediment supplies may have spits at the mouth and mudflats and saltmarshes may be present (Dyer, 2002) (Appendix A).

Spit-enclosed estuaries are found in softer rock and have lower relief than rias

(Dyer, 2002). They have spits at one or both sides of the mouth and may contain saltmarshes, sand and mud flats, ebb and flood channels, and ebb and flood deltas (Dyer, 2002) (Appendix A). Funnel-shaped estuaries increase in width seaward and tend to have large tidal ranges which prevent the formation of spits. They may have saltmarsh, sand flats and mudflats. The ebb-tidal delta may be replaced by linear sand banks in the estuary mouth at higher tidal ranges. Examples include the Ribble Estuary and the Thames Estuary.

Drowned coastal plain tidal inlets are formed where sea-level rise has inundated low lying, low relief coastal plains and are characterised by narrow mouths leading to extensive tidal basins (Dyer, 2002). Tidal inlets may have spits, saltmarsh, sand and mud flats, ebb and flood channels and deltas. There may also be a barrier beach separating the tidal basin from the sea. The symmetrical and asymmetrical sub types refer to the relative position of the spits and flow at the mouth: symmetric tidal inlets have spits that are approximately aligned and the channel is directed straight out to sea; asymmetric inlets have spits that overlap causing the channel to discharge parallel to the coastline (Dyer, 2002).

2.1.2 Rivers, waves and tides

The morphology of estuaries is influenced not just by their origin, but also by the processes acting to supply and redistribute sediment (Hayes, 1975; Boyd et al., 1992; Dalrymple et al., 1992). Hayes (1975) described the sand bodies found in estuaries based on tidal range; Boyd et al. (1992) and Dalrymple et al. (1992) described estuary morphology based on the relative importance of tides, waves and fluvial influences.

Based on Hayes (1975) description, microtidal estuaries (tidal range 0 m to 2 m) are most likely to contain river deltas, barrier islands and tidal deltas (Fig. 2.1). Common sand bodies in mesotidal (2 m to 4 m tidal range) estuaries are tidal flats and salt marshes, tidal deltas and short stubby barrier islands. Macro tidal estuaries (greater than 4 m tidal range) are less likely to have barrier islands or tidal deltas and tend to be broad mouthed and funnel shaped. Common morphologies in macrotidal settings are linear sand banks, tidal flats and saltmarshes.

Boyd et al. (1992) and Dalrymple et al. (1992) described estuaries in terms of the relative magnitude of processes, classifying estuaries and deltas based on the relative importance of tides, waves and fluvial processes (Figs. 2.3 & 2.2). Dalrymple et al. (1992) described wave dominated and tide dominated estuaries as end-member cases, with transitional forms lying in between. Estuaries are also divided into three zones: the outer zone, influenced mainly by marine processes; the mid zone, where energy is is relatively low; and a river dominated inner zone (Dalrymple et al., 1992).

Wave dominated estuaries tend to have relatively small tidal energy and high wave energy in the marine-dominated zone, causing the alongshore movement of

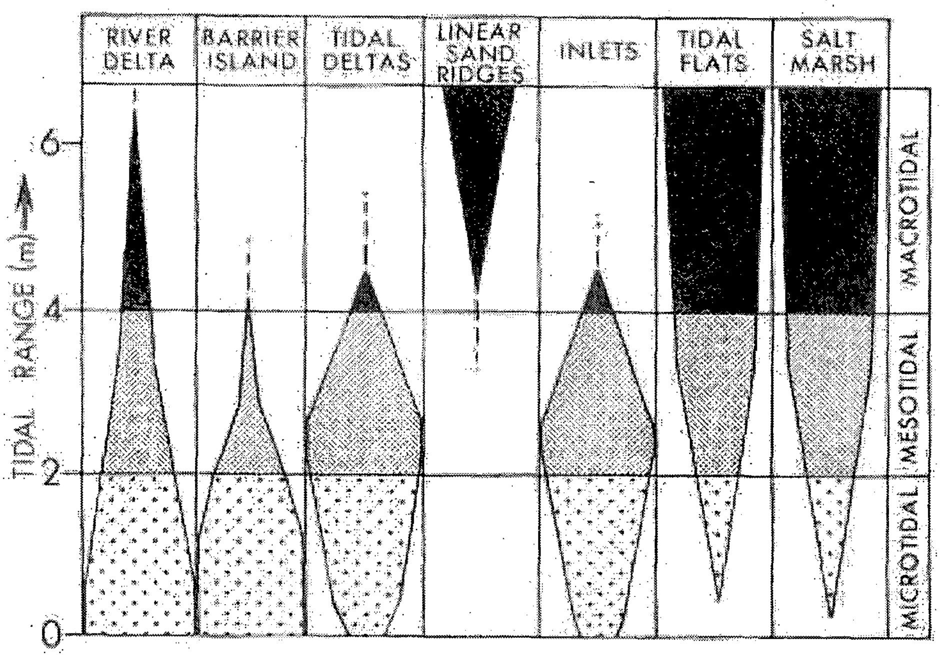

Fig. 2.1: Characteristic morphologies of coastal plain shorelines with differing tidal ranges (Hayes, 1975)

sediment and the formation of spits and barriers (Dalrymple et al., 1992). If tidal energy is moderate, flood-tidal deltas may form. The sand bodies at the estuary mouth reduce both wave and tidal energy entering the central basin of the estuary resulting in a very low energy mid zone, where fine grained sediment is deposited. Fluvial flow in the upper estuary may supply sufficient sediment to build a bayhead delta.

Tide dominated estuaries tend to have larger tidal ranges, although where wave influence is small this is not essential if tidal energy exceeds wave energy at the estuary mouth (Dalrymple et al., 1992). Linear sand bars develop at the mouth, dissipating wave energy and further reducing the influence of waves in the estuary. Tide dominated estuaries tend to be funnel shaped, decreasing in width with increasing distance landward. This convergence causes the tide to become progressively more confined into a smaller cross-section, increasing tidal current speeds in the estuary, until this effect is reduced by frictional dissipation. Sandy sediments tend to be found along the channel length in tide dominated estuaries, with muddy sediments restricted to intertidal areas where current speeds are lower. Compared to wave dominated estuaries, the mid estuary basin tends to have relatively high energies, and the morphologies take the form of a meandering tidal-fluvial channel between saltmarshes (Dalrymple et al., 1992).

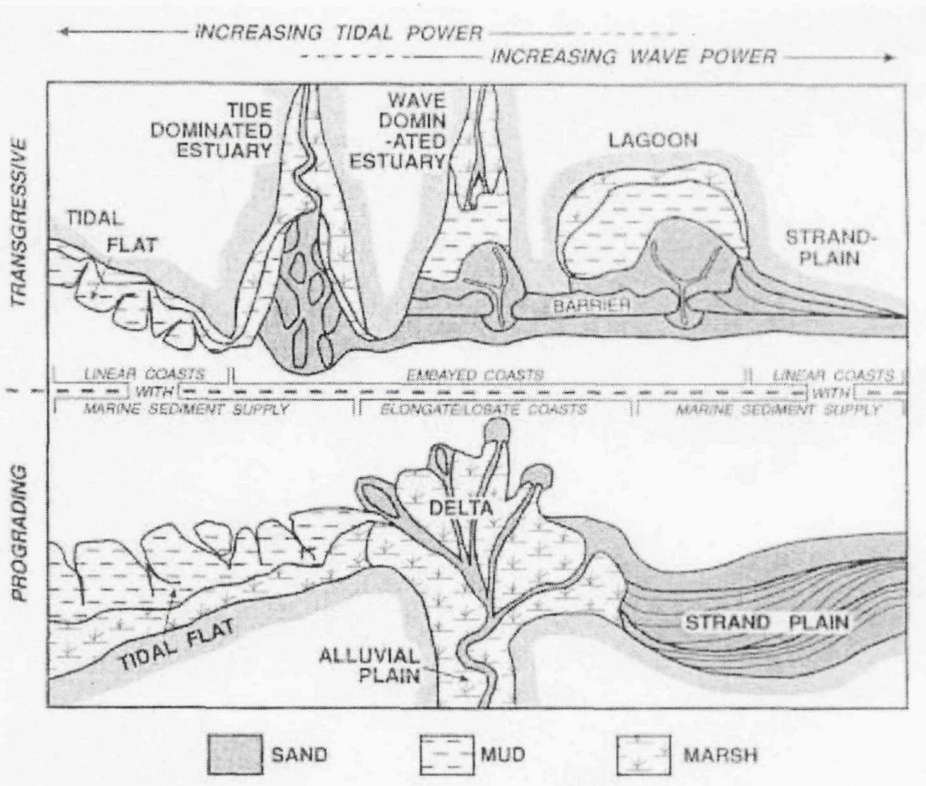

Fig. 2.2: Coastal depositional features influenced by wave, tide and fluvial processes on prograding and transgressive coasts (Boyd et al., 1992)

2.2 Estuary Pressures and Management in the UK

The previous section highlights the variety of morphological forms and processes influencing estuaries. Superimposed on this variety of forms is a range of pressures on the functioning of estuary systems including habitat protection, port development, shipping activities and recreation. In addition, numerous activities carried out in the past, including land reclamation, dredging, flood defences and training wall construction may still be influencing the morphology and function of UK estuaries. These pressures lead to a need to manage estuaries to reduce conflicts between the needs of various users and natural processes. This section discusses current, past and future pressures on estuarine systems in the UK and the need for greater understanding of the processes involved in order to manage these pressures effectively.

2.2.1 Historical legacy

The UK coastline has a long history of land reclamation. Intertidal areas have been embanked and drained since at least Roman times to provide land for agriculture

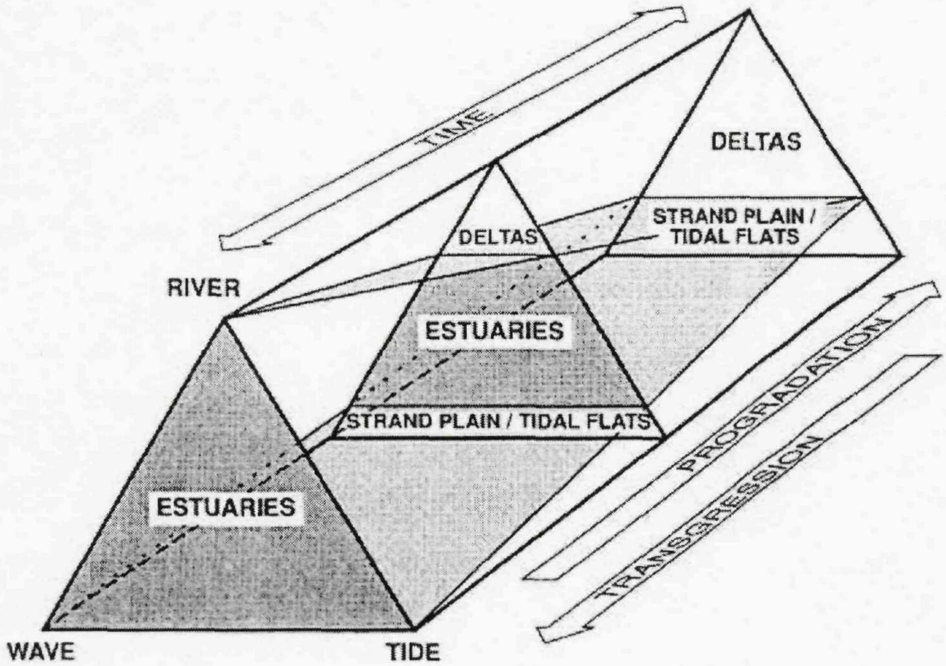

Fig. 2.3: Evolutionary classification of coastal environments (Dalrymple et al., 1992)

(French, 1997). Land reclamation in estuaries was especially intensive in the 1800s and early 1900s when land was reclaimed for both agriculture and port development.

Land reclamation has a number of implications for the morphology and functioning of estuaries. Firstly, there are direct effects including the reduction of intertidal area and the removal of sediment from the estuarine sediment budget. Embankments, built to protect the reclaimed land from flooding, effectively fix the estuary boundary, preventing it from migrating landwards with rising sea levels. The removal of intertidal volume affects water storage within the estuary and may alter the tidal prism or increase the height of high waters. It also changes the cross-sectional profile of the estuary and influences the propagation of tides (Pethick, 2002). Changes to tidal characteristics, including changes in tidal dominance and tidal prism may influence the morphology of the estuary for several decades after the land reclamation took place and timescales of adaption will depend on the magnitude of the disturbance, sediment supply and sediment transport capacity.

Estuaries have historically been favoured sites for port developments due to the relative shelter from waves and proximity to settlements. As ship sizes have increased, natural estuarine channels have tended to be too shallow, meandering and liable to switch locations. Engineering works have been carried out to provide deeper, straighter navigation channels, including capital and maintenance dredging and training wall construction. Capital dredging artificially deepens and widens channels, removing sediment from the estuarine system and changing tidal propagation into the estuary. The implications of capital dredging depend on the specific conditions within that estuary, but may include increased intertidal erosion. Maintenance dredging is not likely to change tidal propagation, but it removes sediments from tidal channels and may result in intertidal erosion by decreasing sediment supply (Morris, 2007). Channel training, by building walls or embankments to constrain ebb currents can also have long lasting affects on estuarine morphology by altering the characteristic tidal flows within the estuary. In the Ribble Estuary, channel training has caused extensive sedimentation outside of the trained channel and this has reduced the tidal prism (Barron, 1938; van der Wal et al., 2002).

The use of hard defences such as embankments and seawalls has progressively reduced sediment supplies in many UK estuaries, both from coastal erosion within the estuary and from erosion of adjacent coastlines. Hard defences on coasts prevent erosion, but may cause problems elsewhere by cutting off sediment supplies (French, 1997). Historically defences were constructed as needed with little thought to the consequences for adjacent coastal stretches.

2.2.2 Present day

Historically, estuaries have been sites of human activity and settlements, with some of the UK's major cities including London, Liverpool and Southampton located on estuaries. The Environment Agency (1999) estimated that 11.5 million people lived within 1 km of an estuary shoreline. The low-lying location and highly populated nature of land surrounding estuaries mean that many estuaries have flood defences along much of their coastline to protect settlements, industry and other high value land. The continued need to defend towns and cities means that estuary boundaries are likely to remain largely fixed, with the exception of limited areas that are found to be suitable for managed realignment.

Today, the wider impacts of coastal defences and coastal management are recognised in shoreline management policy. Shoreline management in the UK is now based on strategic Shoreline Management Plans (SMPs) which identify coastal processes, pressures and management strategies for a number of cells and sub-cells defined based on sediment transport processes (Motyka and Brampton, 1993). SMP boundaries coincide with the sediment cell boundaries, allowing the impacts of shoreline management to be considered for large, self contained, stretches of coastline, rather than only taking local impacts into account. This improves on the historic situation when local authorities and land owners were responsible for shoreline management with little consideration of the impacts elsewhere in the system (French, 2004).

The inclusion of estuaries in the UK shoreline planning process is inconsistent. Some estuaries have their own estuary shoreline management plans (eSMPs), some are included in the relevant open coast SMP, but many are excluded (Pontee and Cooper, 2005). The importance of including estuaries in the shoreline management process has now been recognised by DEFRA (2006b) with the latest guidance for SMPs specifying criteria for including or excluding estuaries. This may lead to a more consistent approach in the future. A number of pressures that estuary management may need to address in the future are discussed below.

2.2.3 Future Pressures

Sea-Level Rise

Sea-level rise is predicted to accelerate over the 21st Century, with a global-mean rise of 9 to 69 cm predicted (Hulme et al., 2002). DEFRA (2006a) guidance for flood and coastal defence gives regional sea-level rise rate predictions for the UK in 30 year blocks between 1990 and 2115 (Table 2.2).

As sea level rises, the natural response of the estuary is to retreat upwards and landwards in a process known as "rollover" (Allen, 1990; Townend and Pethick, 2002). Townend and Pethick (2002) suggest that rollover is achieved by horizontal erosion of the seaward edges of saltmarshes and mud flats which is balanced by vertical accretion at the landward edge of the intertidal. Urban developments, industry and agricultural land tend to be protected from flooding and erosion by hard defences such as seawalls and embankments that constrain the ability of the estuary to respond to changes in sea level. Erosion still occurs at landward edges, but sea defences prevent landward accretion and the estuary's morphology and tidal regime cannot be maintained (Townend and Pethick, 2002). This narrowing of the intertidal zone, caused where coastal defences prevent high water from moving landwards in response to sea-level rise, is termed "coastal squeeze" (Lee and Mehta, 1997; Taylor et al., 2004). Sea-level rise is likely to be a major force driving change within estuaries, possibly resulting in loss of intertidal areas, erosion of shorelines and increased flood risk of low lying areas around estuaries.

Tab. 2.2: Regional net sea-level rise allowances (DEFRA, 2006a)

Administrative or Devolved Region	Vertical land movement (mm/yr)	Net sea-level rise (mm/yr)				Previous allowances (mm/yr)
		1990-2025	2025-2055	2055-2085	2085-2115	
London, East and SE England	-0.8	4	8.5	12	15	6
South West and Wales	-0.5	3.5	8	11.5	14.5	5
NW and NE England, Scotland	0.8	2.5	7	10	13	4

Development

Many activities associated with the port industry may influence estuary hydrodynamics, sediment regimes and morphology. Port development introduces hard, immovable structures into the estuary, locking up sediment and preventing rollover. Capital dredging may be required to accommodate larger vessels and maintenance dredging is often necessary to prevent channels from infilling with marine sediment (Morris, 2007). These disturbances are progressive and incremental and add to the morphological and hydrodynamic disturbances of earlier dredging projects. Capital dredging widens and deepens channels, which can change tidal propagation within the estuary and increase the exposure of intertidal areas erosive forces (Wang et al., 2002; Morris, 2007). Capital and maintenance dredging that remove sediment from the estuary system, reduce the sediment supply to intertidal areas and may cause erosion. Alternative dredging regimes, where dredged sediment is deposited within the estuary are used at some sites and may be effective at offsetting intertidal eroding (Morris, 2007).

Protected Habitats

Much of the estuarine area in the UK is designated under European and national nature conservation designations including Special Areas of Conservation (SACs) (EC Habitats Directive), Special Protected Areas (SPAs) (EC Birds Directive) and Sites of Special Scientific Interest (SSSIs) (UK Habitat Regulations). These directives require that designated sites are maintained or restored to a favourable conservation status and that projects can only be under taken if they have no adverse impact on the integrity of the site. Under exceptional circumstances of overriding public interest, projects may still be allowed at designated sites, but compensations measures must be taken (JNCC, 2007). Coastal defence schemes and port development must comply with the requirements of the Habitats Directive (Lee, 2001).

Managed Realignment

In order to mitigate for habitat loss caused by development, coastal squeeze and to provide natural flood defences, managed realignment of existing sea defences may be an option. This involves removing or breaching existing sea defences and allowing the area behind to be flooded at high tides. Managed realignment is increasing in popularity and could be used more extensively in the future. Whilst it is designed to create intertidal habitat and natural flood defences, managed realignment has the potential to effect the wider estuary (Pontee, 2003). Townend and Pethick (2002) suggest that managed realignments in the Humber Estuary may effect water levels for the whole estuary, depending on the location of the realignment site. Realignments where the old sea defence is breached, rather than removed, increase the tidal prism of the estuary without increasing the cross section of the channel

(Pethick, 2002). This can lead to increased current speeds and may cause erosion in the wider estuary. The sediment demand of the realigned area also needs to be taken into account.

2.3 Large-Scale Estuary Models

In order to manage estuaries effectively, it is important to be able to predict how they are likely to change in the future, both due to natural and anthropogenic forcing. To do this there are a number of issues to consider, including sea-level rise, future development of ports, industry and towns along estuary shoreline and obligations under the Habitats Directive (EEC, 1992).

2.3.1 Timescales

For coastal management purposes, morphological changes on timescales of tens to hundreds of years are important. This is the time span over which coastal morphology and processes adjust to human interventions, such as coastal structures, reclamations and resource extraction and is know as engineering or historical timescale (Stive et al., 2002). Considering change on this timescale allows us to understand the legacy of historical interference, as well as contemporary processes, on coastal systems.

Within the engineering timescale there will be short term variations, at periods of seconds, days and years. Examples include short term fluctuations caused by waves, tides, storm events and seasonal variations (Fig. 2.4). At longer timescales (thousands of years to millennia) are geological changes, such as sea level change and geological processes, that will influence coastal behaviour at engineering timescales by providing boundary conditions.

Cowell et al. (2003a) introduced the concept of the coastal tract as a framework that could be used to integrate data and models of coastal evolution across different spatial and temporal scales. At its lowest level of complexity (first-order), the coastal tract is defined as reaching from the backshore to the edge of the continental shelf and contains three morphological complexes: the lower shoreface, the upper shoreface and the backshore (Fig. 2.5). Estuaries and tidal inlets are morphological units that fit within the backshore morphological complex (Cowell et al., 2003a).

Within the coastal tract framework, the morphological complexes are broken down into progressively smaller morphological units, forming a hierarchy of processes and morphologies (Cowell et al., 2003a). At each level within the framework the morphological sub-systems interact with one another as sediment sharing systems. The coastal behaviour at any given level within the hierarchy is a result of residual affects of higher order processes and is constrained by lower order systems. Higher levels of complexity describe the internal dynamics of a systems, whilst lower levels

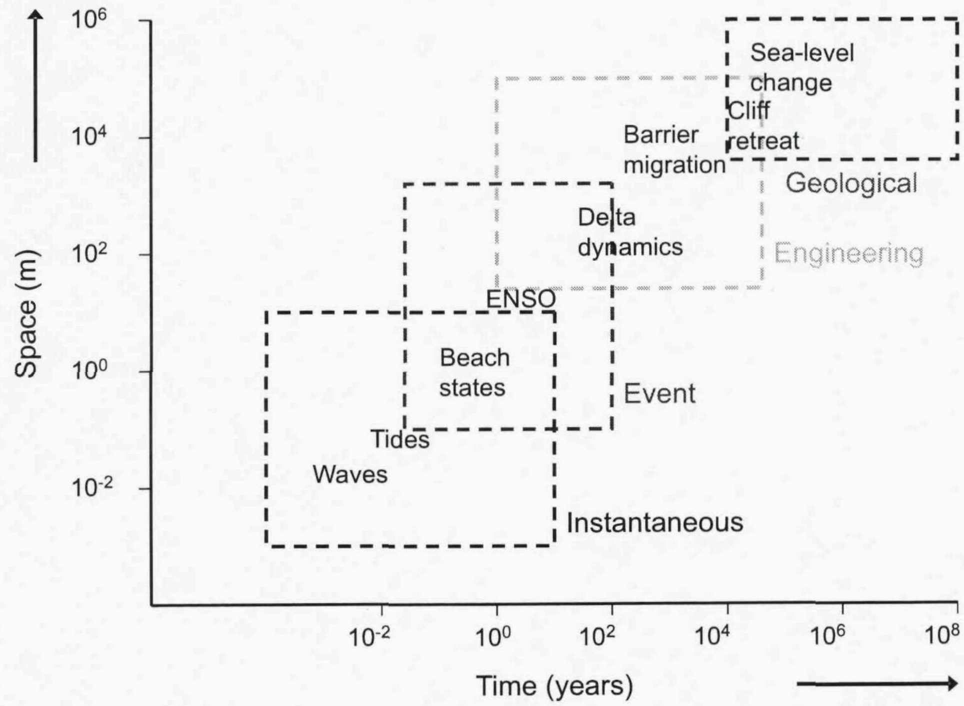

Fig. 2.4: Time and length scales affecting coastal processes and morphology (from Cowell and Thom (1994))

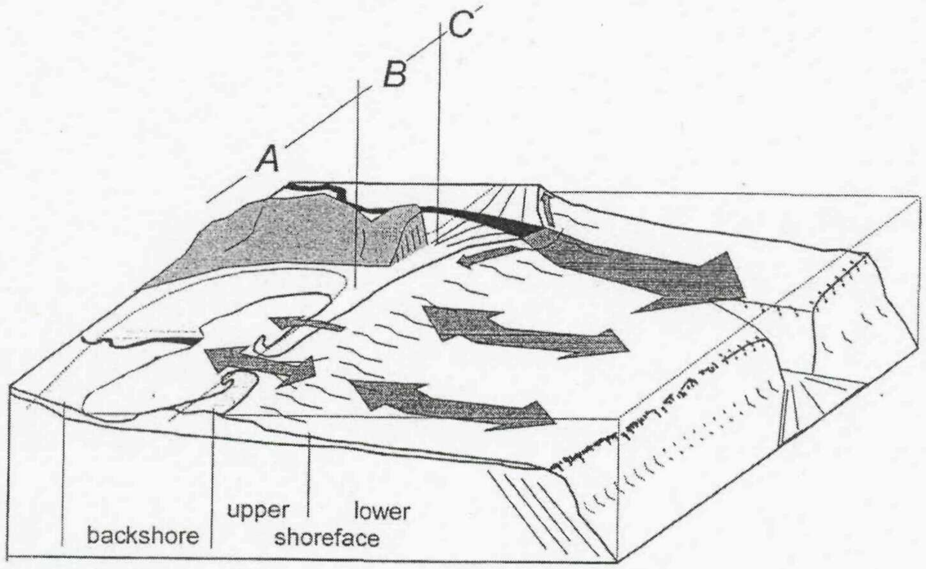

Fig. 2.5: The coastal tract is divided into three morphological complexes: the back-barrier, upper shoreface and lower shoreface. (Cowell et al, 2003a)

provide external boundary conditions (Cowell et al., 2003a). Processes operating at scales much smaller than the scale of interest are regarded as noise.

Much of the existing physical understanding and modelling of large scale coastal evolution concerns processes at small time scales. Traditionally, coastal modelling has involved process-based models, based on physical understanding of small scale coastal behaviour over relatively short timescales (De Vriend et al., 1993). Running these models over longer time periods does not necessarily accurately predict long-term coastal evolution, because process-based models do not accurately describe small residual sediment fluxes and non-linear behaviours that become important at larger scales (De Vriend et al., 1993; Niedoroda et al., 1995).

To overcome problems of "scaling up" process-based models to represent large-scale coastal behaviour, aggregated scale, behaviour-oriented models may be used. Behaviour-oriented models aim to represent the observed behaviour of a coastal system with a simple mathematical model that may or may not be related to underlying physical processes (Capobianco et al., 1999). Aggregated scale and behaviour-oriented modelling has been used to examine the behaviour of open shorelines (Cowell et al., 1995; Niedoroda et al., 1995; Stive and de Vriend, 1995) and tidal inlets (Stive et al., 1997; 1998; van Goor et al., 2003; Kragtwijk et al., 2004) and has been integrated in the coastal tract cascade to model the influence of inlets on the shoreface (Cowell et al., 2003b). This type of modelling is also known as top-down modelling and includes methods where estuary is described by a few key parameters, e.g channel volume, flat height or tidal asymmetry and conceptual models such as rollover (Allen, 1990; Townend and Pethick, 2002).

2.3.2 Equilibrium

The concept of equilibrium has been used by coastal engineers for several decades to predict how coasts will change in the future. The idea that feedback between form and processes will tend to yield an equilibrium form is a much older geomorphological concept, pioneered by Gilbert (1877) (cited in Summerfield (1991)). Equilibrium has been used extensively in river geomorphology and these ideas have led to the development of equilibrium or regime relationships in estuaries (HR Wallingford et al., 2006).

Equilibrium concepts are used within a range of scientific disciples, including physics, mathematics and geomorphology. Thorn and Welford (1994) provide an overview of equilibrium concepts and particularly the use of the terms 'dynamic equilibrium' and 'steady state' within the field of geomorphology. In the present context, useful definitions are given by Ahnert (1967) (cited in Thorn and Welford (1994)), who described dynamic equilibrium as "the balance between process rates" and steady state as "the constant form ... that accompanies dynamic equilibrium". Howard (1988) suggested a similar, mathematically based, approach to geomorpho-

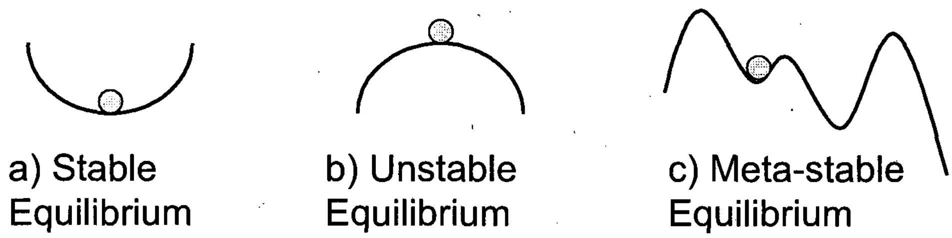

Fig. 2.6: Possible equilibrium states for geomorphic systems (adapted from Thorn and Welford (1994))

logical equilibrium; that equilibrium consists of a "temporal relationship between one or more external variables, or inputs, and a single internal variable, or output". This definition of equilibrium states that variation in the inputs must cause a measurable change in the output variable and that the value of the output is related to the inputs by a single-valued time-invariant functional relationship (Howard, 1988).

Both Ahnert (1967)'s and Howard (1988)'s definitions of dynamic equilibrium require negative feedback between form and processes, such that when the input processes change, the output form of the morphology of interest will change in a way that is predictable from knowledge of the changes in input forcing. Steady state is the constant form that will eventually arise if the forcing inputs remain constant for sufficiently long periods.

In contrast to physical definitions of equilibrium, which defined equilibrium in terms of energy, Ahnert (1967) (cited in Thorn and Welford (1994)) considered equilibrium in terms of mass, leading Thorn and Welford (1994) to suggest the term "mass flux equilibrium" to describe equilibrium in geomorphic systems. In geomorphology, mass is more easily, and more commonly, measured than energy, making equilibrium definitions in terms of mass more applicable (Thorn and Welford, 1994).

Dynamic equilibrium in geomorphology is assumed to result in a stable equilibrium state, with negative feedback operating between processes and form to return the system to a steady state. However, other equilibrium states are possible, including unstable equilibrium and meta stable equilibrium (Fig. 2.6). Howard (1988) recognised that equilibrium relationships may be limited to a certain range. In unstable equilibrium, a small disturbance may cause a system to move away from equilibrium and positive feedback will prevent it from returning to its original, unstable, position. In meta-stable equilibrium, the system will be stable, unless it receives a disturbances above a certain threshold, which may move it to a new equilibrium state, or become unstable (Thorn and Welford, 1994).

Equilibrium theories in coastal engineering include shoreface equilibrium, such as the "Bruun Rule" (Bruun, 1962; 1983) and models based on this concept (Cowell et al., 1995; Niedoroda et al., 1995; Stive and de Vriend, 1995), inlet stability relationships (O'Brien, 1931; 1969; Jarret, 1976; Hume and Herdendorf, 1993) and equilibrium relationships describing channel and shoal properties within tidal basins (Renger and Partenscky, 1974; Eysink, 1990).

Various definitions of equilibrium in coastal environments are given in the literature, including "the profile of equilibrium which the water would ultimately impart, if allowed to carry its work to completion" (Fenneman, 1902); "a long-term profile produced by a particular wave climate and type of coastal sediment" (Schwartz, 1982) and "the state where no net [sediment] transport occurs, when considered over a suitably long period" (Roberts et al., 2000). These definitions describe a steady state, where if forcing remains constant over time, coastal morphologies, including beaches, inlets and estuarine morphologies, will evolve towards an average form that is in balance with the forcing. Lee and Mehta (1997) suggest that equilibrium is rarely attained in nature as forcing is constantly changing, and equilibrium should therefore be viewed as a target shape. For the purposed of this thesis, the definitions of Fenneman (1902); Schwartz (1982); Roberts et al. (2000) will be considered to define steady state, whereas dynamic equilibrium will be defined as in Ahnert (1967) and Howard (1988) as the balance between and output form and input forcing processes.

Coastal Profile Equilibrium

It is generally accepted that, for a specific grain size and constant wave climate, a sand shoreface will tend towards a steady state equilibrium profile where there is no net change in the profile shape over time scales of years to decades (Zhang et al., 2004). An overview of mathematical models describing shoreface equilibrium and response to changes in forcing is given by Dean and Maurmeyer (1983).

The concept of shoreface equilibrium underlies a range of models of shoreface evolution including the "Bruun Rule" and a variety of aggregated-scale models of coastal evolution (Cowell et al., 1995; Niedoroda et al., 1995; Stive and de Vriend, 1995). Bruun (1962) suggested that, under conditions of rising sea level, the equilibrium profile would translate upwards and landwards whilst maintaining its form (Fig. 2.7). To achieve this, sand must be eroded from the upper part of the profile and deposited in the lower part (Zhang et al., 2004). The "Bruun Rule" assumes that there is a closure depth, beyond which there is no net movement of sediment on the time scale of interest; that there is no net movement of sediment in a longshore direction; and that the shoreface is sediment rich (Pilkey et al., 1993). Numerous modifications to the basic principles of the "Bruun Rule" have been proposed including corrections for the loss of fine sediments from the eroding profile (Bruun, 1983) and for sediment sources or sinks affecting the profile (Hands, 1983; Stive, 2004).

Cooper and Pilkey (2004) criticise the "Bruun Rule" on a number of points.

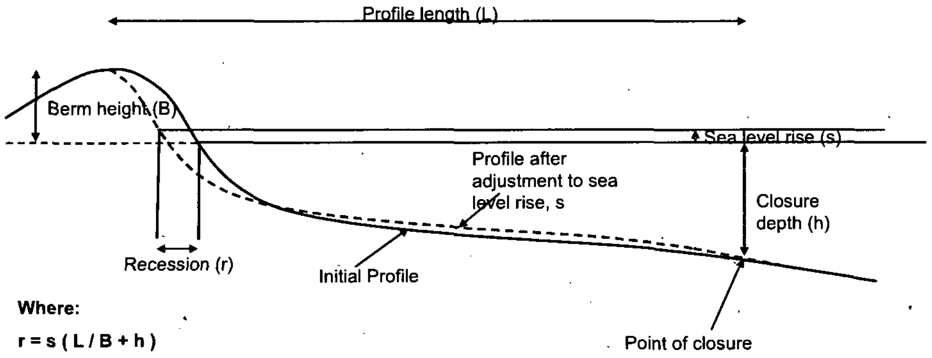

Fig. 2.7: The Bruun Rule describes the landwards and upwards translation of the shoreface in response to sea-level rise. (Cooper and Pilkey, 2004).

They argue that the assumptions of a sediment rich shoreface and closed sediment balance are too restrictive and state that the predicted behaviour has never been adequately proven in the field. However, a number of studies have found reasonable agreement between observed shoreline retreat and retreat predicted using the "Bruun Rule", particularly where the rate of sea-level rise was high (Hands, 1983; Mimura and Nobuoka, 1995; Zhang et al., 2004). Nicholls and Stive (2004) suggest that the "Bruun Rule" is incomplete rather than incorrect and suggest that it can be implemented, along with other more comprehensive models, as part of a sediment budget approach to coastal morphology.

Equilibrium on muddy shores

Some attempts have been made to describe equilibrium profiles for muddy shores (Lee and Mehta, 1997; Kirby, 2000; Roberts et al., 2000). Equilibrium is defined for mud flats as the "profile shape which leads to zero net sediment transport at each point on the mudflat" (Roberts et al., 2000).

Lee and Mehta (1997) examined the relationship between profile shape on mud shores and wave forcing. A wave attenuation coefficient, representing the dissipation of energy on the shore, was found to be important in determining the profile shape with large values tending to give concave profiles associated with erosion and lower values giving convex, accretionary profiles.

Kirby (2000) also distinguished between erosional and accretional profiles, describing them as end-members in a continuum of profile shapes. Erosional profiles are concave and occur where wave processes dominate or where the mud flat is sediment starved. Accretion dominated profiles are high and convex and are preferable for coastal protection and for habitat provision (Kirby, 2000). Kirby (2000) used profiles generated from hypsometry (area-height curves) for whole estuaries, rather than individual cross-sections, recognising the importance of wider sediment dynamics for mudflat evolution.

Roberts et al. (2000) related mud flat profiles to tidal range and sediment concentration, using a model within which sediment movement was determined by cross-shore currents and wave action. Higher tidal ranges tended to give steeper mudflats, whilst higher sediment concentrations gave less steep slopes. In reality, shore parallel currents are likely to be equally important in determining the intertidal profile, but these cannot be included without considering the shape of the whole estuary (Roberts et al., 2000).

These authors point out an important difference between equilibrium mud flat profiles and those on sandy shorefaces: on mud shores the eroded material is not redeposited offshore, but is lost to the environment (Lee and Mehta, 1997; Kirby, 2000). Recovery of the profile of muddy shores following erosion is dependent on the supply of sediment from wider sources, including along and across shore. This complicates the issue of equilibrium profiles for mud flats, as Roberts et al. (2000) and Kirby (2000) point out, mudflat equilibrium is coupled with equilibrium of the whole estuary.

Equilibrium in Estuaries

The earliest dynamic equilibrium relationships for estuaries considered the relationship between the cross-sectional area of the inlet mouth and tidal prism (O'Brien, 1931; 1969; Jarret, 1976; Hume and Herdendorf, 1993; Townend, 2005). This can be extended to cross-sections along the length of the estuary, also called regime theory, (Spearman et al., 1998), developed from concepts of regime in river channels (HR Wallingford et al., 2006). Relationships of this type are generally of the form (Eq. 2.1):

$$A = cP^n \tag{2.1}$$

where A is the cross section area of the inlet mouth, P is the tidal prism and c and n are coefficients. Varying values of c and n have been reported depending on the inlets used and the presence or absence of jetties (Jarret, 1976). Hume and Herdendorf (1993) found that prism-area relationships for New Zealand estuaries were improved when estuaries were grouped by morphological type. Townend (2005) examined prism area relationships for a sample of 66 UK estuaries. Prism-area relationships were strongest when estuaries were categorised by morphological type and had similar regression lines to the New Zealand estuaries described by Hume and Herdendorf (1993).

Despite strong correlations between cross-section area and tidal prism (r^2 generally greater than 0.9) there remains a large amount of scatter amongst the data. Coefficients have been found to vary depending on the exact data set used, suggesting that although tidal prism is important in determining inlet cross-section area, other factors are also operating. Sediment supply, littoral drift, geological constraints and wave action may also influence inlet cross-section areas (HR Wallingford et al., 2006). Other physical forcing variables have been used to replace tidal prism, for example maximum current velocity (Spearman et al., 1998).

Bruun (1978) suggested the stability of an inlet could be described based on the ratio of the tidal prism (P) to longshore transport (Q). Ratios of P/Q greater than 150 tend to give stable inlets as the tidal flow will be strong relative to longshore drift. Ratios of P/Q of less the 100 become less stable and more likely to close because the tidal flow is not strong enough to maintain the inlet.

Attempts have been made to find a physical basis for the observed relationships (Kraus, 1998; Hughes, 2002). Kraus (1998) replaced c in Eq. 2.1 with an equation based on sediment properties, channel width and longshore sediment transport rate. Kraus (1998) applied this equation to Bruun's (1978) data with reasonable success, but Townend (2005) found that it did not perform well for UK estuaries, partly because of difficulties in estimating the parameter values. Hughes (2002) also analysed the physical basis for prism-area relationships, based on sediment properties and thresholds for motion. This relationship was found to be a reasonable predictor of cross-section area in UK estuaries (Townend, 2005).

Cross-section area relationships can be applied to upstream cross-sections of an estuary as well as at the mouth. Spearman et al. (1998) suggested that an estuary could be in equilibrium or "regime" throughout its length, with cross sections described by a characteristic relationship between morphology and forcing. Further, following disturbances to the morphology or hydrodynamics, the estuary evolution will tend to reestablish equilibrium. Spearman et al. (1998) used equilibrium concepts, coupled with a one-dimensional flow model to investigate the response of the Lune Estuary to the construction of training walls. The relationship between peak discharge and cross section area at several cross-sections was found to be the same in the 1840s (prior to training wall construction) as in 1995, a century after training wall construction. This indicates that the Lune Estuary was able to reestablish the same equilibrium relationship following the major morphological disturbance caused by training wall construction.

Equilibrium concepts have also been applied to predict the water volume of estuarine channels (Renger and Partenscky, 1974; Eysink, 1990), the surface area of the channels (Renger and Partenscky, 1974; Townend, 2005) and the surface area of the intertidal flats (Renger and Partenscky, 1974). This work has been much less extensive than work on inlet cross-sectional areas. The main relationships and their applications are described below.

Renger and Partenscky (1974) used basin hypsometry (the surface area and volume relative to a horizontal plane) to describe the volume capacity of tidal channels. For a sample of 22 tidal basins along the German North Sea coast they found consistent relationships between the channel volume (water volume below mean low water (V_{MLW})) and total basin area (A_{MHW}) (Eq. 2.2) and between surface area at mean low water (A_{MLW}) and basin area (A_{MHW}) (Eq. 2.3). Renger and Partenscky (1974) used these relationships to predict the effect of changes in basin area caused by the proposed construction of a new harbour in the Elbe Estuary.

$$\frac{V_{MLW}}{{A_{MHW}}^2} = 8 \cdot 10^{-9} m^{-1} \quad (2.2)$$

$$\frac{A_{MLW}}{{A_{MHW}}^{1.5}} = 2.5 \cdot 10^{-5} m^{-1} \quad (2.3)$$

Townend (2005) examined similar relationships for UK estuaries. It was found that the general form of the relationships held for a sample of UK estuaries containing various morphological types, but the value of the coefficient varied. Townend (2005) found that both channel volume and surface area showed a strong correlation with tidal prism, giving improved r^2 values compared to Renger and Partenscky (1974)'s relationships (Table 2.3).

Eysink (1990) hypothesised that cross-sectional area-prism relationships, integrated along the length of the channel, should give relationships for the water volume of the channel. Channel volume data from Dutch Wadden Sea basins were found to have a strong correlation with tidal prism, in the form of Eq. 2.4. Eysink (1990) also suggested relationships between basin area and relative intertidal area. These differed on different stretches of coast, possibly due to the relative importance of local weather effects (Eysink, 1990).

$$V_c = cP^{3/2} \quad (2.4)$$

where V_C is the channel water volume below mean low water, c is an empirical coefficient and P is the tidal prism.

Eysink (1990) used equation 2.4, and a similar dynamic equilibrium relationship for ebb-tidal delta volume (Walton and Adams, 1976), to investigate the effect of closure works, reduction in tidal prism caused by accretion and increased sea level on hypothetical tidal basins. Eysink (1990) suggested that, following a disturbance, the basin would evolve towards a new morphology which satisfied the original equilibrium relation. In the case of sea-level rise, the response of a basin is more complex and the tidal flats become important. If sedimentation on tidal flats keeps pace with

Tab. 2.3: Relationships of the form $y=Cx^n$ between basin properties (Townend, 2005).

Independent Variable, y	Dependent Variable, x	C	n	r^2
S_{lw}	S_{hw}	0.011	1.18	0.83
V_{lw}	S_{hw}	0.00028	1.45	0.77
S_{lw}	P	0.42	0.96	0.92
V_{lw}	P	0.073	1.13	0.92

sea-level rise, there will be no increase in tidal prism, but the channel volume will increase due to the increase in sea level. Sedimentation will also take place in the channel, but the relative change in water depth caused by sea-level rise will be less in the channel than on the shallower flats and changes in sediment transport, and hence sedimentation, are predicted to be less in the channels. If sedimentation on the tidal flats does not keep pace with sea-level rise, tidal prism will increase and the equilibrium volume of the channels will also increase (Eysink, 1990). Sediment deposition on intertidal areas appears to be a key factor in determining the response of the whole basin to sea-level rise.

Ebb-tidal deltas are bodies of non-cohesive sediment directly seaward of the estuary mouth. They are most common on meso- and micro-tidal shores where sediment supplied by littoral drift is flushed from the inlet mouth and is deposited where tidal currents slow down. The ebb-tidal delta is expected to play an important role in the interaction between estuaries and the adjacent coast because of its capacity to store sand, affecting sand bypassing to the downdrift shore. Ebb-tidal deltas may also provide protection to adjacent beaches by dissipating wave energy, especially during storms (Fitzgerald, 1988).

Relationships have been observed between the sediment volume of the ebb-tidal delta and the tidal prism in the US (Walton and Adams, 1976). The relationship is given by Eq. 2.5

$$V_d = aP^b \tag{2.5}$$

where V_d is the sediment volume of the delta, P is the tidal prism and a and b are coefficients. Coefficients a and b were found to vary slightly depending on the exposure of the delta to waves (Walton and Adams, 1976). Coasts with lower wave energy had larger deltas relative to tidal prism volume than coasts with higher wave energies. Buonaiuto and Kraus (2003) found that wave height correlated with the maximum bed slopes found on ebb-tidal shoal, reinforcing the importance of waves in influencing ebb-tidal delta morphology.

2.3.3 Tidal Asymmetry

Tidal asymmetry is an important concept to consider in relation to estuary equilibrium. It has been suggested that an estuary in equilibrium should have symmetrical tides, with flood and ebb durations being equal. Van Goor *et al.* (2003) suggest that residual sediment transport resulting from tidal asymmetry causes morphological changes which reduce the asymmetry. When there is no tidal asymmetry, morphological equilibrium has been established.

Tidal asymmetry occurs when (a) there is a difference between the duration, and hence velocities, of the ebb and flood tides and (b) there is a difference in the duration of the slack water periods preceding ebb and flood tides (Dronkers, 1986). When the flood duration is shorter than ebb, the flood tide has higher current velocities, the estuary is ebb-dominant and sediment tends to be imported and trapped within the estuary. When ebb-tides have the shorter duration and ebb velocities are higher than flood velocities the estuary is ebb dominant and coarse sediment tends to be flushed from the estuary. Tidal asymmetry in estuaries arises from two sources: firstly, the characteristics of the tide entering the estuary and secondly, tidal propagation within the estuary (Dronkers, 1986).

Interaction of the tidal wave with the estuary morphology as the tidal wave propagates into the estuary can enhance tidal asymmetry. The relative amplitudes, velocities and phases of the M_2 and M_4 tidal harmonics can be used to describe the asymmetry of the tidal wave. The ratio of the amplitudes (a_{M_4}/a_{M_2}) is a direct measure of the asymmetry, and the difference between the phases of the components indicates the direction of the asymmetry ($2\theta_{M_2} - \theta_{M_4}$) (Friedrichs and Aubrey, 1988).

Friedrichs and Aubrey (1988) related the tidal distortion and resulting asymmetry to two properties of estuary geometry, the ratio a/h (tidal amplitude/water depth) and V_S/S_C (volume of water storage above flats/volume of channels).

The ratio a/h represents distortion of the tidal wave in the channel. This occurs because the tidal wave propagates as a shallow water wave and wave celerity (c) is dependent on water depth (h)($c = \sqrt{gh}$). As water depth is significantly greater at high water, for large values of a/h, high water (wave crest) travels faster than low water (trough) and may over take it, resulting in flood asymmetry (Friedrichs and Aubrey, 1988).

Ebb dominance occurs when the relative intertidal storage volume (V_S/V_C) is great enough to overcome the effects of channel friction. This occurs when V_S/V_C is large relative to a/h . Low intertidal velocities, caused by shallow water above the flats, may cause high tide to propagate more slowly than low tide (Friedrichs and Aubrey, 1988). This effect may be further enhanced by variations in cross section area over tidal cycle (Boon and Bryne, 1981).

Dronkers (1998) suggested that for equilibrium morphology, energy dissipation should be equal during ebb and flood tides. Dronkers (1998) proposed that the ratio of ebb and flood durations was dependent on the relationship between the ratios of high and low water channel depths and high and low water surface areas (Eq. 2.6). Theoretically, $\gamma = 1$ should describe the equilibrium condition. In practise, it was found that $\gamma = 1.1$ gave a more reliable fit to data from a number of Dutch inlets, and may vary for other sites (Dronkers, 1998).

$$\gamma = \left(\frac{h+a}{h-a}\right)^2 \cdot \frac{S_{LW}}{S_{HW}} \tag{2.6}$$

where h is the mean hydraulic depth, given by $h{=}a{+}V_{LW}/S_{LW}$, a is the tidal amplitude, S_{LW} is the surface area at low water and S_{HW} is the surface area at high water.

Fortunato and Oliveira (2005) investigated the influence of intertidal flats on tidal asymmetry in more detail. Large tidal amplitudes were found to promote flood dominance and the presence of intertidal flats enhanced ebb-dominance. Greatest ebb-dominance was found to occur when the tidal flats were positioned at or above mean water level (Fortunato and Oliveira, 2005).

2.3.4 Application of Equilibrium Relationships

Equilibrium relationships have been applied to numerous inlets and estuaries to examine long-term behaviour. Several site specific studies have used equilibrium theory to predict the impact of engineering interventions to estuaries and inlets (Elias et al., 2003; van de Kreeke, 2004; Bertin et al., 2005). Equilibrium relationships have also been used in numerical models to predict possible future states (Eysink, 1990; van Dongeren and de Vriend, 1994; Wang et al., 1998; Stive et al., 1998; Spearman et al., 1998; Dennis et al., 2000).

Case Studies

Elias et al. (2003) examined the evolution of the Texel Inlet (Dutch Wadden Sea) following the closure of a large part of the basin in 1932. Closure removed a large area of shallow and intertidal areas and increased the tidal prism due to changes in the tidal wave characteristics within the basin. Prior to closure, the basin was thought to be close to equilibrium. Immediately following closure, the channel area was too large relative to the intertidal area and the basin was in a non-equilibrium state (Elias et al., 2003).

After the closure of the Texel Inlet basin, rapid sedimentation of the tidal basin was observed (Elias et al., 2003). This was most rapid between 1933 and 1977. Since 1977, alternating periods of sedimentation and erosion have occurred, suggesting that the basin is close to its new dynamic equilibrium (Elias et al., 2003). The observed evolution of the Texel basin towards its new equilibrium was not asymptotic but showed an overshoot, of approximately 20% of the channel volume, before returning to the predicted equilibrium trend.

Van de Kreeke (2004) investigated changes to the cross-section area of the Frisian Inlet (Dutch Wadden Sea) after basin reduction. Before the closure, the inlet was thought to be in a stable equilibrium state (van de Kreeke, 2004). The equilibrium cross-section area was predicted to decrease following basin reduction and evolve towards a new equilibrium state over a period of 30 years. Observed area changes up to 1990 were inline with predictions, but more recent data is not given.

Equilibrium concepts have also been used to explain natural and anthropogenic induced changes in a tidal lagoon (Marennes-Oléron Bay and Maumusson Inlet, France) (Bertin et al., 2005). Sediment infilling due to natural causes and to extensive oyster farming caused a substantial reduction in the water volume of the basin, in the tidal prism and in the inlet cross section area. Prism-area relationships were applied to the inlet and provided a good predictor for the observed changes. Bertin et al. (2005) suggest that, whilst it is generally assumed that the changes in tidal prism drive the change in cross-section area, it is possible that changes in cross-section area influence tidal propagation within the basin and so induce sedimentation. This seems unlikely to be entirely true, as the sedimentation in this case is caused, at least partly, by human activities. It is possible however that the reduction in inlet cross-section does affect tidal propagation and may cause positive feedback, enhancing sedimentation in the basin and inlet reduction (Bertin et al., 2005).

Numerical Models

Eysink (1990) used equilibrium equations to investigate the effect of closure works, reduction in tidal prism caused by accretion and sea-level rise on hypothetical tidal basins. Following a disturbance, the channel and delta were expected to evolve logarithmically towards a new equilibrium, with the time taken dependent on the elements characteristic adaption time. The elements did not interact or affect each others evolution.

Van Dongeren and de Vriend (1994) used the channel cross-sectional area, tidal flat surface area and tidal flat height as equilibrium parameters in a model simulating the morphological development of tidal basins in response to external forcing factors including sea-level rise and land reclamation. This model assumes that the channel cross-sectional area and the flat area will develop asymptotically in response to changes in forcing. If insufficient sediment is supplied development will occur at a slower rate than predicted by the model (van Dongeren and de Vriend, 1994).

In the van Dongeren and de Vriend (1994) model, sediment exchange between the channel and the flats is controlled by sediment transport formulae that satisfy mass balance equations. Unlike Eysink's (1990) model, the channel and flats interact and influence each others development. However, the van Dongeren and de Vriend (1994) model deals with elements in series and the outcome is sensitive to the order of the calculations (Wang et al., 1998). Wang et al. (1998) overcame this problem, in the ESTMORF model, by using the concept of a characteristic sediment concentration belonging to each element.

The ESTMORF model represents estuaries and tidal basins as a series of cross-sections, each divided into three elements: the channel, the lower tidal flats and the upper tidal flats. The elements are characterised by the equilibrium channel cross sectional area and equilibrium flat heights for the low and high tidal flats. Differences between elements' equilibrium volumes' and their actual volumes' are used to calculate equilibrium concentration parameters and sediment exchange between elements is controlled by an advection-diffusion equation based on residual flows

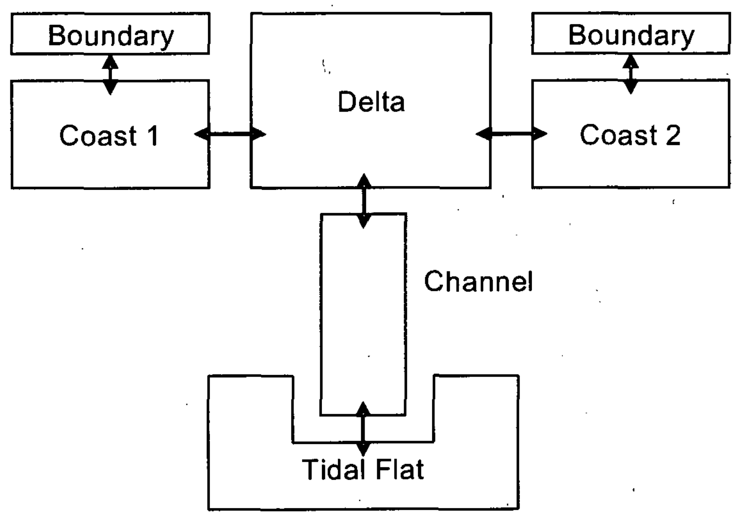

Fig. 2.8: ASMITA schematisation (Adapted from Stive et al. (1998))

(Wang et al., 1998).

ESTMORF has been applied to model the effect of closure on "Het Frische Zeegat" tidal inlet and was reasonably successful at hindcasting the observed evolution (Wang et al., 1998). ESTMORF was also applied to the Western Scheldt Estuary to predict morphological changes caused by proposed management schemes (Fokkink et al., 1998). In the UK, ESTMORF has been applied to investigate the influence of the nodal tidal cycle in the Humber Estuary (Jeuken et al., 2003) and to investigate the impacts of a proposed port development at Dibden Bay in Southampton Water (Wang, 2000).

ASMITA[1] is based on similar concepts to ESTMORF and was first presented as a behaviour-model "describing morphological interaction between a tidal lagoon or basin and its adjacent coastal environment" (Stive et al., 1998). The model consists of a schematisation of a tidal inlet system with the major morphological elements being viewed at an aggregated scale (Fig. 2.8). The major assumption of ASMITA is that, under constant hydrodynamic forcing, each element tends towards a morphological equilibrium which can be defined as a function of hydrodynamical forcing. Empirical relationships are used to define the equilibrium volume of each element (Stive et al., 1998).

In ASMITA, sediment is transferred between adjacent model elements by a diffusive-type transport that is driven by the difference between the elements' equilibrium volume and its actual volume (Stive et al., 1998). Sediment availability within the system is governed by a global equilibrium concentration imposed at the seaward boundary. Sediment demand or surplus within the system may be created by sea-level rise or human interventions (van Goor et al., 2003).

[1] Aggregated Scale Morphological Interaction between Tidal basin and the Adjacent coast

ASMITA has been applied to simulate the effects of closure of tidal basins, dredging and dumping of sediment and sea-level rise on both hypothetical and real tidal basins. Real basins to which ASMITA has been applied include inlets in the Dutch Wadden Sea and lagoons on the Po Delta, Italy (Stive et al., 1997; 1998; van Goor et al., 2003; Kragtwijk et al., 2004). A reduced version of ASMITA (Bijsterbosch, 2003) has also been applied to predict indirect erosion at tidal inlets due to sea-level rise, on a worldwide scale, in the DIVA tool[2] (DINAS-COAST Consortium, 2006)[3]. In the DIVA tool, estuary equilibrium state is based on equations and coefficients derived for the Dutch Wadden Sea (Bijsterbosch, 2003).

Van Goor et al., (2003) used a three element version of ASMITA (without the coastal elements) to investigate whether tidal basins could maintain geomorphological equilibrium under rising sea levels and introduced the concept of an upper limit for the rate of sea-level rise (SLR_{CRIT}). As the rate of sea-level rise increases, the elements deviate from their equilibrium volumes'. For a constant rate of sea-level rise, below SLR_{CRIT}, the estuary will evolve towards a new, steady state, equilibrium. When the rate of sea-level rise is accelerating, or is greater than SLR_{CRIT}, steady state cannot be achieved and the estuary or tidal inlet deviates increasingly from its equilibrium state. Above SLR_{CRIT} insufficient sediment is imported resulting in total loss of intertidal areas. This is sometimes referred to as "drowning".

Van Goor *et al.* (2003) found that the adaptation time and SLR_{CRIT} varied between elements and between inlets. Tidal flats and ebb-tidal deltas were found to adapt faster than channels and smaller inlet systems reacted more rapidly than larger ones (van Goor et al., 2003). SLR_{CRIT} tended to be smallest for the tidal flat element, indicating the susceptibility of tidal flats to loss as a result of sea-level rise (van Goor et al., 2003).

Kragtwijk et al. (2004) further investigated time-scales of development using ASMITA and obtained a set of time-scales describing the main features of the morphological development of inlets. System time-scales were found to be a function of basin geometry and sediment exchange parameters (Kragtwijk et al., 2004). The model elements interact on a number of timescales (Kragtwijk et al., 2004) and do not evolve logarithmically towards equilibrium as assumed in earlier models (e.g. Eysink, 1990). Instead they interaction between elements may cause bumps or overshoots in the evolution towards new equilibrium (Kragtwijk et al., 2004). This is consistent with Elias et al. (2003)'s observations of the Texel Inlet.

Van de Kreeke (2006) used a schematisation similar to that of ASMITA to develop a model for studying the adaption of the Frisian Inlet, Dutch Wadden Sea, following a reduction in the basin area. In the model the ebb-tidal delta and the channel are included but the tidal flats are excluded, because they are believed to

[2] Dynamic and Interactive Vulnerability Assessment

[3] Dynamic and INteractive ASsessment of National, Regional and Global Vulnerability of COASTal Zones to Climate Change and Sea-Level Rise

have a much longer adaption time than the other two elements. Sediment transport in the model is based on perceived sediment transport pathways that will be balanced when the system is in equilibrium. The sediment pathways include sediment transport through the inlet and sediment bypassing to the downdrift coast. The model predicted that, following reduction in basin area, the ebb-tidal delta would erode and the channel would accrete (van de Kreeke, 2006). Over short time periods the observed morphological behaviour was similar to that predicted by the model. However, when summed over the study period, net changes differed greatly from the model predictions (van de Kreeke, 2006).

The development of ebb-tidal deltas (ebb-shoals) and sand bypassing processes at new tidal inlets has been examined using a reservoir model (Kraus, 2000). The model was based on the assumptions that a number of elements and sediment transport pathways in an ebb-shoal complex could be identified and tended to evolve towards a stable equilibrium volume. After a new inlet is opened, the ebb-tidal delta develops first and receives sand from longshore drift. When the equilibrium volume is reached, all additional sediment inputs are bypassed to the next element in the complex and eventually sand is bypassed to the downdrift beach. The model proved to be reasonably successful in predicting the evolution of sediment bypassing at Ocean City Inlet, Maryland (Kraus, 2000).

Although the reservoir model was developed to predict bypassing at new inlets it is possible that it could be used to predict the effects of disturbances to the delta on sand bypassing. Disturbance to the volume of the ebb-shoal, for example by sand extraction, is likely to affect the rate of sediment bypassing by creating additional space in that reservoir. The equilibrium (reservoir) volume of the ebb-tidal delta is strongly related to the tidal prism of the tidal basin and inlet behind it (Walton and Adams, 1976) and to sediment grain size, with coarser sediments tending to form smaller ebb-tidal deltas with longer bypassing times (Burningham and French, 2006). Changes in tidal prism due to sea-level rise or human interventions are likely to influence sediment bypassing.

The morphological interaction between the ebb-tidal delta and the inlet basin are not included in the reservoir model but are likely to have a strong influence on sediment bypassing, because they are a sediment sharing system (Cowell et al., 2003b). Equilibrium volume in the delta is unlikely to be achieved unless the tidal basin is also in equilibrium, because the delta acts as a buffer, supplying or storing sediment depending on conditions in the basin (van Dongeren and de Vriend, 1994). This interaction is complex and is likely to influence sand bypassing in ways not predicted by the reservoir model of Kraus (2000).

2.4 Discussion

The behaviour-oriented models described in this review rely on the assumption that coastal morphology tends to evolve towards an equilibrium configuration. Relationships between tidal prism and various dimensions of tidal inlets are well documented, supporting the assumption that tidal inlets and estuary systems tend towards equilibrium states (O'Brien, 1969; Jarret, 1976; Walton and Adams, 1976; Eysink, 1990). However, the majority of evidence for these relationships comes from barrier islands, inlets and lagoon systems in the United States or the Wadden Sea which tend to be sand rich, not geologically constrained and many have low river flow. Notable exceptions are the work of Hume and Herdendorf (1993) on equilibrium relations in New Zealand estuaries and the work of Townend (2005) on UK estuaries. Both of these studies found that equilibrium relationships were best when estuaries were grouped by morphological type.

Despite the strong correlations that have been found between tidal prism and basin dimensions, there is still a large amount of scatter, indicating that any individual estuary does not necessarily fit the regression line predicted by the sample of estuaries. This causes problems using these types of relationships to predict the dynamic equilibrium relationship for a specific estuary. Several authors have suggested that empirical equilibrium relationships should be selected on an estuary specific basis (Wang et al., 1998; Spearman et al., 1998; Dennis et al., 2000). Other authors have assumed that generic relationships derived from a sample of estuaries at a particular location can be applied to describe inlets elsewhere in the world (Stive et al., 1997; Bijsterbosch, 2003). This may be reasonable when the target estuary is morphologically similar to the sample used to derive the relationship and when no data is available to establish an estuary specific equilibrium relation.

Dennis et al. (2000) suggested that "long-term prediction [of equilibrium relationships] is an unattainable goal on a universal basis and thus solutions may only be possible for individual groups of estuaries having similar properties". This idea is supported by Hume and Herdendorf (1993) and Townend (2005) who found that scatter was reduced when prism-area relationships were plotted by morphological type. Further work is needed to assess how useful morphology based relationships are for predicting equilibrium, as despite strong correlations, deviations from the regression equation still exist for individual estuaries. Where possible, it is preferable to use data for the estuary of interest to define equilibrium relations specific to that estuary.

In general, models using equilibrium concepts have been shown to be able to reproduce the long term evolution of a number of tidal basins and estuaries with reasonable success. ESTMORF, which requires that the equilibrium equations should be selected for each application based on empirical data, has been used to model the evolution of tidal basins in the Netherlands and UK estuaries. ASMITA has also been applied to a number of tidal basins but has tended to use same equilibrium relationships. This appears to have given reasonable results, but may be because the model has been applied mainly to Wadden Sea basins for which the relationships were derived, or to inlets with similar morphological characteristics, such as the Po Delta in Italy (Stive et al., 1997).

Evidence suggests that equilibrium concepts and morphological models using them are useful for predicting future estuary morphologies and responses to changes in forcing and disturbances where an estuary specific equilibrium state can be defined or where the equilibrium relation used is based on tidal basin systems with similar morphological characteristics.

It is generally assumed that following a disturbance an estuary will evolve towards a new equilibrium that fulfills the characteristic dynamic equilibrium relationship seen before the disturbance. However, as Spearman et al. (1998) suggests, "some consideration must also be given towards the possibility of the impact on an estuary being so large that the characteristic regime relationship changes". To date, little consideration has been given to this idea and further work is needed to establish whether disturbances of a certain magnitude can disrupt a system to such and extent that the estuary cannot evolve towards a new equilibrium or that the characteristic equilibrium relationship is changed (i.e. meta-stable equilibrium).

The available evidence suggests that equilibrium concepts have the potential to form useful tools for estuary management. They could potentially be applied to investigate the effect of sea-level rise, changes in sediment supply, the effects of dredging, land reclamation and managed realignment. Before equilibrium concepts can be widely applied, further work is needed to test the validity of generic dynamic equilibrium relationships to UK estuaries, especially for applications to individual estuaries. Further work is also needed to assess the usefulness and limitations of using equilibrium relationships to investigate the impact of very large disturbances. These issues will be examined in detail in Chapter 6 of this thesis.

3. METHODOLOGY

3.1 Overview

This thesis uses a number of distinct methodologies to investigate estuarine morphodynamics and the validity, usefulness and limitations of equilibrium concepts. The methodologies employed included a generalised empirical study of potential dynamic equilibrium relationships in a sample of English and Welsh estuaries, using data from the FutureCoast (Dyer, 2002) and Estuaries Database (EMPHASYS, 2000) data sets. Intensive empirical case studies, comprising of the historical analysis of eight English estuaries, were also undertaken to examine large-scale estuary behaviour in estuaries with a range of morphological types.

Data from the historical analysis was used for the application and validation of ASMITA, a numerical model based on equilibrium concepts. Limited model development and testing was also undertaken to make the model more applicable to the estuarine morphologies found in the UK.

3.2 Study Site Selection and Characteristics

Out of the ninety six estuaries discussed by Dyer (2002) in the national FutureCoast database, a sample of eight estuaries have been selected for detailed study following a review of their main characteristics and the availability of data. These are the Ribble Estuary, Dart Estuary, Southampton Water, Portsmouth Harbour, Langstone Harbour, Chichester Harbour, Thames Estuary, and the Humber Estuary (Fig. 3.1). This sample was selected to cover a broad range of the morphological types found in England, based on the behavioral characterisation of estuaries given in FutureCoast (Dyer, 2002) (Fig. 3.2) (Appendix A).

Dyer (2002)'s classification of UK estuaries is summarised in Chapter 2 (Table 2.1). The main types are glaciated valleys, including fjords and fjards, which are not found in the UK; drowned river valleys, including rias, spit-enclosed estuaries and funnel shaped estuaries; and drowned coastal plains.

In the UK, rias and spit-enclosed estuaries are the two dominant morphological types. These categories are further sub-divided based on the type of spits present. The main types are represented in the study sample by the Dart Estuary (type 3b), Southampton Water (type 4a) and the Humber Estuary (type 4a). This selection covers the most common sub-types of the dominant categories, but two sub-types (rias with spits (type 3a) and spit-enclosed filled valleys (type 4c)) are not included because suitable historic survey data were not available.

In addition to the dominant UK morphological types, two funnel shaped estuaries (Ribble Estuary and Thames Estuary) and three tidal inlets (Portsmouth Harbour, Langstone Harbour and Chichester Harbour) are included. These categories are over represented in the sample estuaries, relative to their prevalence in the UK. The inclusion of three neighbouring tidal inlets is justified on the basis of their intrinsic interest as potentially linked systems and their similarities to tidal basins in the Dutch Wadden Sea where ASMITA has previously been applied. In addition, it allows dynamic equilibrium relationships to be analysed for three morphologically similar systems, which gives insight into the potential for generic dynamic equilibrium relationships, such as those used in the Wadden Sea. The funnel shaped estuaries were included to asses how well equilibrium relationships could be generalised to estuaries with differing morphologies, especially where waves may play an important role in addition to tidal forcing, such as the Ribble. The data set containing volumes and areas for the Thames Estuary was supplied in a ready to use format by HR Wallingford and is included to increase the total number of estuaries in the sample as well as increasing the morphological diversity.

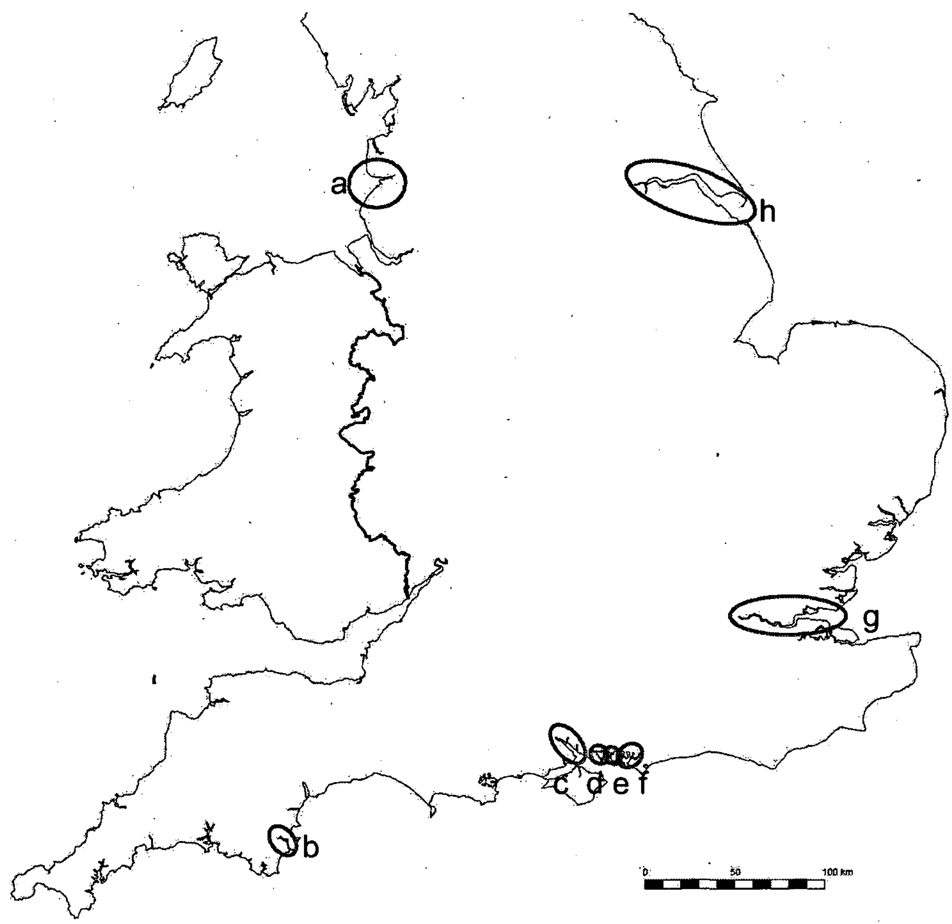

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Fig. 3.1: The locations of the nine study sites. (a) Ribble Estuary, (b) Dart Estuary, (c) Southampton Water (d) Portsmouth Harbour, (e) Langstone Harbour, (f) Chichester Harbour, (g) Thames Estuary and (h) Humber Estuary.

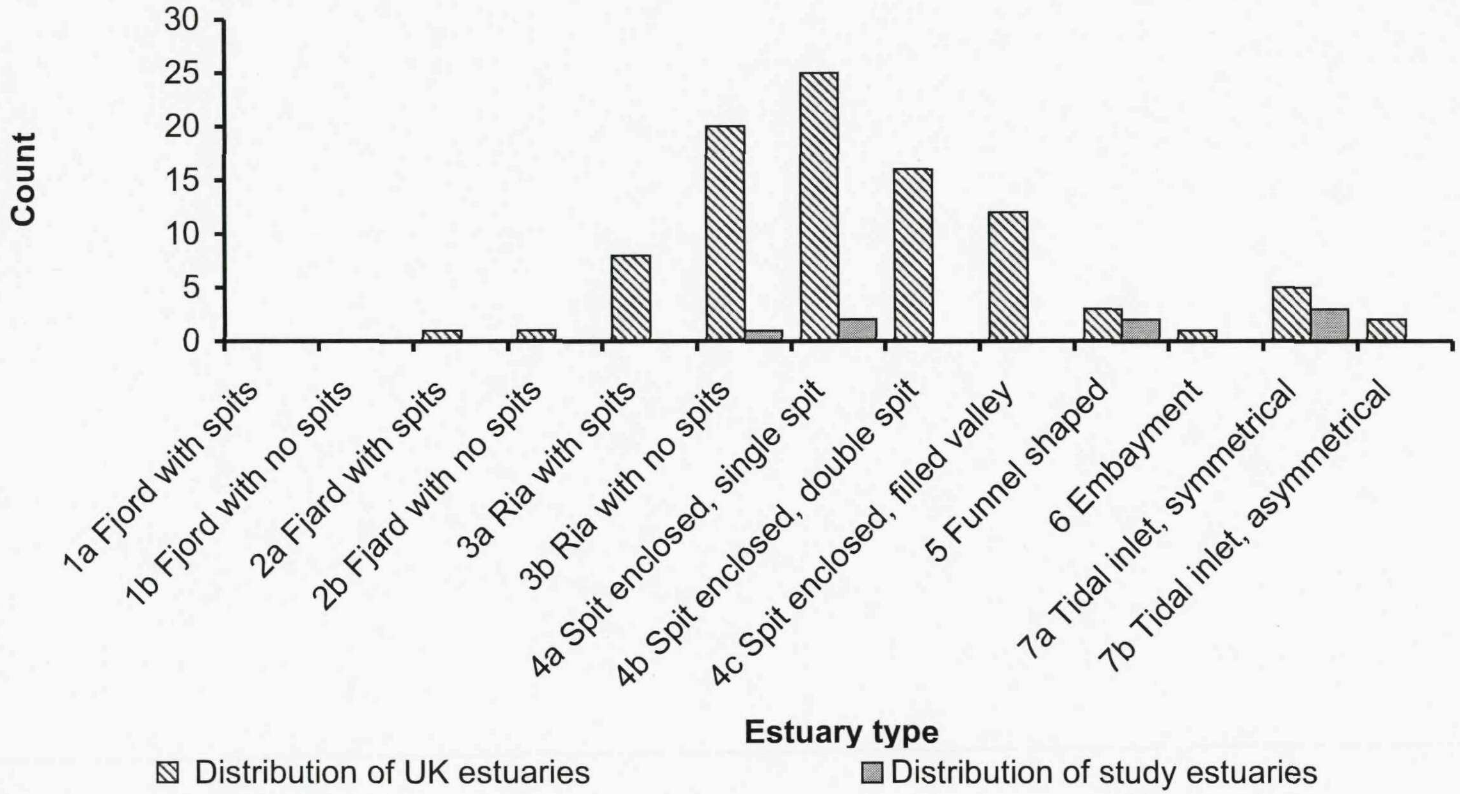


Fig. 3.2: Distribution of estuary behavioural types (Dyer, 2002) in the UK and in the study population

Tab. 3.1: Summary of the main features of the study estuaries (Dyer, 2002)

Estuary	Morphological Type	Area (ha)	Length (km)	Tidal range (m)	Mean river flow (m^3s^{-1})	Tidal asymmetry	Predicted behaviour	Human influences
Ribble	Funnel shaped (type 5)	11920	28.4	7.9	43.87	Flood dominant	Weak sink for mud and sand	Reclamation Channel training Dredging
Dart	Ria without spits (type 3b)	863	19.8	4	11.07	Ebb dominant	Strong sink	
Southampton Water	Single spit enclosed estuary (type 4a)	3975	20.2	4	18.1	Ebb dominant	Strong sink for fine sediment	Extensive reclamation Dredging
Portsmouth Harbour	Symmetrical tidal inlet (type 7a)	1593	10.8	4.1	0.63	Strongly ebb dominant	Weak sink for fine and coarse sediment	Much reclamation Dredging
Langstone Harbour	Symmetrical tidal inlet (type 7a)	1925	7.7	4.2	0.36	Strongly ebb dominant	Weak sink	Reclamation Aggregate extraction
Chichester Harbour	Symmetrical tidal inlet (type 7a)	2946	8.1	4.2	0.71	Weakly ebb dominant	Strong sink for mud	Gravel extraction from ebb-tidal delta
Thames Estuary	Funnel shaped (type 5)	20000	82.5	5.1	92.5	Ebb dominant	Weak source for mud	Defended coastline Dredging
Humber	Single spit enclosed estuary (type 4a)	64800	144.7	6	223.74	Ebb dominant	Strong sink	Training walls Extensive reclamation and dredging

The major features of the sample estuaries are summarised in table 3.1. The study estuaries cover a range of morphological types, sizes, river flows and tidal regimes. The extent and type of anthropogenic influence varies between the estuaries: Chichester Harbour and the Dart Estuary have been relatively unchanged by human interventions; other study estuaries have been subject to extensive reclamations, dredging and enclosure by sea defences. The predicted behaviour of the estuaries also varies, ranging from strong sediment sinks to sediment sources (Dyer, 2002). Behaviour predictions were derived from numerous sources including analysis of sediment budgets, tidal asymmetry, stratification and existing morphology (Dyer, 2002). Detailed description of the study estuaries and adjacent coastlines are given in the case study analysis in Chapter 4.

3.3 Data Collection and Analysis

3.3.1 Data Sources

Data on the historic morphologies of the study estuaries and adjacent coastlines comes from a variety of sources. Bathymetry data for the estuaries were obtained predominantly from historic hydrographic charts. Published hydrographic charts and survey data have been obtained from the UK Hydrographic Office (UKHO) as scanned image files. For the Humber Estuary and Southampton Water, digital point elevation data were supplied by ABPmer. Data for the Thames Estuary was supplied by HR Wallingford as volumes and areas relative to chart datum. The time range covered by the data varied between estuaries and is detailed in Appendix 3.2.

In addition to the maps and charts, literature relating to the study sites has been reviewed. Information such as rates of dredging, dates of land reclamations and other human interventions is needed to understand the morphological evolution of estuaries and coastlines. Much relevant data are available in unpublished reports and shoreline management plans.

Data on a wider selection of English and Welsh estuaries was obtained from FutureCoast (Dyer, 2002) and from the Estuaries Database (EMPHASYS, 2000). These data sets were used to give background information on the sample of estuaries studied and for additional data for investigating dynamic equilibrium relations in English and Welsh estuaries as a whole.

Tab. 3.2: Summary of data used for each estuary

Estuary	Data Type	Date	Scale	Source
Ribble	Admiralty Charts	1904	Not given	UKHO
		1951	1:75,000	UKHO
		1977	1:75,000	UKHO
		1990	1:75,000	UKHO
Dart	Admiralty Charts	1853	Not given	UKHO
		1900	1:5228	UKHO
		1952	1:5200	UKHO
		1972	1:6250	UKHO
		1983	1:6250	UKHO
		1995	1:6250	UKHO
Southampton Water	Point elevation data	1783	Unknown	ABPmer
		1911	Pre-digitised	ABPmer
		1926	Pre-digitised	ABPmer
		1951	Pre-digitised	ABPmer
		1965	Pre-digitised	ABPmer
		1976	Pre-digitised	ABPmer
		1996	Pre-digitised	ABPmer
Portsmouth Harbour	Admiralty Charts	1914	1:7480	UKHO
		1937	1:7480	UKHO
		1960	1:7500	UKHO
		1975	1:7500	UKHO
		1982	1:7500	UKHO
		1993	1:7500	UKHO
Langstone Harbour and Chichester Harbour	Admiralty Charts	1955	1:20,000	UKHO
		1961	1:20,000	UKHO
		1968	1:20,000	UKHO
		1974	1:20,000	UKHO
		1997	1:20,000	UKHO
Thames	Volume and area data	1910	Pre-digitised	HR Wallingford
		1920	Pre-digitised	HR Wallingford
		1970	Pre-digitised	HR Wallingford
		1980	Pre-digitised	HR Wallingford
		1990	Pre-digitised	HR Wallingford
Humber	Point elevation data	1925	Pre-digitised	ABPmer
		1936	Pre-digitised	ABPmer
		1956	Pre-digitised	ABPmer
		1966	Pre-digitised	ABPmer
		1976	Pre-digitised	ABPmer
		1987	Pre-digitised	ABPmer
		1998	Pre-digitised	ABPmer

3.3.2 Data Processing

The data from the hydrographic charts, Ordnance Survey (OS) maps and surveys were stored, manipulated and analysed using the ArcView GIS 9.0 software package.

Georeferencing

Hydrographic charts were georeferenced using the latitude/longitude information on the charts. Surveys and older hydrographic charts, which do not contain latitude and longitude information were georeferenced using fixed landmarks for which the the British National Grid (BNG) coordinates were known. Between six and ten control points with known coordinates were entered for each chart, keeping the root mean square (RMS) error as low as possible (max RMS = 10 m). The images were then transformed using a first order polynomial (affine) transformation to position the image within the coordinate system. The data were transformed from its original projection into BNG, to match the OS map data.

Digitising

Following georeferencing, spot heights, spot depths, bathymetric contours and coastline were digitised from the hydrographic charts and surveys. Coastlines for Southampton Water and the Humber Estuary were digitised from current and historic OS maps obtained via the Edina Digimap service. Height and depth values for pre-1970 hydrographic charts were converted to metres. All height and depth data were reduced to ordnance datum (OD Newlyn) using the datum information published on the chart.

Interpolation

The point and contour data were interpolated using ArcView 9.0's "Topography to Raster" interpolation method. This method is designed for the creation of hydrologically correct digital elevation models and is the only interpolation technique available that can accept both point elevation and contours as inputs; for these reasons it was deemed to be the most appropriate method for these data sets. The "Topography to Raster" interpolation method is based on the ANUDEM algorithm (Hutchinson (1989), cited in ESRI (2007)), and uses an iterative finite difference, discretized thin plate spline technique. The coastline data were excluded from the interpolation due to difficulties in accurately assigning a height value and is used purely to define the estuary boundary.

Deriving data from the GIS

The area and volume of the tidal flats, channel and ebb-tidal delta were calculated using the Area/Volume tool in ArcView 9.0. The data were used in ASMITA (Sec-

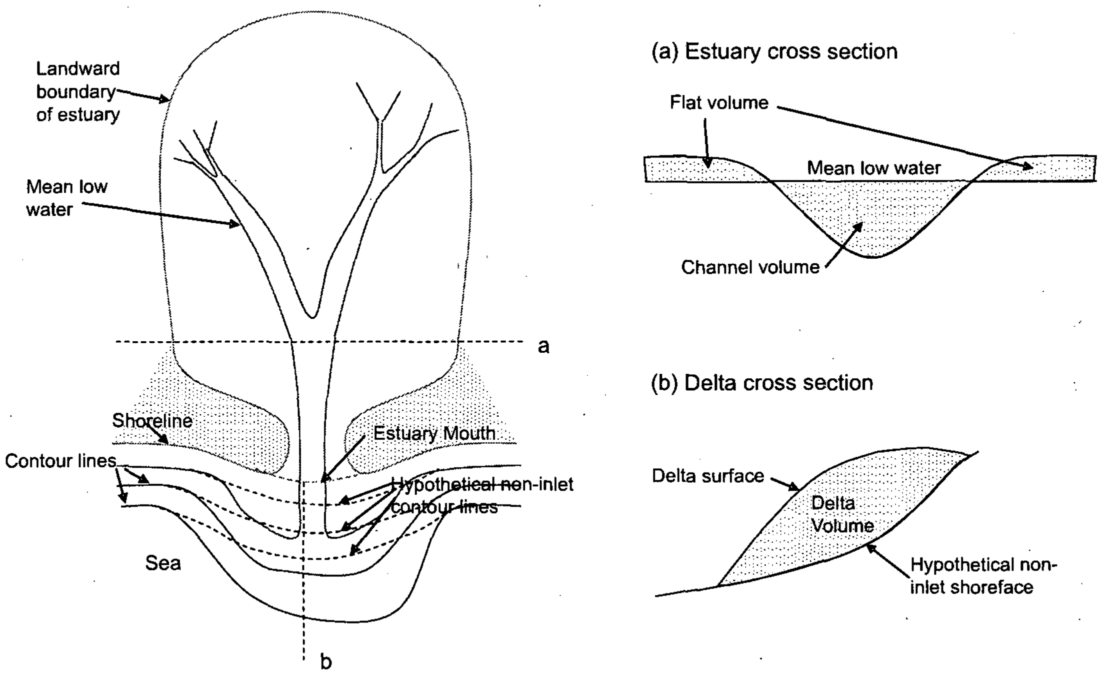


Fig. 3.3: Definition sketch of morphological elements

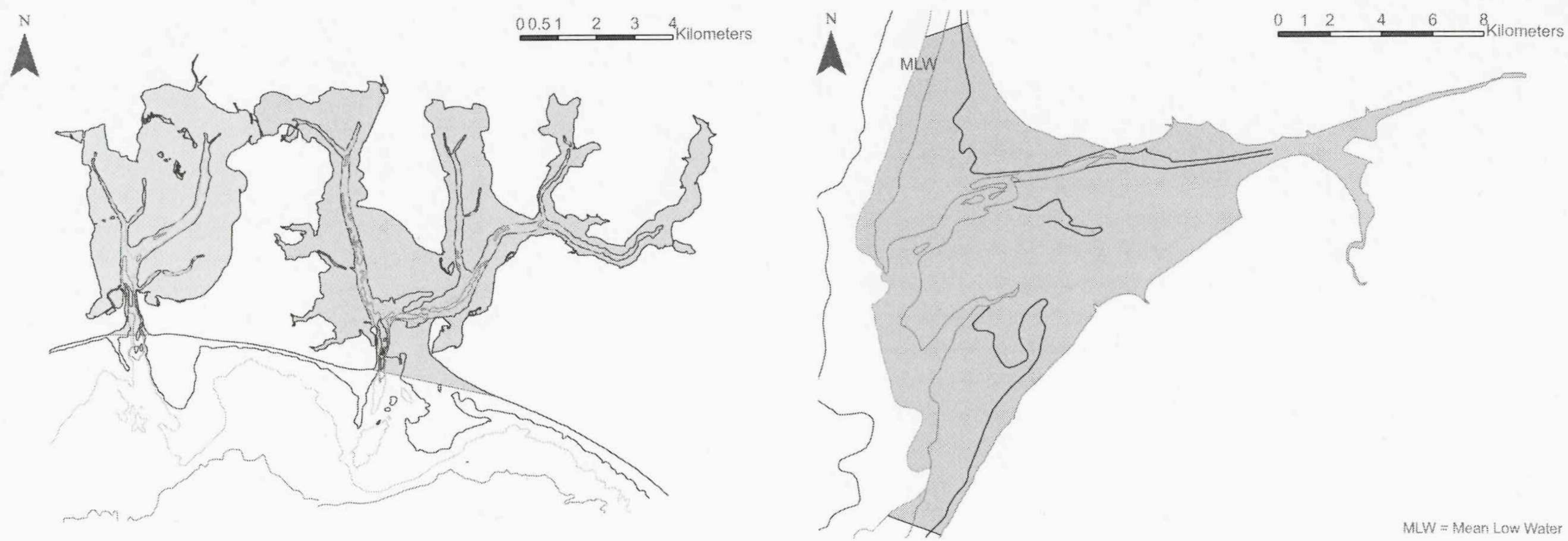
tion 3.5.1) and as a result the elements followed ASMITA's definitions (Fig. 3.3).

- The intertidal flats are the sediment body lying within the landward boundary of the estuary and above mean low water
- The channel is the water body lying within the estuary below mean low water
- The ebb-tidal delta is the excess sediment volume, lying seaward of the estuary mouth, above a hypothetical, non-inlet shoreface.

The intertidal flats and channels comprise the estuary or basin area. The seaward boundary of the estuary can be difficult to define. On estuaries with narrow mouths (e.g. Langstone Harbour), or with spits (e.g. Southampton Water) the seaward boundary can be defined as the narrowest point at the mouth. However, some estuaries, such as the Ribble, widen steadily seaward and do not have an obvious mouth (Fig. 3.4). In the case of the Ribble Estuary, the mouth was taken as the mean low water contour, extrapolated across the channel mouth.

The ebb-tidal delta is defined as the excess sediment volume above a hypothetical, non-inlet shoreface (Hicks and Hume, 1997). The non-inlet shorefaces are created by extrapolating bathymetric contours across the inlet mouth and delta area, and interpolating between the contours to form an non-inlet surface (Fig. 3.3). The Raster Calculator function in ArcView 9.0 was used to subtract the non inlet surface from the delta surface. This creates a new raster of the residual volume above the no-inlet shoreface and the delta volume is the volume above the 0 m contour of the residual volume raster.

Coastline data for different years was compared for each study estuary to identify major changes in coastline position. Large coastline changes were taken as evidence of human interventions, such as reclamation, whilst smaller changes were likely to be caused by natural processes, smaller human interventions or map inaccuracies (see section 3.4 for further discussion). Further details of human interventions are sometimes available in the literature, but often map information is the best information available to indicate what changes have taken place on the coastline.



(a) Langstone Harbour and Chichester Harbour

(b) Ribble Estuary

Fig. 3.4: Defining the seaward boundary for different estuary shapes

3.4 Error Analysis

The data sources and processing methods used in this project are subject to errors which are difficult to quantify. Potential sources of error include surveying techniques, chart compilation, digitising errors, vertical datum corrections and difficulties defining the estuary boundaries.

Surveying Techniques

Surveying techniques have changed over the period of interest. The earliest charts would have used sounding poles or lead lining to measure the depth relative to still water level, and triangulation to determine the position. Lead lining could result in errors caused by the lead line not being taut (overestimates) or not being resting on the actual seabed (underestimates) (van der Wal and Pye, 2003). For later surveys, echo sounders were used. Most recently surveys have been carried out with high resolution multibeam swathe bathymetry systems, with greatly improved accuracy (van der Wal and Pye, 2003).

Sampling densities with lead lining and echo sounders were lower than with modern techniques, with typical line spacing of 50 m to 100 m for an echo sounder (van der Wal and Pye, 2003) resulting in small irregularities in the sea bed being missed. Repeat surveys rarely used the same point or lines as earlier surveys. The sampling density in intertidal areas is generally low, as these areas are not important for navigation.

The International Hydrographic Standards (IHO, 2003), covering the period from 1968 to 1998, state that random errors in depth measurement for hydrographic charts should not exceed 30 cm, with 90% probability. Post 1998, the standards were reviewed and tightened (Mills, 1998) to reflect the increasing accuracy of survey techniques. When investigating historical changes in the Ribble estuary, van der Wal and Pye (2003) used 0.5 m as significant elevation change. Based on this criteria, the expected error range for the volumes and areas used in the current study was calculated by adding or subtracting 0.5 m (for pre 1968 charts) or 0.25 m (post 1968 charts)(Friend et al., 2006) to the digitised values and recalculating the areas and volumes. These values were selected so that the error range is more likely to be overestimated than underestimated, so we can be reasonable confident that the true volumes and areas lie within the error range. The percentage error associated with these estimates varies with depth (Table 3.3).

Chart Compilation

Published charts are not the ideal data source because the data has already been interpreted and filtered. In general, the survey data is used to give the best impres-

Tab. 3.3: Percentage error at different depths for 0.5 m and 0.25 m surveying errors

Depth (m)	% Error (0.5 m)	% Error (0.25 m)
1	50	25
5	10	5
10	5	2.5
15	3.3	1.67
20	2.5	1.25
30	1.67	0.83

sion of the area possible. Depth values are always rounded down, to the nearest foot (0.3048 m) for older charts and to the nearest 0.1 m for post 1970s charts.

An additional problem is that the publication date of the chart is not the date of the survey. Early charts were often based on single surveys, from a single year. Modern charts are likely to be compiled from a number of surveys conducted on different dates (van der Wal and Pye, 2003), with only areas that are expected to have undergone large changes being resurveyed between charts.

To quantify the error associated with using published charts rather than original surveys, fair chart data sets were compared with published chart data for areas of the Dart Estuary, Chichester Harbour and Langstone Harbour. The spot heights from the fair charts, assumed to be of higher accuracy than the published chart (Kyriakidis et al., 1999), were digitised in ArcGIS 9.0 and interpolated using the "Topo to raster" interpolation (see section 3.3.2). The volume and area of the fair chart data were compared with the volume and area data from the admiralty chart data sets.

The volumes, areas and percentage differences between the fair chart and published Admiralty chart data are shown in Table 3.4. The maximum error is 10% of the fair chart value, but the majority of the volumes and areas from Admiralty charts were within 5% of the fair chart value. In both Chichester and Langstone Harbours, the greatest error is seen in the volume above the 0 m contour, approximately the flat volume. This is not unexpected as the area is data poor relative to the channels, in both the fair chart and admiralty chart data sets. In the Dart, percentage errors were approximately 5% for the volume and area above 0 m and for the volume below, and were less than 2% for the area below 0 m.

Digitising and Interpolation Errors

Small errors in the position of features may occur during digitising. When interpolated these errors may lead to errors in the volume and area calculations. Error arising from digitisation and interpolation was estimated by digitising a section of the 1997 chart for Chichester Harbour multiple times and calculating the volumes

Tab. 3.4: Comparison between fair chart and published admiralty chart data sets

		Published chart	Fair chart	Difference	% difference
Dart (Sand Quay)	Volume above 0 m	30100	31385	-1285	-4.09
	Volume below 0 m	4342072	4543907	-201835	-4.44
	Area above 0 m	8162	7776	386	4.96
	Area below 0 m	201987	205298	-3311	-1.61
Langstone Harbour Entrance	Volume above 0 m	1647447	1813800	-166353	-9.17
	Volume below 0 m	59968449	62566052	-2597603	-4.15
	Area above 0 m	789521	801976	-12455	-1.55
	Area below 0 m	8718978	8700448	18530	0.21
Chichester Harbour (Emsworth Channel)	Volume above 0 m	321017	296211	24806	8.37
	Volume below 0 m	4493288	4744166	-250878	-5.29
	Area above 0 m	60480	56330	4150	7.37
	Area below 0 m	227294	235344	-8050	-3.42

Tab. 3.5: Percentage differences between mean volume and area and sample volume and area for multiple digitisations of the same location

	% difference from mean				
	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5
Area Above 0 m	1.16	0.52	-0.26	0.68	-2.09
Volume Above 0 m	-0.53	-0.18	1.80	-0.45	-0.64
Area Below 0 m	-0.91	-0.32	0.07	-0.43	1.59
Volume Below 0 m	0.70	-0.02	-0.58	-0.24	0.14

and areas for each digitisation. The volumes and area were then compared with the sample mean and the percentage difference of each sample from the mean was calculated (Table 3.5).

The maximum error arising from variations in digitisation and interpolation was 2.1%. In general areas and volumes above the reference level tended to have the greatest relative error. The relatively low data density over the intertidal areas causes small differences in digitisation to have a greater effect than in areas with higher data density.

Vertical Datum

Soundings on modern charts are reduced to a local chart datum that is roughly equivalent to the Lowest Astronomical Tide (LAT), defined as "a plane so low that the tide would seldom fall below it" (van der Wal and Pye, 2003). Earlier charts have had soundings reduced to Mean Low Water Springs (MLWS). The relationship between chart datum (CD), ordnance datum (OD) and mean tide levels varies spatially, depending on tidal characteristics. It is not uncommon for chart datum to differ within a single estuary, with step changes at certain points along the es-

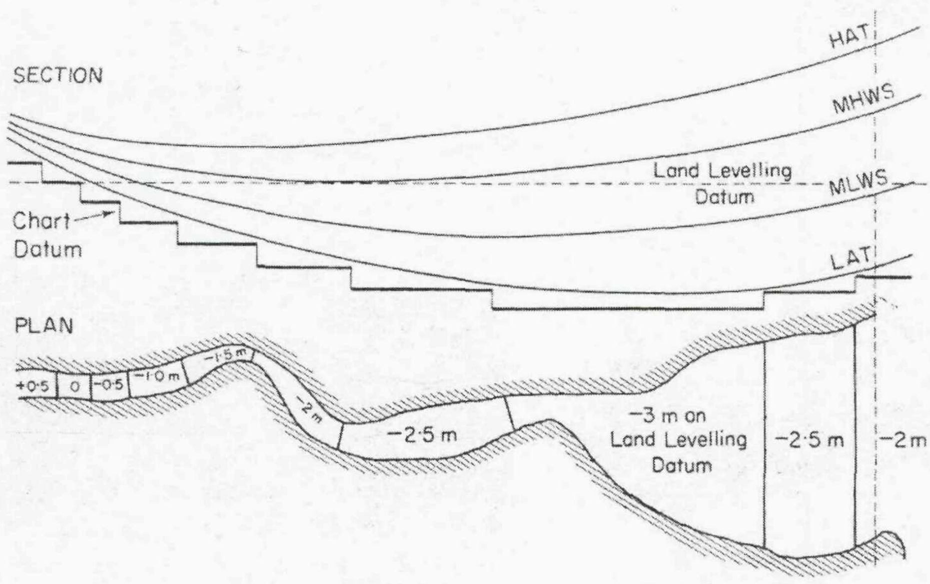


Fig. 3.5: Changes in Chart Datum (CD) in a typical estuary (Ingham, 1975)

tuary (Fig. 3.5). This introduces an additional potential error in cases where the boundary is poorly defined.

All data were reduced to ordnance datum. Where the difference between chart and ordnance datum was the same over the whole chart this was done by simply adding or subtracting the difference from the chart datum values. Where the relationship between chart datum and ordnance datum varied over the chart, points or areas for which the datum correction was known were digitised and interpolated to give continuous raster of correction values over the whole estuary. The correction raster was subtracted from the interpolated bathymetry raster to give a new bathymetry raster, relative to ordnance datum.

Defining Estuary Boundaries

The seaward boundary of estuaries and the ebb-tidal delta is difficult to define objectively. Subjective judgements of the estuary mouth and delta boundaries may result in errors when calculating the area and volume of estuarine elements. Error from this source is difficult to quantify, but may be minimised by using the same boundaries for each date for the same estuary, unless changes in the position of the coastline, estuary mouth or delta make this impossible.

Total error

The total error from quantifiable sources is summarised in Table 3.6. The total error represents the worst case scenario, assuming all errors are in the same direction. In reality it is unlikely that random errors from surveying, digitising and interpolation will all be in the same direction, so the likely error should be much smaller.

Tab. 3.6: Estimated error arising from quantifiable sources

Source	Estimated Error	
	Pre 1968	Post 1968
Survey	± 0.5 m	± 0.25 m
Chart compilation	±5 to 10 %	±5 to 10 %
Digitising and interpolation	±2 %	±2 %
Total Error	**±0.5 m plus 12%**	**±0.25 m plus 12%**

Errors arising from chart compilation could be assumed to be systematic, because measured depths are always rounded down so that the shallowest depth is reported. However there is no evidence for systematic errors in chart compilation in the cases examined here, with volumes and areas derived from published charts under and over estimating fair chart values. The probability distribution of the errors is unknown; however the mean square errors from all sources have been estimated (Table 3.7) and these values are used for error bars on graphs representing the observed volumes and areas. The implication of these uncertainties is that observed changes may be too small to be confident that real changes in morphology have occurred. For this reason, only changes outside the range to the error bars are viewed as true morphology changes.

Tab. 3.7: Summary of average error from quantifiable sources and mean square error (MSE) for the different elements of each study estuary. A is area in x 10^6 m^2, V is volume in x 10^6 m^3 and the subscripts f, c and d are the flats, channels and ebb-tidal delta respectively.

		Error Source				
		Survey	Chart Compilation	Digitising & Interpolation	MSE	MSE as %
Ribble	A_f	7.6	10.2	2.0	12.8	13%
	V_f	51.0	45.0	9.0	68.6	15%
	A_c	7.6	3.1	0.6	8.2	27%
	V_c	15.2	3.7	0.7	15.6	43%
Dart	A_f	0.7	0.1	0.0	0.7	49%
	V_f	0.7	0.1	0.0	0.7	76%
	A_c	0.7	0.6	0.1	0.9	15%
	V_c	3.2	2.8	0.6	4.3	15%
Southampton Water	A_f	1.4	1.1	0.2	1.8	16%
	V_f	5.2	2.4	0.5	5.7	24%
	A_c	1.4	2.0	0.4	2.5	12%
	V_c	8.7	10.7	2.1	14.0	13%
Portsmouth Harbour	A_f	0.9	1.0	0.2	1.4	14%
	V_f	3.8	1.4	0.3	4.0	29%
	A_c	0.9	0.8	0.2	1.2	16%
	V_c	2.9	3.3	0.7	4.5	14%
	A_d	3.4	1.2	0.2	3.6	31%
	V_d	5.8	1.0	0.2	5.9	57%
Langstone Harbour	A_f	1.0	1.2	0.2	1.6	13%
	V_f	2.9	1.8	0.4	3.4	19%
	A_c	1.0	0.7	0.1	1.3	17%
	V_c	1.8	1.3	0.3	2.2	17%
	A_d	1.4	2.0	0.4	2.5	13%
	V_d	4.9	3.0	0.6	5.8	19%
Chichester Harbour	A_f	1.3	1.7	0.3	2.2	13%
	V_f	4.4	2.8	0.6	5.2	18%
	A_c	1.3	1.2	0.2	1.8	15%
	V_c	3.0	2.5	0.5	3.9	16%
	A_d	2.0	2.2	0.4	3.0	14%
	V_d	5.6	3.6	0.7	6.7	18%
Humber	A_f	7.8	10.6	2.1	13.3	13%
	V_f	40.1	31.0	6.2	51.0	16%
	A_c	7.8	21.3	4.3	23.1	11%
	V_c	79.4	128.4	25.7	153.2	12%

3.5 Numerical Modelling

3.5.1 ASMITA

ASMITA Concepts

ASMITA was first presented as a behaviour-model "describing morphological interaction between a tidal lagoon or basin and its adjacent coastal environment" (Stive et al., 1998). The model consists of a schematisation of a tidal inlet system with the morphology being viewed at an aggregated scale consisting of morphological elements (Fig. 3.6). The major assumption of ASMITA is that, under constant hydrodynamic forcing, each element tends towards a morphological equilibrium which can be defined as a function of hydrodynamic forcing and basin properties (van Goor et al., 2003). Empirical relationships are used to define the dynamic equilibrium volume of each element (Stive et al., 1998).

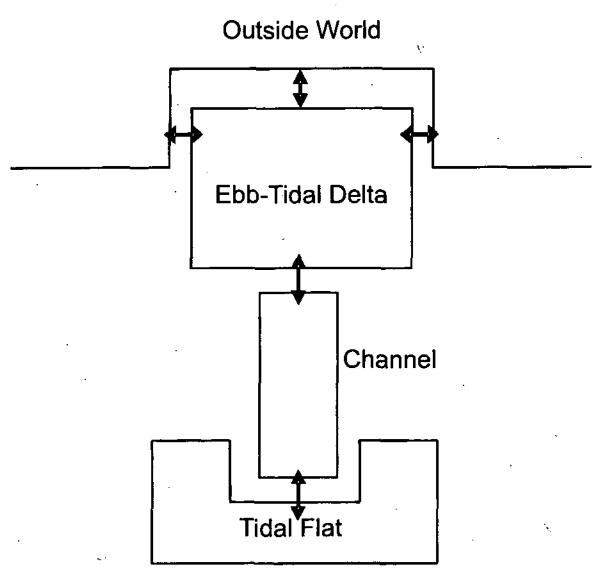


Fig. 3.6: Three element schematisation of an estuary used in AMSITA

The elements are defined as (also see section 3.3.2):

- **Tidal Flats:** The sediment volume above mean low water
- **Channel:** The water volume below mean low water
- **Ebb-tidal Delta:** The excess sediment volume above a hypothetical non-inlet shoreface, seaward of the estuary mouth

The elements interact through sediment exchange and this interaction plays an important role in the morphological evolution of the whole system, as well as that of the individual elements (van Goor et al., 2003). Long-term, residual sediment exchange is assumed to occur between adjacent model elements and it is assumed that development of the tidal inlet does not affect the availability of sediment in the outside world (van Goor et al., 2003). Sediment exchange between model elements is driven by the difference between the elements' equilibrium volume and its actual volume (Stive et al., 1998).

The evolution of the elements and of the system towards equilibrium is described in terms of sediment demand, sediment availability and sediment transport capacity. The sediment demand may be positive (demand) or negative (surplus) and is the difference between an element's equilibrium volume and its actual volume (Fig. 3.7). Within the model, sediment demand and availability are expressed in terms of sediment concentrations (van Goor et al., 2003). Differences in concentration between elements cause horizontal sediment exchange to occur between elements.

The sediment concentrations and sediment transport parameters used in the model are abstractions and may not appear physically meaningful as they cannot be directly measured in the real world. However they can be estimated based on real world conditions (see Section 3.5.2) and appear to give good predictions of estuarine morphological behaviour.

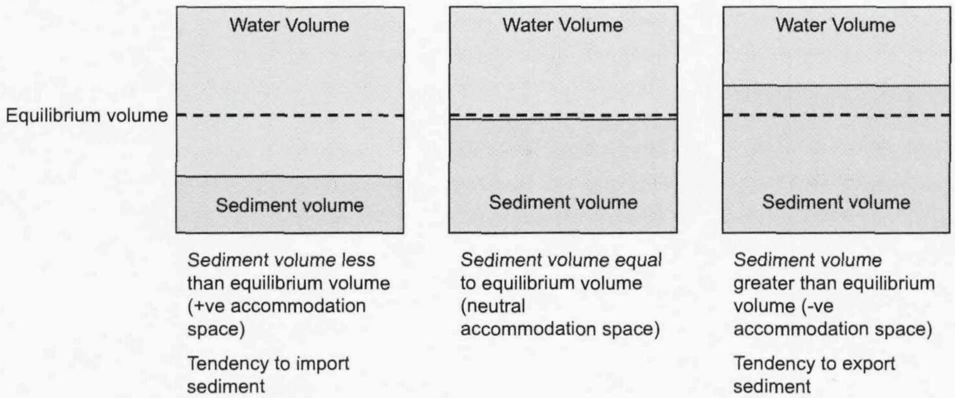


Fig. 3.7: Schematic of accommodation space concept

Model Formulation

ASMITA characterises each model element by a single variable: its volume (Kragtwijk et al., 2004). It is assumed that each model element tends towards an equilibrium volume which can be defined using empirical equations.

The equilibrium equations used for flat volume (V_{fe}), channel volume (V_{ce}) and delta volume (V_{de}) are given in equations 3.1, 3.2 and 3.3.

$$V_{fe} = \alpha_f * A_b * H \tag{3.1}$$

$$V_{ce} = \alpha_c * P^{b_c} \tag{3.2}$$

$$V_{de} = \alpha_d * P^{b_d} \tag{3.3}$$

Where H is tidal range, A_b is basin area *(FlatArea + ChannelArea)*,(a and b are empirically derived coefficients; the subscripts *f*, *c* and *d* refer to the flats, channel and delta respectively and P is the tidal prism:

$$P = (1 - \alpha_f) * A_b * H \tag{3.4}$$

When all model elements are in equilibrium, the sediment concentration throughout the whole system is equal to the sediment concentration in the outside world, called the global equilibrium concentration (C_E). The sediment concentration in the outside world is assumed to be unaffected by the evolution of the inlet and so the global equilibrium concentration is constant.

Each element also has a local equilibrium concentration, which refers to equilibrium from a perspective of local demand (van Goor et al., 2003). Local equilibrium concentration is equal to the global equilibrium concentration when the element is in equilibrium. The local equilibrium concentration indicates the extent to which the elements actual volume (V_n) deviates from its equilibrium volume (V_{ne}). The local equilibrium concentrations for the flats, channel and delta are given by equations 3.5, 3.6 and 3.7.

$$c_{fe} = C_E * \frac{V_f}{V_{fe}}^r \tag{3.5}$$

$$c_{ce} = C_E * \frac{V_{ce}}{V_c}^r \tag{3.6}$$

$$c_{de} = C_E * \frac{V_d}{V_{de}}^r \tag{3.7}$$

Where C_E is the global equilibrium concentration and the subscripts *f*, *c* and *d* refer to the flats, channel and delta respectively. r is greater than 1 and is usually taken as between 2 and 5 in compliance with a third power relationship for sediment transport and a non-linear function of flow velocity (van Goor, 2001; Wang, 2005). The difference between local equilibrium concentration (C_{ne}) and global equilibrium concentration (C_E) represents the sediment demand of the element (van Goor, 2001). When C_{ne} is larger than C_E the element has a negative sediment demand and a tendency for erosion. When C_{ne} is smaller than C_E the element has a positive sediment demand and a tendency towards accretion.

The extent to which the sediment demand of an element is satisfied depends on sediment availability in the adjacent elements. Sediment availability is represented in ASMITA as the difference between an element's actual concentration (c_n) and its local equilibrium concentration (c_{ne}). This difference drives volume changes within the elements, described by equations 3.8, 3.9 and 3.10.

$$\frac{dV_f}{dt} = w_{s_f} * A_f * (c_f - c_{fe}) - A_f * \frac{d\zeta}{dt} \tag{3.8}$$

$$\frac{dV_c}{dt} = w_{s_c} * A_c * (c_{ce} - c_c) + A_c * \frac{d\zeta}{dt} \tag{3.9}$$

$$\frac{dV_d}{dt} = w_{s_d} * A_d * (c_d - c_{de}) - A_d * \frac{d\zeta}{dt} \tag{3.10}$$

Where Ws_n is the vertical exchange coefficient for element n, c_n is the actual concentration, C_{ne} is the equilibrium concentration and $\frac{d\zeta}{dt}$ is the rate of relative sea-level rise. When the modelled sediment concentration is smaller than the local equilibrium concentration, erosion will occur within the element. When the modelled sediment concentration is large, sediment accretion will occur.

Sediment erosion and accretion within an element must be balanced by transfers across the element boundaries, with adjacent elements or the outside world. Sediment exchange between adjacent elements is described in terms of the difference between the actual sediment concentrations of the two elements, as described in equations 3.11, 3.12 and 3.13 (Fig. 3.8).

$$\delta_{fc} * (c_f - c_c) = W_{s_f} * A_f * (c_f - c_{fe}) \tag{3.11}$$

$$\delta_{fc} * (c_c - c_f) + \delta_{cd} * (c_c - c_d) = W_{s_c} * A_c * (c_{ce} - c_c) \tag{3.12}$$

$$\delta_{do} * (c_d - C_E) + \delta_{cd} * (c_d - c_c) = w_{s_d} * A_d * (c_d - c_{de}) \tag{3.13}$$

Where δ_{fc}, δ_{cd} and δ_{do} are coefficients for horizontal exchange between the flat and channel, the channel and delta, and the delta and outside world. Typical values for these coefficients as used in the Wadden Sea simulations (van Goor et al., 2003) are given in table 3.8.

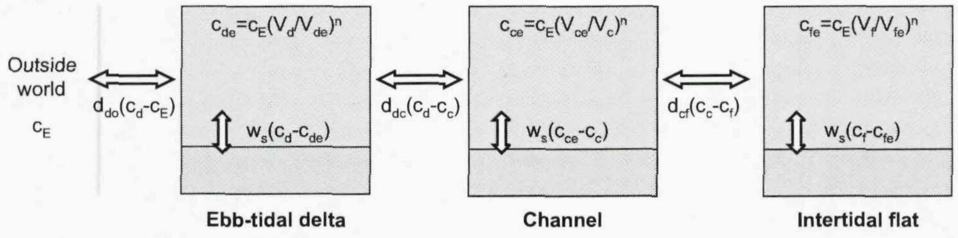


Fig. 3.8: Schematic of sediment exchanges within and between elements for the three element ASMITA model

Sea-level rise creates additional sediment accommodation space by increasing the difference between an element's actual volume and its equilibrium volume (see equations 3.8, 3.9 and 3.10). The critical rate of relative sea-level rise (SLR_{CRIT}), defined as the rate causing 100% loss of intertidal sediment, can be calculated for each element using ASMITA (van Goor et al., 2003).

Tab. 3.8: Values of equilibrium and sediment exchange parameters used by van Goor et al. (2003) for Wadden Sea basins, based on calibration by Buijsman (1997)

Parameter	**Flat**	**Channel**	**Ebb-tidal Delta**
Equilibrium Coefficients			
a	0.25	0.00001	0.006
b	-	1.55	1.23
Sediment Transport Coefficients			
Vertical Exchange (Ws) (m/s)	0.00001	0.00001	0.00001
Horizontal Exchange (m^3/s)	1500	1500	1500
Global Equilibrium Concentration (CE)	0.0002		

3.5.2 ASMITA Application

Development

A number of modifications and extensions to the basic ASMITA concepts were made for this study to allow the most common morphological types found in the UK to be better represented. Developments include changes to the standard three element schematisation of the estuary, inclusion of human disturbances and the use of dynamic equilibrium relationships specific to the estuary being studied.

Not all estuaries conform to the basic three-element schematisation used in ASMITA. In some estuaries, no clearly defined ebb-tidal delta is present (e.g. Dart). For such systems it is not sensible to model the evolution of a delta that does not exist in reality. In other estuaries, there are strong arguments for splitting the estuary into additional elements (e.g. Southampton water is divided into inner and outer channels and flats; the intertidal area in the Ribble is split into high and low flats) (see section 3.6). The basis of the model is the same under these circumstances, but the model equations are rewritten in generic terms (Wang, 2007 (pers. com); Townend, 2007 (pers. com.)). The user can define the equilibrium equation for each element and specify multiple interactions with other elements.

Human interventions may change an elements' actual volume, area or equilibrium volume. Dredging changes the current volume of an element and this is corrected accordingly within the modified model. Land reclamation and realignment change the area as well as the volume, and this in turn changes the tidal prism, which affects the equilibrium volumes of channel and delta elements.

In the past, ASMITA has used equilibrium coefficients derived from Wadden Sea inlets. These are unlikely to be suitable for all UK estuaries because of differing morphologies and tidal regimes. This thesis investigates how equilibrium relationships may vary across a diverse sample of estuaries (Chapter 6). For initial applications the equilibrium coefficients were modified to better describe the situation in a particular estuary. This was done for the study estuaries using the historic data to to estimate the equilibrium coefficients. Where the coefficients were approximately equal over time, it was assumed that the estuary was in equilibrium and an average value of the coefficient was used. When the data suggested considerable variation in the equilibrium coefficients, coefficients for a period when the estuary was believed to be in equilibrium were selected. This was usually the earliest data set as many of the disturbances occurred more recently.

The version of ASMITA used for this project was developed in Fortran by Wang (pers. com. 2007) and adapted for the current project to allow the inclusion of variable rates of sea-level rise, dredging, dumping, reclamation and realignment. The advantage of the Fortran version is its flexibility as any number and configuration of model elements can be used and different equilibrium relationships can be specified for each element.

Estimating parameters from physical processes

Applying ASMITA to model estuary evolution requires a number of inputs, both derived directly from physical properties of the estuary and more aggregate parameters outlined below. Measurable inputs include element volumes, areas and tidal range. Equilibrium equations can be estimated directly from area and volume data. The sediment exchange coefficients used in ASMITA are not directly measurable properties of the real system and must be estimated for each estuary. These sediment exchange coefficients were estimated based on the following guidelines (Wang, 2005):

- **Vertical exchange coefficient (w_{s_n}):** same order of magnitude as, and proportional to the average fall velocity. w_{s_n} was assumed to be the same for each element within the estuary unless clear differences in sediment properties were present (e.g. outer Thames) and was estimated from reported grain size data, translated into fall velocity.

- **Coefficient r:** equal to the power law in the sediment transport formula and typically 3 for mud and 5 for sand (Wang, per. com. 2007).

- **Horizontal exchange coefficient (δ_{nm}):** estimated based on Equation 3.14:

$$\delta_{nm} = (D * A)/L \tag{3.14}$$

  where

  - A is the area available for sediment exchange, assumed to be the length of the element boundary multiplied by the height of the boundary (i.e. average depth at boundary)

- L is the length scale of exchange, defined as the distance between the midpoints of two adjacent elements and
- D the diffusion coefficient, which takes into account sediment characteristics and current speeds, which affect the rates at which sediment can diffuse between elements:

$$D = u^2 * h/w_{sn} \tag{3.15}$$

where u is the peak flow velocity , h is average water depth and w_{s_n} is the vertical exchange coefficient.

- **Global equilibrium concentration (C_E):** Once the other parameters have been estimated, C_E is used to fit the model to the observed morphological time scale.

Model uncertainty

Van Goor et al. (2003) suggest that the uncertainty associated with the sediment exchange parameters is approximately ±50 %. The uncertainty of the model predictions was investigated based on the estimated parameter values and this estimate of uncertainty. This leads to a range of possible outputs for estuary evolution and for measures such as the critical rate of sea-level rise. This method is recommended by Cunge (2003) to avoid problems with calibrating deterministic models. Cunge (2003) suggests that rather than calibrating to limited data sets, deterministic models can be considered validated if the predicted and observed data lie within an acceptable interval, or if the differences between predictions and observations can be satisfactorily explained.

The "goodness of fit" of the model predictions to the observed data was measured using a Brier's skill score (BSS) (Sutherland and Soulsby, 2003).

$$BBS = 1 - \frac{MSE(P - O)}{MSE(B - O)} \tag{3.16}$$

Where MSE(P,O) is the mean square error between the predicted and observed and MSE(B,O) is the mean square error between a baseline condition and the observed data. In this case the baseline condition assumes that each element volume does not change from its initial conditions. The Briers skill score compares the goodness of fit of the model prediction against that of a null hypothesis, here represented by the assumption that the estuary bathymetry continues to be the same as the baseline condition and are positive when the model gives better performance than the baseline assumption. A BSS of 1 indicates perfect agreement between the model predictions and the observed data; a score of 0 means that the predictions are equal to the baseline. In addition to comparing model results with a baseline assumption, the BSS can be used to compare different models runs, for example

ASMITA simulations using different equilibrium coefficients. Brier's skill scores are presented for model runs in chapter 5.

3.6 Estuary Schematisation and Data Templating

Before an estuary can be modelled in ASMITA, a schematisation defining the morphological elements must be defined. This is used to aggregate the data into a form that can be used in ASMITA in a process known as data templating (Cowell et al., 2003a).

The data templating process makes use of the available data to identify the key morphological elements and their interactions. The aim is to produce the simplest conceptual model that captures all of the relevant behaviour of the estuary at the timescale of interest. For example, simple estuary schematisations might contain tidal channels and intertidal flats. However, for a particular estuary it may be necessary to add additional elements, for example splitting the intertidal zone into upper and lower elements, in order to capture the observed behaviour in a model. The use of more complex schematisations is justified when there are large spatial differences in the morphological behaviour of the estuary. This could occur if part of the intertidal is rapidly accreting or eroding, but other areas are relatively stable. Alternatively, part of the estuary may be heavily modified by human interventions whilst the remained is unaffected. In these cases it is desirable to be able to localise these effects by creating additional elements. This can theoretically be extended to produce more complex models with numerous elements and interactions, but this adds additional uncertainty to the model predictions by increasing the number of model parameters that must be estimated.

Conceptual schematisations for each estuary are presented in Chapter 4, and the historical analysis of morphological changes is carried out based on the elements defined by conceptual models. These schematisations are also used to aggregate the data for use in ASMITA.

4. HISTORICAL ANALYSIS OF A SAMPLE OF UK ESTUARIES

4.1 Introduction

In this chapter, detailed descriptions of the the study estuaries are presented. The Ribble, Dart, Humber, Southampton Water and Thames Estuaries are dealt with individually, while Portsmouth, Chichester and Langstone Harbours are considered together because they have similar morphological characteristics and adjacent geographical locations.

Data presented here includes a summary of the main processes and morphologies characterising each estuary, details of anthropogenic influences and a historical analysis of morphological changes. Key aggregate morphological parameters are presented, along with indicators of equilibrium status for each estuary. In addition, conceptual models, which form the basis for numerical modelling, are given.

The results for each estuary are presented by geographical location, starting with the Ribble in the northwest and progressing anticlockwise around the UK coast to the Humber in the east (see Fig. 3.1).

4.2 Ribble Estuary

4.2.1 Overview

The Ribble Estuary is a funnel shaped estuary on the west coast of England, draining into the Irish Sea (Fig. 4.1). It is approximately 15 km wide at the mouth and has a channel length of 28 km (van der Wal et al., 2002). The Ribble Estuary was formed by the drowning of the Ribble River valley during Holocene sea-level rise and has shown net sedimentation since inundation (Dyer, 2002). It has been suggested that prior to human interventions, the Ribble estuary may have been in a state of dynamic equilibrium (Dyer, 2002). Since the early 1800s the Ribble Estuary has been subjected to a number of man-made modifications, including large scale reclamations, training wall construction and channel dredging.

The Ribble Estuary is characterised by extensive intertidal sand and mud flats and has large expanses of salt marsh. The estuary is used for a variety of commercial and recreational purposes including grazing, shellfish gathering, sand extraction and water sports. The estuary is popular with tourists, with Blackpool and Southport having concentrations of tourist facilities (Ribble Estuary Strategy Steering Group, 1997). The surrounding countryside is used for walking, cycling and horse riding.

The Ribble Estuary is an internationally important wildlife site, providing feeding and roosting grounds for migrating birds including pink footed geese and wigeon. Much of the Ribble Estuary is designated as a SSSI. There are also a number of National and Local Nature Reserves within the estuary and on the adjacent coast. In addition, the Ribble Estuary is is a Special Protected Area and a RAMSAR site (Ribble Estuary Strategy Steering Group, 1997) (Fig. 4.2). The nature designations protect saltmarsh habitat in the inner estuary and sand flat and dune habitats in the outer estuary. The dunes support a number of rare species, including natterjack toads, sand lizards and a rare endemic plant, the dune helleborine.

Morphology and Processes

The tidal regime in the Ribble Estuary is macrotidal and flood dominant. Tidal range is largest at the estuary mouth (mean spring tidal range is 8 m at Formby) and decreases landwards (3.6 m at Preston). Peak tidal velocities are around 1 m/s. Freshwater input is low relative to the tidal prism of the estuary and most of the sediment supplied by the river is deposited at Preston Docks (van der Wal et al., 2002). The mid and outer estuary is exposed to moderate wave energy, from waves generated within the Irish Sea. Relative sea-level rise is estimated to be between 1 and 2 mm/yr (Woodworth et al., 1999).

The estuary boundaries are difficult to define, but Dyer (2002) suggested that Marshside, in the south, and Lytham, in the north, are the points where open coast processes became dominant. There are no natural hard points in the Ribble shoreline

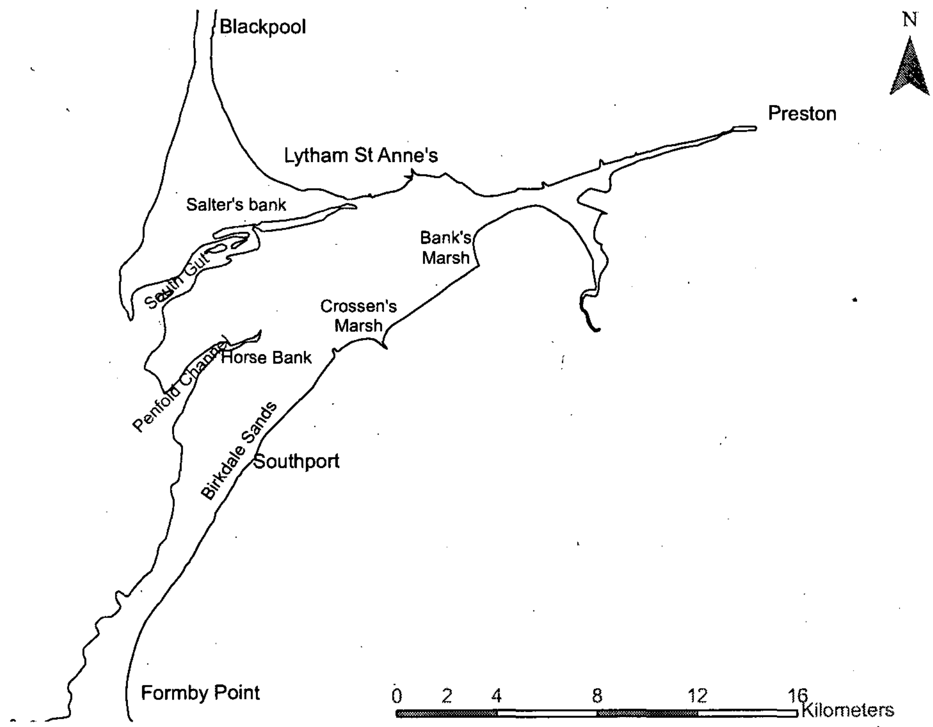


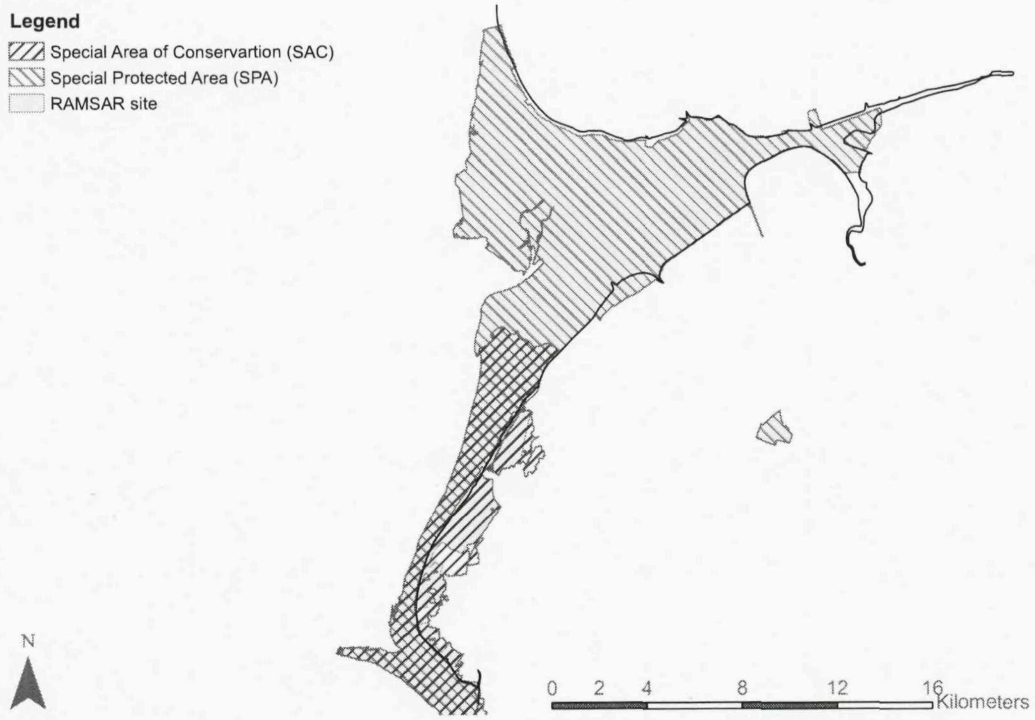
Fig. 4.1: Plan of the Ribble Estuary

and the soft coastline is readily shaped by natural forcing processes. As a funnel shaped estuary, the Ribble has low tidal scour and is susceptible to infilling with sediment (Dyer, 2002). Modification of tidal regime caused by land reclamations and channel training has enhanced infilling with fine sediment by reducing tidal prism and ebb current velocities.

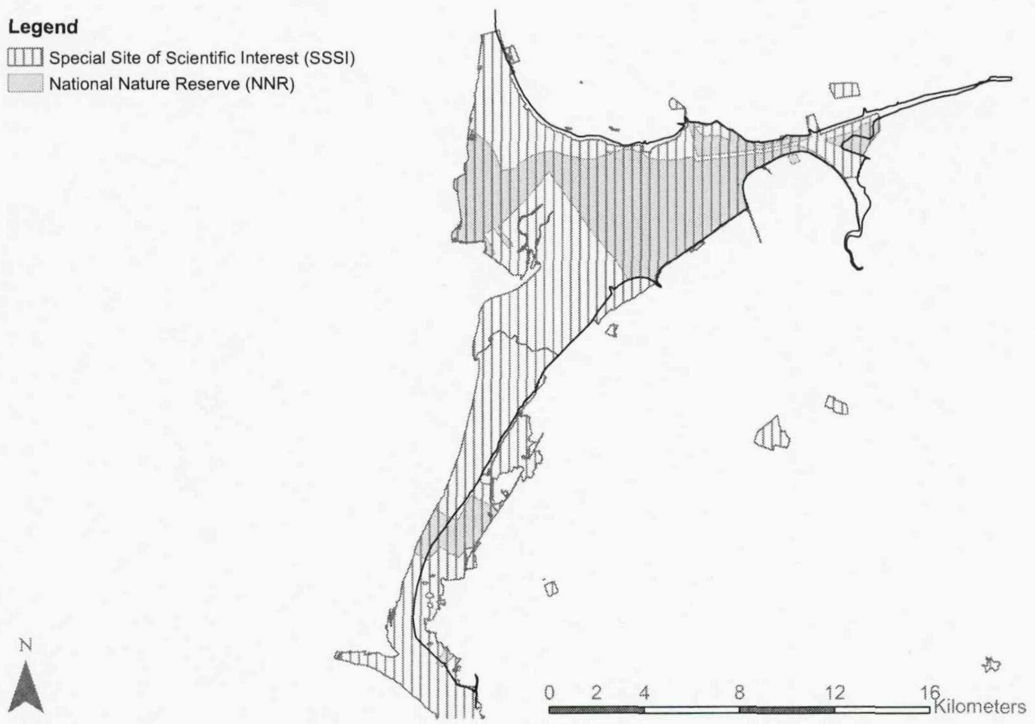
Sources of sediment to the Ribble Estuary are believed to be mainly from the Irish Sea (Dyer, 2002; van der Wal et al., 2002). Littoral drift from the north and south of the estuary also contributes material. Formby Point, to the south of the Ribble estuary has been experiencing erosion since the beginning of the twentieth century, with much of the eroded sediment being carried northward, into the Ribble Estuary (van der Wal et al., 2002).

Anthropogenic Influence

The Ribble Estuary has a long history of human interference. Since the early 1800s, attempts have been made to fix and straighten the main channel of the Ribble Estuary to provide a navigation channel to the Port of Preston. Although numerous experimental methodologies were tried (Barron, 1938), the construction of training walls, combined with dredging, was found to be most effective. Training wall construction began in the inner estuary in 1806, with the majority of construction occurring in phases between 1840 and 1910. In the 1930s, the training walls were



(a) International Designations



(b) National Designations

Fig. 4.2: Areas protected under (a) international and (b) national nature protection designations in the Ribble Estuary (Natural England, 2007)

Tab. 4.1: Summary of key changes anthropogenic activities causing changes in the morphological regime of the Ribble Estuary (data from Williams (2004))

Date	Event	Consequences
1806	Channel training and land reclamation for agriculture beings along the Ribble Estuary	Reduced tidal prism and current velocities Mud accumulates at the expense of sand
1840 - 1910	Training wall constructed and cut through outer banks. Channel dredging from 1847 onwards.	Ebb tides constrained to navigation channel Flood tides outside of main channel increase intertidal sedimentation
1932 - 1937	Training Wall extended 24 km downstream	Ebb flows concentrated into main channel Flood tides outside of the training walls move sediment into the estuary Infilling of the North and South channels in the outer estuary
1950-1980	Salt marsh growth slowed	Suggested that the estuary was close to a new dynamic equilibrium
1960's	Sand extraction begins at Salter's Bank	
1966	First sand extraction from Horsebank	
1980	Channel maintenance abandoned	Disturbs dynamic equilibrium Main channel moves outside of training walls in outer estuary

extended to fix the course of the channel in the outer estuary. The main events, and their consequences for estuary morphology, are detailed in table 4.1.

One consequence of training wall construction was increased sedimentation on the intertidal areas outside of the trained channel. These areas were gradually embanked and reclaimed mainly for agriculture (Fig. 4.3 and Table 4.2). Sedimentation and land reclamations have reduced the tidal prism of the Ribble estuary, decreasing the ability of ebb-tides to flush sediment seaward. This has set up a positive feedback: sedimentation reduces tidal prism, decreasing flushing and further increasing sedimentation (van der Wal et al., 2002).

As well as channel training to fix the position of the navigation channel, dredging was also undertaken in the Ribble to allow larger ships to pass upstream to the

Tab. 4.2: Summary of reclamations in the Ribble Estuary (from van der Wal et al. (2002))

Year	Site	Area (m^2)
1854	Clifton Marsh	666000
1859	Hesketh Marsh	2961000
1864	Freckleton Marsh	2470000
1878	Penwortham, Howick and Hutton	995000
1881	Southport	143000
1883	Hesketh New Marsh	4319000
1884	Southport	366000
1891	Southport	1400000
1895	Southport	366000
1895	Bonny Barn Marsh and Banks Marsh	4390000
1899	Hutton Marsh	277000
1899	Hutton Marsh	1094000
1900	Southport	251000
1927	Hutton Marsh - Embankment breached	-344000
1929	Southport	179000
1967	Southport	522000
1968	Marshside Marsh	565000
1969	Southport	206000
1970	Lea Marsh	239000
1974	Marshsie and Crossens Marsh	1103000
1975	Southport	185000
1980	Hesketh Out Marsh	3539000
1982	Clifton Marsh (landfill)	894000

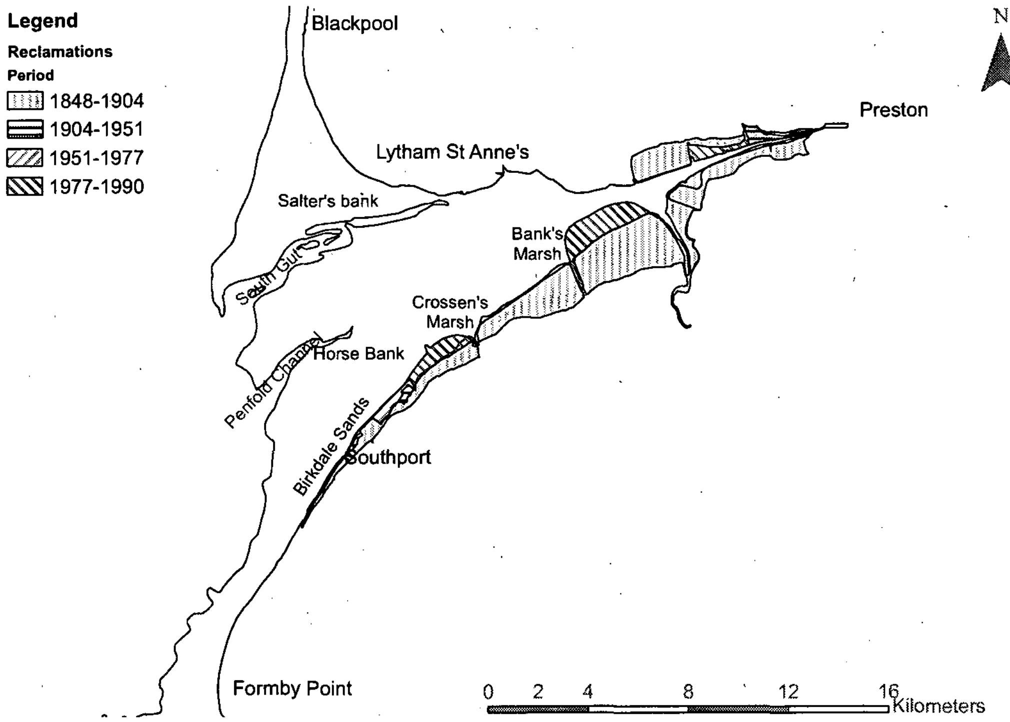


Fig. 4.3: Reclamations carried out in the Ribble Estuary between 1848 and 1990

Tab. 4.3: Estimates of dredging rates in the Ribble Estuary (from van der Wal et al. (2002))

Period	**Volume dredged (m^3)**	**Average dredging rate (m^3a^{-1})**
1847 - 1904	3,000,000	53000
1904 - 1951	38,000,000	80900
1951 - 1979	30,000,000	1070000

docks at Preston. Estimates of dredging rates between 1847 and 1979, shortly before Preston Dock closed, were given by van der Wal et al. (2002) (Table 4.3). Accretion rates in the Ribble Estuary slowed between 1950 and 1980, suggesting that a new dynamic equilibrium with forcing had been reached (Dyer, 2002). Following the closure of the dock in 1981, dredging and training wall maintenance ceased, disturbing the state of dynamic equilibrium. Ebb channels have now migrated outside of the training walls and the navigation channel is silting up (van der Wal et al., 2002).

Sand extraction has been carried out at Salter's Bank in the Ribble Estuary since the 1960s and it is estimated that 2 x10^6m^3 of sand have been removed from this site. Sand extraction is also carried out at Horse Bank and it is estimated that 4.5 x10^6m^3 of sediment were extracted between 1966 and 1994 and sand extraction is ongoing (van der Wal et al., 2002; Williams, 2004).

4.2.2 Historical Analysis

Initial experiments were carried out using a two element version of ASMITA to model the Ribble Estuary. From the initial results it was decided that a better representation of morphology and processes could be achieved by dividing the Ribble into three elements (Fig. 4.4). These were: (1) the channel, below mean low water; (2) the lower intertidal flats, between mean low water and mean high water neaps; and (3) the upper intertidal flats, above mean high water neaps. These elements reflect the Ribble's large intertidal area and high tidal range, better representing the morphological elements present in the estuary and improving numerical modelling results. They also approximately divide the intertidal area into sandy (lower) and muddy (upper) areas. The upper intertidal flat includes salt marsh and its evolution will therefore be influenced by vegetation, which will increase the sediment trapping efficiency and reduce erosion (Moller, 2006). Land reclamation directly affected the upper intertidal region, whilst the lower intertidal may have only been affected indirectly. Training walls largely prevent sediment exchange between the channel and upper intertidal flats. The lower intertidal zone interacts with the channels, upper flats and open sea, where it is affected by both tides and waves. The seaward boundary of the estuary was defined as the spring mean low water contour extrapolated across channel entrances (Fig. 3.4).

Figure 4.5 and table 4.4a show the area and volume evolution of the elements of the Ribble Estuary between 1904 and 1990. Basin area decreased over this period, due to land reclamation and changes in the position of the low water contour at the seaward boundary. Despite land reclamations, the area of the upper flats (above mean high water neaps) increased over the study period. This suggests high levels of accretion caused the position of the mean high water neap contour to move seaward. There is a slight decrease in the area of the lower flat element over the same period. Channel area was approximately stable between 1904 and 1951, and decreased between 1951 and 1990.

Volume changes in the Ribble Estuary (Fig. 4.5b) indicate a long term trend of accretion, particularly on the upper intertidal flats. Between 1904 and 1990, the volume of the lower flats decreased, following a similar pattern to changes in area. The average height of the lower flat (H_{f_l}) element was approximately constant (Table 4.4b). The volume of the upper flats increased over the same period and the rate of increase appears to be accelerating. Volume changes on the upper flats exceed area changes and the average upper flat height (H_{f_u}) has increased by over 1 m. The channel volume has decreased since 1951, indicating sedimentation and infilling in the channels. These findings are supported by the observations of van der Wal et al. (2002) who reported major infilling of channels and sediment accumulation in the upper intertidal zone.

Hypsometry curves for the Ribble Estuary (Fig. 4.6) show the distribution of

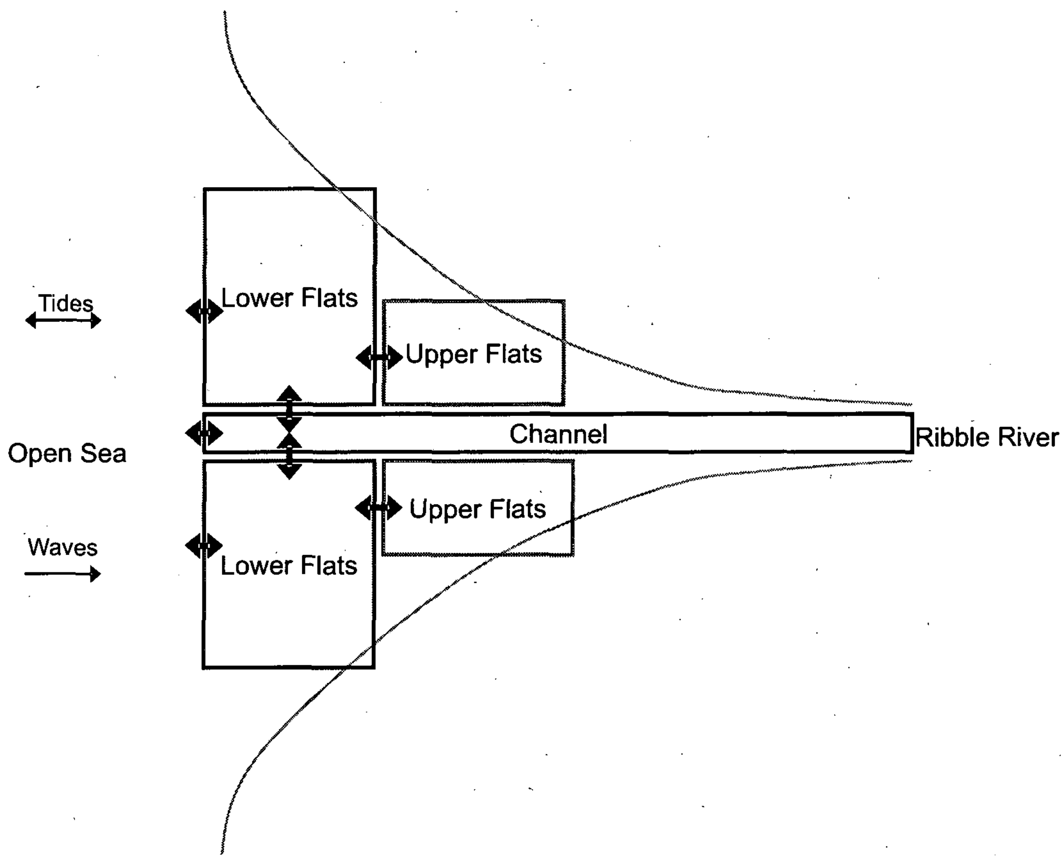
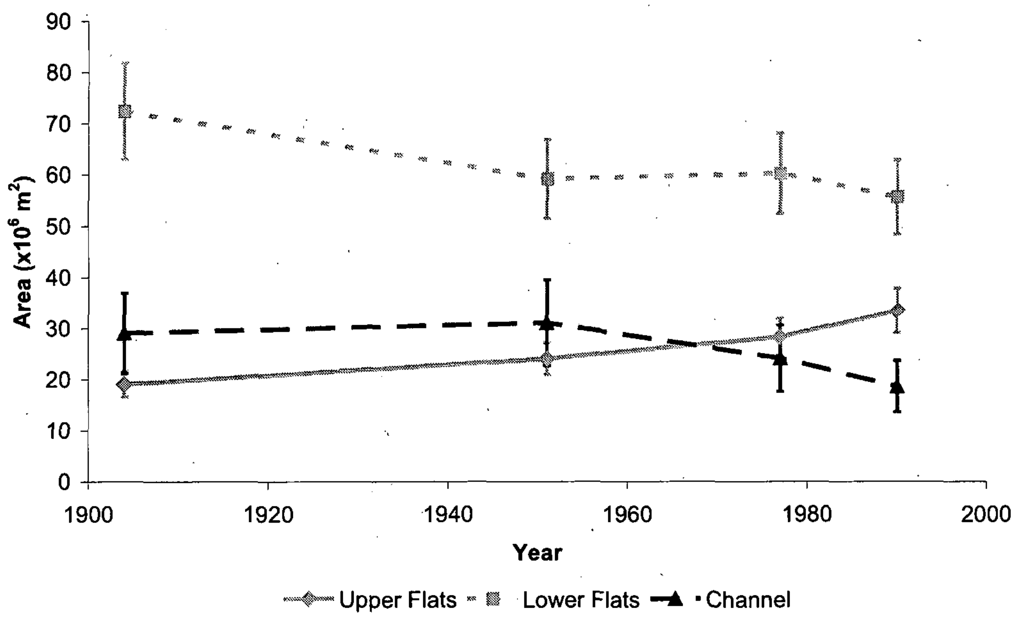
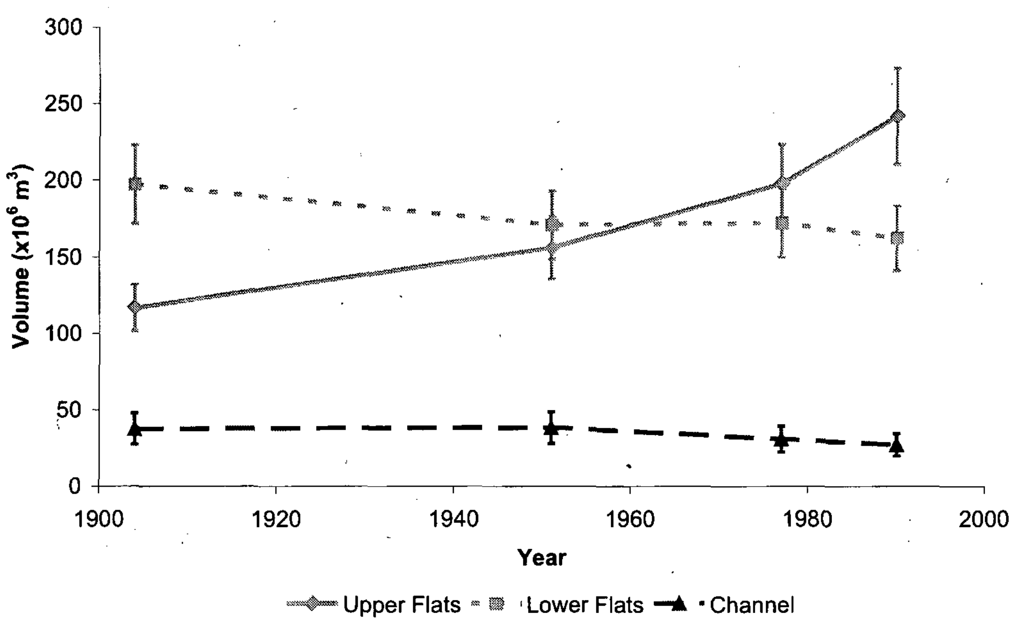


Fig. 4.4: Schematic representation of the Ribble Estuary



(a) Area



(b) Volume

Fig. 4.5: Area and Volume changes of flat and channel elements in the Ribble Estuary. Error bars are the percentage mean square error for each element (see Table 3.7)

area and volume with elevation for 1904, 1951, 1977 and 1990. Area hypsometry profiles tend to be slightly convex, described by Kirby (2000) as accretional profiles. Volume curves have similar shapes for all dates, but the trend for accretion can be seen in the increasing elevation of the profiles.

Table 4.4a details the major morphological changes in the Ribble Estuary over the study period. In addition to the changes in area and volume described above, tidal prism has decrease by approximately 30% because of land reclamations and sedimentation within the estuary. The ratios H_f/H, A_f/A_b and V_c/P can be used to assess the equilibrium status of an estuary. In equilibrium, these measures should be approximately constant. The ratios H_{f_u}/H and A_{f_u}/A_b increased over the study period, suggesting that the upper flat element is not in equilibrium with tidal range or basin area. The upper flat equilibrium coefficient (α_{f_u}) increased by more than 100% over the study period.

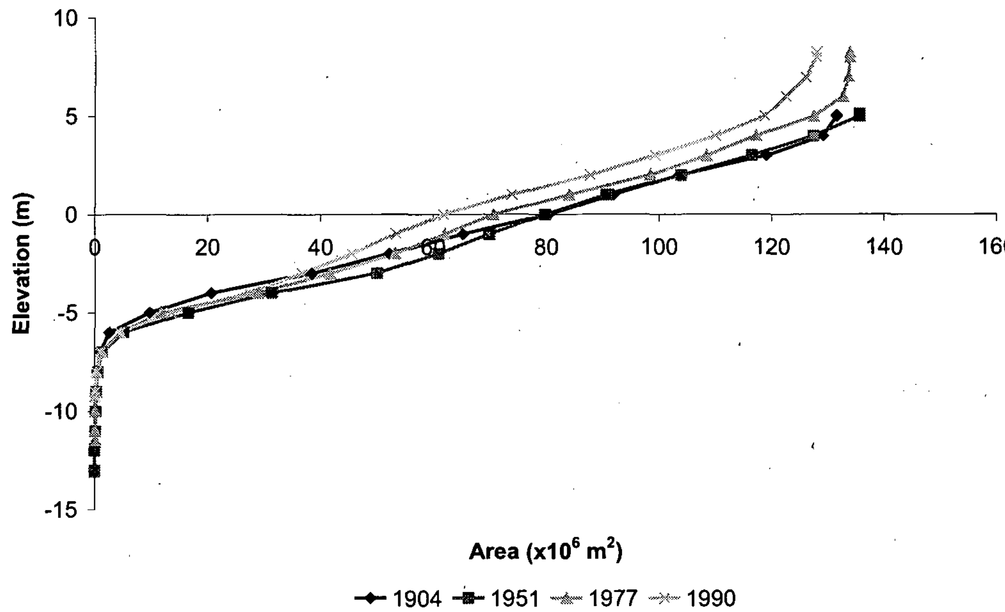
H_{f_l}/H tended to increase over the study period, but the magnitude of increase was much smaller and the standard deviation was 0.01. A_{f_l}/A_b decreased slightly over the study period. Overall, the equilibrium coefficient for the lower flat element (α_{f_l}) was approximately constant, suggesting that changes in area were compensated for by changes in average height and the lower flat element can be described in terms of an equilibrium volume. Sand extraction from the lower flat element does not appear to affect this stability, possibly because volume changes caused by sand extraction are small compared to overall changes in the estuary (Williams, 2004).

V_c/P, indicating the equilibrium status of the channel, was remarkably stable throughout the study period, indicating a strong relationship between tidal prism and channel water volume. This suggests that the channel is in equilibrium with forcing despite considerable human interference.

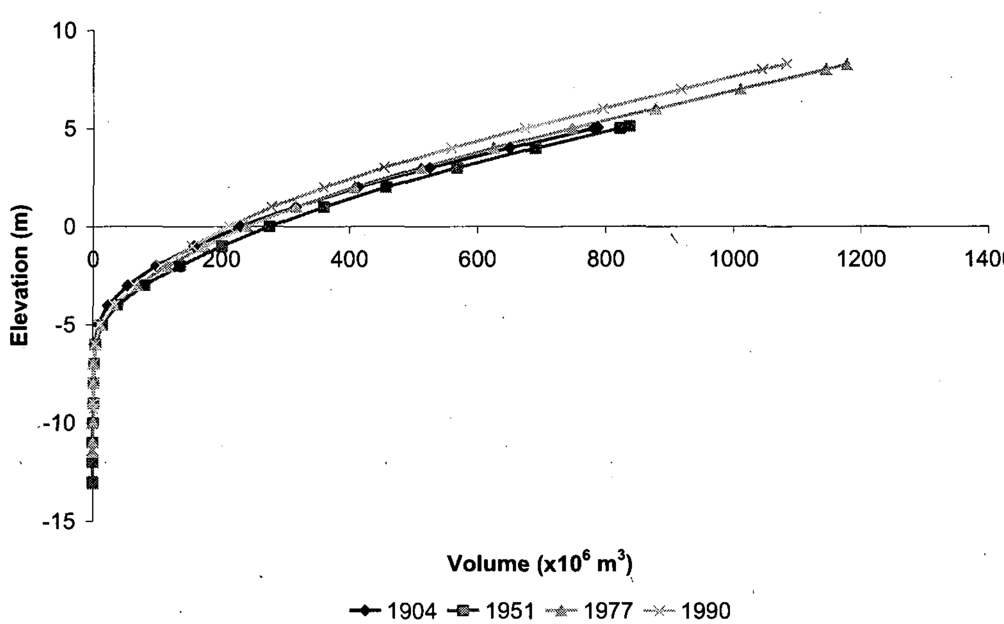
4.2.3 Discussion

Human activities have dominated the evolution of the Ribble for the past 200 years. It has been suggested that the Ribble estuary was in dynamic equilibrium prior to the onset of channel training and land reclamation in the early 1800s. Channel training induced large scale accretion on intertidal areas, which were subsequently reclaimed. Intertidal sedimentation and reclamation lead to reductions in the tidal prism of the estuary, which enhanced further sedimentation. The Ribble Estuary is currently accreting at rates far exceeding those needed to keep pace with sea-level rise, suggesting that human activity is currently more important in morphological evolution of the Ribble. This may change in the future as human activities are reduced and sea-level rise accelerates.

The observed changes in the Ribble Estuary suggest that the intertidal volume is currently out of equilibrium with forcing. The increasing rate of change indicates that a new equilibrium state may not be approached for some time. The channel



(a) Area



(b) Volume

Fig. 4.6: Hypsometry curves showing the distribution of (a) area and (b) volume with elevation for the Ribble Estuary. Mean low water is at -1.48 m.

volume however, is closely related to the tidal prism, suggesting that channel volume is in dynamic equilibrium. More data is needed to asses what a new equilibrium for the Ribble Estuary might look like.

Tab. 4.4a: Summary of measured changes in the Ribble Estuary including flat area (A_f), flat volume (V_f), channel area (A_c), channel volume (V_c), basin area (A_b), tidal prism (P). Areas are in x10^6 m^2, volumes are in x10^6 m^3; the subscripts f_u, f_l and c refer to the upper flats, lower flats and channels respectively.

Year	A_{f_u}	V_{f_u}	A_{f_l}	V_{f_l}	A_c	V_c	H	A_b	P
1904	19.11	110.67	84.27	203.94	29.11	37.59	7.9	132.49	732.04
1951	24.09	155.80	59.20	170.64	31.15	38.37	7.9	114.43	577.60
1977	28.31	197.42	60.26	171.84	24.14	30.88	7.9	112.71	521.14
1990	33.48	241.33	55.65	161.93	18.64	27.10	7.9	107.77	448.12
Mean	26.25	176.31	64.85	177.09	25.76	33.48	7.9	116.85	569.72
SD	6.12	55.98	13.10	18.44	5.58	5.43	0	10.80	120.49

Tab. 4.4b: Summary of derived changes in the Ribble Estuary including average flat height (H_f), average channel depth (H_c), average flat height relative to tidal range (H_f/H), ratio of flat area to basin area (A_f/A_b), flat equilibrium coefficient ($A_{f_l}/A_b * H_{f_l}/H$ (α_{f_l})) and channel volume relative to tidal prism or channel equilibrium coefficients (V_c/P or α_c). Heights are in m, ratios have no dimensions; the subscripts f_u, f_l and c refer to the upper flats, lower flats and channels respectively.

Year	H_{f_u}	H_{f_l}	H_c	H_{f_u}/H	A_{f_u}/A_b	α_{f_u}	H_{f_l}/H	A_{f_l}/A_b	α_{f_l}	V_c/P (α_c)
1904	6.11	2.72	1.29	0.77	0.16	0.12	0.34	0.60	0.21	0.06
1951	6.47	2.88	1.23	0.82	0.21	0.17	0.36	0.52	0.19	0.07
1977	6.97	2.85	1.28	0.88	0.25	0.22	0.36	0.53	0.19	0.06
1990	7.21	2.91	1.45	0.91	0.31	0.28	0.37	0.52	0.19	0.06
Mean	6.69	2.84	1.31	0.85	0.23	0.20	0.36	0.54	0.19	0.06
SD	0.49	0.08	0.10	0.06	0.06	0.07	0.01	0.04	0.01	0.00

4.3 Dart Estuary

4.3.1 Overview

The Dart Estuary is a ria without spits, located on the Devon coast, in the southwest of England. The estuary is approximately 20km long from its mouth to the tidal limit at Totnes (Fig. 4.7). It is set in a hard rock geology and the estuary is deep, narrow and steep sided. The outer estuary is characterised by a high relief rocky shoreline. In the inner estuary there are some small, muddy intertidal areas. Approximately 80% of the Dart Estuary is subtidal. The channel bed is comprised of sands and gravels which have been dredged in the past to provide aggregate for the construction industry (Dart Estuary Environmental Management, 2004).

The Dart Estuary is in a relatively natural state and human interference has been limited to dredging and the construction of training walls in the upper estuary. The towns of Dartmouth and Kingswear are the main settlements on the Dart Estuary and have defended frontages. The estuary is part of the South Devon Area of Outstanding Natural Beauty and is an important nursery for European sea bass, as well as habitat for little egret and grey heron. Large reed beds in the upper estuary also provide habitat for smaller birds such as reed buntings and warblers (Devon Wildlife Trust, 2004).

In this past, larger boats navigated the estuary up to Totnes, where there was a timber yard and wharf for ocean going coasters (Dart Estuary Environmental Management, 2004). Today, smaller commercial vessels continue to use Totnes as a port, but the main traffic is tourist boats and private, recreational vessels.

Morphology and Processes

The Dart Estuary is mesotidal, with a spring tidal range of 4 m at the mouth (1.8 m on neap tides). The tidal range increases landward due to the strongly convergent shape of the estuary (Devon Wildlife Trust, 2004). Peak flow velocities occur in mid flood and ebb flows, with slack water at high and low water. For the current study, the Dart Estuary has been divided into two elements (1) the channel, which widens towards the mouth and (2) the intertidal flats, which are narrow towards the mouth (Fig. 4.8).

On spring tides there is ebb-dominant tidal asymmetry at the mouth, with flood duration (6.7 hours) being longer than ebb duration (ebb 5.7 hours). Further upstream at Totnes, spring tide asymmetry reverses and becomes flood dominant, with durations of 5.0 and 7.3 hours for flood and ebb respectively. On neaps, the tides are approximately symmetrical.

River flow may be significant relative to the volume of the tidal prism. Under average conditions, river flow is approximately 2% of tidal prism, but under high flow it may be as much as 40% of the tidal prism (Dyer, 2002). The Dart River and other

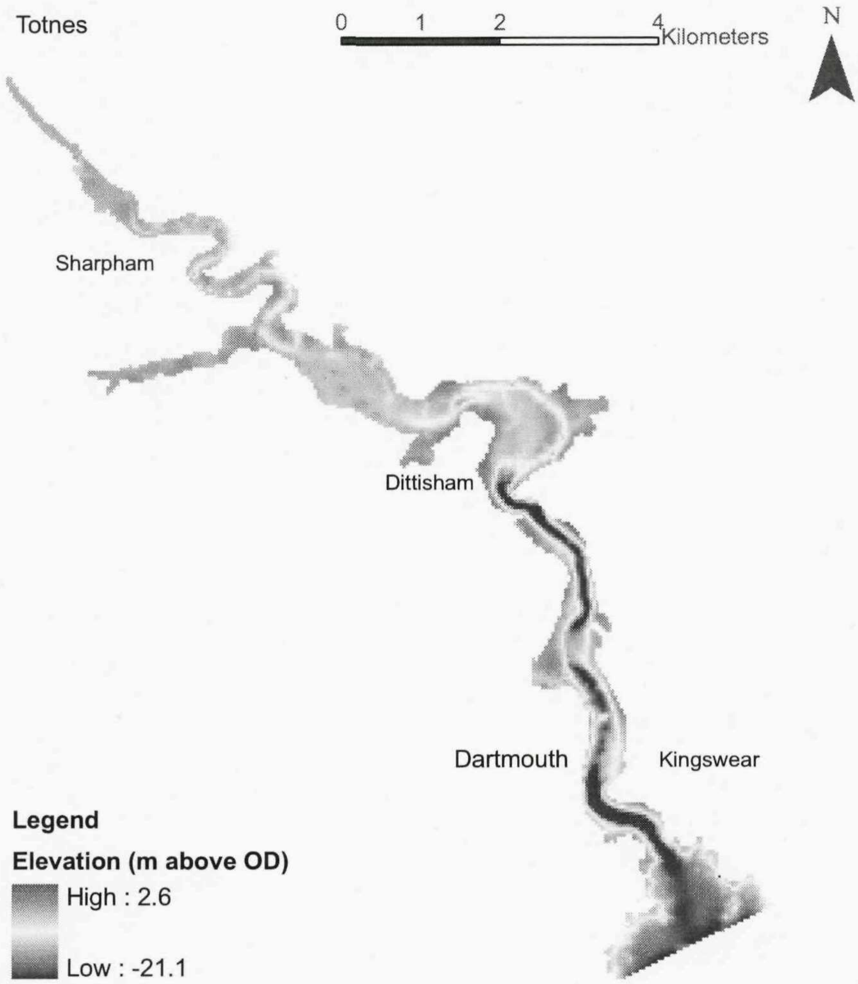


Fig. 4.7: Plan of the Dart Estuary

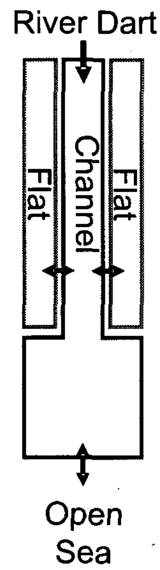


Fig. 4.8: Schematic representation of the Dart Estuary

tributaries may be the main source of sediment to the upper estuary, particularly when flows are high and bedload transport into the estuary is possible (Dart Estuary Environmental Management, 2004). With average or low river flows, the majority of sediment from fluvial sources is likely to be suspended silts and muds, which are deposited on the intertidal areas in the upper estuary. The supply of sediment from fluvial sources has not been quantified (Dart Estuary Environmental Management, 2004), so the significance of sediment input from this source cannot currently be confirmed.

Anthropogenic Influence

In the past, dredging of the upper estuary for aggregates was largely uncontrolled and it has been suggested that dredging records are unlikely to be found (Dart Estuary Environmental Management, 2004). In 1947, the training wall around Sharpham marshes was breached by dredging too close to the bank. Dredging ceased in 1984 when stability of estuary banks was deemed to be threatened. Since this date there has been sedimentation in the upper estuary of approximately 200,000 m^3 (Dart Estuary Environmental Management, 2004). Sedimentation has mainly taken place in intertidal areas, but there are concerns that the navigation channel may be shoaling. Dredging may resume in the future to maintain the navigation channels in the upper estuary, but it is unlikely that dredging for aggregates would be sustainable (Dart Estuary Environmental Management, 2004).

4.3.2 Historical Analysis

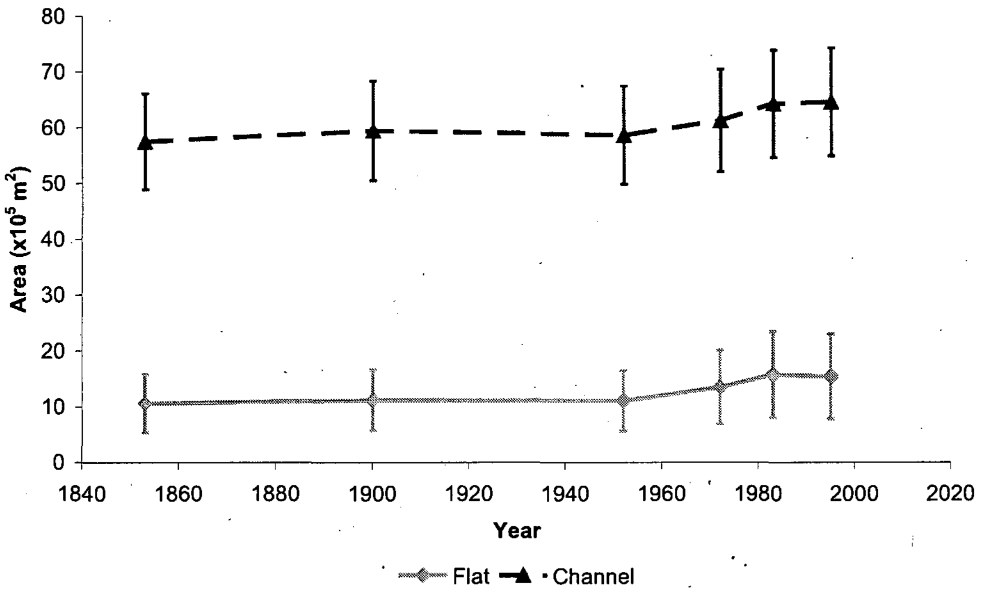
There have been no major reclamations along the Dart Estuary. Dates for the construction of training walls, and even for the weir at Totnes are unknown, and precede the earliest data set used in the current study. Dredging occurred in the upper estuary in the past, but no information on the quantities taken or areas dredged is available.

In general, the volumes and areas of the channels and intertidal flats in the Dart Estuary appear to have been relatively stable since the mid 1800s (Fig. 4.9). Channel and flat areas increased slightly between 1952 and 1983. This was caused by the breaching of the training wall at Sharpham Marshes, allowing a previously freshwater area to be inundated by tides. Since dredging ceased in the 1980s, intertidal flat volumes have increased by approximately 200,000 m^3. A similar volume of sedimentation was also estimated by Dart Estuary Environmental Management (2004) using historical bathymetry charts. The methodology and data sources used by Dart Estuary Environmental Management (2004) were similar to the current study and are therefore subject to the same, considerable, uncertainties.

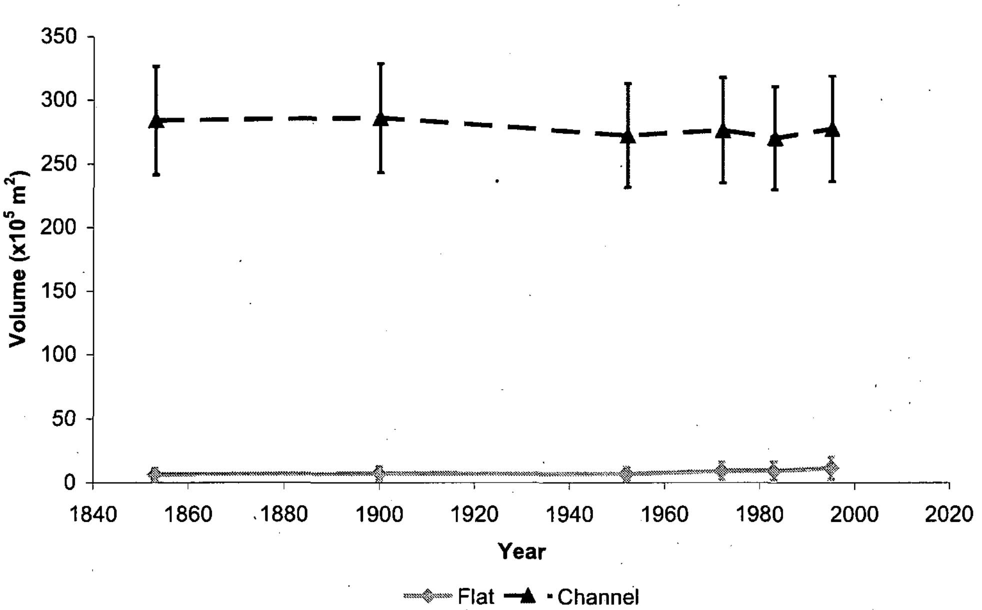
Hypsometry curves for the Dart Estuary show very little change in the distribution of volume and area with depth over the study period (fig. 4.10). The main observed change is the increase in maximum area between 1952 and 1983. The water volume between approximately -2 m and -12 m has tended to decrease slightly over the study period, indicating sedimentation (Fig. 4.10b).

Table 4.5 details key measures describing the geometry of the Dart Estuary over the study period. Flat area, channel area and basin area have increased over the study period, due to the addition of area at Sharpham Marshes following the training wall breach. Flat volume has increased slightly over the study period. Channel volume appears to be relatively constant. Average flat height has varied between 0.62 m and 0.76 m above MLW (mean=0.67 m, st. dev.=0.05 m), and appears to have increased following the cessation of dredging in the 1980s. Average channel depths appear to have shoaled slightly over the study period.

The relationship between average intertidal flat height and tidal range, used as one indicator of equilibrium status, has been relatively constant over time, with a mean value of 0.17 and a standard deviation of 0.01. The ratio of intertidal flat area to basin area (A_f/A_b) has increased slightly over the study period, with a mean value of 0.18 and a standard deviation of 0.02. The intertidal flat equilibrium coefficient, α_f has also tended to increase over the study period, suggesting that flat volume may not be in dynamic equilibrium with forcing. The relationship between channel volume and tidal prism was more variable and tended to decrease over the study period. This indicated that the channel volume has changed only slightly in response to increases in tidal prism.

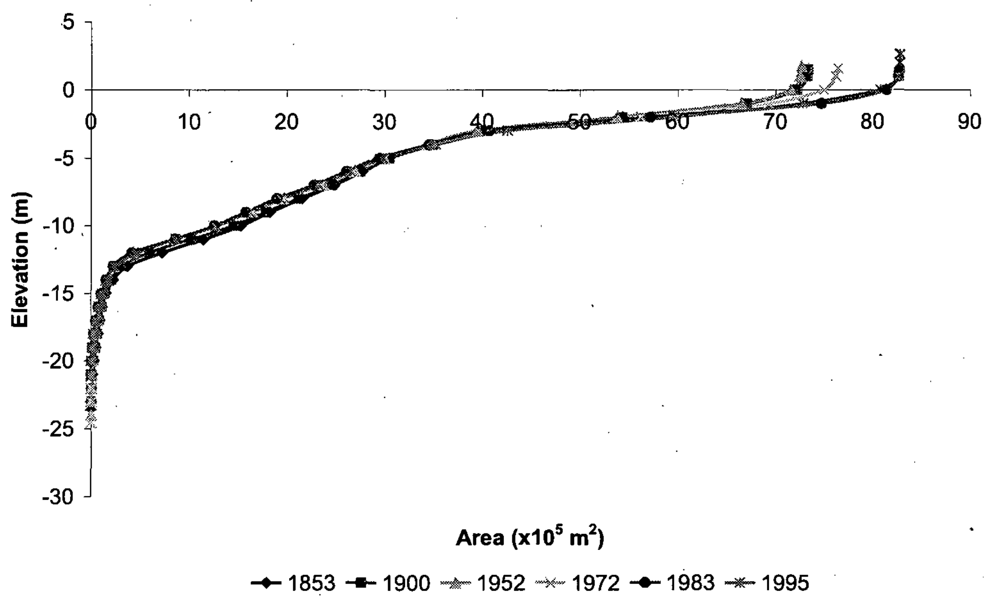


(a) Area

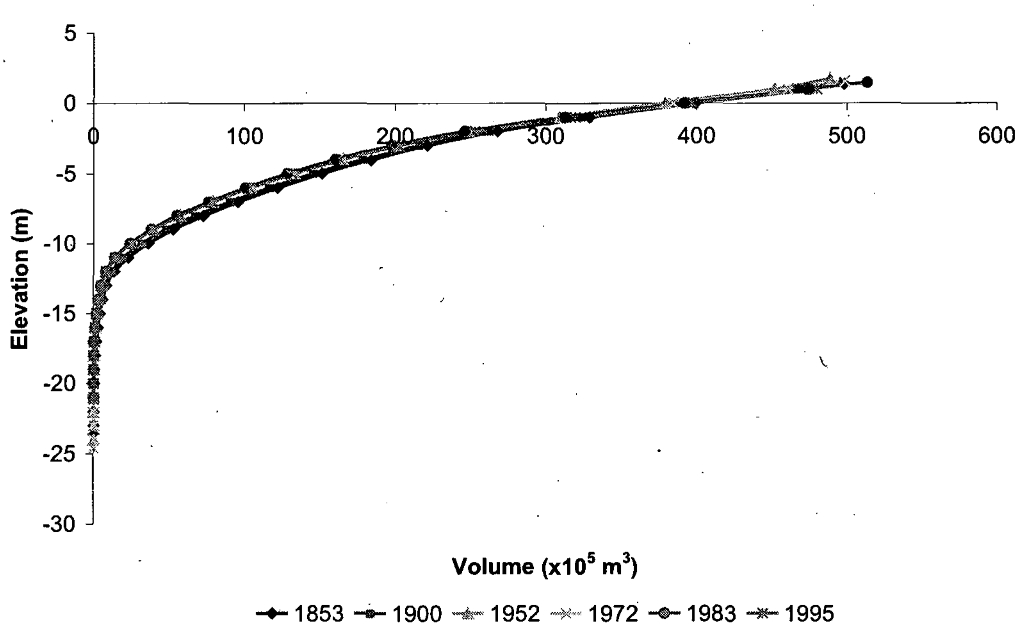


(b) Volume

Fig. 4.9: Area and Volume changes of flat and channel elements in the Dart Estuary. Error bars are the percentage mean square error for each element (see Table 3.7)



(a) Area



(b) Volume

Fig. 4.10: Hypsometry curves showing the distribution of (a) area and (b) volume with elevation for the Dart Estuary. Mean low water is at -1.02 m.

Tab. 4.5: Summary of key changes in the Dart Estuary between 1853 and 1955 including: flat area (A_f), flat volume (V_f), channel area (A_c), channel volume (V_c), basin area (A_b), tidal prism (P), average flat height (H_f), average channel depth (H_c), average flat height relative to tidal range (H_f/H), ratio of flat area to basin area (A_f/A_b), flat equilibrium coefficient (α_f) and channel volume relative to tidal prism (V_c/P (channel equilibrium coefficients, α_c). Areas are in x10^5 m^2, volumes are in x10^5 m^3.

Year	A_f	V_f	A_c	V_c	H	A_b	P	H_f	H_c	H_f/H	V_c/P (α_c)	A_f/A_b	α_f
1853	12.19	7.57	60.55	295.86	4.00	72.74	283.38	0.62	4.89	0.16	1.04	0.17	0.026
1900	12.65	8.27	60.67	290.00	4.00	73.31	284.97	0.65	4.78	0.16	1.02	0.17	0.028
1952	12.52	8.15	60.13	276.11	4.00	72.66	282.47	0.65	4.59	0.16	0.98	0.17	0.028
1972	13.52	9.30	62.85	276.81	4.00	76.37	296.17	0.69	4.40	0.17	0.93	0.18	0.030
1983	17.36	10.78	65.36	276.03	4.00	82.72	320.10	0.62	4.22	0.16	0.86	0.21	0.033
1995	17.00	12.89	65.77	283.42	4.00	82.77	318.18	0.76	4.31	0.19	0.89	0.21	0.039
Mean	14.21	9.49	62.55	283.04	4.00	76.76	297.55	0.67	4.53	0.17	0.95	0.18	0.031
SD	2.35	2.01	2.52	8.35	0.00	4.83	17.45	0.05	0.27	0.01	0.07	0.02	0.005

4.3.3 Discussion

The data sets used to describe the historic morphologies of the Dart Estuary were subject to large error estimates. The major source of potential error is from surveys. Due to the steep sided nature of the estuary, small errors in depth measurement during survey translate to very large errors in the calculation of volumes and areas based on this data. This is especially apparent in the intertidal areas, where error estimates are greater than 50% of the total area or volume. Observed changes in the area and volume of the channel and intertidal flat elements are within the error estimates for the Dart Estuary. This implies that the observed trends may be caused by data errors. The trend for sedimentation observed by Dart Estuary Environmental Management (2004) was also based on historic bathymetry charts and is likely to have the same error sources as the data presented here.

The equilibrium status of the Dart Estuary is unclear. Intertidal flat heights appear to have varied slightly relative to tidal range, with a possible trend for accretion in recent years. Channel volumes have tended to decrease relative to tidal prism, but due to the lack of sediment entering the system, this may represent a time lag between the change in forcing and the re-establishment of dynamic equilibrium. The observed stability in the Dart Estuary may represent a lack of sediment input, rather than an equilibrium state, although it may be fair to describe the Dart as in dynamic equilibrium with forcing and sediment inputs.

It is possible that the method used to calculate tidal prism over-estimates the increase caused by the breach of the training wall at Sharpham Marshes. It is assumed that this additional area has full tidal exchange with the main estuary and contributes to the tidal prism. In reality, the exchange between the marshes and the main estuary is restricted by the size of the breach.

River flows may be important in the Dart Estuary, both in terms of sediment delivery and in contributing to the flow through the estuary. During periods of high flow, fluvial discharge may be as much as 40% of the tidal prism, and may therefore have a significant impact on the morphology of the estuary. Sediment supplied by fluvial sources has not been measured, but is likely to be the main source of sediment in the upper estuary.

The cessation of dredging in the 1980s may also have influenced the equilibrium status of the Dart Estuary. No data is available on dredging volumes, so it is impossible to compensate for this when assessing equilibrium. The accretion seen on the intertidal flats since dredging was stopped may indicate recovery to an equilibrium state following disequilibrium imposed by the dredging.

Understanding of the morphological changes in the Dart Estuary is hampered by a lack of data covering natural processes and human interferences. The contribution of fluvial sediment and past dredging appear to be significant factors influencing the morphology of the Dart Estuary, but to date cannot be quantified.

4.4 Southampton Water

4.4.1 Overview

Southampton Water is bounded by Calshot Spit in the west and the Hamble estuary to the east (Bray et al., 2004) (Fig. 4.11). It is a narrow, spit-enclosed estuary with a naturally deep channel (Dyer, 2002). The western side of Southampton water is sheltered from wave action and dominant winds by Calshot Spit and has extensive mudflats and salt marshes which are protected under international and national nature conservation designations (Fig. 4.12). Both the saltmarsh and mudflats are currently eroding (Bray et al., 2004; Williams, 2006). The eastern side of Southampton Water, between the Itchen and Hamble estuaries, consists of mainly gravel and mud beaches. Much of the eastern shoreline is industrialised or urban.

Southampton Water, and the Test, Itchen and Hamble river estuaries that flow into it, are remnants of the Solent River system, inundated by the Holocene transgression approximately 6500 years ago (Bray et al., 2004). The area is formed of soft, sedimentary rocks and clays. Marshes and muflats are comprised of alluvial silt and peat (Halcrow, 2004). All of these sediments are vulnerable to erosion.

Since inundation, submergence and erosion of the northeast coast of has lead to enlargement of the estuary (Bray et al., 2004). During the last 7000 years, deposition of fine sediments has taken place at an average rate similar to local sea-level rise (1.1–1.5 mm a^{-1}) (Hodson and West, 1972) although Dyer (1980) suggests that sedimentation rates were locally variable, ranging from 2 - 10 mm/year.

Southampton Water has been a port since medieval times and increased in importance in 1842 when the first dock of the Eastern Docks was opened (Barton, 1979). Since this time, Southampton Water has undergone significant changes to accommodate the development of docks for commercial shipping (Fig. 4.13). Large areas of the estuary's intertidal mud flats and salt marshes have been reclaimed for port and other development (Table 4.6; Fig. 4.14). In 1783, Southampton Water had an intertidal area of 16 km^2, 56 % of this has since been lost to land reclamation. The channels have also been artificially deepened and widened by capital dredging (Table 4.7).

Morphology and Processes

Southampton Water is a semi-diurnal, mesotidal estuary with a partially mixed salinity structure. Mean spring tidal range is 4.05 m and mean neap tidal range is 2 m (Bray et al., 2004). The tidal regime is complex and is characterised by a young flood stand and double high water. The duration and slack water period of flood tides are long relative to ebb tides. Ebb-tides have greater velocities, but this ebb-dominance decreases upstream (Bray et al., 2004).

High ebb velocities favour net seaward transport of coarse grained material car-

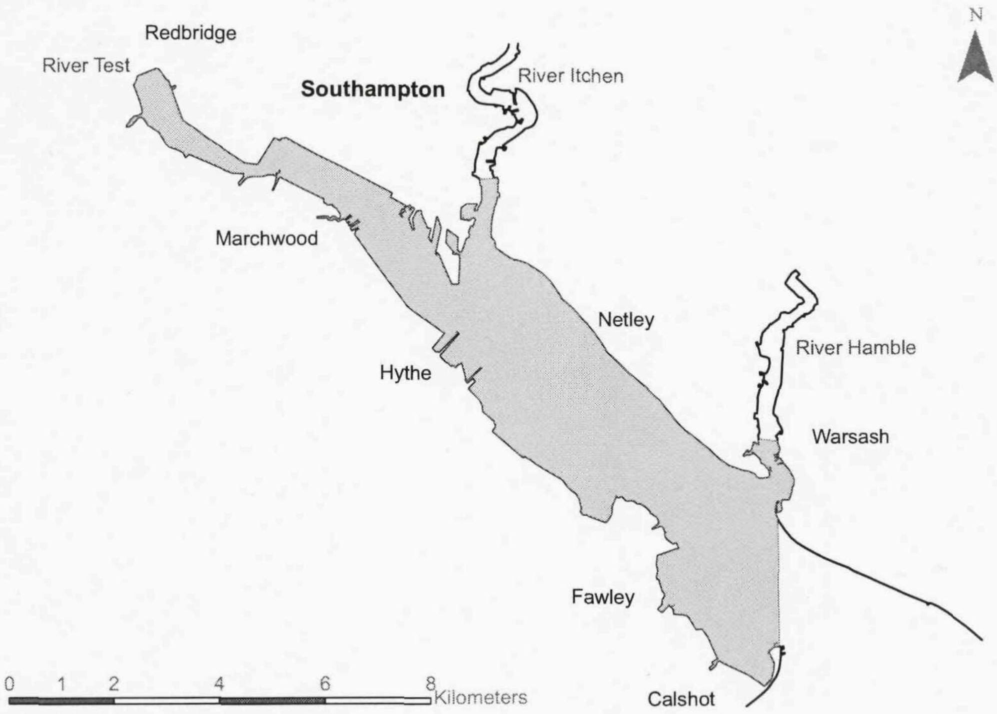


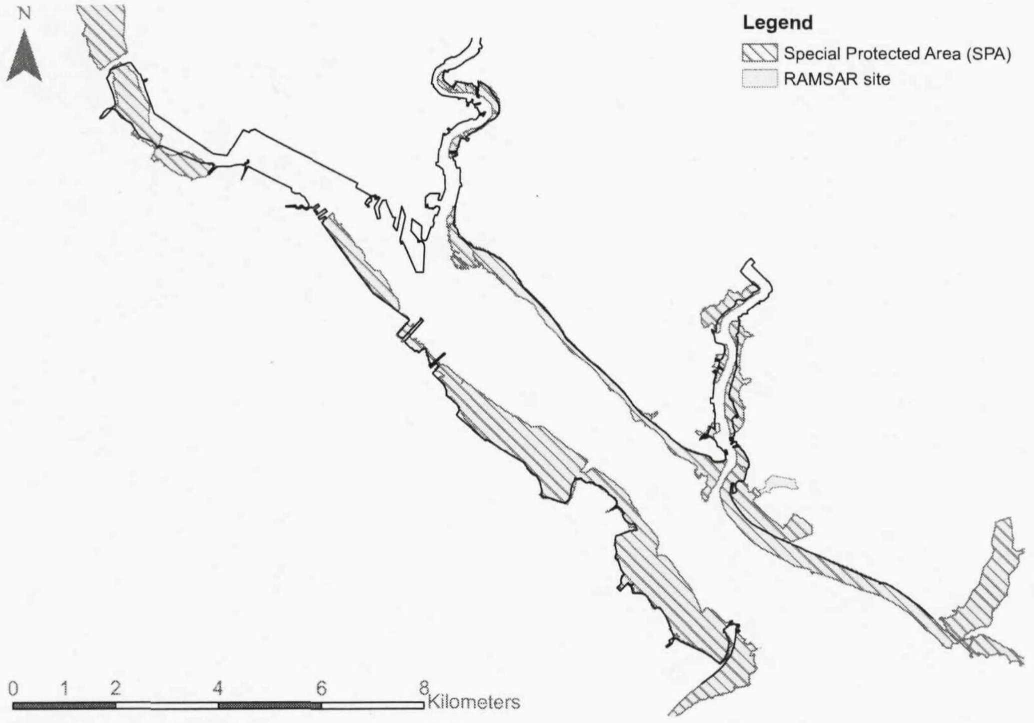
Fig. 4.11: Plan of Southampton Water

ried as bedload. The long flood period and long slack water durations on flood tides favour the transport of fine material, carried as suspended load, into the estuary (Bray et al., 2004).

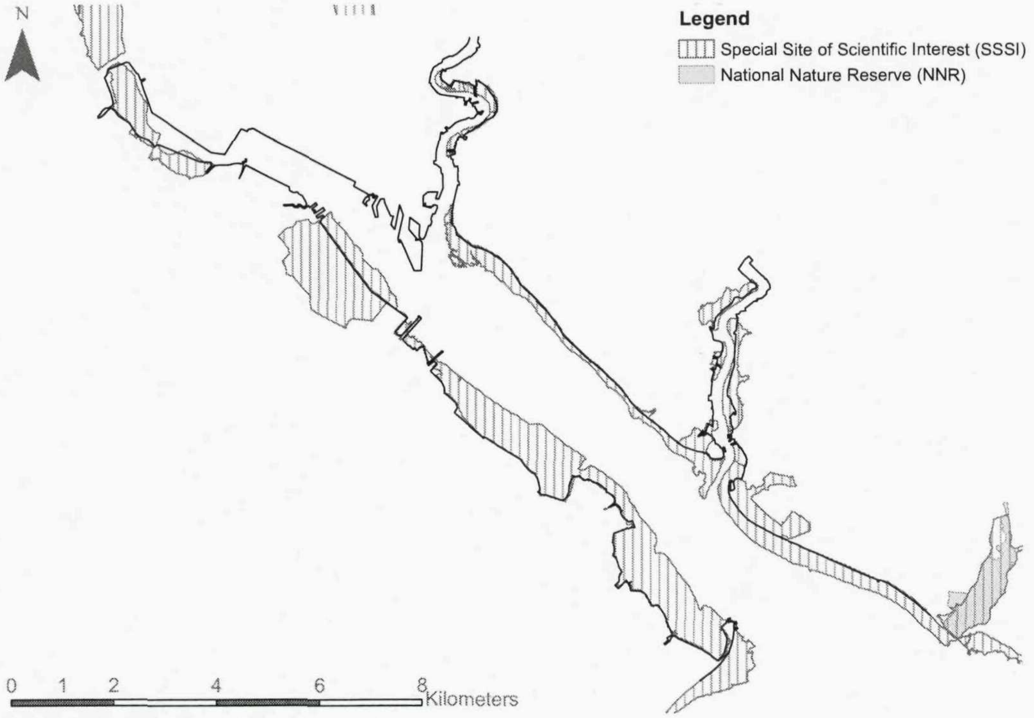
Wave action within Southampton Water is limited, particularly on the western shore which is sheltered by Calshot Spit. The fetch of waves reaching the outer estuary is limited to approximately 10 km (Halcrow, 2004) due to Southampton Water's sheltered position behind the Isle of Wight and significant wave heights within the Solent are generally less than 1.8 m (Velegrakis, 2000). Within Southampton Water, waves are much less significant than tides for sediment transport processes (Bray et al., 2004).

The sediment budget of Southampton Water has been studied by Bray et al. (2004). Sediment is supplied to the estuary from a number of sources, including fluvial sediment from the three tributaries, marine sediment from the Solent and sediment from coastal erosion. The sediment contribution from rivers is relatively small and is comprised of mainly fine sediment in suspension (Bray et al., 2004). Gradients in suspended sediment concentration suggest that the main source of suspended sediment is from the seaward direction. Fluvial sediment supply has been estimated to contribute a maximum of 17,000 $\text{m}^3 a^{-1}$ to the estuary (Bray et al., 2004).

Sediment is also supplied to Southampton Water from erosion of the unprotected

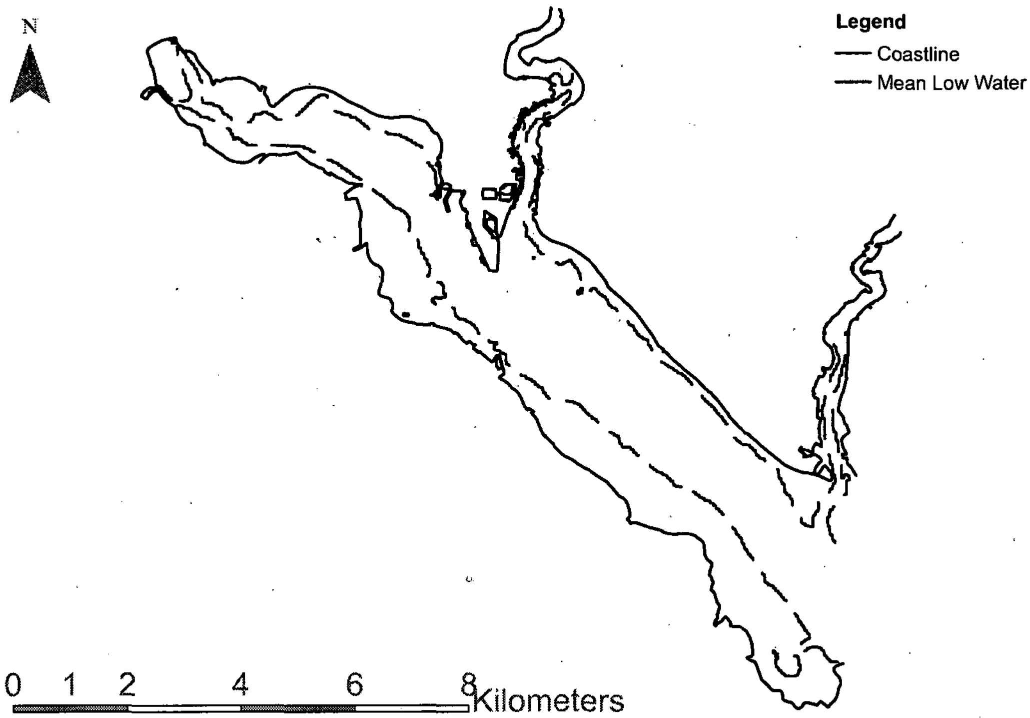


(a) International Designations

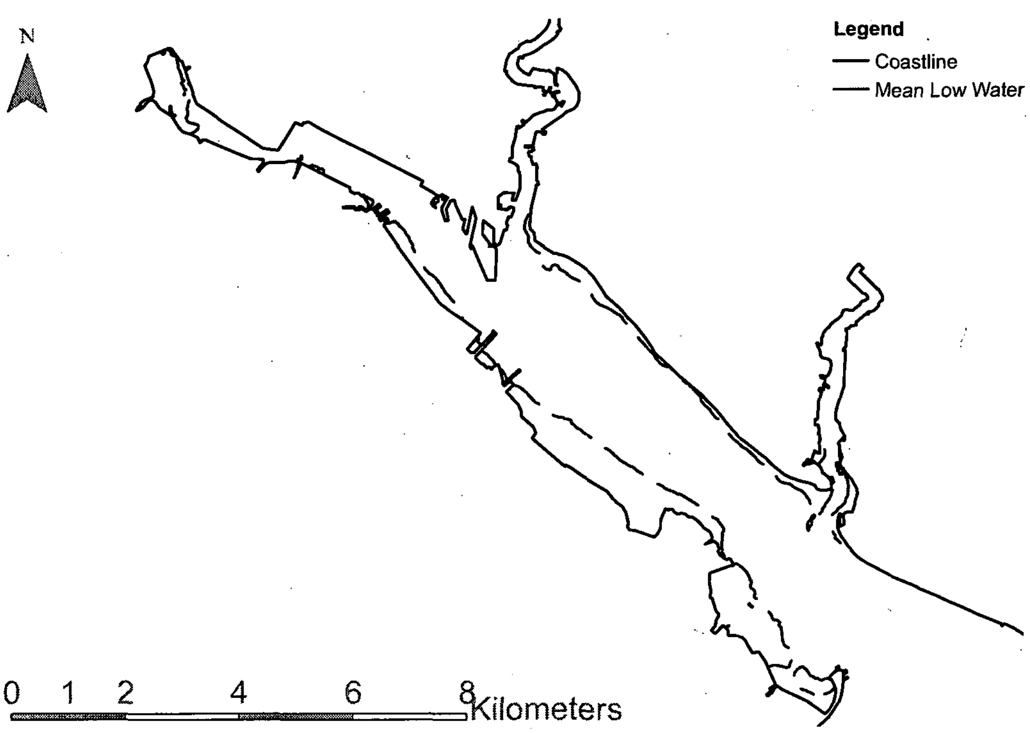


(b) National Designations

Fig. 4.12: Areas protected under (a) international and (b) national nature protection designations in Southampton Water (Natural England, 2007)



(a) 1911



(b) 1996

Fig. 4.13: Coastline and mean low water mark in Southampton Water in 1911 and 1996

stretches of shoreline in the estuary. Low cliffs between the Hamble and Itchen Rivers are estimated to be eroding at 0.1 m a^{-1} to 0.5 m a^{-1} (Bray et al., 2004) with around 20% to 25% of the eroded material being retained locally on beaches. On the northwest shore, salt marshes are undergoing frontal retreat, with saltmarsh cliffs forming at the boundary with the mud flats. Mudflats are also eroding and have narrowed and steepened.

Bray et al. (2004) summarised Southampton Water as a "low flux system, whose morphology and sediment budget are no longer in equilibrium with estuary hydrodynamics as a result of marginal land claim and other artificial modifications of the tidal prism".

Anthropogenic Influence

Southampton Water has a long history of use and modification by humans. The first significant changes began in the late 1800s when land was reclaimed for the Eastern Docks (Table 4.6) and dredging commenced in the main navigation channel (Table 4.7). Since this time, approximately 56% of the estuary's intertidal area has been reclaimed (Fig. 4.14). Docks have been developed in the inner estuary, requiring progressively deeper navigation channels to be created by capital dredging. These changes have dominated the morphological evolution of Southampton Water over the past 200 years.

There are a number of pressures facing Southampton Water for the future; including pressures on the landscape and ecological value of the estuary from existing industry, new development, coastal protection and flood defence works. Dredging for the existing port facilities can lead to losses of intertidal habitats. Coastal protection and flood defence schemes, needed to protect urban areas and infrastructure, may contribute to intertidal loss by removing sediment supplies to the estuary and by causing coastal squeeze (Halcrow, 2004).

Large areas of intertidal habitat in Southampton Water are protected under national and international nature protection legislation, and much of this protected habitat is already facing erosion. In the future, human pressures need to be balanced against the desire to maintain the functioning of the estuary and the need to protect these designated habitats. In addition to the human-induced pressures, the rate of sea-level rise is predicted to accelerate and is likely to have additional affects, including enhancing coastal squeeze and increasing the sediment demand of the estuary. If insufficient sediment is available to meet the extra demand caused by sea-level rise, further intertidal erosion will be seen.

Tab. 4.6: Details of major reclamations in Southampton Water

Year	Reclamation	Area (m2)	Source
1800s-1911	Eastern Docks area, between the Test and Itchen Rivers	800000	ABP Research and Consultancy (1995)
1920s	Marchwood Power Station and Military Port	80000	ABP Research and Consultancy (1995)
1920s-1970s	Reclamation of Esso Oil Refinery	800000	ABP Research and Consultancy (1995)
1927-1934	Western Docks	1620000	Barton (1979); ABP Research and Consultancy (1995)
1930-1955	Dibden Bay Phase 1	360000	ABP Research and Consultancy (1995)
1950-1951	Fawley	460000	ABP Research and Consultancy (1995)
1956-1960	Dibden Bay Phase 2	400000	Coughlan (1979); ABP Research and Consultancy (1995)
1960-1961	Dibden Bay Phase 3	360000	Coughlan (1979); ABP Research and Consultancy (1995)
1963-1970	Dibden Bay Phase 4	640000	Coughlan (1979); ABP Research and Consultancy (1995)
1967-1968	Western Dock extension 1	60000	Coughlan (1979); ABP Research and Consultancy (1995)
1970-1972	Western Dock extension 2	320000	Coughlan (1979); ABP Research and Consultancy (1995)
1972-1976	Western Dock extension 3	450000	Coughlan (1979); ABP Research and Consultancy (1995)

Tab. 4.7: Summary of capital dredging in Southampton Water. Information on volumes is only available for a few dredges.

Year	Description	Volume (m3)	Source
1889	Docks to Fawley dredged to 7.4 m below CD		ABP Research and Consultancy (1993)
1893-1896	Main channel above Fawley dredged to 9.3 m below CD		ABP Research and Consultancy (1993)
1907	Channel deepen below Calshot		ABP Research and Consultancy (1993)
1913-1914	Widening of swinging grounds off Ocean Dock		ABP Research and Consultancy (1993)
1922-1927	Deepening and widening of channel		ABP Research and Consultancy (1993)
1931-1936	Deepening and widening of channel		ABP Research and Consultancy (1993)
1938	Hythe to Cracknore deepened to 36 ft below CD		ABP Research and Consultancy (1993)
1950-1951	Material remove used for infilling reclamation at Fawley	3000000	Bray et al. (2004); ABP Research and Consultancy (1993)
1966-1977	Development of Upper Test for container terminal. Dredged material used for filling the reclamation	7000000	ABP Research and Consultancy (1993)

4.4.2 Historical Analysis

Over the past 200 years, Southampton Water has undergone huge changes in coastline position and estuary morphology (Figs. 4.13 and 4.14). Chronologies of the major reclamations and dredging projects are given in tables 4.6 and 4.7. These man made changes have influenced the hydrodynamics and morphology of Southampton Water.

Initial experiments using a two element version of ASMITA indicated that to understand the evolution and behaviour of Southampton Water it was necessary to split the estuary into two sections, which differ in the degree of anthropogenic disturbance and in morphological changes (Fig. 4.15). This helps in identifying the major drivers for morphological change within the estuary. In the inner section of the estuary, defined as the arm of the estuary receiving freshwater input from the Test River, upstream of the confluence with the River Itchen, human modifications have been more extensive. The northeast shore is highly developed and contains long stretches of docks and coastal defences protecting the city of Southampton. Much of the land area has been reclaimed from the estuary. The southwest shoreline of the upper estuary is less developed and has also undergone extensive reclamation. Reclamations in the upper estuary have caused decreases in area of both the intertidal flats and the channel and the tidal prism has also decreased.

A series of capital dredging projects to deepen and widen the navigation channels in Southampton Water have been undertaken to accommodate the increasing size of container ships at the Southampton Docks (Table 4.7) and more are proposed for the future. This has resulted in an increase in channel volume in the upper estuary.

In the outer estuary (below the confluence of the Test and Itchen Rivers, and including estuarine parts of these rivers), anthropogenic modifications have been less extensive. Some reclamations have been made at Fawley oil refinery and Fawley power station. There has also been some capital dredging of the main channel. The main observed changes in the outer section of Southampton Water are a reduction in intertidal area and volume and an increase in channel area and volume. The tidal prism has decreased slightly, but this is explained by changes in the upstream, inner section of the estuary.

Changes in area and volume of the intertidal flat and channel elements for inner and outer sections of Southampton Water are shown in figure 4.16. Channel area in the outer estuary has increased slightly. The intertidal flat area has been reduced in both the inner and outer sections, and channel area has decreased in the inner section (Fig. 4.16a). Intertidal flat volume has decreased in both sections of the estuary. In the inner section, the loss of intertidal flat volume has been dramatic and almost all of the intertidal volume has been lost. Channel volumes have been relatively stable in the outer estuary, but have increased dramatically in the inner section (Fig. 4.16b).

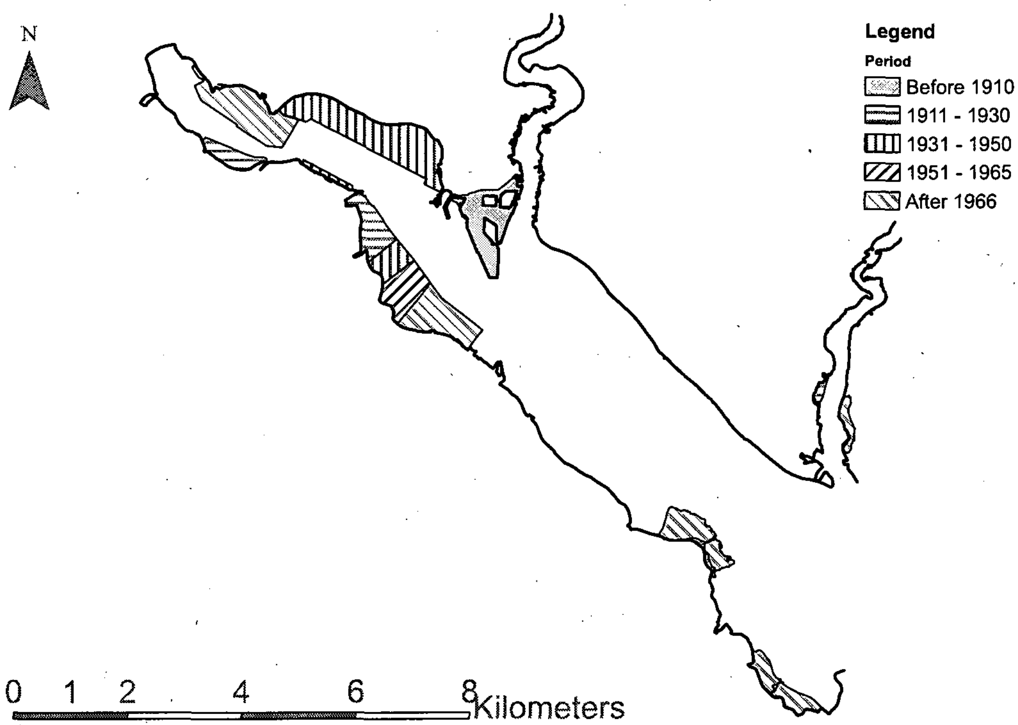


Fig. 4.14: Reclamations carried out in Southampton Water

Table 4.8 gives details of changes in the area and volume of the channels and intertidal flats in Southampton water over time. Changes in tidal prism, average elevations and the ratios of average flat height to tidal range (H_f/H), flat area to basin area (A_f/A_b and channel volume and tidal prism (V_c/P) are also shown. The latter are parameters are used as indicators of the equilibrium status of the flats and channels respectively. Tidal prism (P) has been reduced by approximately 30% in the inner section, and by approximately 12% in the entire estuary. Over the same period, the total area (basin area) of the inner section has been reduced by more than 50%. The average intertidal flat height in the inner section has decreased from 2.28 m to 0.69 m, and the average channel depth has increased from 2.38 m to 7.09 m. In the main section, average flat height and channel depth remained approximately constant throughout the study period.

The ratio of average intertidal flat height to tidal range (H_f/H), intertidal flat area to basin area (A_f/A_b) and channel volume and tidal prism (V_c/P), are expected to be approximately constant when an estuary is in dynamic equilibrium. In the outer section, both H_f/H and V_c/P return a relatively constant value, suggesting flat height and channel volume are tending towards equilibrium with forcing. A_f/A_b is more variable and shows a decreasing trend over the study period. The intertidal flat equilibrium coefficient (α_f) tends to decrease over time.

In the inner estuary, all three measures vary considerably over time, suggesting

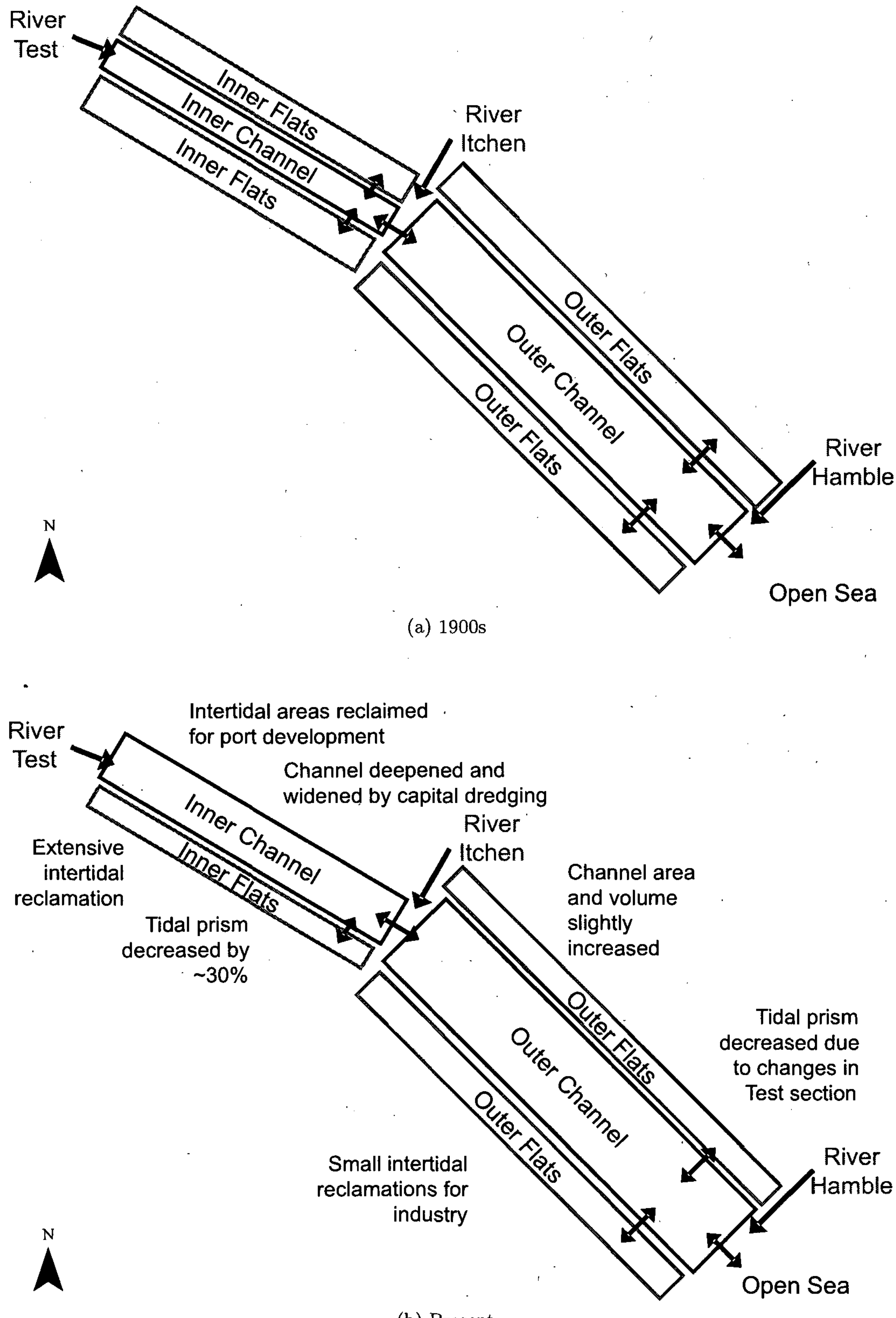


Fig. 4.15: A conceptual model of the major morphological changes in Southampton Water between the early 1900s and the present day

this part of the estuary is out of equilibrium. H_f/H decreased from 0.56 to 0.17, A_f/A_b decreased from 0.49 to 0.19 and V_c/P increased to around three times its 1926 value. The intertidal flat equilibrium coefficient (α_f) decreased from 0.28 to 0.03 in the inner estuary.

Figure 4.17 shows the hypsometry of Southampton Water between 1783 and 1996. Changes in area have occurred mainly around the high water mark and between 2 m and 15 m depth. This supports the suggestion that the observed changes in Southampton Water are largely due to anthropogenic causes: the changes around the high water mark reflect changes in shoreline position significantly influenced by land reclamation, whilst the changes below 2 m depth are likely to be largely due to dredging activity.

Changes in the distribution of volume with elevation (Fig. 4.17b) have occurred throughout the elevation range of Southampton Water. The volume hypsometry follows a similar curve for each of the dates shown, but there is a tendency for greater water volumes at lower elevations as time progresses.

Figure 4.15 is a conceptual model summarising the main anthropogenic, hydrological and morphological changes occurring in Southampton Water between the early 1900s and the present day. In the inner estuary, channel area, flat area, flat volume and tidal prism have decreased substantially, due to extensive land reclamation. Channel volume has increased as a result of capital dredging. In the outer estuary the changes have been much smaller, with only limited area changes due to reclamations and minimal channel alterations. This conceptual model of Southampton Water is used to provide the schematisation for the numerical modelling of Southampton Water and as a framework to understanding the modelling results.

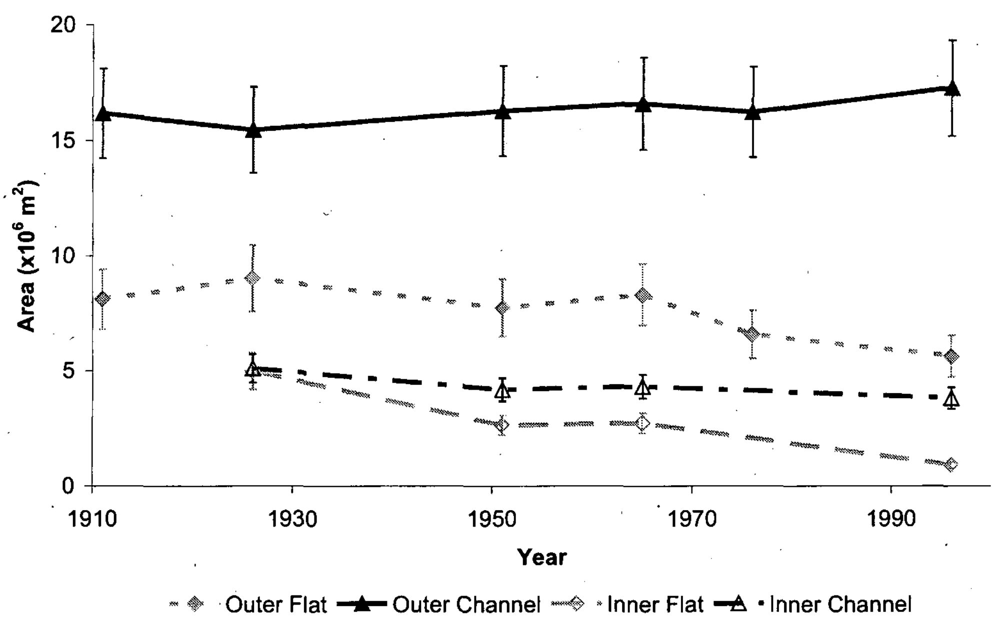
4.4.3 Discussion

Over the last 200 years, morphological changes in Southampton Water have been dominated by anthropogenic changes to the estuary. Major changes in the inner section have been caused by extensive reclamations and capital dredging for port development. In the outer section of the estuary, both anthropogenic disturbance and morphological change has been much smaller. In addition to land reclamation and dredging activities, much of the shoreline is now fixed in position with hard structures such as sea-walls and docks. This will influence the natural ability of Southampton Water to respond to pressures such as accelerated sea-level rise.

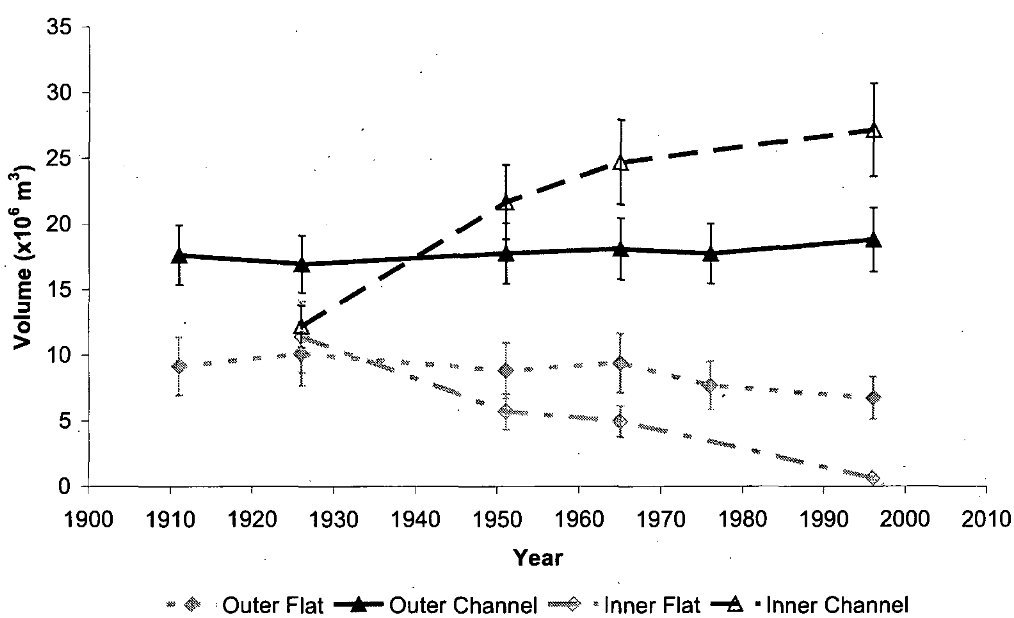
The major changes in Southampton Water are summarised in figure 4.15 and include: major loss of intertidal area and volume and a large increase in the channel volume of the inner estuary. Around 85% of the intertidal loss is accounted for directly by land reclamation. The remainder is conversion of intertidal area to channel area, resulting in wider channels and narrower, steeper intertidal flats. It is not clear how this is relates to channel dredging, but it has been suggested that dredging, close to the edges of intertidal flats may have caused some erosion at the flat margin (Barton, 1979; Bray et al., 2004). Other suggestions for the cause of the intertidal losses include a shortage of sediment, coastal defences and sea-level rise (Bray et al., 2004).

The extent of anthropogenic disturbance and morphological change differed greatly between the outer and inner estuary. The inner section has been heavily modified by man and has undergone large morphological changes. The inner estuary is no longer in dynamic equilibrium with forcing. The outer estuary has undergone much less disturbance, and the measures examined here, show that intertidal flat height and channel volume tends towards a dynamic equilibrium with tidal range and tidal prism respectively. Equilibrium areas and equilibrium flat volume are considered separately in Chapter 6 due to their additional complexities. This preliminary analysis, suggests that models such as ASMITA, which assume an estuary tends towards a dynamic equilibrium, may work well for the outer estuary section, but are unlikely to predict the changes seen in the inner section.

The lack of dynamic equilibrium seen in the inner estuary is likely to be caused by the frequent and ongoing nature of the disturbances. Land reclamations and capital dredging have been seen in almost every decade between 1900 and 1980. With disturbances of this frequency, it is unlikely that the inner section of the estuary would be able to reestablish equilibrium between disturbances and consequently the estuary was forced further and further from its equilibrium state. In addition to these discreet disturbances, ongoing maintenance dredging has also prevented the inner section from reestablishing equilibrium.

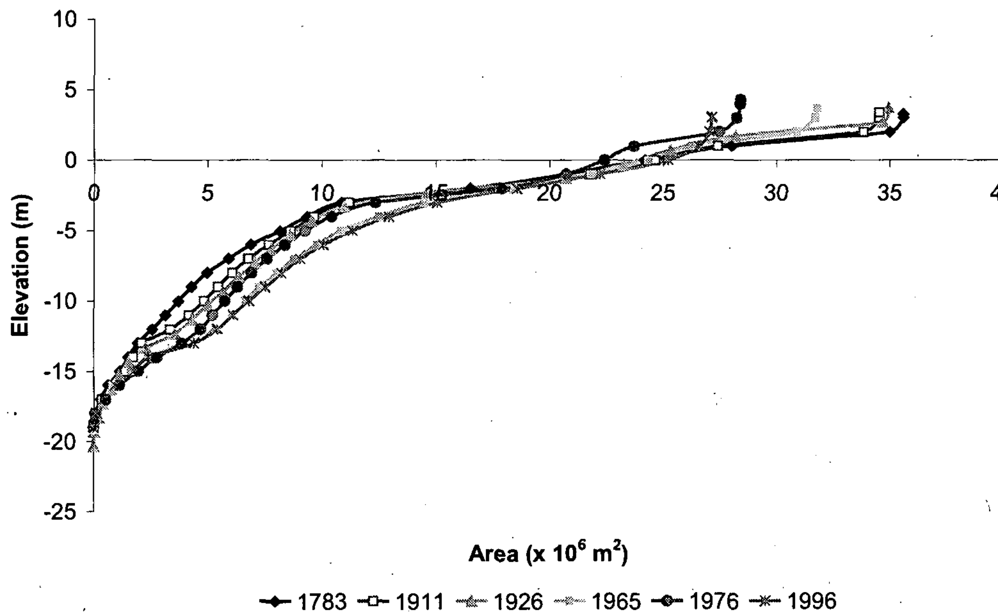


(a) Area

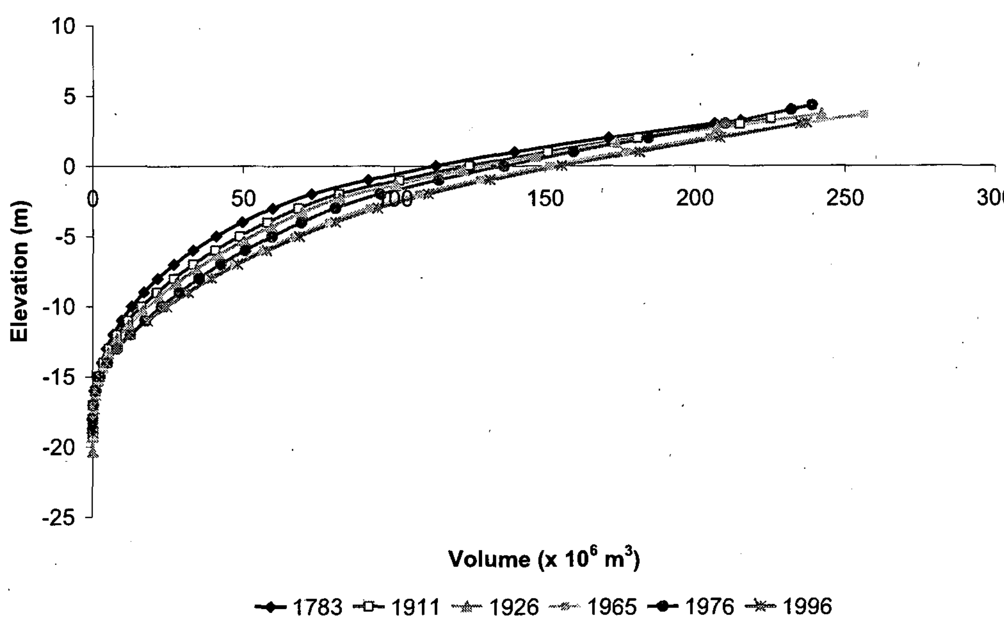


(b) Volume

Fig. 4.16: Area and Volume changes of flat and channel elements in Southampton Water. Error bars are the percentage mean square error for each element (see Table 3.7)



(a) Area



(b) Volume

Fig. 4.17: Hypsometry curves showing the distribution of (a) area and (b) volume with elevation. Mean low water is at -1.31 m.

Tab. 4.8: Summary of key changes in Southampton Water between 1926 and 1998, including in flat area (A_f), flat volume (V_f), channel area (A_c), channel volume (V_c), basin area (A_b), tidal prism (P), average flat height (H_f), average channel depth (H_c), average flat height relative to tidal range (H_f/H and channel volume relative to tidal prism (V_c/P).

Section	Year	A_f	V_f	A_c	V_c	A_b	P	H_f	H_c	H_f/H	V_c/P (α_c)	A_f/A_b	α_f
Southampton Water (Inner)	1926	5.00	11.38	5.11	12.20	10.11	29.57	2.28	2.38	0.56	0.41	0.49	0.28
Southampton Water (Inner)	1951	2.65	5.70	4.19	21.67	6.84	21.99	2.15	5.17	0.53	0.99	0.39	0.21
Southampton Water (Inner)	1965	2.73	4.94	4.33	24.69	7.06	23.66	1.81	5.70	0.45	1.04	0.39	0.17
Southampton Water (Inner)	1996	0.91	0.63	3.83	27.13	4.74	18.56	0.69	7.09	0.17	1.46	0.19	0.03
Southampton Water (Outer)	1911	8.10	9.15	16.17	17.64	24.27	118.72	1.13	1.09	0.28	0.15	0.33	0.09
Southampton Water (Outer)	1926	9.03	10.09	15.47	16.93	24.50	118.70	1.12	1.09	0.28	0.14	0.37	0.10
Southampton Water (Outer)	1951	7.75	8.81	16.30	17.76	24.05	110.60	1.14	1.09	0.28	0.16	0.32	0.09
Southampton Water (Outer)	1965	8.32	9.37	16.62	18.09	24.94	115.31	1.13	1.09	0.28	0.16	0.33	0.09
Southampton Water (Outer)	1976	6.59	7.64	16.26	17.73	22.85	108.56	1.16	1.09	0.29	0.16	0.29	0.08
Southampton Water (Outer)	1996	5.65	6.71	17.31	18.78	22.97	104.87	1.19	1.08	0.29	0.18	0.25	0.07
Southampton Water (Total)	1911	13.09	20.53	21.29	29.84	34.38	118.72	1.57	1.40	0.39	0.25	0.38	0.15
Southampton Water (Total)	1926	14.03	21.46	20.58	29.13	34.61	118.70	1.53	1.42	0.38	0.25	0.41	0.15
Southampton Water (Total)	1951	10.40	14.50	20.49	39.43	30.89	110.60	1.39	1.92	0.34	0.36	0.34	0.12
Southampton Water (Total)	1965	11.05	14.31	20.95	42.78	32.00	115.31	1.29	2.04	0.32	0.37	0.35	0.11
Southampton Water (Total)	1976	9.32	12.58	20.59	42.42	29.91	108.56	1.35	2.06	0.33	0.39	0.31	0.10
Southampton Water (Total)	1996	6.56	7.34	21.14	45.91	27.71	104.87	1.12	2.17	0.28	0.44	0.24	0.07
Southampton Water (Inner)	Mean	2.80	5.52	4.36	22.07	7.19	17.77	1.73	5.09	0.43	0.98	0.39	0.19
	SD	1.45	3.84	0.47	5.85	2.21	13.30	0.72	1.97	0.18	0.43	0.11	0.09
Southampton Water (Outer)	Mean	7.57	8.63	16.36	17.82	23.93	88.29	1.14	1.09	0.28	0.16	0.32	0.09
	SD	1.24	1.24	0.60	0.60	0.85	2.38	0.03	0.00	0.01	0.01	0.04	0.01
Southampton Water (Total)	Mean	10.74	15.12	20.84	38.25	31.58	112.79	1.38	1.84	0.34	0.34	0.34	0.12
	SD	2.68	5.25	0.33	7.10	2.66	5.69	0.16	0.34	0.04	0.08	0.06	0.03

4.5 Portsmouth, Langstone and Chichester Harbours

4.5.1 Overview

Portsmouth, Langstone and Chichester Harbours are neighbouring tidal inlets on the south coast of the United Kingdom (Fig. 4.18). They are classified as symmetrical tidal inlets and have extensive intertidal areas. The three harbours were created by the Holocene inundation of a low relief coastal plain (Dyer, 2002). They are bounded on the seaward side by a sand and shingle barrier beach, thought to have originated several kilometres off shore and been driven landward to its present position by sea-level rise (Havant Borough Council, 1997; Dyer, 2002). Rapid sea-level rise lead to overstepping as the barrier migrated shoreward and sediment deposits from the barrier and from relict ebb-tidal deltas remain offshore and periodically supply sediment to the shoreline (Dyer, 2002).

Portsmouth Harbour

Portsmouth Harbour is the most westerly of the three harbours and is largely sheltered from waves by the Isle of Wight. Around 35% of Portsmouth Harbour's intertidal area has been reclaimed since the 16th century (Bray et al., 2004) for port development, naval facilities and landfill sites (Havant Borough Council, 1997). The southern part of the harbour is dominated by commercial and military docks. The northern part of harbour is designated under national and international nature protection designations (Fig. 4.19) and contains a number of important habitats, including cord grass marsh, mudflats and eel grass bed habitats. It also supports internationally important wintering populations of wildfowl (Havant Borough Council, 1997). Much of the shoreline of Portsmouth Harbour is defended, with only two natural stretches remaining. The southern part of the harbour, where port activity is concentrated, is dredged regularly to maintain the navigation channel. Capital dredging has also been undertaken to allow bigger ships access to the docks.

Langstone Harbour

Langstone Harbour is located between Portsmouth and Chichester Harbours and has small channels connecting it to the other two harbours at its landward end. The flow between Harbours is east to west, with Langstone receiving a net import of water from Chichester Harbour of approximately 3.5 $x10^6m^3$ on spring tides (0.97 $x10^6m^3$ on neaps) and a net export to Portsmouth Harbour of 0.73 $x10^6m^3$ on spring tides (0.2 $x10^6m^3$ on neaps) (Gao and Collins, 1994). These volumes are small (less than 2%) compared with the volume of tidal exchange at the harbour mouth. Approximately 9% of the area of Langstone Harbour has been reclaimed since 1770 (Bray et al., 2004) (Fig. 4.22) most notably Farlington marshes in 1773

(Hampshire and IOW Wildlife Trust, 2006), and Milton Common in 1962 (Havant Borough Council, 1997). The known reclamations are shown in Figure 4.22.

Langstone Harbour contains extensive saltmarshes and intertidal mudflats indicating the sediment deposition has kept pace with sea-level rise in the past (Bray et al., 2004). Langstone Harbour is an internationally important wildlife site with a number of designations, including Site of Special Scientific Interest (SSSI) and a RAMSAR site (Fig. 4.19). Offshore of the harbour mouth there is a large ebb-tidal delta (The Winner) which has been dredged for aggregate extraction in the past. As with Portsmouth Harbour, much of the shoreline is protected by flood or erosion defences including walls or revetments enclosing landfill sites (Havant Borough Council, 1997).

Chichester Harbour

Chichester Harbour is the largest of the three harbours and is located in the eastern part of the Solent. It has extensive sand and gravel spits at the mouth (Dyer, 2002) and the interior of the harbour is generally shallow and muddy. Chichester Harbour is internationally important site for birds and for its coastal habitats, and is covered by a number of nature designations including being a Local Nature Reserve, RAMSAR site, Special Protection Area, Site of Special Scientific Interest and Area of Outstanding Natural Beauty (Fig. 4.19). The harbour also contains oyster fisheries and is used for recreation.

Chichester harbour has a large ebb-tidal delta which has been dredged for gravel in the past. There have been no significant reclamations but some areas of upper saltmarsh have been lost to farmland over a period of many centuries (Havant Borough Council, 1997). Some dredging takes place to maintain the channels for navigational purposes. The shoreline is generally less developed than that of Portsmouth or Langstone Harbours and has large undefended stretches, some of which are eroding.

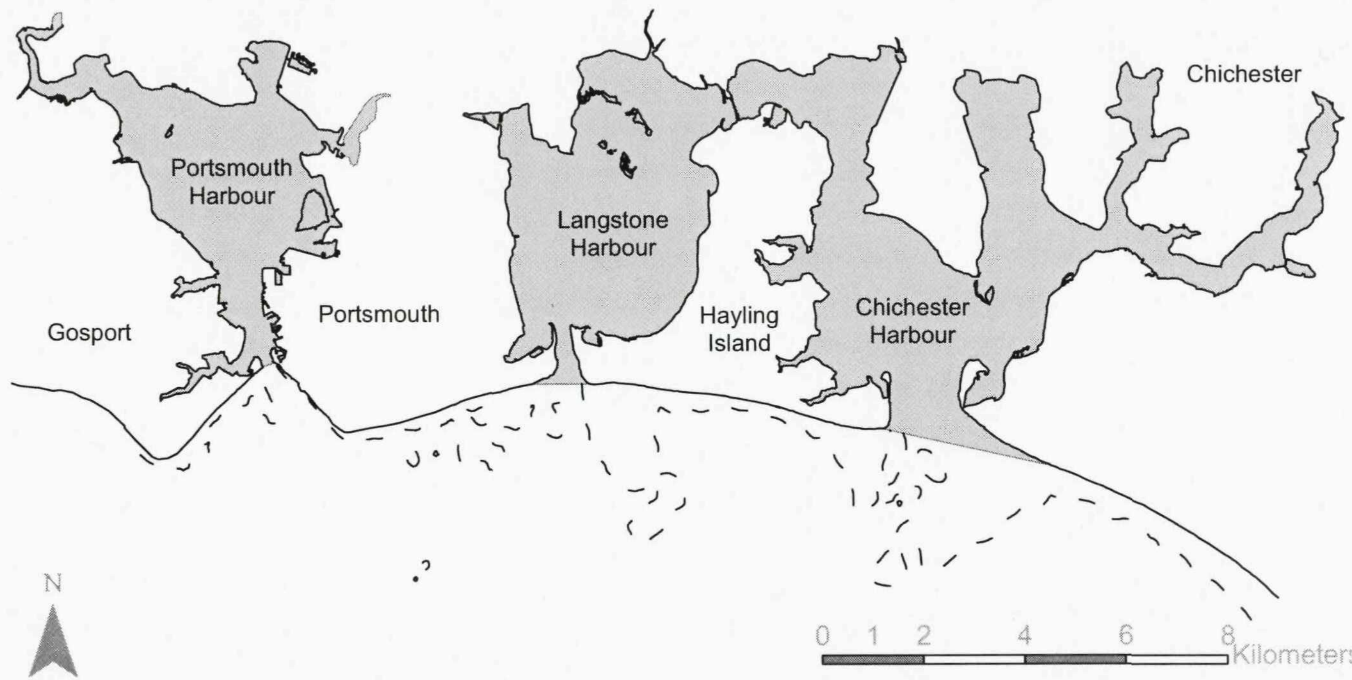


Fig. 4.18: Plan of Portsmouth Harbour, Langstone Harbour and Chichester Harbour

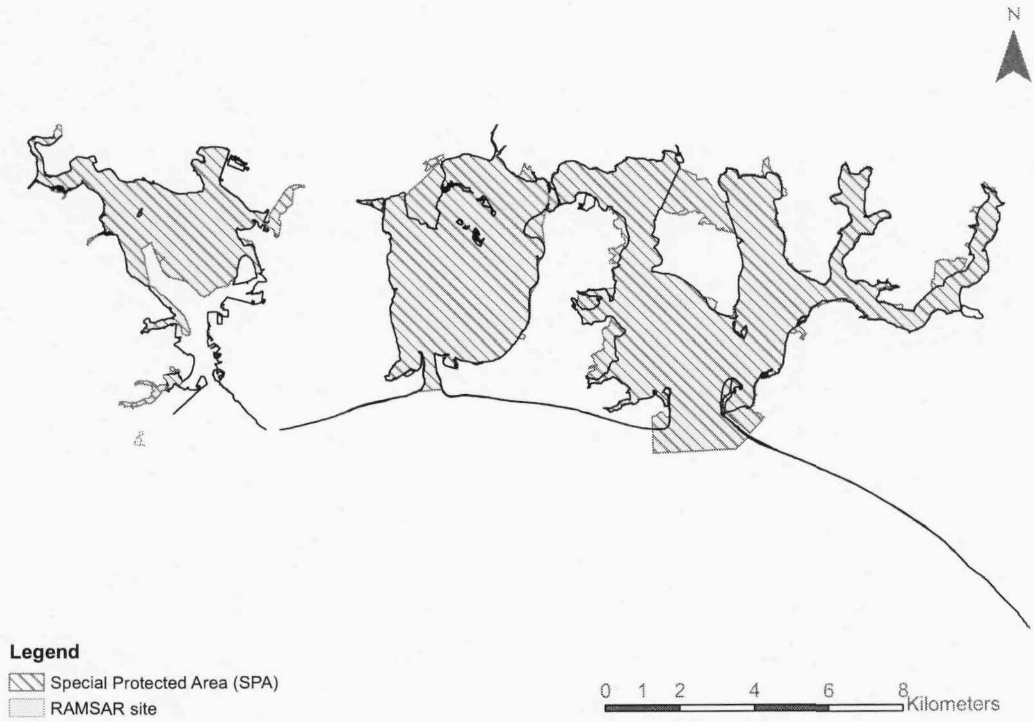
Morphology and Processes

Portsmouth, Langstone and Chichester Harbours are classified as symmetrical tidal inlets in FutureCoast (Dyer, 2002). Intertidal flat, channel and ebb-tidal delta elements can be defined for all three harbours, represented schematically in figure 4.20. All three harbours have recurved spits at mouth. At Portsmouth and Chichester Harbours the spits are orientated into the inlet throughout their length, indicating relative sediment starvation (Dyer, 2002). The spits at Gunner Point and Eastney Beach, at the mouth of Langstone Harbour, only turn inwards at the tips indicating a sediment surplus.

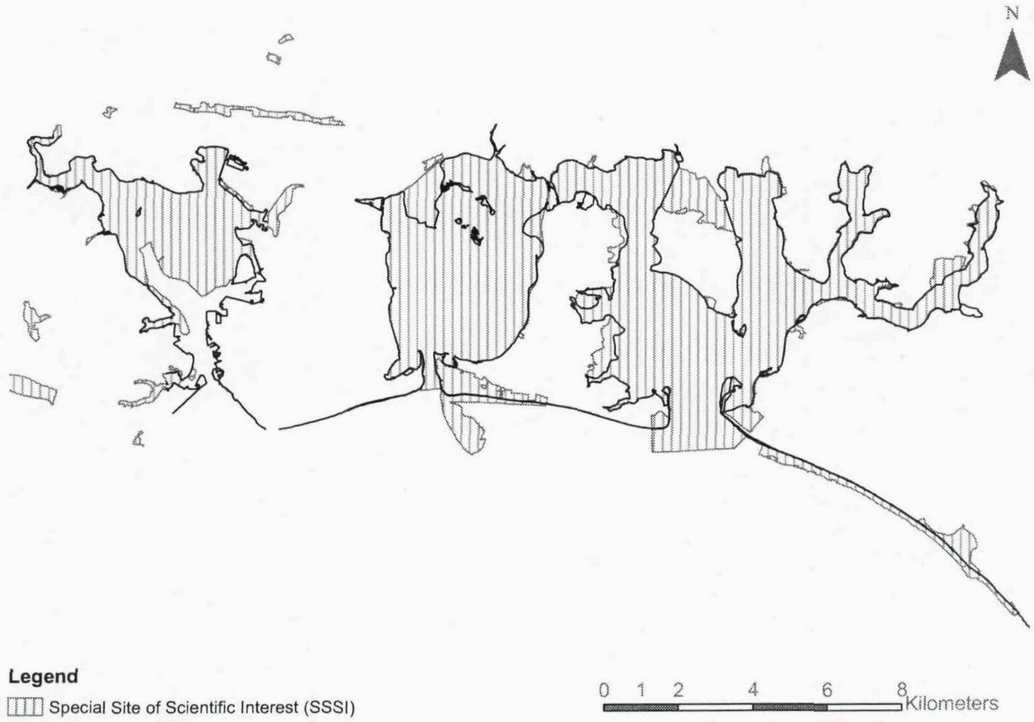
Sediment input into the harbours is mainly from littoral drift, with some wave driven transport onto the ebb-tidal deltas at Langstone and Chichester Harbour entrances (Bray et al., 2004). Little or no sediment is supplied from fluvial sources, which are present in all three harbours, but have low flow rates. Littoral drift along the coast between the harbours is predominantly from east to west (Bray et al., 2004), although there are local reversals. The harbour entrances form local littoral drift convergences, and it is believed that littoral sediment cannot move sediment directly across the inlets (Bray et al., 2004). Ebb-tidal delta processes may however allow sediment bypassing as waves drive sediment onshore to the adjacent beaches and into the harbour mouths. It is likely that ebb-tidal delta by-passing operated in the past at Chichester and Langstone Harbour, but Harlow (1982) suggested that by-passing has decreased, and the West Winner and deep channel at the entrance to Langstone Harbour may now be a barrier preventing littoral drift from reaching Portsmouth from Hayling.

Tidal ranges increase slightly from west to east; Portsmouth Harbour has a mean spring tidal range of 4.1 m, in Langstone and Chichester Harbours it is slightly greater, at 4.2 m. Wave heights at the coast also increase in this direction, as the sheltering affect of the Isle of Wight decreases. Extreme wave heights are predicted to be 1.2 m at the entrance to Portsmouth Harbour, 2.1 m at Langstone and 2.8 m at the Chichester entrance (Havant Borough Council, 1997).

All three harbours have ebb dominant tidal asymmetry, with tidal currents reaching higher velocities on ebb-tides. Ebb current velocities are sufficient to sweep the majority of coarse grained sediment, deposited in the channels by littoral drift, seaward as bedload. Sediment is deposited when current velocities slow down, outside of the inlet, and forms extensive ebb-tidal deltas. From here, some of the material is driven back onshore and becomes part of local beaches. Suspended sediment, carried into the harbours on flood tides, may settle out of suspension and be deposited due to the relatively long flood and slack water periods. In general, the intertidal areas of the Harbours appear to be accreting sufficiently to keep pace with sea-level rise, so significant volumes of suspended sediment must be trapped.



(a) International Designations



(b) National Designations

Fig. 4.19: Areas protected under (a) international and (b) national nature protection designations in Portsmouth, Langstone and Chichester Harbours (Natural England, 2007)

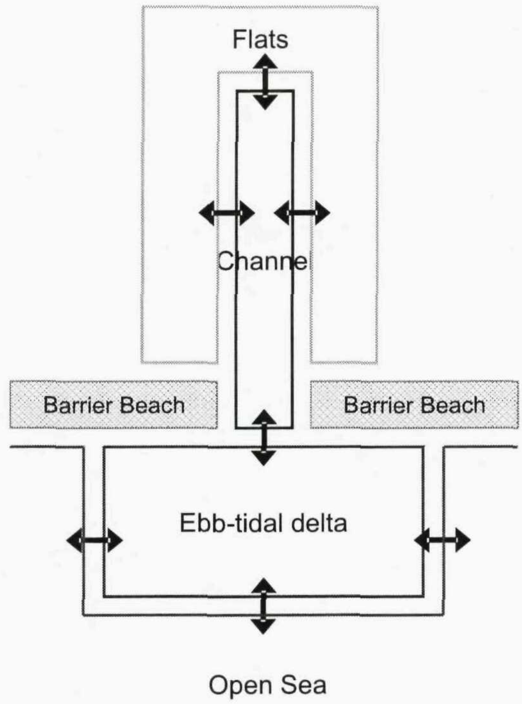


Fig. 4.20: A schematic representation of Portsmouth, Langstone and Chichester Harbours

Anthropogenic Influence

Past reclamations in Portsmouth and Langstone Harbours have removed large areas of intertidal area and have effectively removed previously erodable sediment from the sediment budget (Figs. 4.21 and 4.22). Details of the area and volumes of reclamations occurring between 1914 and 2004 (Portsmouth Harbour) and 1955 and 2004 (Langstone Harbour) are given in tables 4.9 and 4.10. The largest reclamation in Portsmouth Harbour during the study period was in the northeast corner of the harbour and joined Horsey Island to the mainland to create what is now Port Solent. Although it is known that earlier reclamations exist, anthropogenic changes are less well documented in Portsmouth Harbour than in nearby Southampton Water. In Langstone Harbour, the reclamation of Farlington Marshes in the 1700s removed a large area of intertidal habitat. More recently, land at Milton Common was reclaimed in the 1960s for land fill.

Existing land reclamations include port facilities and landfill sites and are likely to require ongoing protection in the future. One possible exception is Farlington Marshes in Langstone Harbour, which has potential as a managed realignment site in the future. However, the reclaimed area of Farlington marshes now contains grazing marsh, which is protected under the Habitats Directive (EEC, 1992) and must be compensated for if lost. In addition, the marsh surface in the reclaimed

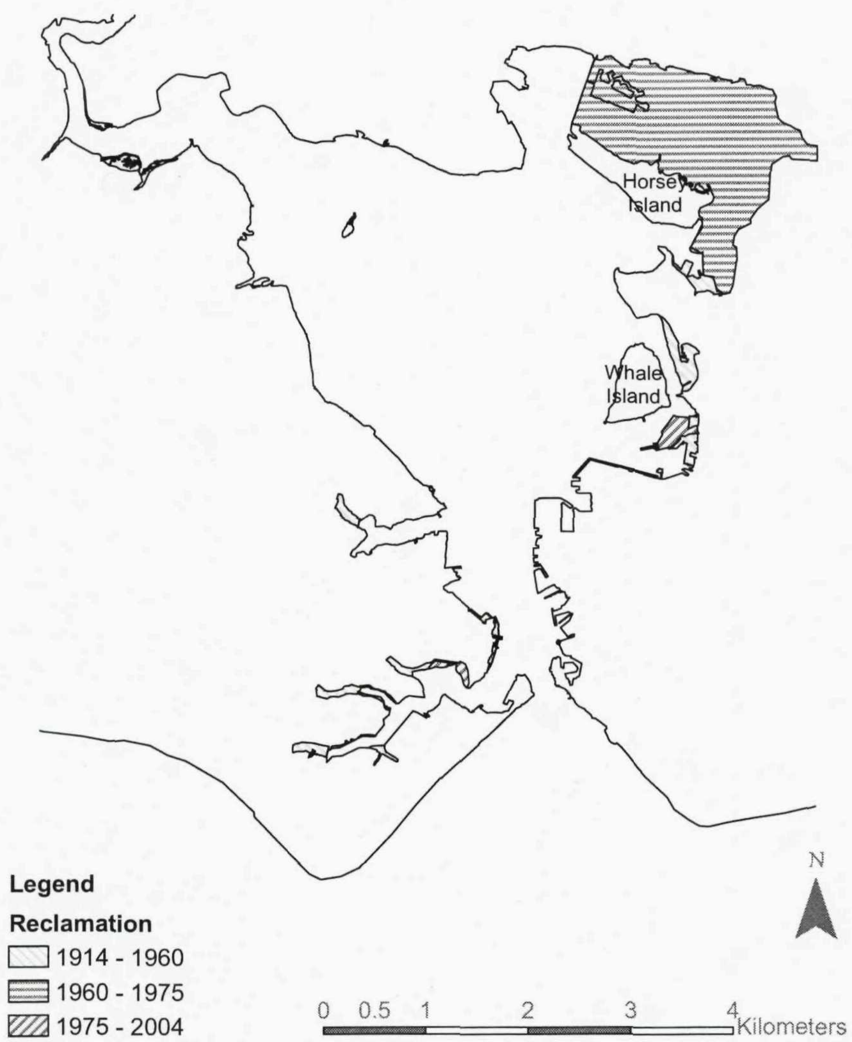


Fig. 4.21: Reclamations in Portsmouth Harbour between 1914 and 2004

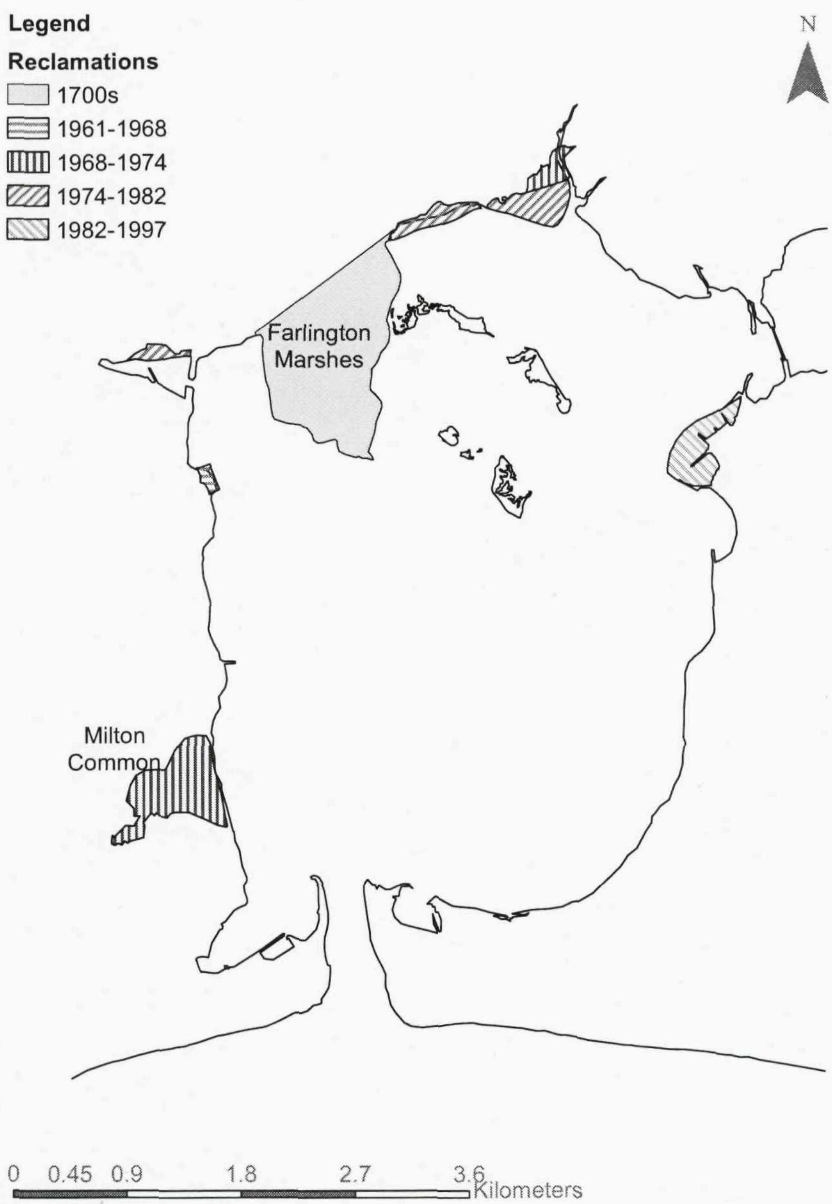


Fig. 4.22: Reclamations in Langstone Harbour between 1700 and 2004

area is well below the saltmarsh surface in the main estuary, and it is unlikely that saltmarsh would be created without further interventions, should the embankments be breached.

Further large scale reclamations are unlikely in all three harbours as the potential negative impacts on habitats and sediment budgets are recognised. The Portsmouth Harbour Plan (Portsmouth City Council, 2000) states that there will be "a presumption against further reclamation of the intertidal foreshore of the Harbour" although small scale reclamations at previously approved sites may be allowed.

Dredging to maintain navigation channels and for aggregate extraction removes sediment from the local sediment budget each year. In addition, capital dredging in Portsmouth Harbour has deepened the approach channels and harbour entrance, possibly changing tidal propagation into the Harbour. Portsmouth Harbour entrance has undergone capital dredging since 1783, when the navigation channel was deepened to a minimum depth of 4.3 m below chart datum (Bray et al., 2004). It has since been progressively deepened by capital dredging projects and today is maintained at over 12 m below chart datum. It is estimated that a major capital dredging project between 1881 and 1928 removed 25,000 m^3a^{-1} from Portsmouth Harbour (Bray et al., 2004). Between 1987 and 1997, an estimated 1,530,000 tonnes of sediment were removed from Portsmouth Harbour by capital dredging, and a further 600,000 tonnes from maintenance dredging of existing channels. Portsmouth City Council (2000) suggests that maintenance dredging now takes place rarely and is restricted to the main channels outside of the SSSI. New capital dredging projects will only be permitted if there are likely to be no damaging consequences for the environment and dynamics of the Harbour.

Langstone was a port until 1914 and navigation channels were dredged between 1882 and 1914 (Bray et al., 2004). Today dredging in Langstone Harbour is mostly for aggregate extraction. Between 1987 and 1997 it is estimated that 120,000 m^3a^{-1} were removed from the Langstone Bar and East Winner at the Harbour mouth. Sinah Sands, inside the Harbour mouth, was also subject to aggregate extraction until 1995 at an estimated rate of several thousand tonnes per annum (Bray et al., 2004). Dredging for aggregates has also been carried out at the entrance to Chichester Harbour. It is estimated that between 1974 and 1982 600,000 m^3 of sediment was removed from the Chichester Bar. Between 1988 and 2000, less than 20,000 m^3 of sediment was removed. Some of the material dredged from the Chichester Harbour entrance has been used for local beach recharge schemes and does not represent a loss to the system.

Tab. 4.9: Areas and volumes of reclamations in Portsmouth Harbour, calculated from GIS data

Period		Area (m^2)	Volume (m^3)
1914 - 1960	Above MLW	111600	112600
	Below MLW	74700	59800
1961 1975	Above MLW	2121800	4685800
	Below MLW	89500	37800
1976 - 2004	Above MLW	5000	5100
	Below MLW	32400	52800

Tab. 4.10: Areas and volumes of reclamations in Langstone Harbour, calculated from GIS data

Period		Area (m^2)	Volume (m^3)
1968 - 1974	Above MLW	17500	9150
	Below MLW	250000	343700
1975 - 1982	Above MLW	95000	21400
	Below MLW	0	0
1982 - 2004	Above MLW	115000	44000
	Below MLW	0	0

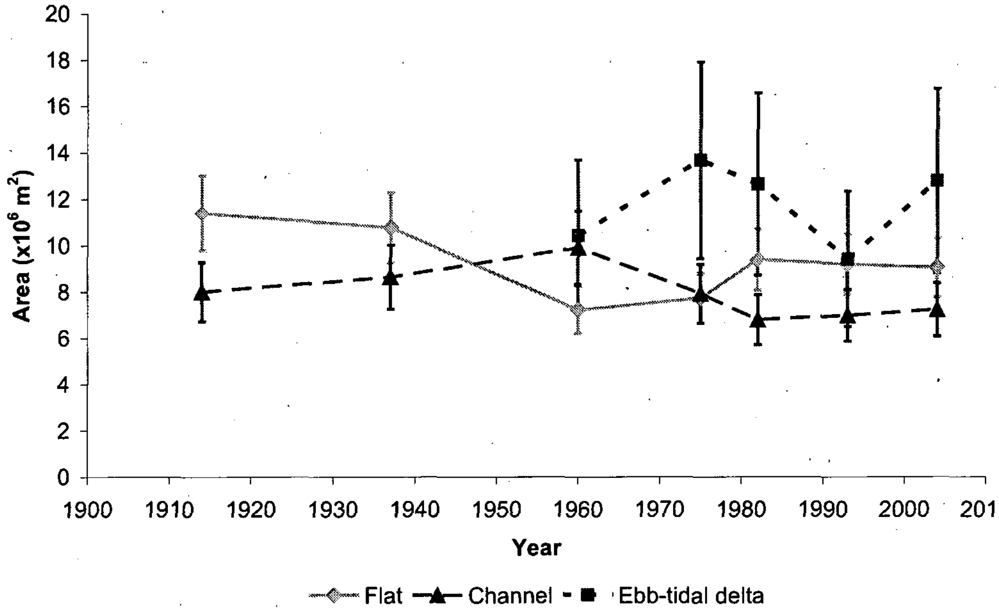
4.5.2 Historical Analysis

Portsmouth Harbour

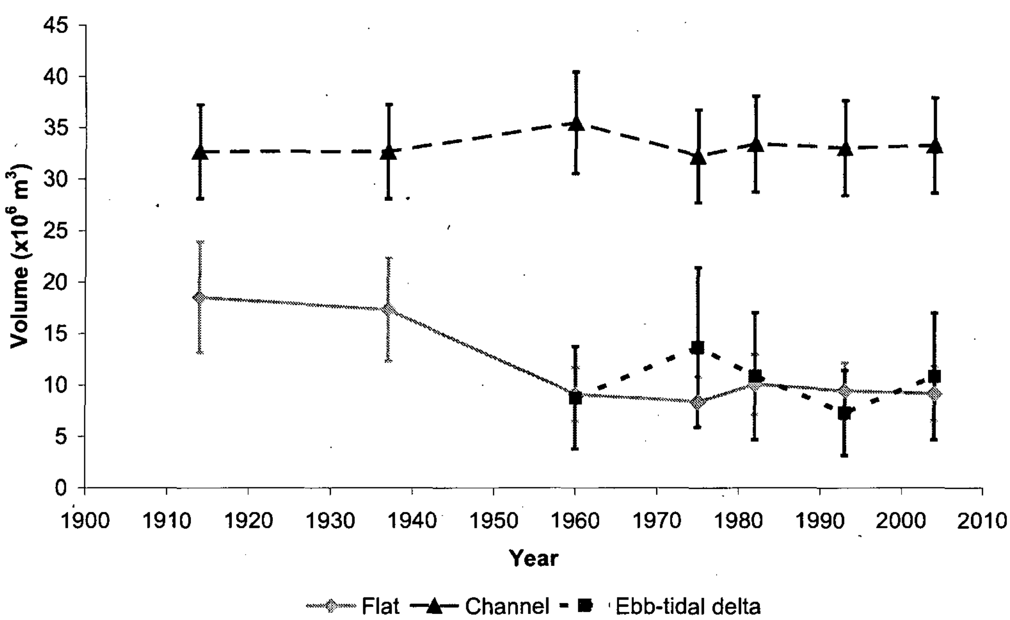
Volume and area changes observed in the intertidal flats, channels and ebb-tidal delta of Portsmouth Harbour are shown in figure 4.23. Basin area has decreased over the study period due to land reclamations. Changes in the area of the flats and channels can be split into three distinct periods (Fig. 4.23a). Between 1914 and 1960, intertidal flat area decreased and channel area increased. During this period, approximately 185,000 m^2 was reclaimed from Portsmouth Harbour.

The second period of change is from 1961 to 1982, during which flat area increased slightly while channel area decreased. This period also had the largest land reclamation, with approximately 2,500,000 m^2 being reclaimed at Horsey Island. The third period of change is from 1982 to 2004, in which area changes were smaller, but flat areas tended to decrease slightly and channel areas to increase. The area of the ebb-tidal delta was more variable and is subject to higher errors in its calculation.

Intertidal flat volumes decreased dramatically between 1914 and 1960, after which they remained relatively constant (Fig. 4.23b). Channel volumes were approximately stable over the study period, although small variations were observed. Ebb-tidal delta volumes were variable and tended to match changes in ebb-tidal delta area.

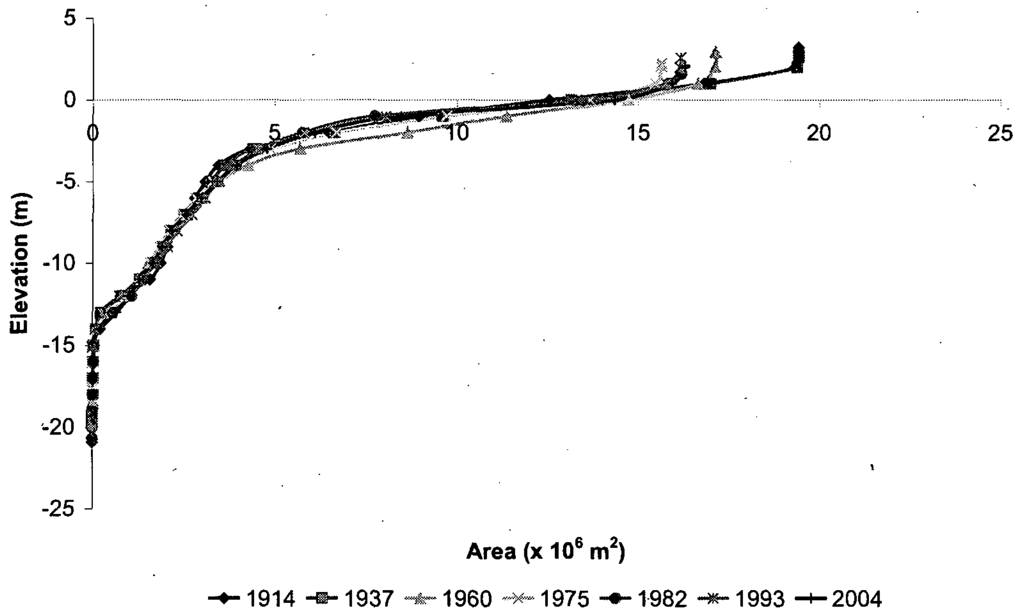


(a) Area

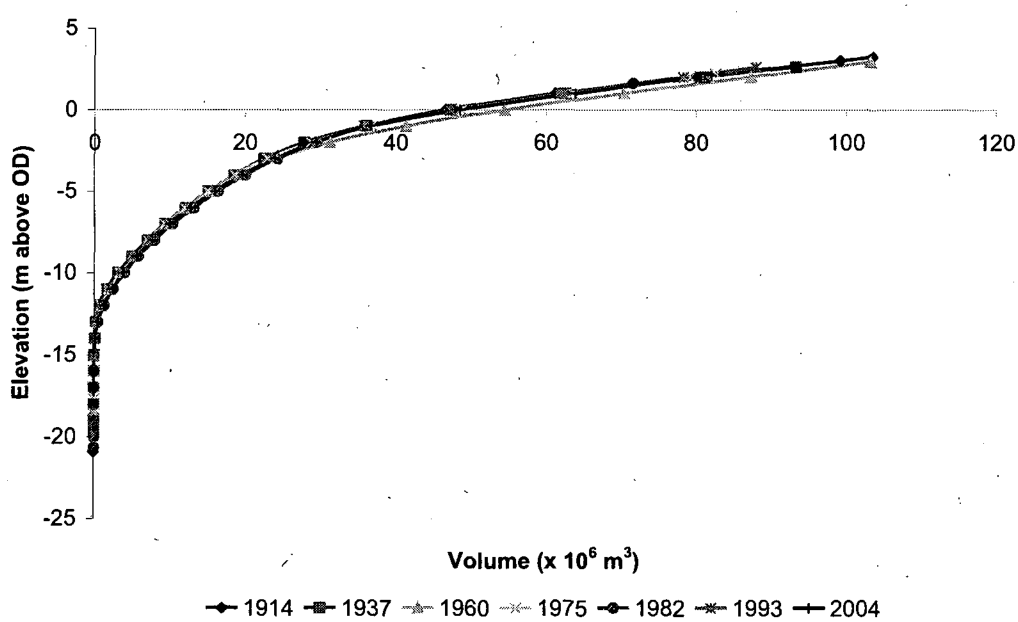


(b) Volume

Fig. 4.23: Area and Volume changes of flat, channel and ebb-tidal delta elements in Portsmouth Harbour. Error bars are the percentage mean square error for each element (see Table 3.7)



(a) Area



(b) Volume

Fig. 4.24: Hypsometry curves showing the distribution of (a) area and (b) volume with elevation for Portsmouth Harbour. Mean low water is at -1.43 m.

Hypsometry curves for Portsmouth Harbour (Fig. 4.24) show that there has been little change in the distribution of volume with elevation over the study period. The distribution of area with elevation has been more variable; the most obvious changes are around the high water mark, showing the decrease in area caused by land reclamations. In general, the hypsometry profiles have become flatter between approximately -1 m and -10 m and more concave in the intertidal region, indicating erosional mudflat profiles (Kirby, 2000).

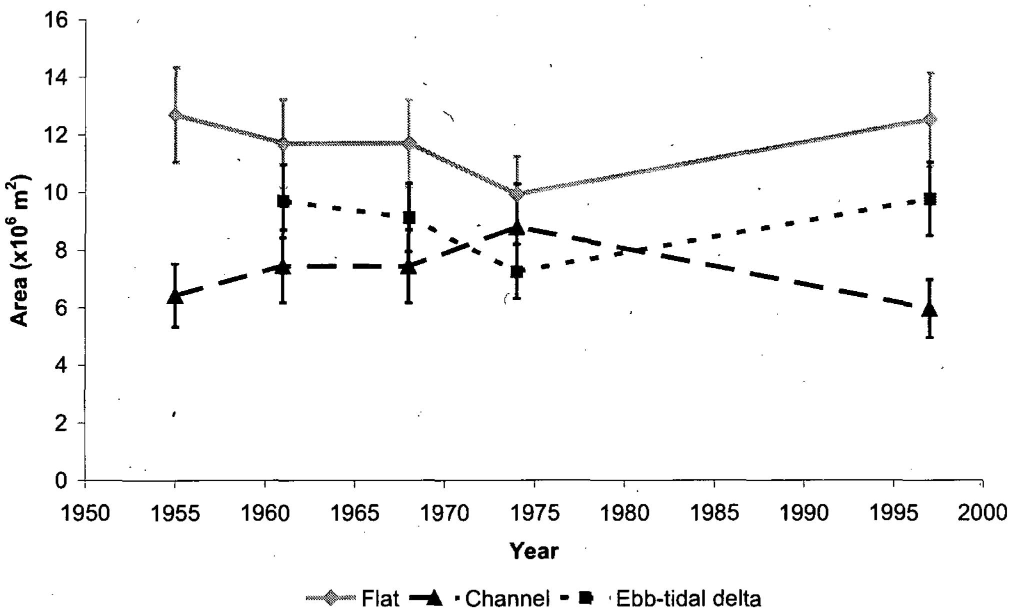
Table 4.11 gives details of changes in Portsmouth Harbour over time. Basin area has been reduced from 19 x$10^6 m^3$ in 1914, to 16 x$10^6 m^3$ in 2004. Losses of area were observed in both the flat and channel elements. In 2004, flat volume has reduced to approximately 50% of its 1914 value and channel volume has increased slightly. Losses in flat volume appear to be caused by both a decrease in area and a reduction in average flat height. The average channel depth has also increased over the study period, allowing channel volumes to remain relatively constant despite losses in channel area. The volume of the ebb-tidal delta varied over the study period but did not show a strong relationship with changes in tidal prism.

The ratios H_f/H, A_f/A_b and V_c/P (Table 4.11) varied over the study period. H_f/H decreased from 0.40 in 1914 to 0.25 in 2004 (mean=0.30, st. dev.=0.07). Most of this change occurred between 1937 and 1975, and may represent the evolution of the Harbour towards a new dynamic equilibrium following disturbances by dredging and land reclamation. A_f/A_b varied over time, but did not follow any obvious trend. The intertidal flat equilibrium coefficients (α_f) tended to decrease over time. V_c/P also varied over time and has shown a increasing trend over time. It has been almost constant since 1960 and again may represent evolution to a new equilibrium state.

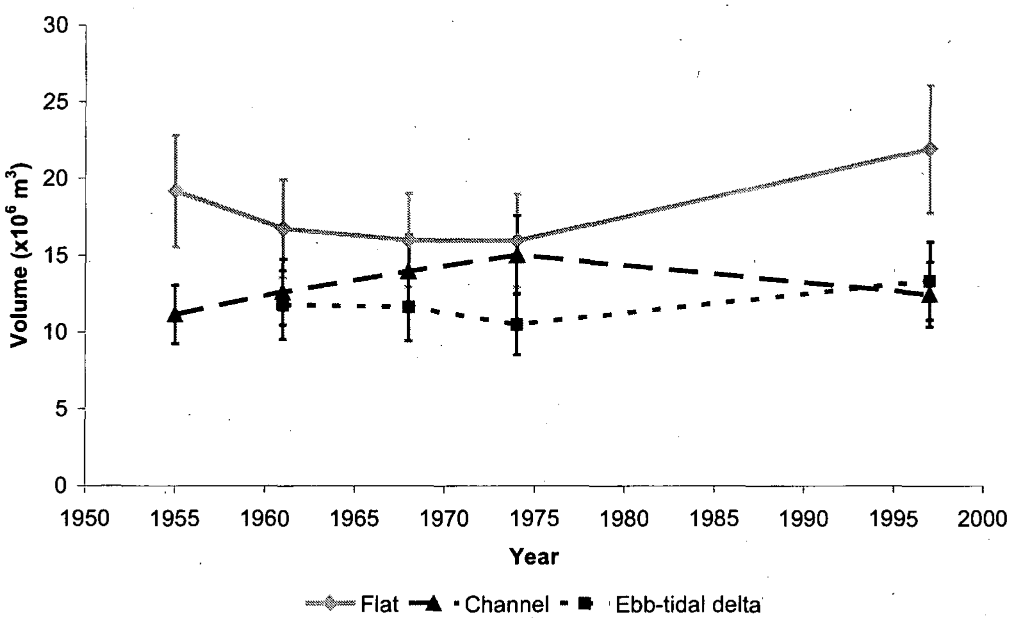
Langstone Harbour

Volume and area changes for the intertidal flats, channels and ebb-tidal delta of Langstone Harbour are shown in figure 4.25. Intertidal flat and channel areas varied significantly over the study period, but no overall trend was observed. Between 1955 and 1974, flat areas tended to decrease and channel areas tended to increase. Between 1975 and 1997, this pattern reversed and intertidal flat area increased and channel area decreased. The total change was small for both elements and was within the error estimates. The ebb-tidal delta followed a similar pattern to the flats.

Intertidal flat volume, like area, was variable but showed little overall change. The changes in flat volume follow a similar pattern to changes in flat area, although the magnitude of changes differs. This indicates that the height of the intertidal flats, as well as the area has been variable over time. The lack of overall change in the flats suggests that sedimentation is keeping pace with sea-level rise. Channel volume increased between 1955 and 1974. This was followed by a period of decreasing

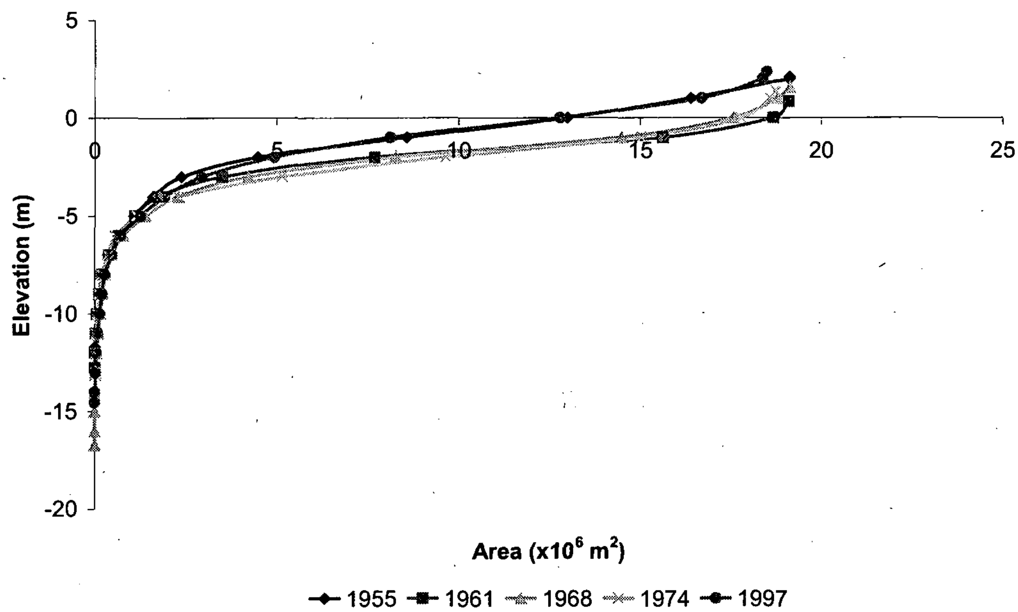


(a) Area

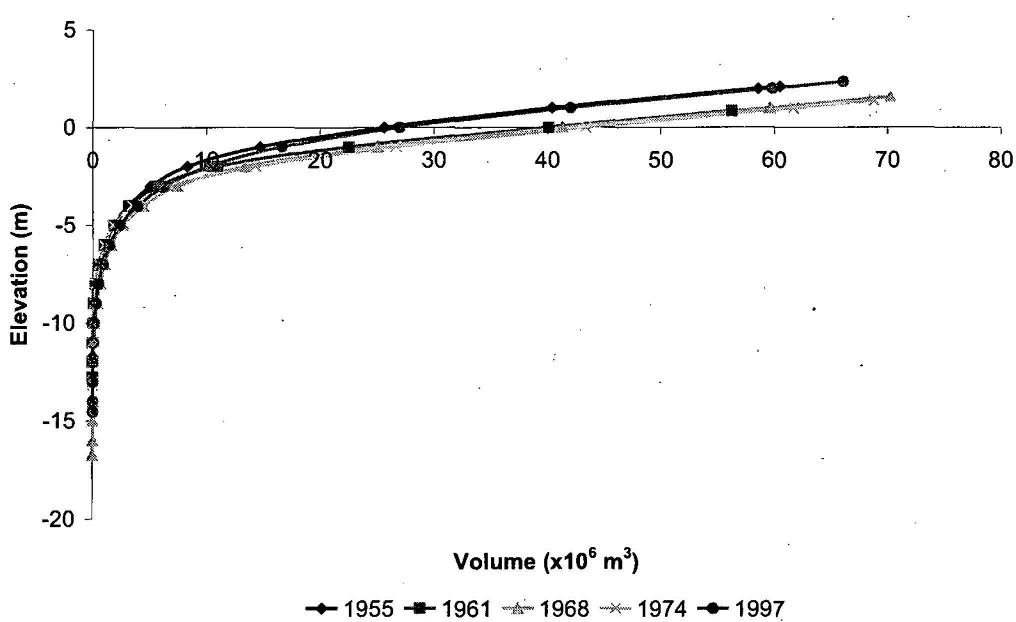


(b) Volume

Fig. 4.25: Area and Volume changes of flat and channel elements in Langstone Harbour. Error bars are the percentage mean square error for each element (see Table 3.7)



(a) Area



(b) Volume

Fig. 4.26: Hypsometry curves showing the distribution of (a) area and (b) volume with elevation for Langstone Harbour. Mean low water is at -1.48 m.

channel volume until 1997. Overall, net change in the channel volume was small and was within error estimates of the data.

The area hypsometry curves (Fig. 4.26a) for 1955 and 1997 show higher, less concave profiles between -5 m and high water than the profiles for 1961, 1968 and 1974. These are lower and more concave, indicating erosional profiles (Lee and Mehta, 1997; Kirby, 2000). The volume hypsometry curves follow the same pattern (Fig. 4.26b). This supports the observed changes in intertidal flat volume and area, suggesting a period of erosion followed by accretion.

Detailed data on volume and area changes in Langstone Harbour are given in Table 4.11. Basin Area has been relatively constant throughout the study period, despite small variations caused by land reclamations. Intertidal flat area and volume decreased and then recovered, resulting in very little net change. Channel area and volume has varied over the study period and shows a small net increase. The ratios H_f/H, A_f/A_b and V_c/P also varied over the study period and the equilibrium status of Langstone Harbour is unclear.

Chichester Harbour

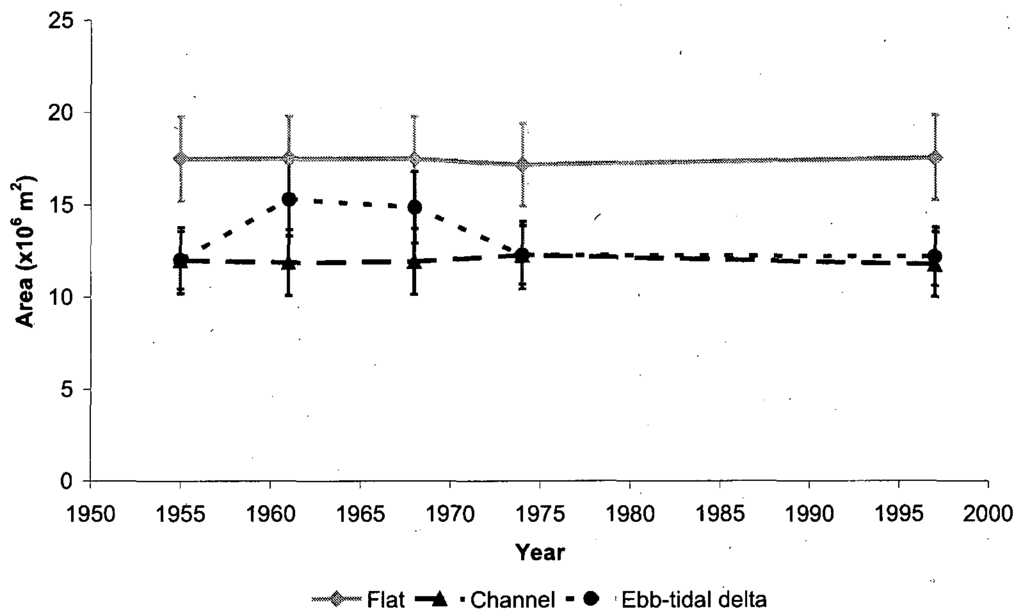
In Chichester Harbour, the areas of the tidal flat and channel have not changed significantly during the study period (Fig. 4.27). Ebb-tidal delta area showed small variations and decreased slightly over the period. Flat volume was more variable than area, showing a pronounced decrease in 1968 (Fig. 4.27b). This was followed by an increase in flat volume and over the study period a net increase is observed. Channel and ebb-tidal delta volumes were less variable and showed little net change.

Hypsometry curves show higher, less concave profiles in 1955 and 1997, and lower, more concave profiles in 1961, 1968 and 1974. This is similar to the pattern observed in Langstone Harbour, and again appears to indicate a period of erosion, followed by recovery/accretion.

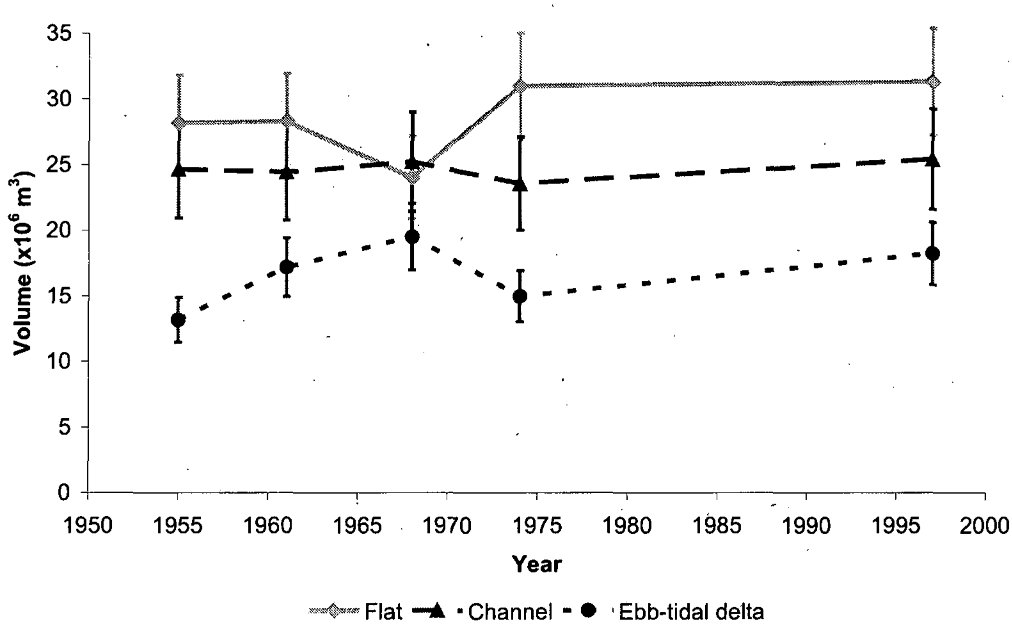
The ratios H_f/H, A_f/A_b and V_c/P varied slightly over the study period (Table 4.11). H_f/H showed greater variation, with a mean value of 0.39 and a standard deviation of 0.04. A_f/A_b was less variable, with a standard deviation of 0.01. V_c/P was more consistent, with a mean of 0.26 and a standard deviation of 0.01. This suggests that the channel is close to equilibrium, but that flat height and area is more variable and may not be near equilibrium. This is investigated further in Chapter ??.

4.5.3 Discussion

All three Harbours appear to have undergone periods of erosion over the study period. In Portsmouth Harbour, intertidal area and volume was lost between 1914 and 1960 and then remained approximately constant. Channel area increased between 1914 and 1960, then decreased. Channel volume however, was relatively constant

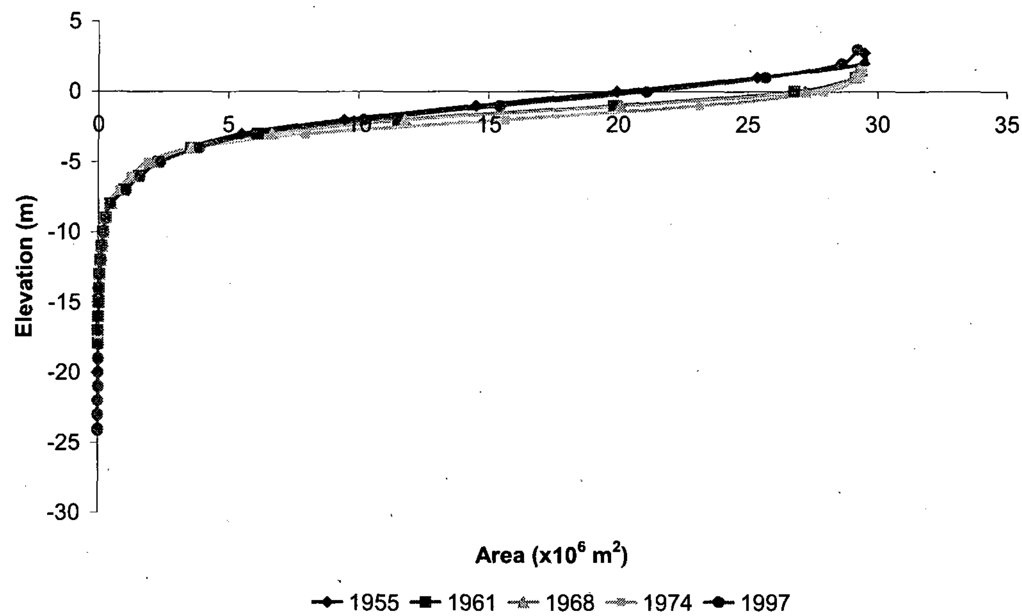


(a) Area

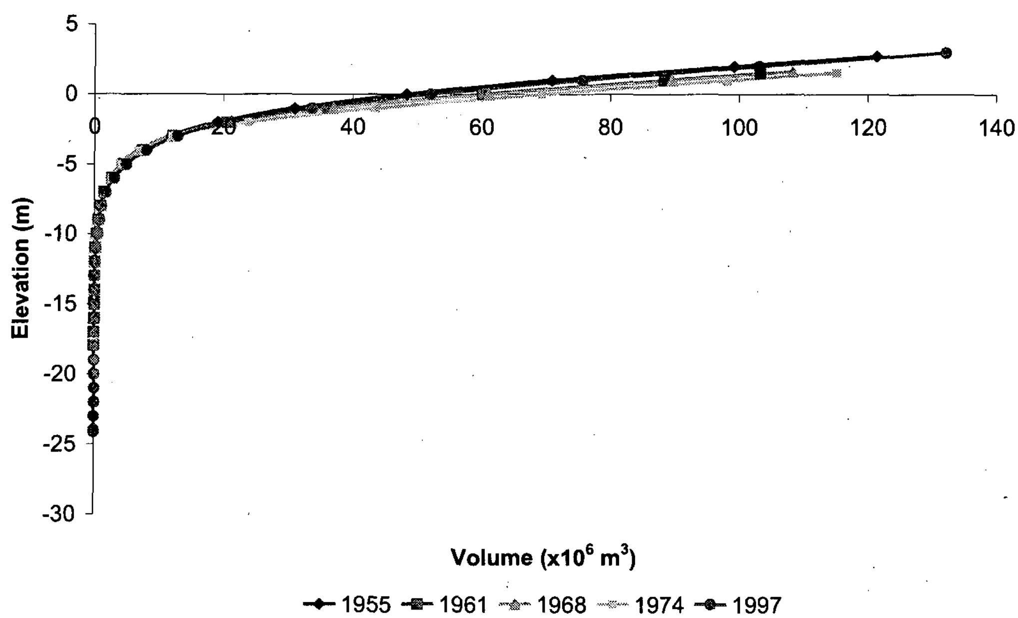


(b) Volume

Fig. 4.27: Area and Volume changes of flat and channel elements in Chichester Harbour. Error bars are the percentage mean square error for each element (see Table 3.7)



(a) Area



(b) Volume

Fig. 4.28: Hypsometry curves showing the distribution of (a) area and (b) volume with elevation for Chichester Harbour. Mean low water is at -1.48 m.

because changes in average depth compensated for changes in area. These changes are thought to be at least partially caused by human interference in the Harbour, including large land reclamations and capital dredging. However, a decrease in the average flat height also contributed to the decrease in flat volume. This suggests that changes in sediment supply or in the ability of the intertidal area to trap sediment may be an additional cause of the observed changes.

In Langstone a period of erosion was observed between 1955 and 1974, in which intertidal flat area and volume decreased, and channel area and volume increased. This was followed by a period of accretion during which the areas and volumes of the channels and flats recovered to similar levels as 1955. Volume changes in Langstone Harbour come from both changes in area and changes in the average height and depth of the flats and channels. In Chichester Harbour, the changes were more limited, but there is evidence for a period of erosion between 1961 and 1968, followed by a period of accretion lasting until at least 1997. The observed changes in intertidal flat volume in Chichester Harbour relate mainly to changes in the average flat height, as flat area was almost constant throughout the study period.

One possible explanation for the periods of erosion observed in all three harbours is a reduction in saltmarsh vegetation. *Spartina anglica*, a vigourous hybrid of saltmarsh cordgrass, colonised areas of the Harbours in the 1900s, spreading rapidly and colonising areas that were previously mud flat (Havant Borough Council, 1997; Raybould et al., 2000). The vegetation cover increased accretion in these areas. In the 1950s, *Spartina anglica* began to die back, reducing its ability to trap sediment and allowing saltmarshes to erode. This could explain the relatively rapid losses of intertidal flat area and volume prior to the mid 1970s in all three Harbours. *Spartina* marshes have not recovered from these losses however, so vegetation dynamics cannot explain the recent accretion observed in Langstone and Chichester Harbours.

Fluctuations in sediment supply may also be important in determining the pattern of erosion and accretion in the Harbours. Sediment in all three Harbours come from marine sources, both from littoral drift and from off shore sediment deposits (Bray et al., 2004). There are few data on the rates of sediment input on the time scales of the observed changes and although estimates of the average annual sediment budget along this stretch of coast have been made by Harlow (1979) and Bray et al. (2004) these focus on long-term trends rather than medium term fluctuations.

The equilibrium status of the three Harbours is unclear because of the variability of element volumes. In Portsmouth Harbour, it is possible that intertidal flat height and channel volume have evolved towards new equilibrium relationships with forcing. In Langstone and Chichester Harbours, H_f/H and V_c/P are variable and do not indicate evolution towards new equilibrium relations. H_f/H shows a weak trend of increase over time in both Langstone and Chichester Harbours, and there is a general trend for increasing flat height.

The ability of an equilibrium based model such as ASMITA to reproduce the observed changes in the harbours is questionable and is complicated by difficulties in selecting appropriate equilibrium coefficients. These issues are investigated further in Chapter 5

Tab. 4.11: Summary of key changes over time in Portsmouth, Langstone and Chichester Harbours, including flat area (A_f), flat volume (V_f), channel area (A_c), channel volume (V_c), ebb-tidal delta area (A_d), ebb-tidal delta volume (V_d), basin area (A_b), tidal prism (P), average flat height (H_f), average channel depth (H_c), average flat height relative to tidal range (H_f/H and channel volume relative to tidal prism (V_c/P). Areas are in x10^6 m^2, volumes are in x10^6 m^3; the subscripts f and c refer to the flats and channels respectively.

Harbour	Year	A_f	V_f	A_c	V_c	A_d	V_d	H	A_b	P	H_f	H_c	H_f/H	V_c/P (α_c)	A_f/A_b	α_f
Portsmouth	1914	11.41	18.52	8.01	32.66			4.1	19.42	61.11	1.62	4.08	0.40	0.53	0.59	0.23
Portsmouth	1937	10.78	17.30	8.65	32.64			4.1	19.43	62.36	1.60	3.77	0.39	0.52	0.55	0.22
Portsmouth	1960	7.22	9.07	9.91	35.45	10.45	8.74	4.1	17.13	61.18	1.26	3.58	0.31	0.58	0.42	0.13
Portsmouth	1975	7.72	8.32	7.93	32.19	13.68	13.64	4.1	15.65	55.84	1.08	4.06	0.26	0.58	0.49	0.13
Portsmouth	1982	9.40	10.03	6.80	33.36	12.64	10.83	4.1	16.19	56.36	1.07	4.91	0.26	0.59	0.58	0.15
Portsmouth	1993	9.20	9.40	6.98	32.97	9.42	7.27	4.1	16.18	56.96	1.02	4.72	0.25	0.58	0.57	0.14
Portsmouth	2004	9.05	9.12	7.24	33.21	12.79	10.79	4.1	16.29	57.67	1.01	4.59	0.25	0.58	0.56	0.14
Langstone	1955	12.69	19.18	6.43	11.15			4.2	19.12	61.13	1.51	1.73	0.36	0.18	0.66	0.24
Langstone	1961	11.70	16.73	7.45	12.61	9.70	11.77	4.2	19.15	63.72	1.43	1.69	0.34	0.20	0.61	0.21
Langstone	1968	11.69	15.97	7.44	13.95			4.2	19.13	64.37	1.37	1.88	0.33	0.22	0.61	0.20
Langstone	1974	9.94	15.94	8.80	15.02	7.26	10.51	4.2	18.73	62.75	1.60	1.71	0.38	0.24	0.53	0.20
Langstone	1997	12.52	21.90	5.96	12.45	9.77	13.33	4.2	18.48	55.72	1.75	2.09	0.42	0.22	0.68	0.28
Chichester	1955	17.50	28.15	11.99	24.64			4.2	29.49	95.71	1.61	2.05	0.38	0.26	0.59	0.23
Chichester	1961	17.51	28.26	11.87	24.43	15.31	17.19	4.2	29.38	95.14	1.61	2.06	0.38	0.26	0.60	0.23
Chichester	1968	17.49	24.00	11.93	25.19			4.2	29.42	99.55	1.37	2.11	0.33	0.25	0.59	0.19
Chichester	1974	17.18	30.96	12.28	23.55	12.30	14.97	4.2	29.46	92.76	1.80	1.92	0.43	0.25	0.58	0.25
Chichester	1997	17.54	31.26	11.76	25.38	12.19	18.22	4.2	29.30	91.82	1.78	2.16	0.42	0.28	0.60	0.25
Portsmouth	Mean	9.26	11.68	7.93	33.21	11.79	10.25	4.1	17.19	58.78	1.24	4.24	0.30	0.57	0.53	0.17
	SD	1.50	4.30	1.09	1.06	1.78	2.41	0.0	1.59	2.68	0.27	0.50	0.07	0.03	0.06	0.05
Langstone	Mean	11.69	18.61	7.38	13.45	8.98	12.81	4.2	19.07	61.50	1.60	1.83	0.38	0.22	0.62	0.23
	SD	0.99	2.53	1.03	1.58	1.03	1.63	0.0	0.36	2.97	0.21	0.14	0.05	0.03	0.06	0.04
Chichester	Mean	17.91	30.17	12.13	24.61	13.30	17.78	4.2	30.04	95.98	1.68	2.03	0.40	0.26	0.59	0.23
	SD	0.81	3.98	0.34	0.62	1.33	1.79	0.0	1.09	3.81	0.18	0.09	0.04	0.01	0.01	0.02

4.6 Thames Estuary

4.6.1 Estuary Overview

The Thames Estuary lies on the east coast of the United Kingdom (Fig. 4.29). The Thames Estuary, and others along the Essex coast, were previously tributaries and flood plains to the Thames Basin and were inundated by rising sea levels during the Holocene transgression (Dyer, 2002). Following inundation large volumes of sands and gravels were deposited within the estuaries forming linear banks. For this study, the Thames Estuary was defined between the tidal limit at Teddington and the seaward boundary, stretching between Southend-on-Sea and the mouth of the Medway Estuary.

The Thames Estuary is a funnel shaped estuary with an extensive river catchment (Dyer, 2002). It is the site of London, the nation's capital, with a population of 8 million. The banks are defended by sea walls and the Thames Barrier protects London from tidal/storm surges that could cause extensive flooding. Other barriers have been constructed across down stream tributaries. There are docks and industry along the banks of the estuary.

The lower part of the Thames estuary, seaward of Gravesend has numerous nature protection designations, including Local Nature Reserves, Sites of Special Scientific Interest (SSSI) and internationally important designations (Fig. 4.30). Intertidal areas, including mudflats, salt marsh and grazing marsh are important habitats under these designations.

Morphology and Processes

The Thames Estuary is macrotidal, with a spring tidal range of 5.1 m (Dyer, 2002). It is ebb-dominant, with higher current velocities on ebb tides than on floods, and is a weak source of sediment to the adjacent coast. The mean annual wave height offshore of the Essex coast is around 1 m (van der Wal and Pye, 2004) and tidal processes dominate sediment transport.

Sediment characteristics in the Thames differ along the estuary. The inner estuary (upstream of Lower Hope Point) has mainly fine, muddy sediment; seaward of this point the sediment is mainly sandy. Sediment enters the Thames Estuary from fluvial and marine sources, with additional inputs from sewage and industry. WPRL (1964) and HR Wallingford (2006b) have attempted to quantify the sediment budget of the Thames Estuary. Fluvial sediment supply is estimated to be between 118,000 and 234,000 dry tonnes a^{-1} including sediment from the River Thames, tributaries and sewage treatment works, with a best estimate of 200,000 tonnes a^{-1} (HR Wallingford, 2006b). This amounts to approximately 0.5 $\times 10^6 m^3 a^{-1}$ of sediment (van der Wal and Pye, 2004). Nicholls et al. (2000) estimated that erosion of cliffs on the Isle of Sheppey supplies approximately 450,000 tonnes a^{-1} of fine sediment to the outer Thames estuary and southern North Sea. This suggests that there is a potential marine sediment supply that is at least double the fluvial sediment supply and marine sediment supply was greater in the past.

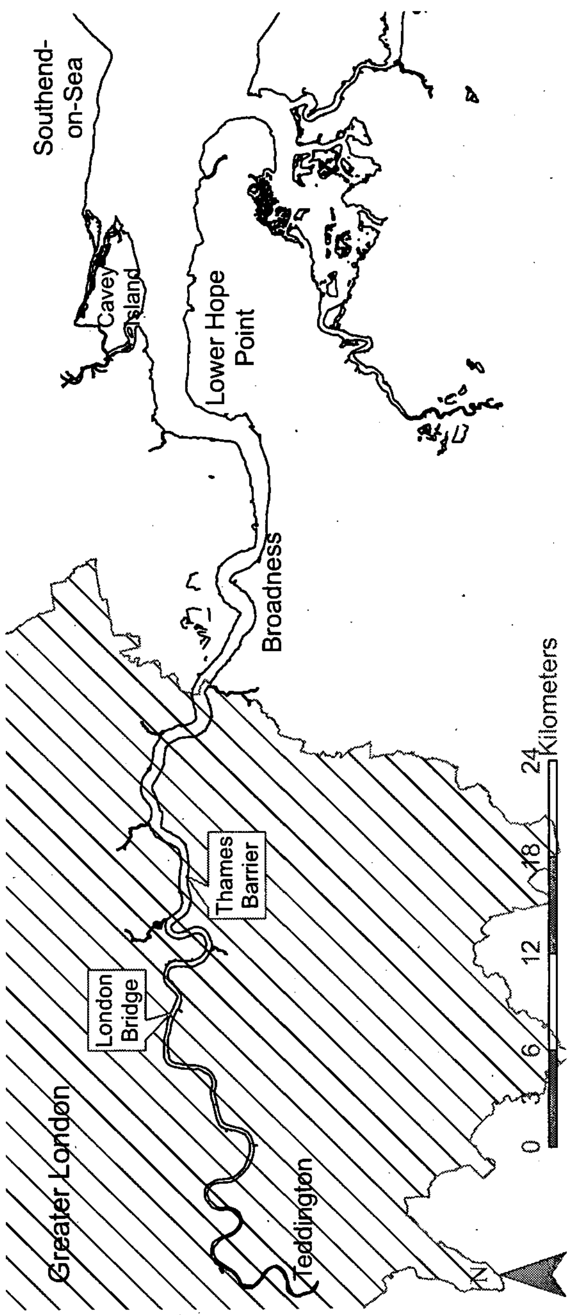


Fig. 4.29: Plan of the Thames Estuary

Management Issues

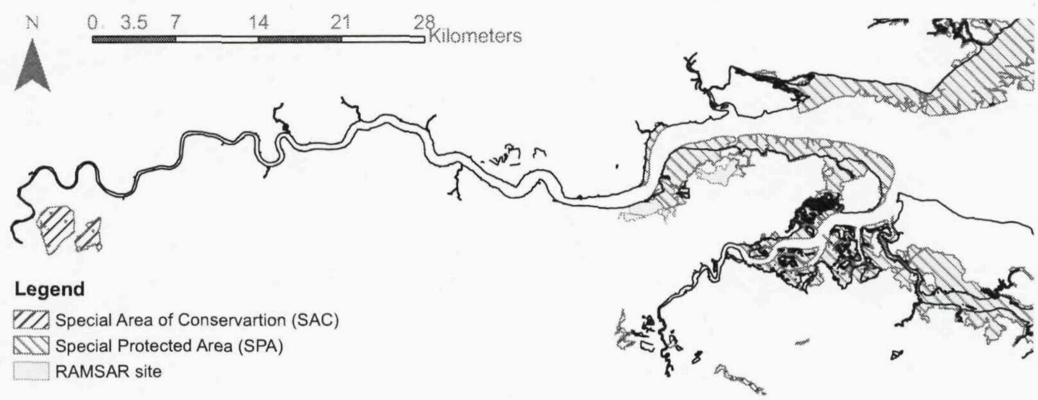
Historically, both capital and maintenance dredging has been carried out in the Thames estuary. Details of capital dredging projects are uncertain, and information such as volumes removed, sediment types and disposal sites are not available and so capital dredging is not reported in this study. Data on historic rates of maintenance dredging were obtained from HR Wallingford (2006b). These were converted from tonnes to m^3 assuming a dry density of 600 kg m^{-3}. It was estimated that between 1910 and 1960, 80% of the dredging took place upstream of Broadness and the remainder between Broadness and Lower Hope Point; between 1960 and 1980, 50% of the dredging was upstream of Broadness and after 1980, 25% of dredging was upstream of Broadness. Details of the historic dredging volumes are give in Appendix B.

In addition to dredging, much of the intertidal area of the Thames Estuary has been reclaimed since Roman times and the coastlines is heavily defended. In the Thames Estuary, the level of flood defences must be maintained or increased to protect London from flooding (Ramsbotton and Lavery, 2007).

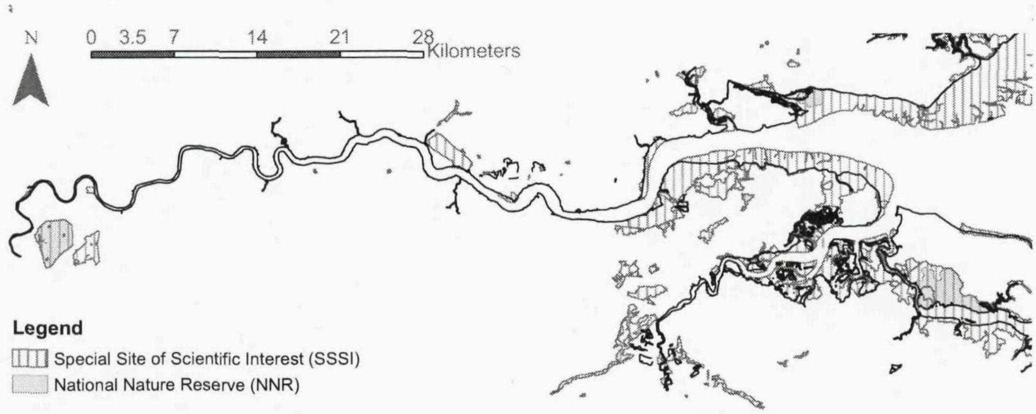
4.6.2 Historical Analysis

Area and volume changes occurring between 1910 and 1990 in the Thames Estuary are shown in figure 4.31. This includes the entire estuary from the tidal limit at Teddington to Southend at the seaward boundary of the Thames Estuary. Intertidal flat area has increased over the study period and channel area has decreased slightly. Overall, basin area has increased slightly between 1910 and 1990. Volumes followed a similar pattern, with flat volume increasing and channel volume decreasing slightly. For a more detailed analysis of the changes in the Thames Estuary, the estuary was divided into three regions, each containing intertidal flat and channel elements. The regions were defined as the inner estuary, between Teddington and Broadness; the mid estuary, between Broadness and Lower Hope Point; and the outer estuary (also called Sea Reach) between Lower Hope Point and Southend (Fig. 4.32).

Area and volume changes in the intertidal flat and channels of each region of the Thames Estuary are given in Figures 4.33 to 4.35. In the inner estuary (Fig. 4.33) flat area and volume increased slightly over the study period. Channel area was approximately constant and channel volume increased slightly. The average height of the intertidal flats and average depth of the channels varied slightly over the study period but did not show net change. The ratios of average flat height to tidal range (H_f/H) and channel volume to tidal prism (V_c/P) showed some variation over the study period (Table 4.12). The mean value of H_f/H was 0.042 (sd = 0.03); the mean of V_c/P was 0.92 (sd = 0.02) suggesting the channel is closer to equilibrium with forcing than the flat height. A_f/A_b tended to increase over the study period



(a) International Designations



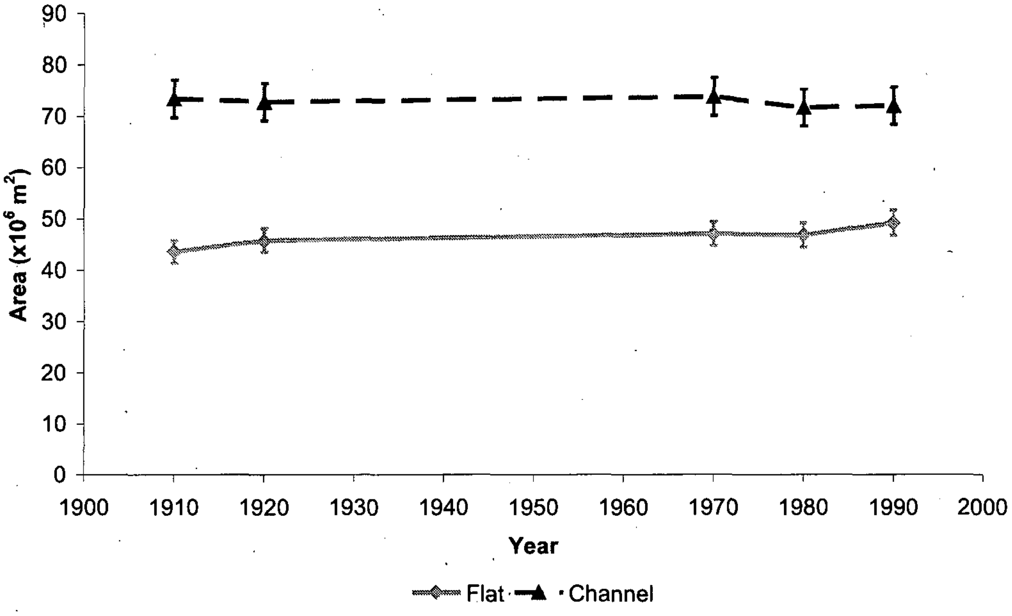
(b) National Designations

Fig. 4.30: Areas protected under (a) international and (b) national nature protection designations along the Thames coastline (Natural England, 2007)

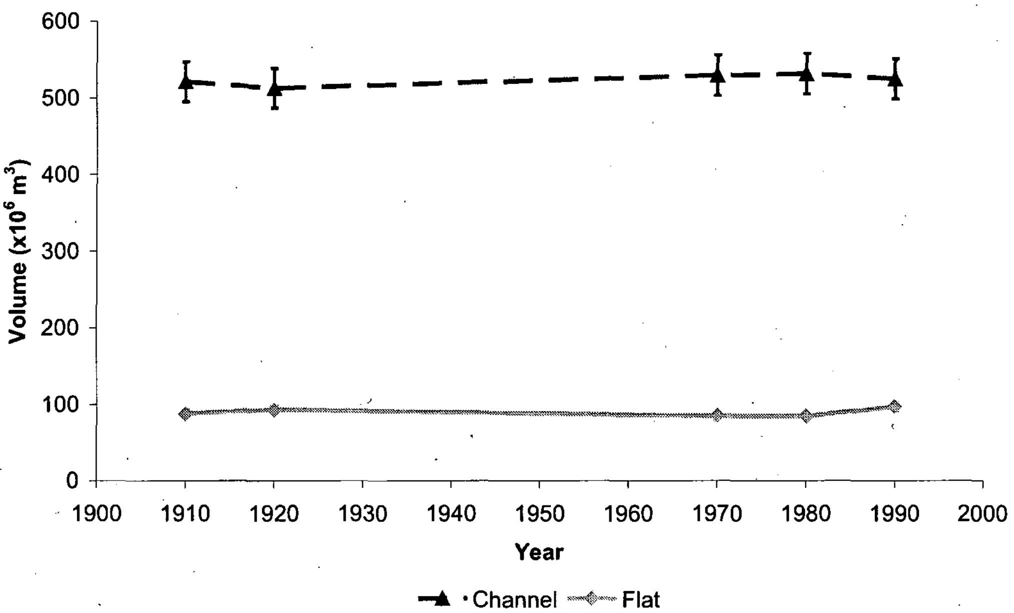
and the intertidal flat equilibrium coefficient (α_f) was almost constant with a mean of 0.11 and a standard deviation of 0.01.

In the mid estuary (Fig. 4.34) flat area and volume tended to increase over the study period. This was accompanied by an initial decrease in average flat height between 1910 and 1970, followed by an increase in flat height between 1980 and 1990. Channel area decreased slightly over the study period and channel volume was approximately stable. Average channel depth increased by 0.3 m between 1910 and 1990. The ratio of average flat height to tidal range H_f/H was more variable than in the inner estuary, although the average value was the same (mean = 0.42, sd = 0.06) (Table 4.12). A_f/A_b again tended to increase throughout the study period and the intertidal flat equilibrium coefficient showed small variations with a mean of 0.11 (sd = 0.01). Average V_c/P was smaller than in the inner estuary (mean = 0.64, sd = 0.03). Both the channel and flat elements had some variation in their equilibrium coefficients, but standard deviations were small, suggesting that the mid estuary is close to dynamic equilibrium.

In the outer estuary, flat area and volume increased slightly and channel volume and area decreased slightly. The average flat height decreased by 0.1 m between 1910 and 1990 and the average channel depth showed a small increase (Table 4.12). The ratio H_f/H was smaller than in the inner and mid estuary regions and was less variable (mean = 0.36, sd = 0.02). A_f/A_b tended to increase over time but the intertidal flat equilibrium coefficient (α_f) showed only small variations. Mean V_c/P was 0.51 (sd = 0.02). The outer estuary appears to be close to equilibrium with forcing.



(a) Area



(b) Volume

Fig. 4.31: Area and Volume changes of flat and channel elements in the Thames Estuary

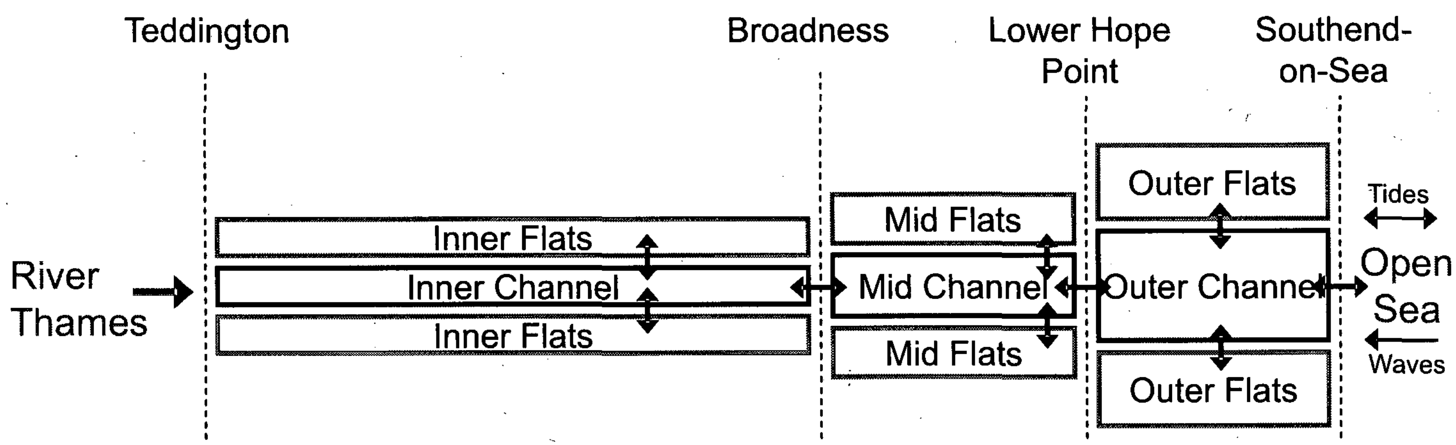
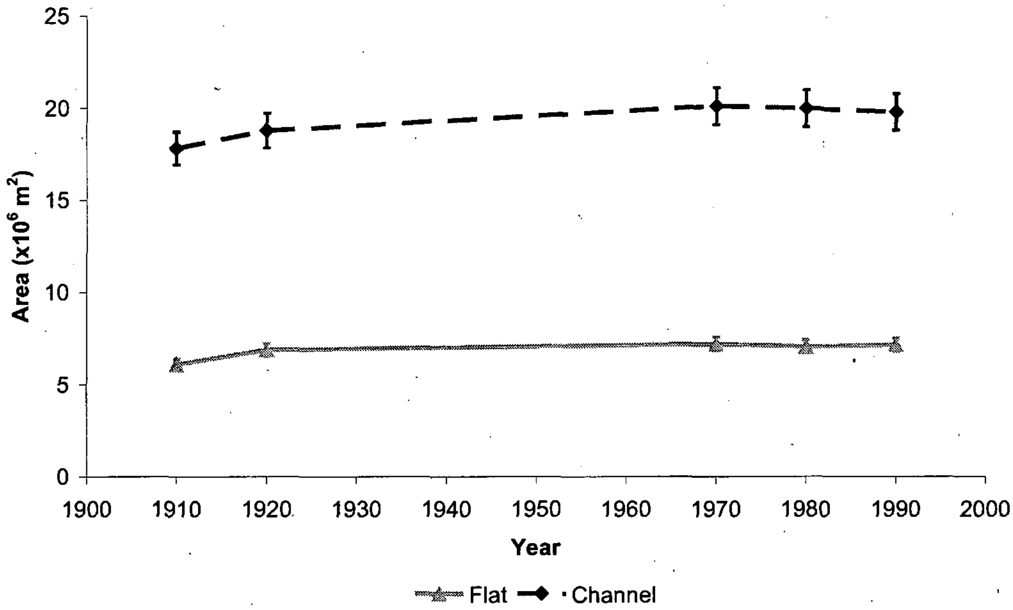
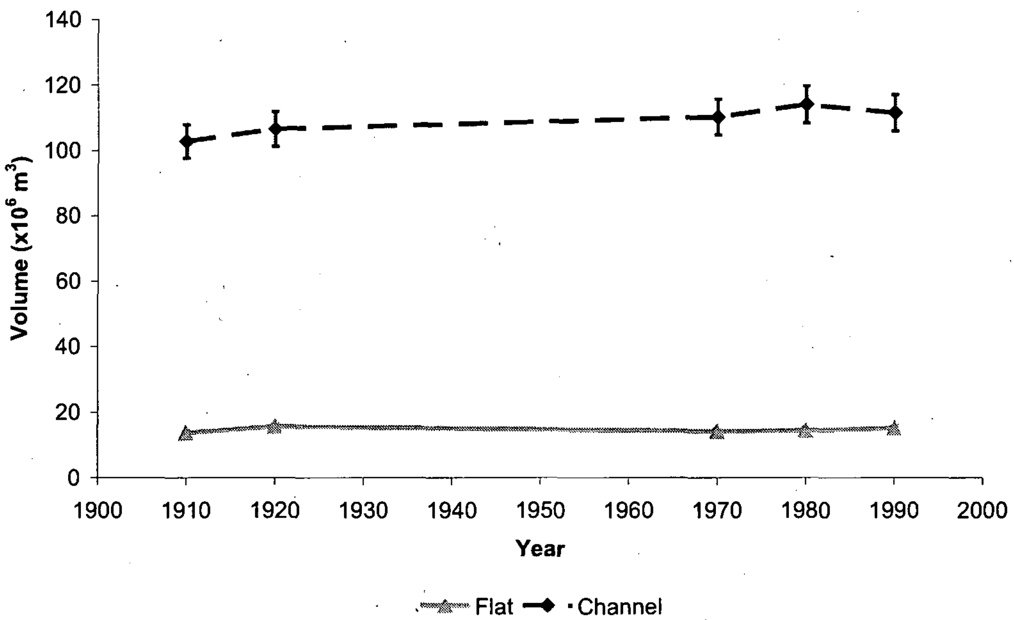


Fig. 4.32: Schematic representation of the Thames Estuary

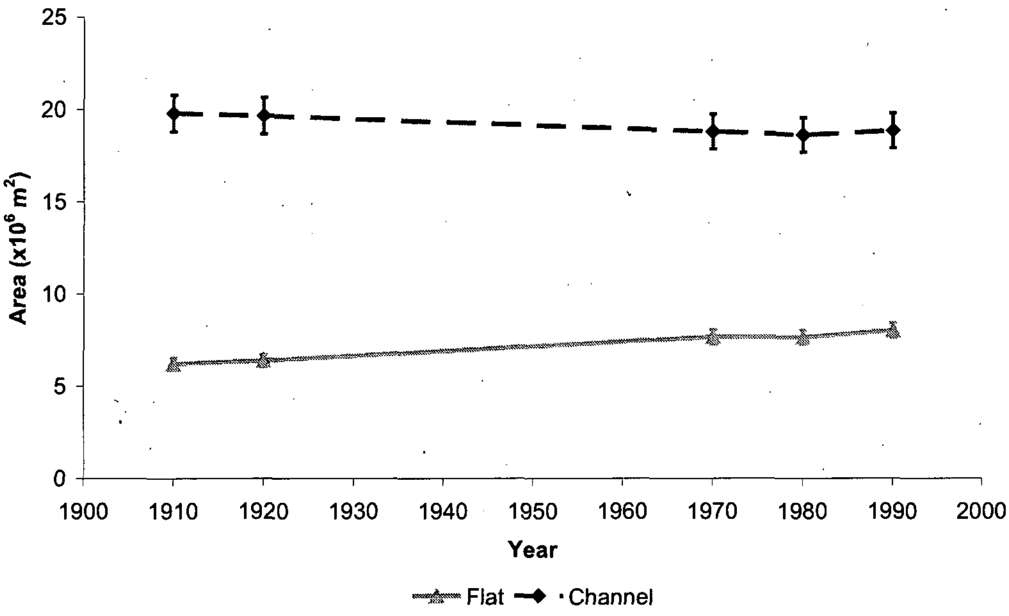


(a) Area

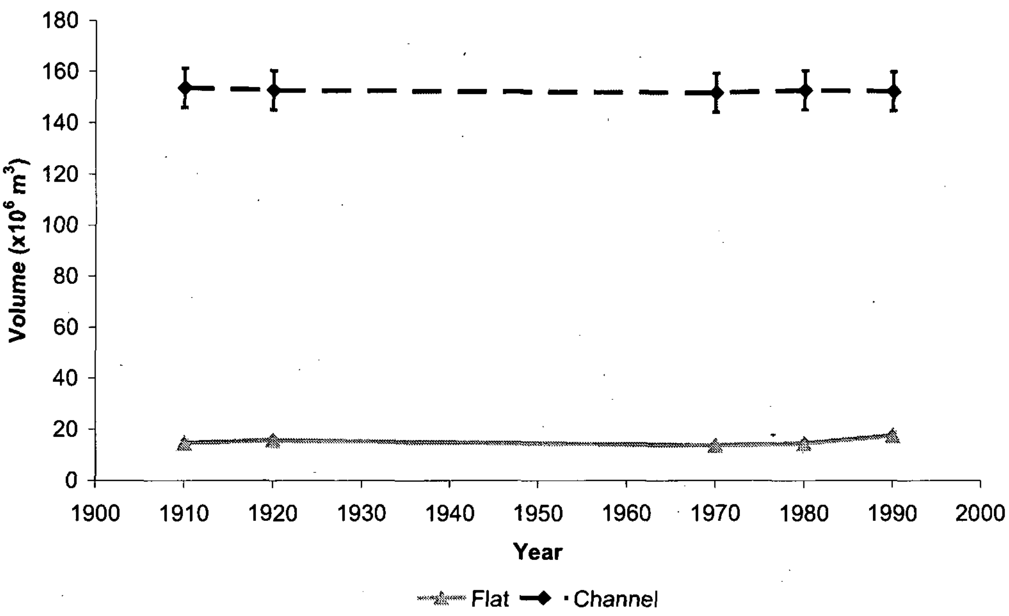


(b) Volume

Fig. 4.33: Area and Volume changes of flat and channel elements between Teddington and Broadness in the Thames Estuary

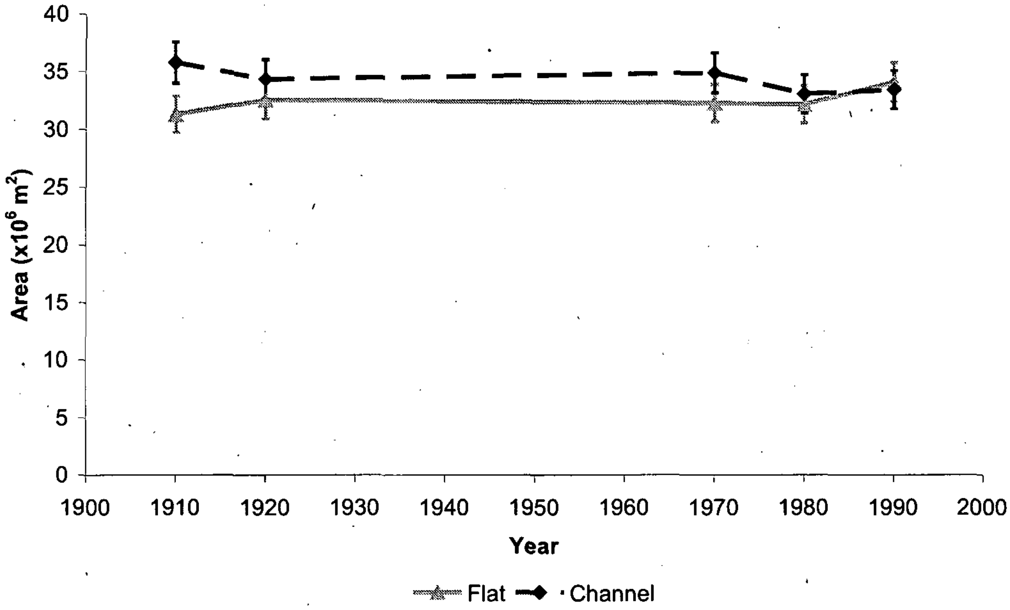


(a) Area

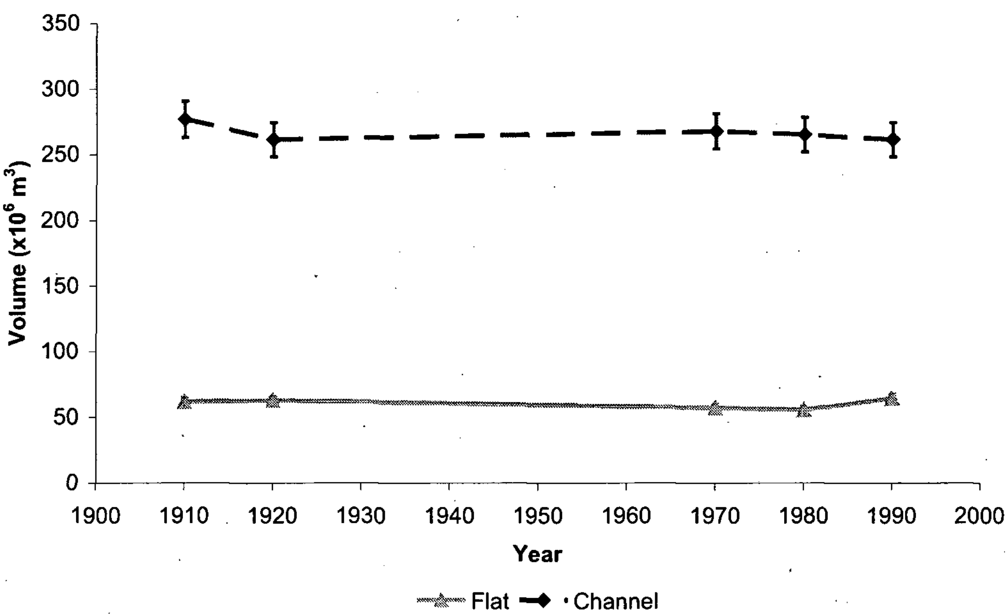


(b) Volume

Fig. 4.34: Area and Volume changes of flat and channel elements between Broadness and lower Hope Point in the Thames Estuary



(a) Area



(b) Volume

Fig. 4.35: Area and Volume changes of flat and channel elements between Lower Hope Point and Southend-on Sea in the Thames Estuary

4.6.3 Discussion

The Thames Estuary is heavily constrained by sea defences which inhibit the capacity for natural adaption to changes in forcing such as sea-level rise. Between 1910 and 1990 the Thames Estuary showed a tendency for accretion in intertidal areas and a slight tendency for erosion/deepening of the subtidal channels. Intertidal flat area and volume was observed to increase in all three regions of the estuary. Channel area and volume increased in the inner estuary and decreased slightly in the mid and outer regions of the Thames Estuary. This may reflect the influence of dredging, which is heaviest in the inner estuary.

In all three regions of the Thames Estuary, average flat height was observed to decrease between 1920 and 1970 (Table 4.12). This was generally followed by increases in average flat height between 1970 and 1990. Changes in channel depth tended to be relatively small, and no consistent pattern between regions can be seen.

The ratio of average intertidal flat height to tidal range (H_f/H), flat area to basin area (A_f/A_b) and channel volume to tidal prism (V_c/P) varied between regions in the Thames estuary (Table 4.12). Average values H_f/H and A_f/A_b were similar for the inner and mid regions of the estuary and the intertidal flat equilibrium coefficient (α_f) was the same. In the outer estuary, the relative height of the flats (H_f/H) was lower, but relative flat area (A_f/A_b) was greater resulting in a larger flat equilibrium coefficient (α_f). Possible explanations for these differences are differences in sediment properties (the outer estuary is sandier than the inner and mid estuary) and greater exposure to waves in the outer estuary.

V_c/P also varied between regions, and tended to decrease with distance seaward. The reason for these differences is not clear, but could include the influence of different sediment types, fluvial flow in the inner estuary, the influence of embankments and differences in dredging regimes. In addition, the most seaward portion of the estuary has the largest tidal prism as the upstream tidal prisms also contribute.

For the Thames Estuary as a whole, H_f/H, A_f/A_b and V_c/P averaged 0.38 (sd = 0.03), 0.39(sd = 0.01) and 1.02 (sd = 0.02) respectively. The standard deviations for the whole estuary are similar to those for individual regions, suggesting that it may be reasonable to model the estuary as a whole. However, dividing the Thames into regions allows some analysis of important changes in areas of the estuary having different characteristics. In the inner estuary, morphological changes do not have significant consequences for estuarine habitats, but may have consequences for coastal defence and navigation. In the outer estuary, morphological changes are less likely to affect the levels of coastal defence or navigation channel, but may have consequences for intertidal habitats.

Tab. 4.12: Summary of changes in the Thames Estuary between 1910 and 1990 including: flat area (A_f), flat volume (V_f), channel area (A_c), channel volume (V_c), ebb-tidal delta area (A_d), ebb-tidal delta volume (V_d), basin area (A_b), tidal prism (P), average flat height (H_f), average channel depth (H_c), average flat height relative to tidal range (H_f/H), ratio of flat area to basin area (A_f/A_b), flat equilibrium coefficient (α_f, given by $A_f/A_b * H_f/H$ and channel volume relative to tidal prism (V_c/P or α_c). Areas are in x10^6 m^2, volumes are in x10^6 m^3; the subscripts f and c refer to the flats and channels respectively.

Region	Year	A_f	V_f	A_c	V_c	H	A_b	P	H_f	H_c	H_f/H	V_c/P (α_c)	A_f/A_b	α_f
Inner	1910	6.09	13.66	17.84	102.75	5.1	23.93	108.38	2.24	5.76	0.44	0.95	0.25	0.11
Inner	1920	6.88	15.67	18.79	106.55	5.1	25.67	115.25	2.28	5.67	0.45	0.92	0.27	0.12
Inner	1970	7.19	14.14	20.13	110.13	5.1	27.32	125.19	1.97	5.47	0.39	0.88	0.26	0.10
Inner	1980	7.05	14.41	20.00	113.95	5.1	27.05	123.55	2.04	5.70	0.40	0.92	0.26	0.10
Inner	1990	7.15	15.12	19.80	111.39	5.1	26.95	122.33	2.11	5.63	0.41	0.91	0.27	0.11
Mid	1910	6.21	14.59	19.79	153.55	5.1	26.00	226.39	2.35	7.76	0.46	0.68	0.24	0.11
Mid	1920	6.38	15.58	19.66	152.48	5.1	26.04	232.47	2.44	7.76	0.48	0.66	0.25	0.12
Mid	1970	7.66	13.55	18.81	151.47	5.1	26.47	246.64	1.77	8.05	0.35	0.61	0.29	0.10
Mid	1980	7.64	14.48	18.63	152.43	5.1	26.27	243.04	1.90	8.18	0.37	0.63	0.29	0.11
Mid	1990	8.01	17.45	18.86	151.94	5.1	26.87	241.91	2.18	8.06	0.43	0.63	0.30	0.13
Outer	1910	31.30	61.59	35.79	276.87	5.1	67.09	506.96	1.97	7.74	0.39	0.55	0.47	0.18
Outer	1920	32.56	62.82	34.35	261.34	5.1	66.91	510.89	1.93	7.61	0.38	0.51	0.49	0.18
Outer	1970	32.29	57.12	34.91	267.67	5.1	67.20	532.24	1.77	7.67	0.35	0.50	0.48	0.17
Outer	1980	32.16	55.64	33.08	265.01	5.1	65.24	520.13	1.73	8.01	0.34	0.51	0.49	0.17
Outer	1990	34.11	64.34	33.45	261.24	5.1	67.56	522.13	1.89	7.81	0.37	0.50	0.50	0.19
Total	1910	43.60	89.84	73.42	533.17	5.1	117.02	506.96	2.06	7.26	0.40	1.05	0.37	0.15
Total	1920	45.82	94.07	72.80	520.37	5.1	118.62	510.89	2.05	7.15	0.40	1.02	0.39	0.16
Total	1970	47.14	84.81	73.85	529.27	5.1	120.99	532.24	1.80	7.17	0.35	0.99	0.39	0.14
Total	1980	46.85	84.53	71.71	531.39	5.1	118.56	520.13	1.80	7.41	0.35	1.02	0.40	0.14
Total	1990	49.27	96.91	72.11	524.57	5.1	121.38	522.13	1.97	7.27	0.39	1.00	0.41	0.16
Inner	Mean	6.87	14.60	19.31	108.95	5.1	26.18	118.94	2.13	5.64	0.42	0.92	0.26	0.11
	SD	0.45	0.80	0.98	4.37	0	1.41	7.01	0.13	0.11	0.03	0.02	0.01	0.01
Mid	Mean	7.18	15.13	19.15	152.37	5.1	26.33	238.09	2.13	7.96	0.42	0.64	0.27	0.11
	SD	0.82	1.48	0.53	0.78	0	0.36	8.38	0.29	0.19	0.06	0.03	0.03	0.01
Outer	Mean	32.48	60.30	34.32	266.43	5.1	66.80	518.47	1.86	7.77	0.36	0.51	0.49	0.18
	SD	1.02	3.75	1.10	6.43	0	0.90	9.94	0.10	0.16	0.02	0.02	0.01	0.01
Total	Mean	46.54	90.03	72.78	527.75	5.1	119.31	518.47	1.94	7.25	0.38	1.02	0.39	0.15
	SD	2.07	5.50	0.89	5.23	0	1.83	9.94	0.13	0.10	0.03	0.02	0.01	0.01

4.7 Humber Estuary

4.7.1 Estuary Overview

The Humber Estuary is a large, spit-enclosed estuary on the east coast of the United Kingdom (Fig. 4.36). The Humber Estuary has a catchment area of 24,500 km^2 and drains approximately 20% of England (Winn et al., 2003). The Humber is a macrotidal estuary and has a well mixed salinity structure. It has extensive intertidal areas, which are of conservation interest and contain a number of economically important infrastructure including docks and other industry. Approximately 90,000 ha of land is protected by the estuary's flood defences, including farm land, industrial and commercial areas and residential areas. Around 300,000 people live in the low-lying area surrounding the Humber Estuary (Environment Agency, 2000).

The Humber Estuary was cut into glacial till following the last ice age, when the melting of ice allowed water to escape from the Humber Lake, eroding a wide shallow river valley (Winn, 2007). The river valley flooded by rising sea levels around 9000 years ago and has since been infilling with marine sands and muds (Institute of Estuarine and Coastal Studies, 1994).

The area of the Humber Estuary has been artificially reduced over the last 200 years by land reclamations. There are major ports at Goole, Hull, Inningham and Grimsby, and berths and navigation channels required dredging to maintain suitable depths. Large areas of the Humber Estuary are also designated for nature conservation (Fig. 4.37). The estuary is an important site for migrating wildfowl and contains redbeds, saltmarsh, sand dunes and saline lagoons.

Morphology and Processes

The Humber Estuary can be divided into four regions, with different processes dominating in each. The outer estuary, defined as the stretch between Spurn Head and Grimsby is dominated by open coastal processes and behaves as a coastal inlet or bay (Environment Agency, 2000). An important morphological feature of the outer estuary is the spit that extends from Kilnsea Warren on the northern bank of the estuary to Spurn Head. The spit overlies glacial tills, which allowed the spit to form despite high current velocities in this region of the estuary. Large intertidal areas have developed in the sheltered area behind the spit.

The middle estuary, from Grimsby to the Humber Bridge, has more typically estuarine processes and morphology. It is constrained at the Humber Gap (Humber Bridge) where the geology changes from glacial till to more resistant chalk. The inner estuary, from Humber Bridge to Trent Falls, is characterised by intertidal sand and mud shoals and meandering channels. Training walls at Trent Falls constrain channel meandering in this section.

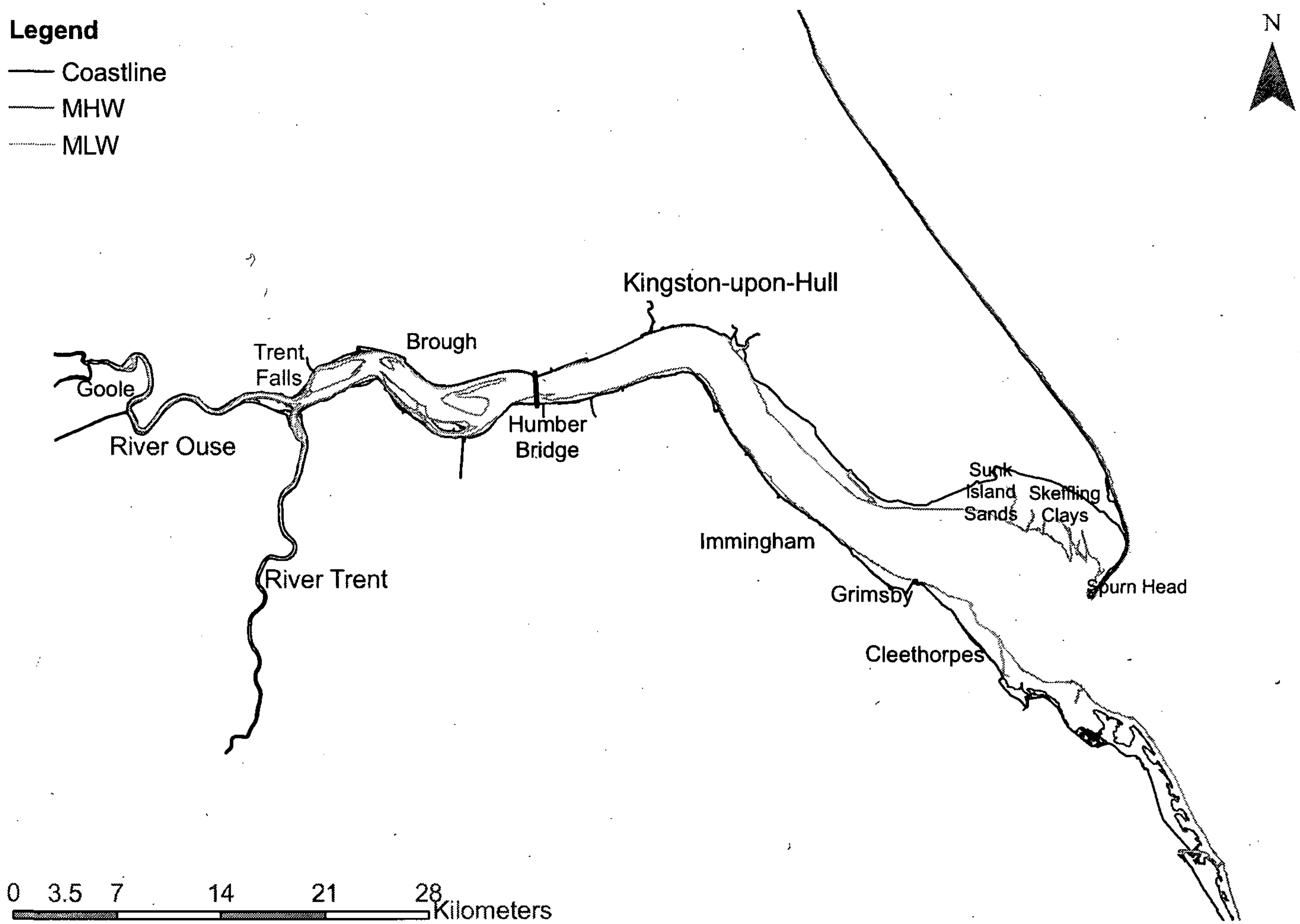


Fig. 4.36: Plan of the Humber Estuary

The fourth region of the Humber Estuary is the tidal river, and includes tidal sections of the Trent and Ouse Rivers above their confluence at Trent Falls. This section is dominated by fluvial processes and constrained by embankments and flood defences.

The Humber Estuary is macro tidal, with a spring tidal range of 6 m at the mouth. Tidal range increases upstream; spring high water at Goole is more than a metre higher than at Spurn (Winn, 2007). The Humber is ebb-dominant from Humber Bridge to the sea, but is strongly flood dominant upstream of Humber Bridge (Dyer, 2002). In addition to the overall pattern of tidal asymmetry, there are differences between channels within the estuary, with some channels carrying predominantly flood flow and others carrying mainly ebb flow (Pontee et al., 1997).

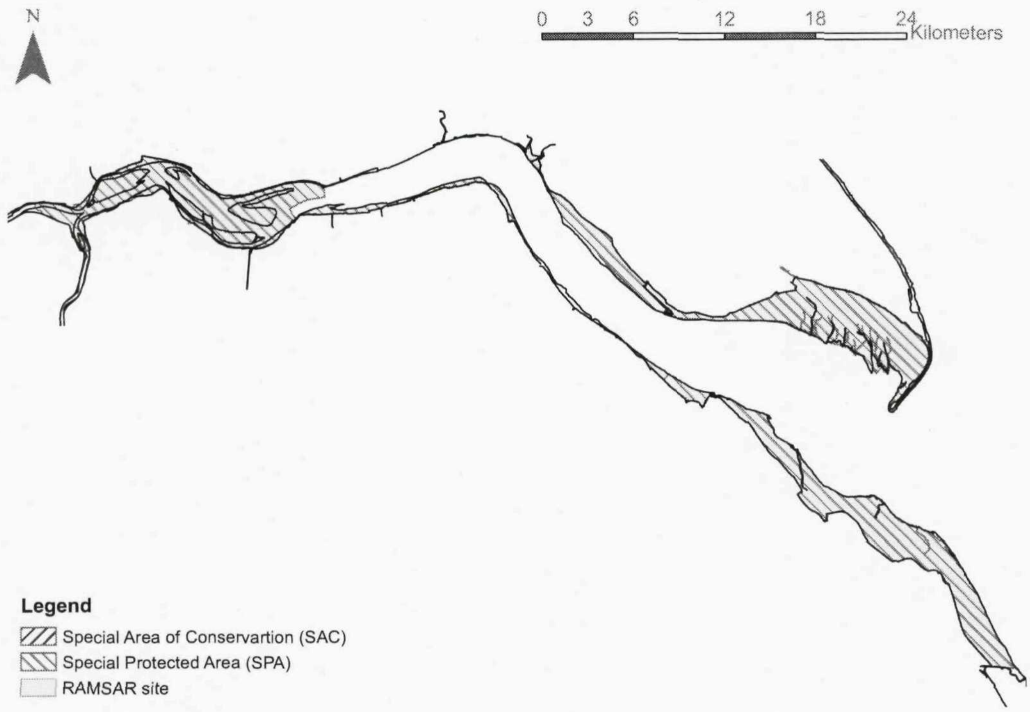
Despite the large catchment of the Humber, fluvial flows are relatively low. Under average conditions river flow is less than 1% of the tidal prism, whilst under flood conditions it may be up to 4.4% (Dyer, 2002). The Humber is well mixed and it is likely that the fluvial influence is restricted to the inner estuary. Significant wave heights in the middle and inner estuary are less than 1 m but are sufficient to resuspend sediment in shallow areas (Pontee et al., 1997). Wave heights in the outer estuary are much greater and may be up to 4 m around Cleethorpes (Environment Agency, 2000).

The Humber Estuary has a large sediment supply from the North Sea and from erosion of the Holderness cliffs to the north. Less than 3% of the sediment found in the Humber Estuary comes from fluvial sources. Suspended sediment concentrations in the estuary are high, with typical values of up to 3200 mg/l^{-1} (Pontee et al., 2004). Approximately 6 million tonnes of sediment from marine sources are estimated to enter the Humber each year, but much of this is flushed from the estuary on ebb tides and does not settle (Winn et al., 2003).

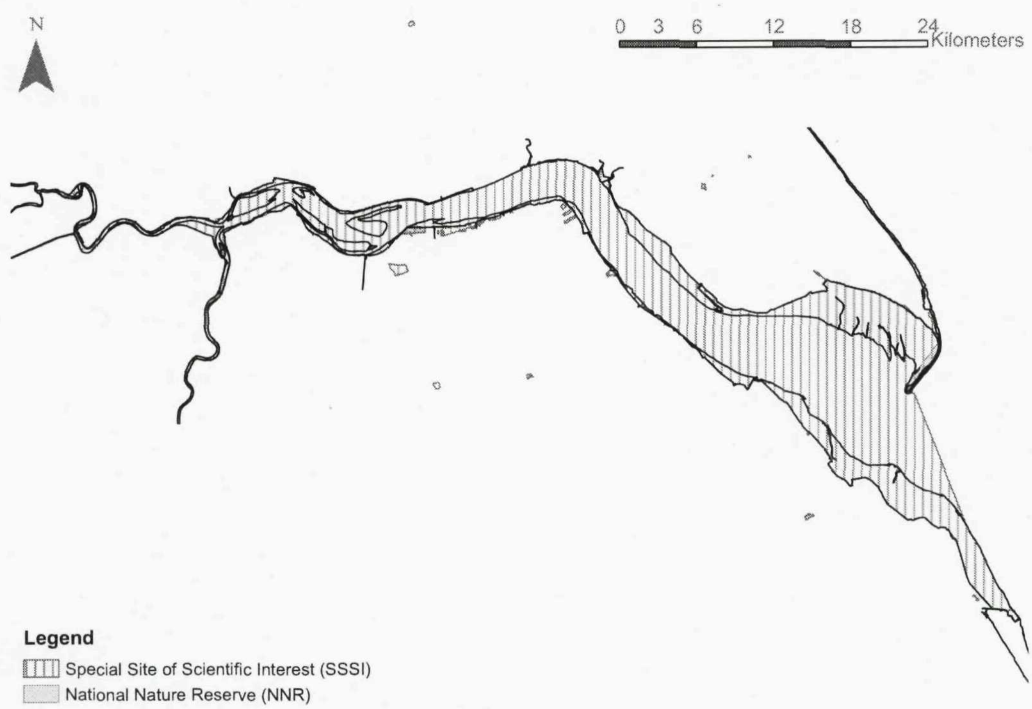
Human Influence

Large areas of the Humber Estuary have been reclaimed in the past. Sunk Island and Cherry Cobb Sands, located on the northern shore of the outer estuary, were reclaimed between 1800 and the present day, removing approximately 4945 ha of intertidal area from the estuary. Other reclamations have been smaller and include reclamations at Read's and Broomfleet Islands (approximately 240 ha) in the inner estuary and reclamations for Grimsby and Hull Docks (250 ha) (Pontee et al., 1997). The majority of reclamations were completed in the 1800s, with only small areas being reclaimed within the study period (1925–1998).

Maintenance dredging is carried out a the various docks within the estuary and in the Sunk Dredged Channel in the outer estuary. Prior to 1968, only the docks and immediate approaches were dredged (Pontee et al., 1997). In 1968 a channel was dredged through Grimsby Middle Shoal and since 1969 dredging has been carried



(a) International Designations



(b) National Designations

Fig. 4.37: Areas protected under (a) international and (b) national nature protection designations in the Humber Estuary (Natural England, 2007)

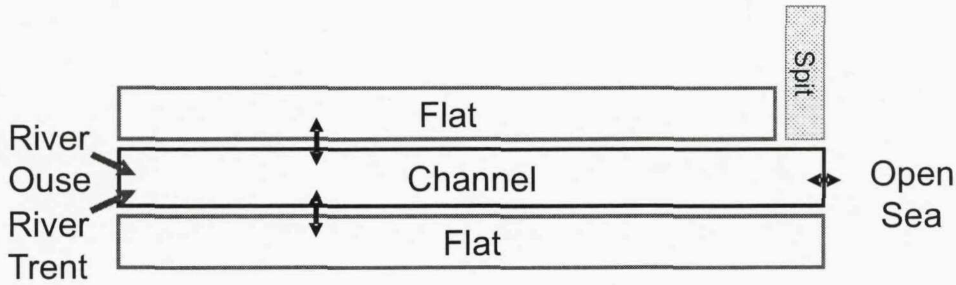


Fig. 4.38: Schematic representation of the Humber Estuary

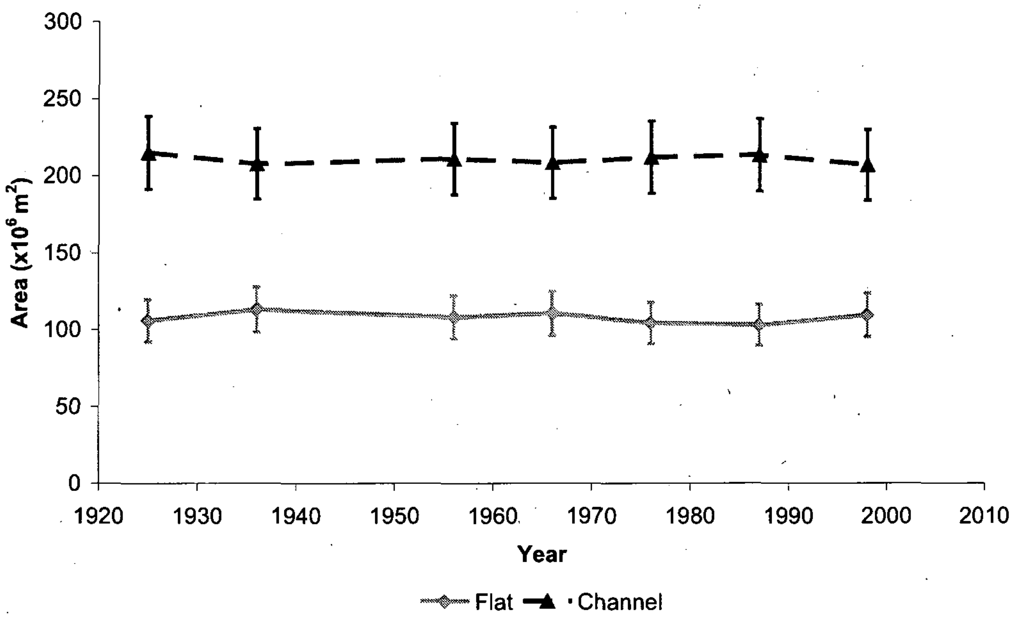
out at Sunk Island Channel. The total volume of sediment dredged from the docks and channels of the Humber between 1968 and 1994 was approximately 242 x10^6m^3, an average of 6.7 x10^6m^{3}a^{-1} (Pontee et al., 1997). Between 1969 and 1994, all of the material dredged from the Humber was disposed of within the estuary, usually at shoals close to the dredging site. Although this does not affect the overall sediment budget of the estuary, it does influence morphology.

4.7.2 Historical Analysis

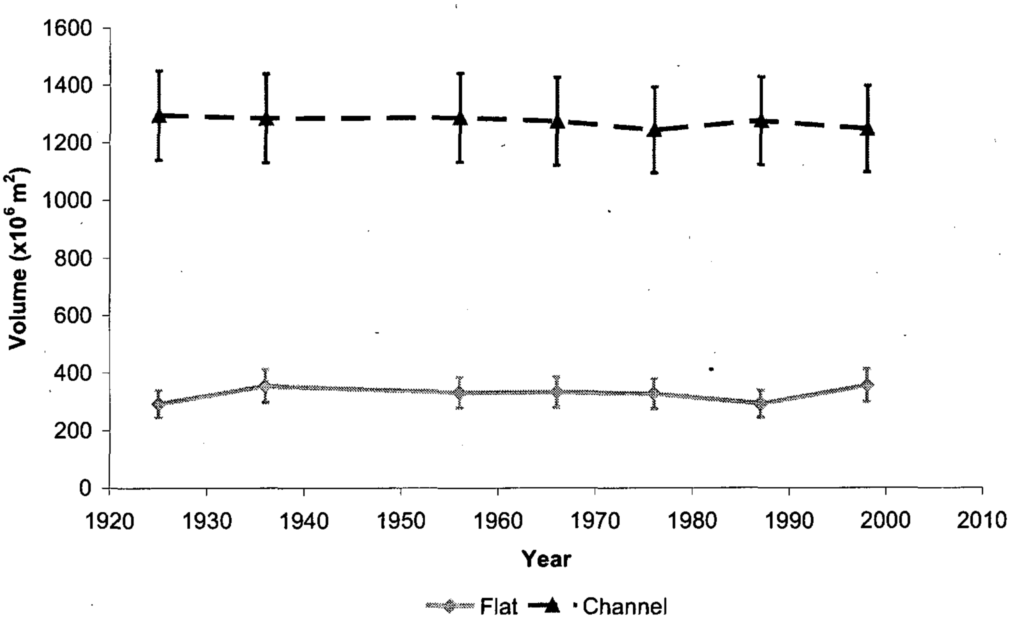
The Humber Estuary has no obvious ebb-tidal delta at its mouth and for the purposes of the current study is dived into two elements; the intertidal flats and channels (Fig. 4.38). The area and volume of the flat and channel elements has remained approximately constant between 1925 and 1998 (Fig. 4.39). Overall, there is a slight increase in flat area and volume (5 x10^6m^2 and 34 x10^6m^3 respectively (Table 4.13)), suggesting an overall trend for intertidal accretion. Channel area has decreased by approximately 6 x10^6m^2 and channel volume has decreased by 63 x10^6m^3, suggesting accretion also occurred in the channels. Basin area has decreased slightly over the study period due to small scale reclamations.

Hypsometry curves for the Humber Estuary show little change over the study period (Fig. 4.40). 1936 and 1998 appear to have larger areas than other years. This anomaly may be caused by small differences in estuary boundaries during interpolation and is likely to be an error. In general, the hypsometry curves show that the Humber is wide and shallow, with gently sloping intertidal areas. The intertidal area tends to be high and convex, indicating accretion dominated mudflats (Kirby, 2000).

Tablele 4.13 shows the details changes in volume and area, tidal prism and average elevations and depth in the Humber Estuary. Tidal prism was estimated to be approximately 1600 x10^6m^3 and varied only slightly over the study period. The ratios H_f/H, A_f/A_b and V_c/P can be used to assess the equilibrium status of the estuary. All three values varied over the study period, but the standard deviations were small (less than 0.03) and the measures appear to vary around a mean value,

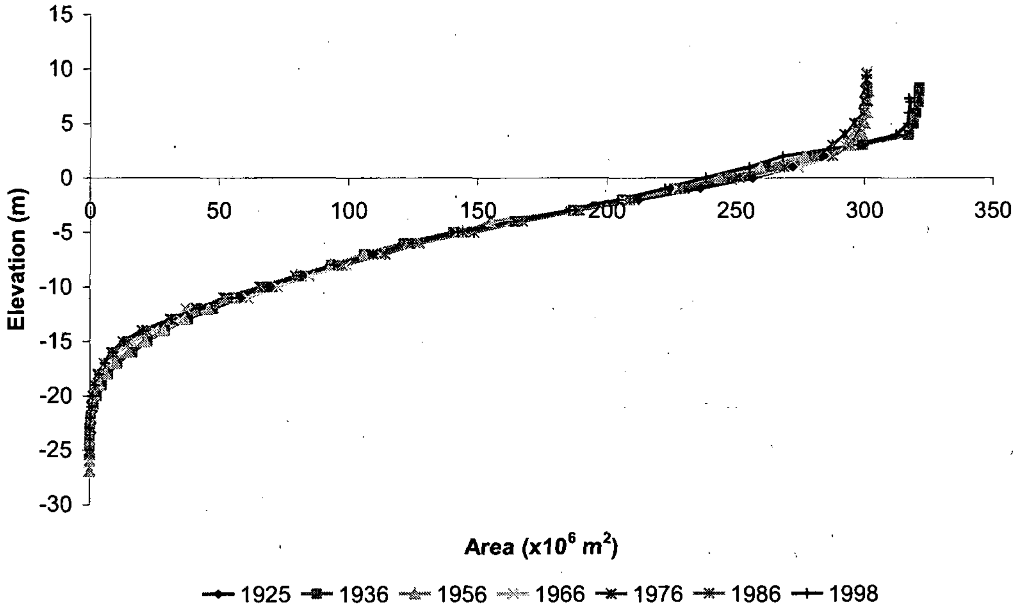


(a) Area

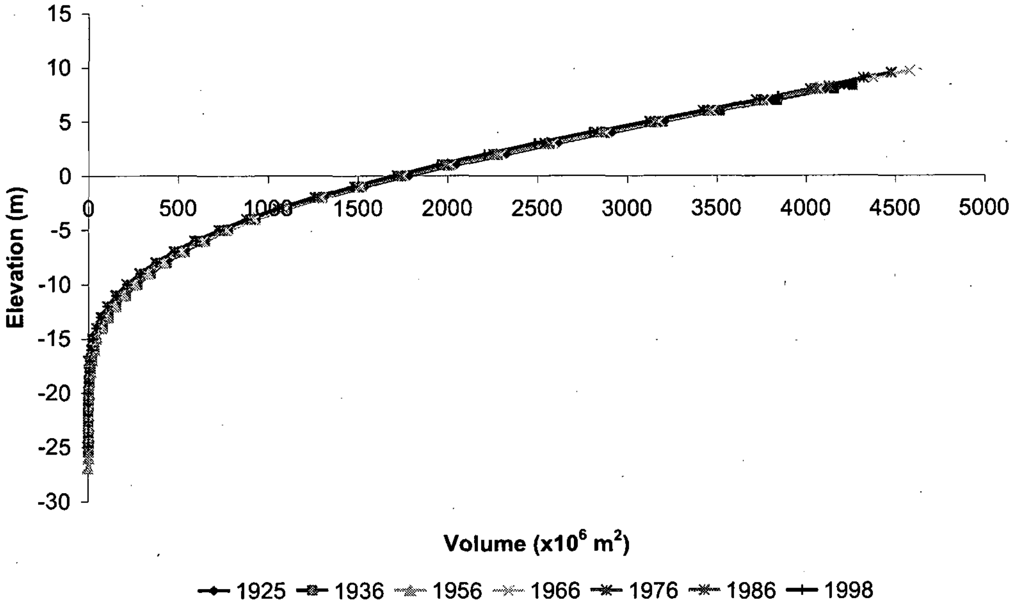


(b) Volume

Fig. 4.39: Area and Volume changes of flat and channel elements in the Humber Estuary. Error bars are the percentage mean square error for each element (see Table 3.7)



(a) Area



(b) Volume

Fig. 4.40: Hypsometry curves showing the distribution of (a) area and (b) volume with elevation in the Humber Estuary.

rather than following a trend of change.

4.7.3 Discussion

The volume and area of the intertidal flats and channels in the Humber Estuary appears to have been approximately constant between 1925 and 1998. The ratios H_f/H and V_c/P varied but had low standard deviations, suggesting that element volumes fluctuate around an equilibrium volume. Despite large scale reclamations in the past and ongoing dredging, the Humber Estuary appears to be close to dynamic equilibrium. Due to the large size of the Humber, it is likely that relatively large human interventions would be needed before significant morphological changes occurred.

The data presented here suggests a slight trend for accretion over the study period. This differs from the findings of Pontee et al. (1997) who found a trend for erosion from approximately 1950 to the present day. Pontee et al. (1997) suggested that the observed volume changes were within 3% of the estuary volume, suggesting they could be well within the error estimates of this study. It is therefore possible that the Humber Estuary is experiencing erosional trends that cannot be seen in the current data set as it is masked by error. In addition, the current data set ignores changes in the position of mean low water caused by cyclical changes in tidal range, such as the 18.6 year nodal tidal cycle. Changes in the position of mean low water relative to ordnance datum are based on average rates of sea-level rise of 1 mm/year.

Tab. 4.13: Summary of key changes in the Humber Estuary between 1925 and 1998 including: flat area (A_f), flat volume (V_f), channel area (A_c), channel volume (V_c), basin area (A_b), tidal prism (P), average flat height (H_f), average channel depth (H_c), average flat height relative to tidal range (H_f/H and channel volume relative to tidal prism (V_c/P). Areas are in x10^6 m^2, volumes are in x10^6 m^3; the subscripts f and c refer to the flats and channels respectively.

Year	A_f	V_f	A_c	V_c	H	A_b	P	H_f	H_c	H_f/H	V_c/P (|$alpha_c$)	A_f/A_b	α_f
1925	105.82	292.21	214.89	1295.45	6.0	320.71	1632.05	2.76	6.03	0.46	0.79	0.33	0.15
1936	113.29	355.23	207.50	1282.39	6.0	320.79	1569.51	3.14	6.18	0.52	0.82	0.35	0.18
1956	108.61	334.21	210.57	1281.13	6.0	319.18	1580.87	3.08	6.08	0.51	0.81	0.34	0.17
1966	111.43	337.03	207.74	1265.43	6.0	319.17	1577.99	3.02	6.09	0.50	0.80	0.35	0.18
1976	105.44	332.47	211.27	1233.20	6.0	316.71	1567.79	3.15	5.84	0.53	0.79	0.33	0.17
1987	104.21	297.92	212.55	1262.27	6.0	316.76	1602.64	2.86	5.94	0.48	0.79	0.33	0.16
1998	110.88	326.90	205.96	1232.79	6.0	316.84	1574.14	2.95	5.99	0.49	0.78	0.35	0.17
Mean	108.53	325.14	210.07	1264.67	6.0	318.59	1586.43	2.99	6.02	0.50	0.80	0.33	0.16
SD	3.47	22.40	3.16	24.31	0.0	1.82	23.20	0.15	0.11	0.02	0.01	0.03	0.03

4.8 Synthesis

The eight study estuaries showed a range of morphological behaviours, which are summarised for each element in table 4.22. The Thames Estuary, Humber Estuary and Chichester Harbour showed relatively small changes in area over their respective study periods (Tables 4.19 to 4.21). The Dart Estuary experienced relatively large changes in intertidal flat area, mainly due to a breach in the training wall at Sharpham Marshes in 1952 (an unplanned realignment) (Table 4.15). Changes in the Dart Estuary remain small compared to the large uncertainty of the data. In Langstone Harbour, changes of up to 32% occurred in the channel element between 1974 and 1997, but net change over the study period was small (Table 4.18).

Large morphological changes were observed in the Ribble Estuary, Southampton Water and Portsmouth Harbour and can be partially explained by human activities such as land reclamation and dredging. The response of these systems to similar human interferences was very different. In the Ribble Estuary, inner flat area increased by 75% between 1904 and 1990, despite large reclamations removing significant parts of this element (Table 4.14). Outer flat area and channel area both decreased over the study period, as they were converted to inner intertidal flats and outer intertidal flats respectively. In Southampton Water, inner intertidal flat area was reduced by more than 80% by land reclamation (Table 4.16). Inner channel and outer flat areas were also reduced by 30% and 25% respectively. Portsmouth Harbour experienced a 16% reduction in basin area between 1914 and 2004 (Table 4.17), with 20% of the original flat area and 10% of the original channel area being lost.

Tab. 4.14: Area changes in the Ribble Estuary expressed as percentage change

	A_c	A_{fo}	A_{fi}	A_b
1904-1951	7.0	-18.3	26.1	-5.1
1951-1977	-22.5	1.8	17.5	-1.5
1977-1990	-22.8	-7.7	18.3	-4.4
Total	-36.0	-23.2	75.2	-10.7
% uncertainty	27	13	13	

Tab. 4.15: Area changes in the Dart Estuary expressed as percentage change

	A_f	A_c	A_b
1853-1900	3.8	0.2	0.8
1900-1952	-1.0	-0.9	-0.9
1952-1972	8.0	4.5	5.1
1972-1983	28.4	4.0	8.3
1983-1995	-2.1	0.6	0.1
Total	39.5	8.6	13.8
% uncertainty	49	15	

Tab. 4.16: Area changes in Southampton Water expressed as percentage change

	A_{fi}	A_{fo}	A_{ci}	A_{co}	A_b
1911-1926		11.5		-4.4	0.7
1926-1951	-47.0	-14.2	-18.1	5.4	-10.8
1951-1965	3.2	7.3	3.3	2.0	3.6
1965-1976	-33.3	-20.8	-5.8	-2.2	-10.2
1976-1996	-50.0	-14.2	-6.1	6.5	-3.6
Total	-81.8	-30.2	-25.2	7.0	-19.4
% uncertainty	16	16	12	12	

Tab. 4.17: Area changes in Portsmouth Harbour expressed as percentage change

	A_f	A_c	A_b
1914-1937	-5.5	7.9	0.0
1937-1960	-33.0	14.6	-11.8
1960-1975	7.0	-20.1	-8.7
1975-1982	21.6	-14.3	3.5
1982-1993	-2.1	2.8	0.0
1993-2004	-1.6	3.6	0.7
Total	-20.6	-9.7	-16.1
% uncertainty	14	16	

Tab. 4.18: Area changes in Langstone Harbour expressed as percentage change

	A_f	A_c	A_b
1955-1961	-7.8	15.9	0.2
1961-1968	-0.1	-0.2	-0.1
1968-1974	-15.0	18.3	-2.1
1974-1997	26.0	-32.3	-1.4
Total	-1.3	-7.4	-3.3
% uncertainty	13	17	

Tab. 4.19: Area changes in Chichester Harbour expressed as percentage change

	A_f	A_c	A_b
1955-1961	0.1	-1.0	-0.4
1961-1968	-0.1	0.5	0.1
1968-1974	-1.8	2.9	0.1
1974-1997	2.1	-4.2	-0.5
Total	0.3	-1.9	-0.6
% uncertainty	13	16	

Tab. 4.20: Area changes in the Thames Estuary expressed as percentage change

	A_f	A_c	A_b
1910-1920	5.1	-0.8	1.4
1920-1970	2.9	1.4	2.0
1970-1980	-0.6	-2.9	-2.0
1980-1990	5.2	0.6	2.4
Total	13.0	-1.8	3.7

Tab. 4.21: Area changes in the Humber Estuary expressed as percentage change

	A_f	A_c	A_b
1925-1936	7.1	-3.4	0.0
1936-1956	-4.1	1.5	-0.5
1956-1966	2.6	-1.3	0.0
1966-1976	-5.4	1.7	-0.8
1976-1987	-1.2	0.6	0.0
1987-1998	6.4	-3.1	0.0
Total	4.8	-4.2	-1.2
% uncertainty	13	11	

Tab. 4.22: Summary of changes in the eight study estuaries

Estuary	Morphological Type	Human influences	Elements	Trend by Element	Rate of sea-level rise (mm/year) (station, dates (source))
Ribble	Funnel shaped	Extensive reclamation for dock development	Upper Flats	Volume has doubled between 1904 and 1990. Area has increase by more than 50% and average flat height has increased by more than 1 m. Upper flats do not appear to be close to equilibrium.	2.58±0.88 (Liverpool Princes Pier, 1959-83 (Woodworth et al., 1999))
	(type 5)	Construction of training walls	Lower Flats	Volume and area have decreased slightly as lower flats have been converted to upper flats. Average flat height has remained relatively constant.	1.04±0.62 (Heysham, 1962-96 (Woodworth et al., 1999))
		Dredging	Channel	Channel area and volume have decreased over the study period and appears to be in equilibrium with tidal prism.	
Dart	Ria without spits		Flat	Flat area and volume have increased slightly between 1853 ad 1995, with most of the change occurring between 1952 and 1983	3.04±1.01 (Devonport, 1962-96 (Woodworth et al., 1999))
	(type 3b)		Channel	Channel area and volume were approximately constant	
Southampton Water	Single spit-enclosed estuary	Extensive reclamation for dock development	Outer Flat	Flat area and volume decreased slightly between 1911 and 1996. Average flat height was approximately constant	1.45±0.60 (Portsmouth, 1962-96 (Woodworth et al., 1999))
	(type 4a)	Capital and maintenance dredging	Outer Channel	Outer channel area and volume were approximately constant	1.5 (Shennan, 1989)
			Inner Flat	Inner flat area and volume was greatly reduced during the study period by reclamations and dredging.	
			Inner Channel	Inner channel area decreased, whilst channel volume increased due to extensive dredging. Tidal prism decreased due to reclamations.	

Tab. 4.22: Summary of changes in the eight study estuaries (cont.)

Estuary	**Morphological Type**	**Human influences**	**Elements**	**Trend by Element**	**Rate of sea-level rise (mm/year) (station, dates (source))**
Portsmouth Harbour	Symmetrical tidal inlet	Much reclamation for dock development	Flat	Flat are decreased slightly. Flat volume was reduced by at least 50%, partly due to a decrease in average flat height.	1.37±0.52 (Portsmouth (Haigh, 2006)) 1.45±0.60 (Portsmouth, 1962-96 (Woodworth et al., 1999))
	(type 7a)	Dredging	Channel	Channel area decreased slightly and channel volume increased. Average channel depth increased by approximately 0.5 m.	1.5 (Shennan, 1989)
			Ebb-tidal Delta	Area and volume of the ebb-tidal delta fluctuated during the study period.	
Langstone Harbour	Symmetrical tidal inlet	Reclamation	Flat	Area and volume varied, but little net change was observed	1.45±0.60 (Portsmouth, 1962-96 (Woodworth et al., 1999))
	(type 7a)	Aggregate extraction from ebb-tidal delta	Channel	Area and volume varied, but little net change was observed	1.5 (Shennan, 1989)
			Ebb-tidal Delta	Area and volume of the ebb-tidal delta fluctuated during the study period.	
Chichester Harbour	Symmetrical tidal inlet	Gravel extraction from ebb-tidal delta	Flat	Areas and volumes showed small variations over the study period	1.45±0.60 (Portsmouth, 1962-96 (Woodworth et al., 1999))
	(type 7a)		Channel	Areas and volumes showed small variations over the study period	1.5 (Shennan, 1989)
			Ebb-tidal Delta	Area and volume of the ebb-tidal delta fluctuated during the study period.	

Tab. 4.22: Summary of changes in the eight study estuaries (cont.)

Estuary	Morphological Type	Human influences	Elements	Trend by Element	Rate of sea-level rise (mm/year) (station, dates (source))
Thames	Funnel shaped	Extensively reclaimed and defended coastline	Inner Flat	Flat volume and area increased slightly over study period	1.22±0.24 (Southend, 1933-83 (Woodworth et al., 1999))
	(type 5)	Dredging	Inner Channel	Channel area was approximately constant and channel volume increased slightly.	
			Mid Flat	Area and volume tended to increase over the study period.	
			Mid Channel	Channel area decreased slightly and channel volume was approximately stable.	2.14±0.15 (Sheerness, 1901-96 (Woodworth et al., 1999))
			Outer Flat	Area and volume increased slightly.	
			Outer Channel	Area and volume decreased slightly.	
Humber	Single spit-enclosed estuary	Extensive reclaimed areas	Flat	Area and volume were approximately constant	1.11±0.52 (Immingham, 1960-95 Woodworth et al. (1999))
	(type 4a)	Dredging of lower channels	Channel	Area and volume were approximately constant	

5. ASMITA: INITIAL APPLICATION AND EVALUATION

5.1 Introduction

In this chapter, initial ASMITA simulations for the study estuaries are presented using the conceptual models already developed and the dynamic equilibrium relationships derived from the data in Chapter 4. Up to three sets of equilibrium coefficients were selected for each estuary, based on (1) mean conditions, (2) initial conditions (assuming the estuary was in equilibrium in the earliest available data set) and (3) end-point conditions (assuming the estuary had evolved to a new equilibrium state by the latest data set) (table 5.1).

The application of ASMITA to the study estuaries aimed to investigate the use of equilibrium relationships within a numerical model, for a variety of estuary morphological types. The skill of ASMITA in predicting the observed changes in morphology is measured using the Brier's Skill Score (Sutherland and Soulsby, 2003) (section 3.5.2), which compares the mean square error (MSE) between observed volumes and ASMITA predictions with the mean square error for a baseline. The baseline assumes that the element volumes remain constant at their initial values.

The results of the initial applications of ASMITA are used to identify strengths and limitations of the equilibrium approach to estuary modelling as it is used in ASMITA. Improvements that could allow ASMITA to be used as an effective tool for estuary managers are also discussed (Section 5.10).

5.2 Ribble

ASMITA was applied to the Ribble Estuary using a three element schematisation including the lower flats, upper flats and channel elements (Fig. 4.4). Equilibrium coefficients for the lower flat and channel elements were found to vary only slightly over time and mean values of these coefficients were used to predict the equilibrium volumes (Table 4.4b). The equilibrium coefficient for the upper flat (α_{fu}) varied much more and showed a tendency to increase over time. For this reason two simulations were made, one using the mean value of α_{fu} and one using the end-point value, derived from the latest available data set. This is based on the assumption that the Ribble may be evolving towards a new dynamic equilibrium following 200 years of human interference. Volume and area data for 1904 was used to describe the initial conditions in the Ribble Estuary (Table 5.2).

Tab. 5.1: Equilibrium coefficients from the Dart Estuary, illustrating initial, mean and end-point conditions

Year	α_c	α_f	Condition
1853	**1.04**	**0.026**	**Initial coefficients, based on earliest data**
1900	1.02	0.028	
1952	0.98	0.028	
1972	0.93	0.030	
1983	0.86	0.033	
1995	**0.89**	**0.039**	**End-point coefficients, based on latest available data**
Mean	**0.95**	**0.031**	**Mean coefficients, based on mean value**
SD	0.07	0.005	

Sediment exchange coefficients (Table 5.3) were estimate from known properties of the estuary using the method described in 3.5.2. The area available for exchange (A) was assumed to be the cross sectional area for exchange between the channel and outside world. For exchange between other elements, A was estimated to be the length of the boundary between two elements, multiplied by the average water depth at the boundary. u is the peak current velocity, estimated to be 1 ms^{-1} in the channel (van der Wal et al., 2002). The horizontal exchange coefficient (w_{sn}) was estimated to be 0.0008, assuming the dominant sediment type in the estuary is sand (van der Wal et al., 2002), although it is known that mud is also present in the high intertidal areas.

Sediment exchange coefficients given in table 5.3 indicate that horizontal sediment exchange (δ) is greatest between the lower flats and the outside world. Despite having lower current speeds than the channel, the area available for sediment exchange (A) is much greater than between the channel and the outside world, leading to greater exchange. Exchange between the upper and lower flats is smallest, due to lower estimates of current velocity in this area. The global equilibrium concen-

Tab. 5.2: Initial volume and area data and equilibrium relationships used for Ribble simulations. A_n is the area of element n, V_n is its volume and V_{ne} is the elements equilibrium volume based on initial conditions.

	A_n ($\mathbf{x10^6m^2}$)	V_n ($\mathbf{x10^6m^3}$)	Condition	**Equilibrium relationship**	V_{ne}($\mathbf{x10^6m^3}$)
Lower flats (fl)	72.42	197.2	Mean	$0.19A_b * H$	22.92
Upper flats (fu)	19.11	116.82	Mean	$0.20A_b * H$	24.13
			End-point	$0.28A_b * H$	33.78
Channel (c)	29.11	37.59	mean	0.06*P	38.34
Basin (b)	120.64				
Tidal Prism (P)		639.04			

Tab. 5.3: Sediment exchange coefficients used in the Ribble Estuary simulations (estimated using Eq. 3.14)

Exchange between	A (m^2)	L (m)	u (ms^{-1})	H (m)	w_{sn}	D	δ
Lower Flats, Outside World	80800	8000	0.85	2.6	0.0008	235	2372
Channel, Outside World	36000	14000	1	5	0.0008	625	1607
Channel, Lower Flats	60000	3000	0.7	1.8	0.0008	110	2205
Upper Flats, Lower Flats	80000	3000	0.3	2.6	0.0008	29	780

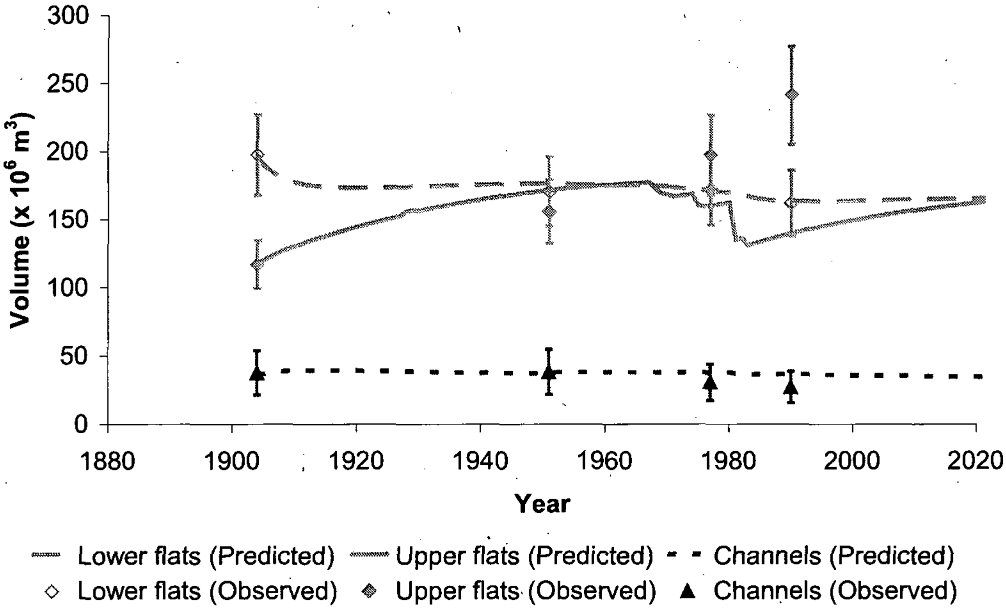
tration (C_E) was estimated to be 0.00012 for the Ribble Estuary, reflecting the relatively high sediment availability. Details of volume and area changes caused by land reclamation and dredging used in the simulations are given in Appendix B.

Observed and predicted volumes for the lower flats, upper flats and channels in the Ribble Estuary are shown in figure 5.1. For figure 5.1a the equilibrium volumes were calculated based on the mean value of the equilibrium coefficients (α_{fl}, α_{fu} and α_c; Table 4.4b). Figure 5.1b uses equilibrium coefficients based on the 1990 data to represent the trend for increasing α_f in the upper flat element.

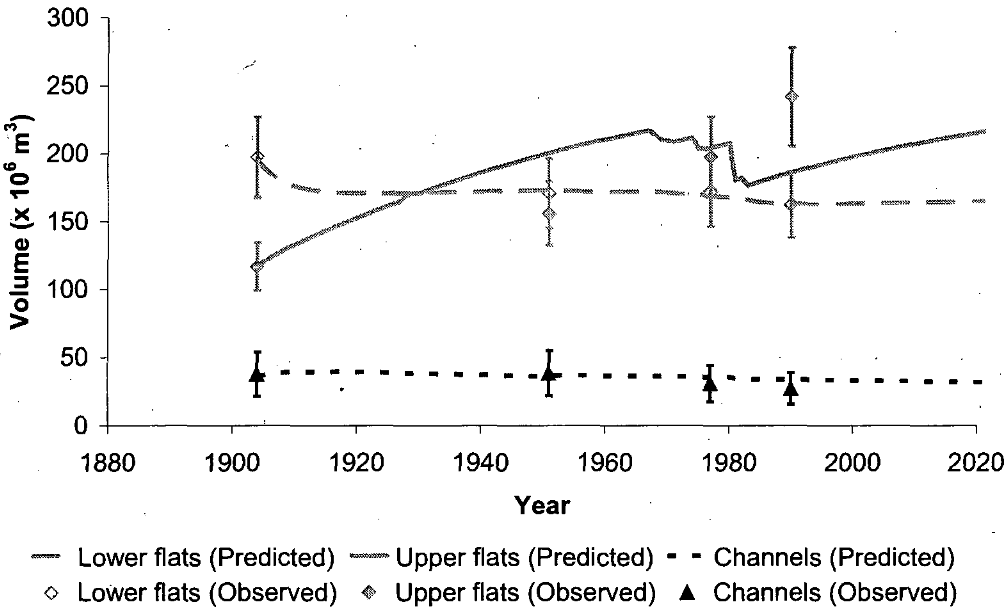
In general, the ASMITA predictions are similar to the observed volumes for the channel and lower flat elements. Using mean equilibrium coefficients, the ASMITA predictions for the upper flat element are close to the observed volume for 1904 and 1955, but do not capture the rapid increase in volume observed in 1977 and 1990. Using end-point equilibrium coefficients, the general pattern of increasing upper flat volume is better represented, but still shows some differences compared with the observed volumes.

Mean Square Error (MSE) and Brier's Skill Scores (BSS) (Sutherland and Soulsby, 2003) were used to assess the skill of ASMITA in reproducing the observed changes in the different equilibrium conditions. The MSE between the observed and predicted volumes was compared with the MSE for the baseline condition (MSE between observed volumes and initial volume for each element). Positive skill scores indicate that predictions are better than the baseline assumption.

Using mean values of the equilibrium coefficients, predictions for upper and lower flat volume were better than the baseline (Table 5.4). Predictions for the channel were not better than baseline; however, very little change was observed in the channel over the study period, so it is not unexpected that assuming no volume change gives such good predictions. Similarly, predictions based on the end-point equilibrium coefficients were better than baseline for both intertidal flat elements, but worse than baseline for the channel (Table 5.4). Predictions made using end-point equilibrium coefficient for the upper flats (α_{fu}) were closer to the observed volumes in all elements indicating that simulations using the end-point coefficients give better results (Table 5.4).



(a) Predictions using mean values of equilibrium coefficients



(b) Predictions using end-point (1990) values of equilibrium coefficients

Fig. 5.1: Observed and predicted element volumes for the Ribble Estuary using mean and end-point values of equilibrium coefficients

It seems likely that predictions could be improved further if equilibrium coefficients were dynamic functions of the morphology of the estuary, rather then being fixed throughout the simulation. However, the Ribble Estuary is funnel shaped and flood dominant, and has a very different morphology to the tidal inlets for which ASMITA was originally designed. The ability of ASMITA to improve on the baseline for this disparate morphology suggests that ASMITA can be generalised to model diverse morphologies, although some improvements may be needed for more accurate predictions.

Tab. 5.4: Mean Square Error (MSE) between predicted and observed volumes in the Ribble Estuary and Brier's Skill Score (BSS) comparing three different predictions

	V_{fl} (x10^6m^3)	V_{fu} (x10^6m^3)	V_c (x10^6m^3)
MSE (Baseline)	12.73	38.34	3.12
MSE (Mean)	10.16	27.30	35.36
MSE (End-point)	4.26	17.87	18.71
BSS (Baseline, Mean)	0.20	0.29	-10.33
BSS (Baseline, End-point)	0.67	0.53	-5.00
BSS (Mean, End-point)	0.58	0.35	0.47

5.3 Dart

A two element version of ASMITA containing intertidal flat and channel elements was applied to the Dart Estuary (see Fig. 4.8 for schematisation). The equilibrium coefficients for the Dart Estuary tended to change over time (Table 4.5), so three simulations were carried out using mean, initial and end-point values of the equilibrium coefficients. Initial volume and area data (from 1853) and equilibrium relationships are shown in Table 5.5.

Sediment exchange coefficients for the Dart Estuary (Table 5.6) were estimated using equation 3.14. As velocity data were not available for the Dart Estuary, D was estimated based on studies of estuaries in the UK and Europe (Wang, 2005). The vertical exchange coefficient (w_s) was estimated as 0.00002 based on the assumption that sediment in the Dart Estuary is mostly fine mud silt from fluvial sources (Dart Estuary Environmental Management, 2004) (Section 4.3.1). The global equilibrium concentration (C_E) was set to 0.00001 to reflect the limited sediment supply from marine sources.

Tab. 5.5: Initial volume and area data and equilibrium relationships used for Dart simulations. A_n is the area of element n, V_n is its volume and V_{ne} is the elements equilibrium volume based on initial conditions

	A_n (x10^{5}m^2)	V_n (x10^{5}m^3)	Condition	Equilibrium relationship	V_{ne} (x10^{5}m^3)
Flat (f)	12.19	7.57	Mean	$0.03 * Ab * H$	8.73
			Initial	$0.026 * Ab * H$	7.56
			End-point	$0.039 * Ab * H$	11.35
Channel (c)	60.55	295.86	Mean	$0.95 * P$	269.22
			Initial	$1.04 * P$	294.73
			End-point	$0.89 * P$	252.22
Basin (b)	72.74				
Tidal Prism (P)		283.39			

Tab. 5.6: Sediment exchange coefficients used in the Dart Estuary simulations

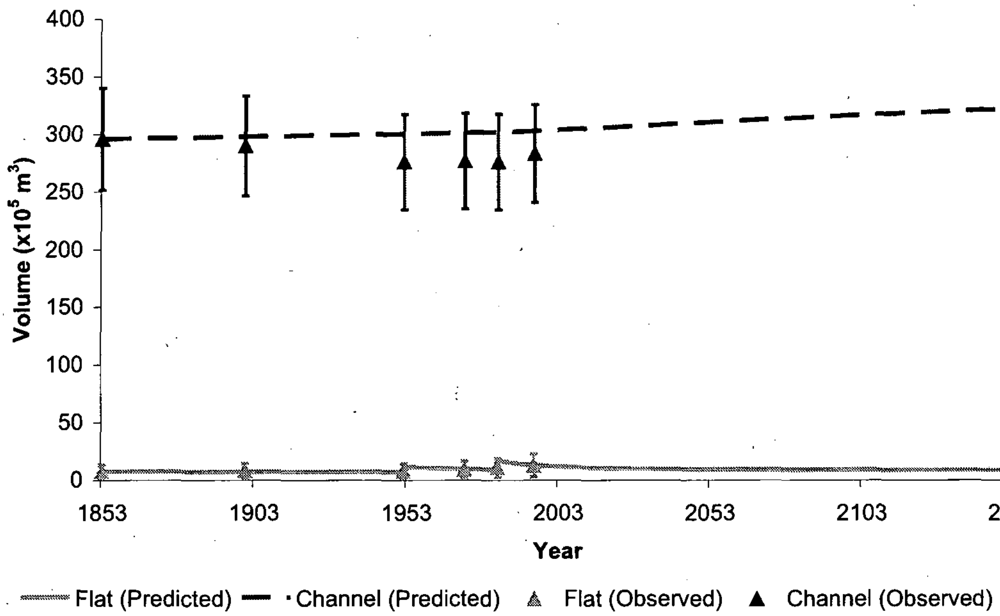
Exchange between	A (m^2)	L (m)	D	δ
Flats, Channel	20000	500	18.75	750
Channel, Outside World	10000	10000	500	500

Observed and predicted volumes for the intertidal flat and channel elements in the Dart Estuary, using mean, initial and end-point conditions to calculate equilibrium coefficients, are shown in figure 5.2. ASMITA predictions are within the error estimates for all three conditions. ASMITA predicts that the channel volume will increase under all three conditions, but this is most noticeable when using the initial value of the equilibrium coefficients.

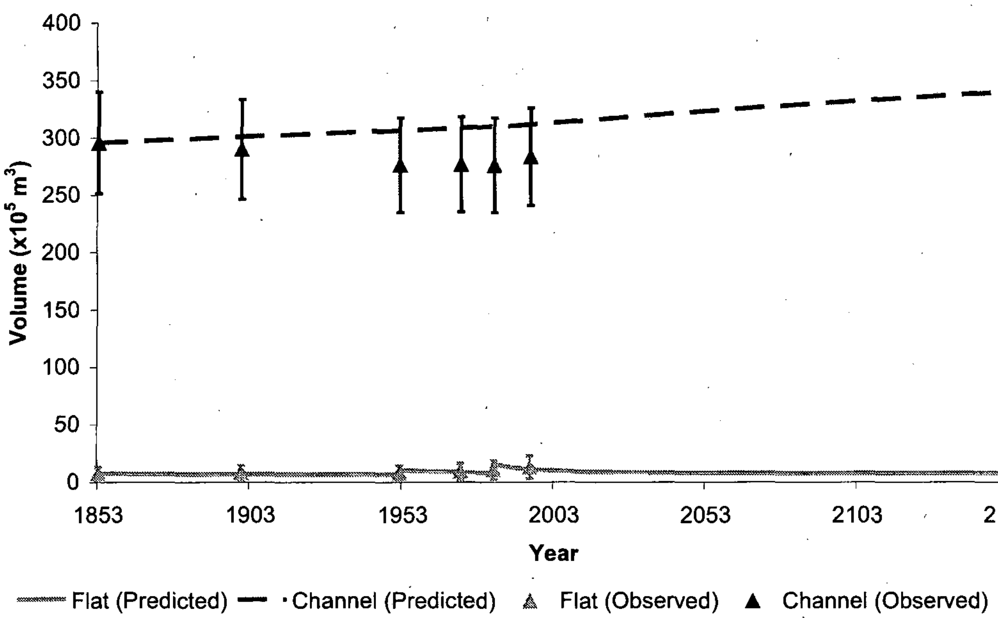
For all conditions, Brier's Skill Scores indicate that ASMITA predictions for the channel were worse than the baseline condition (Table 5.7). ASMITA predictions for the intertidal flat volume were better than the baseline for the simulation using initial conditions to calculate the equilibrium coefficients. In both simulations the volume of the channel was over estimated by ASMITA, however, the changes observed in the Dart Estuary were small compared to the error estimates of the data and this may explain the discrepancy.

Tab. 5.7: Mean Square Error (MSE) between predicted and observed volumes in the Dart Estuary and Brier's Skill Score (BSS) comparing predictions based on different equilibrium assumptions

	V_f (x10^5 m^3)	V_c (x10^5 m^3)
MSE(Baseline)	7.12	217.86
MSE(Mean)	7.35	386.27
MSE(Initial)	5.97	667.89
MSE(End-point)	16.40	258.75
BSS (Baseline, Mean)	-0.03	-0.77
BSS (Baseline, Initial)	0.16	-2.067
BSS (Baseline, End-point)	-1.30	-0.19

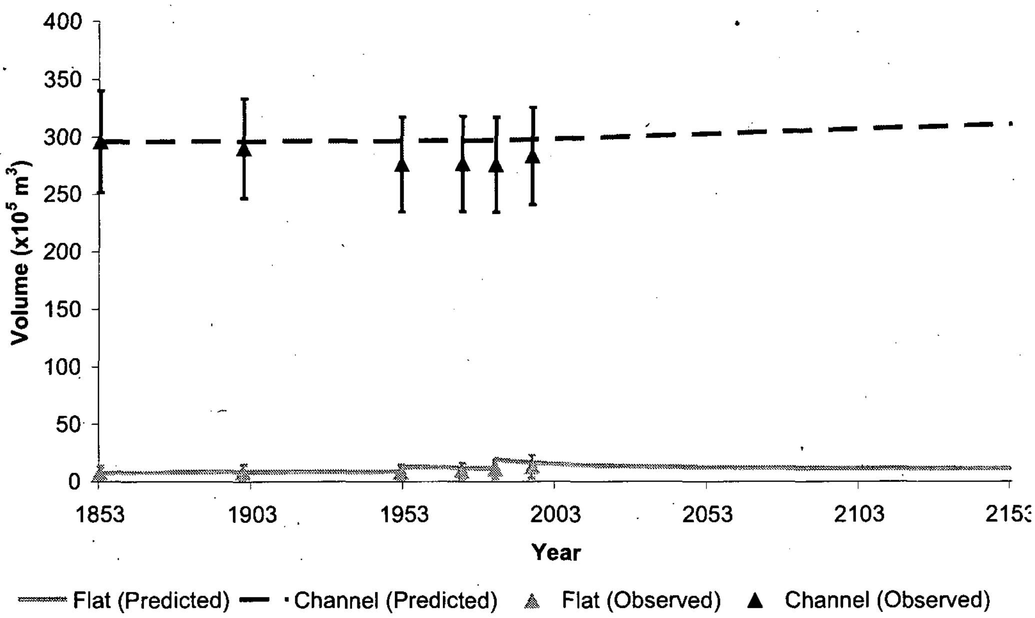


(a) Predictions using mean values of equilibrium coefficients



(b) Predictions using initial values of equilibrium coefficients

Fig. 5.2: Observed and predicted element volumes for the Dart Estuary using mean, initial and end-point relationships to calculate equilibrium volume



(c) Predictions using end-point values of equilibrium coefficients

Fig. 5.2: Observed and predicted element volumes for the Dart Estuary using mean, initial and end-point relationships to calculate equilibrium volume

5.4 Southampton Water

ASMITA was applied to Southampton Water using a four element version consisting of the outer channel, outer flats, inner channel and inner flats (Fig. 4.15a). Two ASMITA simulations were carried out for Southampton Water, using mean and initial equilibrium coefficients to predict the equilibrium volumes of the elements. Initial volume and area data and equilibrium relationships used in the Southampton Water simulations are shown in table 5.8. Model predictions include the effects of managed realignment, by adding or subtracting the relevant areas and volumes at each time step (Appendix B). The effect of running ASMITA without taking account of dredging disturbances is shown in figure 5.4.

ASMITA simulations made using the end-point equilibrium coefficients were also carried out. However, using these coefficients causes element volumes to become negative in ASMITA. This is explained by the combination of high α_c, low α_f and the human induced disturbances (Appendix B) and suggests that the end-point coefficients are artificial values caused by continuing human disturbances.

Tab. 5.8: Initial volume and area data and equilibrium relationships used for Southampton Water simulations. A_n is the area of element n, V_n is its volume and V_{ne} is the elements equilibrium volume based on initial conditions.

	A_n (x10^6m^2)	V_n (x10^6m^3)	Condition	Equilibrium equation	V_{ne} (x10^6m^3)
Outer Channel (c_{outer})	16.17	17.64	Mean	$0.16 * P$	23.74
			Initial	$0.15 * P$	17.81
Outer Flat (f_{outer})	8.10	9.15	Mean/Initial	$0.09 * Ab * H$	8.85
Inner Channel (c_{inner})	5.11	12.2	Mean	$0.98 * P$	28.97
			End-point	$1.46 * P$	43.17
			Initial	$0.41 * P$	12.12
Inner Flats (f_{inner})	5.00	11.38	Mean	$0.19 * Ab * H$	7.78
			End-point	$0.03 * Ab * H$	1.23
			Initial	$0.28 * Ab * H$	11.46
Outer Basin (b_{outer})	24.27				
Inner Basin (b_{inner})	10.11				
Tidal Prism (p)		118.71			
Tidal Prism (P_{inner})		29.57			

The sediment exchange coefficients for Southampton Water (Table 5.9) were estimated using Eq. 3.14. Velocity data were not available so D was taken from earlier studies of Southampton Water using a similar model, ESTMORF (Wang, 2000). The vertical exchange coefficient (w_s) was set to 0.0003 assuming the sediment grain size can be categorised as silt and the global equilibrium concentration (C_E) was 0.00015 (Wang, 2000). The horizontal exchange coefficient was greatest between the outer channel and the outside world and decreased upstream. Exchange between the inner

Tab. 5.9: Sediment exchange coefficients used in the Southampton Water simulations

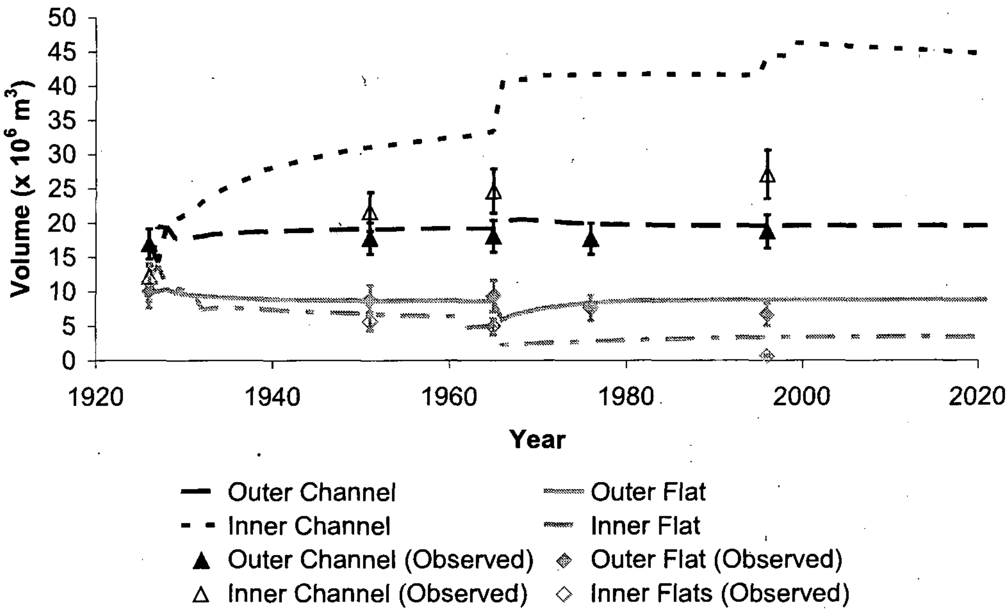
Exchange between	A (m^2)	L (m)	D	δ
Outer Channel, Outside World	9827	4000	500	1228
Outer Channel, Outer Flats	40000	1250	5	160
Outer Channel, Inner Channel	60000	8000	15	112
Inner Channel, Inner Flats	30000	500	1	60

channel and inner flat is smallest due to the limited area for exchange and a low estimated value of D. Wang (2000) assumed there was no exchange between these elements as little exchange can be measured in reality. It should also be noted that the area available for exchange (A) has decreased over time as the intertidal area has been reduced by reclamation and erosion. This suggests that the rate of sediment exchange between the inner flat and inner channel is likely to have decreased over time, so no single value for the horizontal exchange coefficient will accurately describe the exchange throughout the simulation period. The horizontal exchange coefficient should therefore be viewed as an estimate representing a time averaged sediment exchange rate.

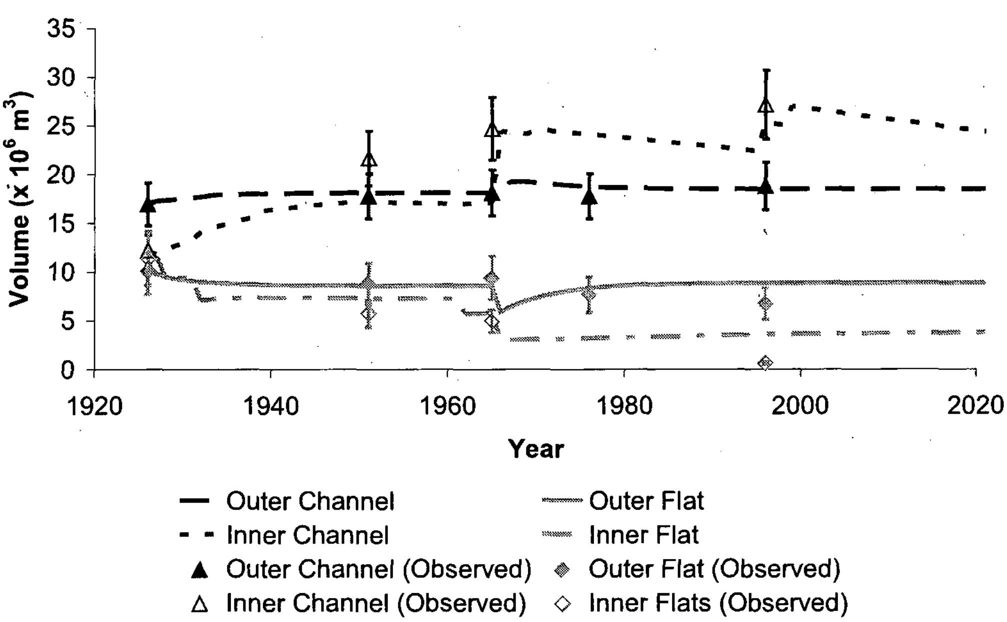
Observed and predicted element volumes for Southampton Water, using mean and initial equilibrium coefficients, are shown in figure 5.3. The most obvious difference between the two conditions is in the inner channel element. Using mean equilibrium coefficients, ASMITA predicted much larger inner channel volumes than were observed. When initial equilibrium conditions were used, the ASMITA predictions for this element were close to observed volumes. ASMITA predictions for the outer channel, outer flats and inner flats were close to observed volumes under both conditions.

Figure 5.4 shows the predicted evolution of Southampton Water without dredging. This highlights the strong influence dredging has in preventing the estuary from returning to equilibrium. Model simulations using ASMITA suggest that, if maintenance dredging were stopped and no other disturbances occurred, the Inner section of Southampton Water would evolve to an equilibrium morphology similar to the one it is assumed to have shown prior to anthropogenic disturbances over a period of 80 to 100 years.

Table 5.10 compares the Mean Square Error and Brier's Skill Scores for the baseline assumption (volumes reman at initial value) and mean and initial equilibrium coefficients. Using the mean equilibrium coefficients, ASMITA predictions for the inner and outer flats were better than the baseline, but outer and inner channel predictions were worse than baseline. ASMITA predications using initial equilibrium coefficients were better than baseline for all four elements, and were better than predictions based on mean equilibrium coefficients for all elements except the inner flat.



(a) Predictions using mean values of equilibrium coefficients



(b) Predictions using initial values of equilibrium coefficients

Fig. 5.3: Observed and predicted element volumes for Southampton Water using mean and initial relationships to calculate equilibrium volume

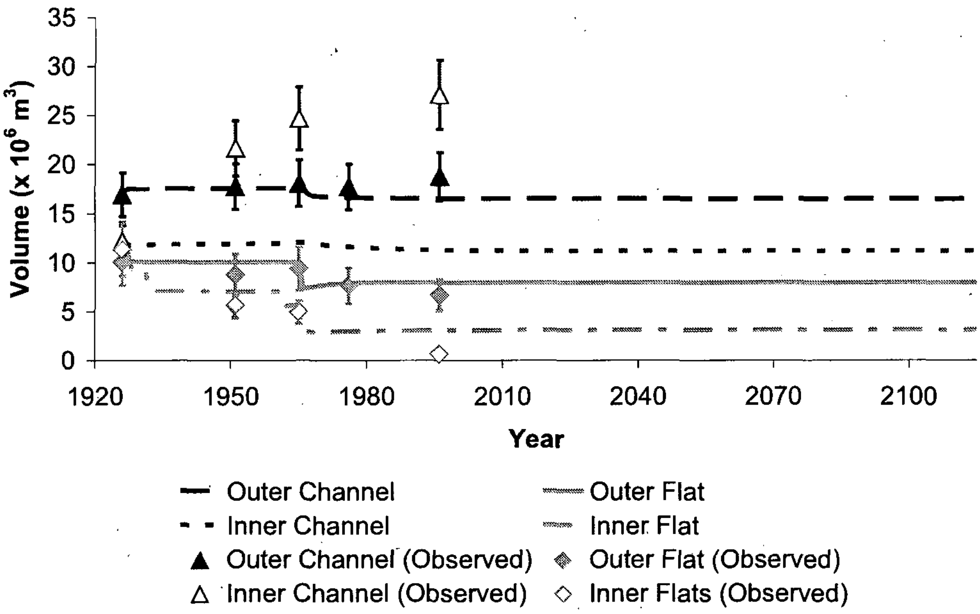


Fig. 5.4: Observed and predicted element volumes for Southampton Water when dredging is not included in ASMITA

Tab. 5.10: Mean Square Error (MSE) between predicted and observed volumes in Southampton Water and Brier's Skill Score (BSS) comparing predictions based different equilibrium assumptions

	V_{Couter} (x10^{6}m^3)	V_{fouter} (x10^{6}m^3)	V_{Cinner} (x10^{6}m^3)	V_{finner} (x10^{6}m^3)
MSE(Baseline)	0.49	0.88	3.61	2.92
MSE(Mean)	0.59	0.47	5.41	0.75
MSE(Initial)	0.22	0.47	2.26	0.87
BSS (Baseline, Mean)	-0.20	0.46	-0.50	0.74
BSS (Baseline, Initial)	0.55	0.47	0.37	0.70
BSS (Mean, Initial)	0.63	0.00	0.58	-0.16

5.5 Portsmouth Harbour

ASMITA was applied to Portsmouth Harbour using a three element version of the model as described in 3.5.1. Three initial simulations were performed using mean, initial and end-point values of the equilibrium coefficients (Table 5.11). These conditions make different assumptions about the equilibrium status of Portsmouth Harbour. Mean equilibrium values assume that, over time, element volume vary around an equilibrium relationship. Initial values assume that Portsmouth Harbour was in equilibrium in 1914, and changes in the equilibrium coefficients can be explained by human disturbances of the system. End-point values assume that Portsmouth Harbour has been out of equilibrium in the past but is evolving towards a new equilibrium (in this case it is assumed that the new equilibrium has been reached by 2004, and that equilibrium relationships for this data also apply to the future evolution of the Harbour).

The initial area and volume data and the equilibrium relationships used for Portsmouth Harbour are given in table 5.11. The equilibrium coefficient for the ebb-tidal delta did not vary significantly over the observed data and the mean value was used for all simulations.

Tab. 5.11: Initial volume and area data and equilibrium relationships used for Portsmouth Harbour simulations. A_n is the area of element n, V_n is its volume and V_{ne} is the elements equilibrium volume based on initial conditions.

	A_n (x10^6m^2)	V_n (x10^6m^3)	Condition	Equilibrium equation	V_{ne} (x10^6m^3)
Flat (f)	11.41	18.52	Mean	$0.17 * Ab * H$	13.54
			Initial	$0.23 * Ab * H$	18.31
			End-point	$0.14 * Ab * H$	11.15
Channel (c)	8.01	32.66	Mean	$0.57 * P$	34.83
			Initial	$0.53 * P$	32.38
			End-point	$0.58 * P$	35.44
Ebb-tidal delta (d)	10.45	8.74	Mean	$0.003 * P^{1.23}$	11.32
Basin (b)	19.42				
Tidal Prism (P)		61.10			

Sediment exchange coefficients were estimated using equation 3.14. The vertical sediment exchange coefficient (w_{sn}) was estimated to be 0.0008 based on a sediment type of fine sand (Bray et al., 2004) and the global equilibrium concentration (C_E) was 0.00003. The horizontal exchange coefficient was greatest between the ebb-tidal delta and the outside world, due the the large area available for exchange and relatively high current speeds. Exchange between the channels and flat was smallest, despite a large area for exchange, as current speeds are estimated to be much lower here.

Tab. 5.12: Sediment exchange coefficients used in the Portsmouth Harbour simulations

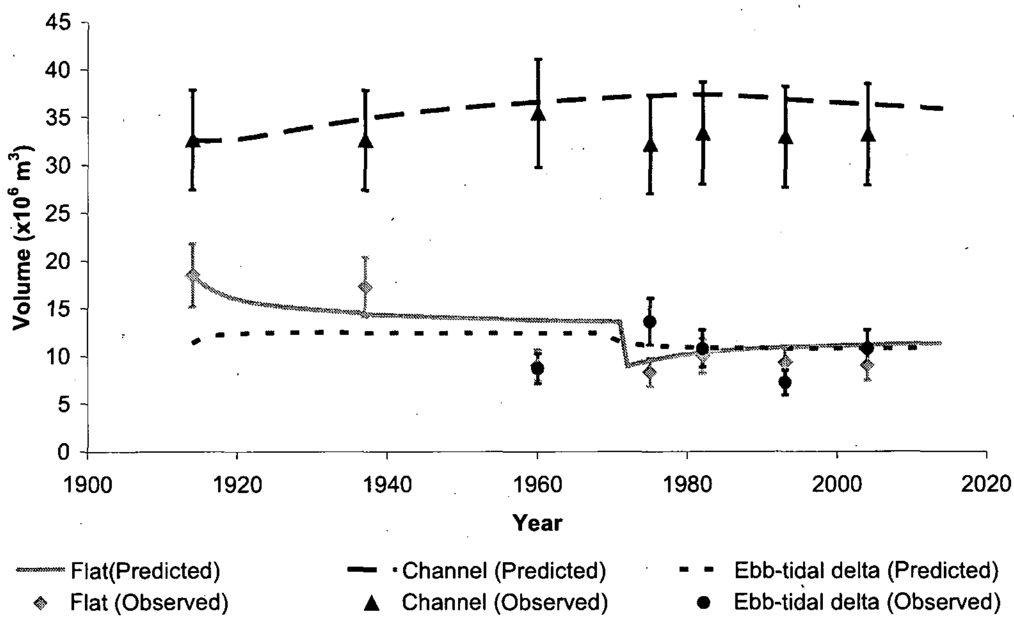
Exchange between	A (m^2)	L (m)	u (ms^{-1})	H (m)	w_{sn}	D	δ
Flat, channel	40000	1200	0.4	0.9	0.0008	18	600
Channel, Ebb-tidal delta	6200	4000	1.1	4.5	0.0008	681	1055
Ebb-tidal delta, Outside World	24000	2000	1	1	0.0008	138	1650

Observed and predicted element volumes for Portsmouth Harbour, using mean, initial and end-point equilibrium coefficients, are shown in figure 5.5. Using the mean equilibrium coefficients, ASMITA predicted the channel volume to be larger than observed, although predictions are within the error estimates of the data. The predictions are close to observations for the intertidal flat element and lie within the error estimates of the data except for in 1960. Observed ebb-tidal delta volumes were more variable and ASMITA does not capture this, although the observed volumes appear to vary around the predicted volumes.

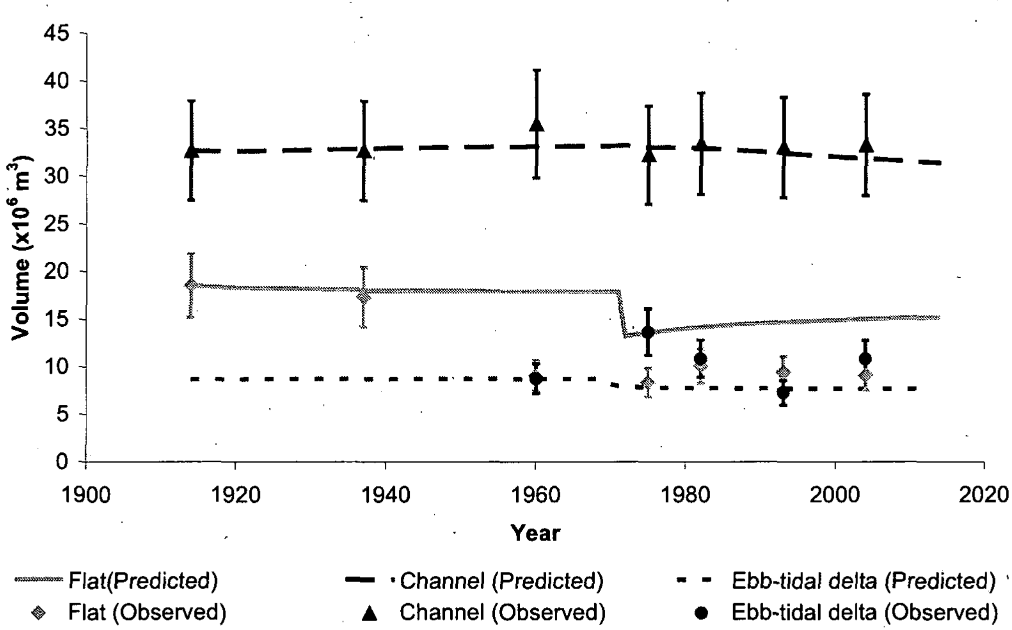
Using initial values of the equilibrium coefficients, ASMITA predictions for the channel element are much closer to the observed volumes. However, the ASMITA predictions for the intertidal flat element are worse under this condition and the majority of predictions are outside of the error estimates. The predictions for the ebb-tidal delta volume tends to under estimate the observed volume in this case.

When end-point equilibrium coefficients are used, ASMITA over predicts the channel volume, with most predictions lying outside the error estimates of the data. The predictions for the intertidal flat are variable; prior to 1974 ASMITA predictions are outside of the error estimates, but for later dates the predictions are a good match to observed data. This could indicate that the equilibrium relationship of the intertidal flats has changed over time, so neither initial nor end-point equilibrium coefficients describe the whole period.

Table 5.13 presents the mean square error and Briers Skill Scores for the baseline and predictions based on all three equilibrium methods. Prediction of the intertidal flat volume is better than baseline for all three equilibrium conditions. Predictions based on the end-point equilibrium coefficients are better than either mean or initial predictions. Model predictions for the channel were worse than the baseline condition for mean and end-point equilibrium coefficients and similar to baseline for initial equilibrium conditions. Little change was observed in the channel element and this explains why the baseline assumption is good relative to the model predictions.



(a) Predictions using mean values of equilibrium coefficients

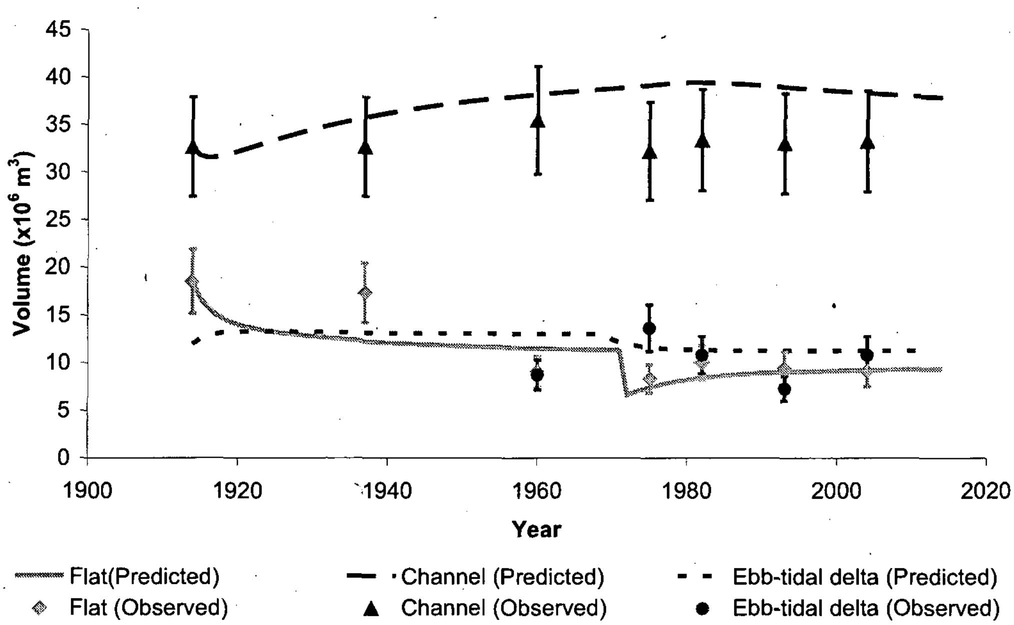


(b) Predictions using initial values of equilibrium coefficients

Fig. 5.5: Observed and predicted element volumes for Portsmouth Harbour using mean, initial and end-point relationships to calculate equilibrium volume

Tab. 5.13: Mean Square Error (MSE) between predicted and observed volumes in Portsmouth Harbour and Brier's Skill Score (BSS) comparing predictions based on different equilibrium coefficients

	V_f (x10^{6}m^3)	V_c (x10^{6}m^3)	V_d (x10^{6}m^3)
MSE(Baseline)	2.99	0.43	3.35
MSE(Mean)	0.89	1.23	0.80
MSE(Initial)	1.94	0.43	1.04
MSE(End-point)	0.85	1.82	0.88
BSS (Baseline, Mean)	0.70	-1.88	0.76
BSS (Baseline, Initial)	0.35	-0.01	0.69
BSS (Baseline, End-point)	0.72	-3.27	0.74
BSS (Mean,Initial)	-1.18	0.65	-0.3
BSS (Mean, End-point)	0.045	-0.48	-0.1
BSS (Initial, End-point)	0.56	-3.23	0.15



(c) Predictions using end-point values of equilibrium coefficients

Fig. 5.5: Observed and predicted element volumes for Portsmouth Harbour using mean, initial and end-point relationships to calculate equilibrium volume

5.6 Langstone Harbour

ASMITA was applied to Langstone Harbour using a three element version of the model as described in 3.5.1. No clear trend for change in the equilibrium coefficients for Langstone Harbour was observed (Table 4.11), so simulations were only based on mean and initial equilibrium coefficients. Initial volume and areas were based on 1955 data (Table 5.14).

Sediment exchange parameters for Langstone Harbour were estimated using equation 3.14. The vertical exchange coefficient w_{sn} was estimated to be 0.0003, reflecting the dominantly muddy sediment properties and tendency for finer sediments than Portsmouth harbour (Bray et al., 2004). The global equilibrium concentration (C_E) was 0.00003. The horizontal exchange coefficient was greatest between the ebb-tindal delta and the outside world and smallest between the flat and channel elements.

Observed and predicted element volumes for Langstone Harbour, using mean and initial equilibrium coefficients, are shown in figure 5.6. There is a large amount of variability in the observed data, particularly in the intertidal flat element and ASMITA predictions for both mean and initial equilibrium conditions are only just within the error estimates of the observed intertidal flat volumes. Predicted volume for the channel and ebb-tidal delta elements appear to be closer to the observed volumes under the mean condition than under the initial condition.

Tab. 5.14: Initial volume and area data and equilibrium relationships used for Langstone Harbour simulations. A_n is the area of element n, V_n is its volume and V_{ne} is the elements equilibrium volume based on initial conditions.

	A_n (x10^6m^2)	V_n (x10^6m^3)	Condition	Equilibrium equation	V_{ne} (x10^6m^3)
Flat (f)	12.69	19.18	Mean	$0.23 * Ab * H$	18.47
			Initial	$0.24 * Ab * H$	19.27
Channel(c)	6.43	11.15	Mean	$0.22 * P$	13.45
			Initial	$0.18 * P$	11.00
Ebb-tidal delta (d)	9.70	11.77		$0.003 * P^{1.23}$	11.33
Basin (b)	19.22				
Tidal Prism (P)		61.12			

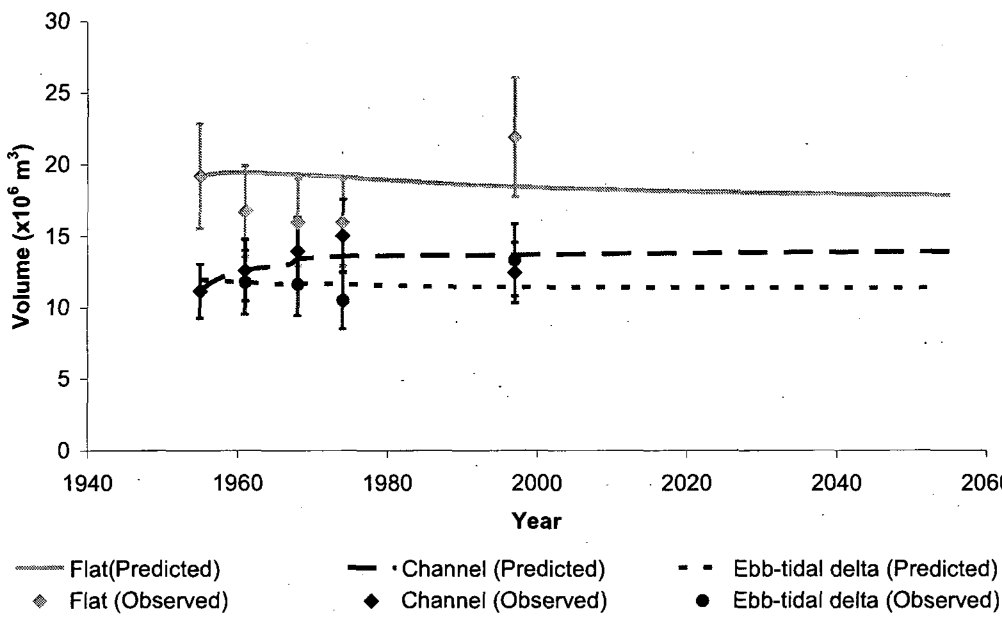
Tab. 5.15: Sediment exchange coefficients used in the Langstone Harbour simulations

Exchange between	A (m^2)	L (m)	u (ms^{-1})	H (m)	w_{sn}	D	δ
Flat, channel	18000	1500	0.4	0.6	0.0003	29	346
Channel, Ebb-tidal delta	4700	4500	1.1	2	0.0003	718	750
Ebb-tidal delta, Outside World	24000	3000	0.8	0.8	0.0003	150	1201

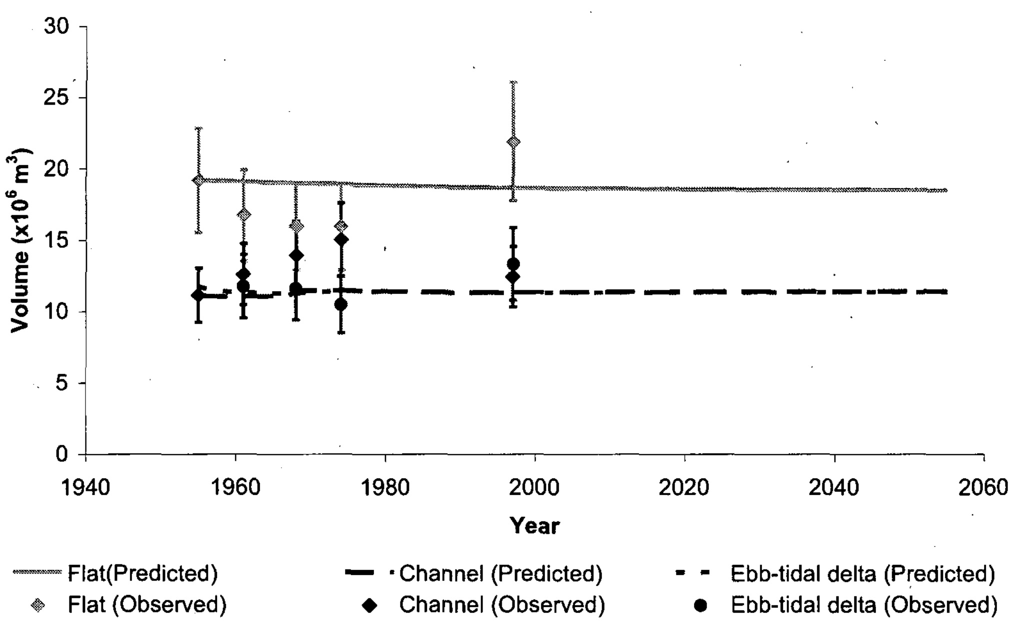
Brier's Skill Scores comparing ASMITA predictions with a baseline condition, in which the element volumes are assumed to remain constant at their initial values, suggest that ASMITA predictions using the mean equilibrium coefficients are slightly worse than the baseline for the flat and ebb-tidal delta elements, but better than baseline for the channel (Table 5.19). Using the initial equilibrium coefficients, ASMITA predictions score the same as the baseline for the intertidal flats, slightly better than baseline for the channel and slightly worse than baseline for the ebb-tidal delta (Table 5.19). In general, BSS scores indicate that the initial condition gives predictions that are a worse match to observed volumes than mean conditions for the channel and ebb-tidal delta elements. Flat predictions are slightly better using initial conditions compared with mean conditions.

Tab. 5.16: Mean Square Error (MSE) between predicted and observed volumes in Langstone Harbour and Brier's Skill Score (BSS) comparing predictions based on different equilibrium coefficients

	V_f (x10^{6}m^3)	V_c (x10^{6}m^3)	V_d (x10^{6}m^3)
MSE(Baseline)	1.17	1.03	0.40
MSE(Mean)	1.27	0.39	0.44
MSE(Initial)	1.17	0.94	0.45
BSS (Baseline, Mean)	-0.09	0.62	-0.10
BSS (Baseline, Initial)	0.00	0.09	-0.13
BSS (Mean, Initial)	0.08	-1.40	-0.02



(a) Predictions using mean values of the equilibrium coefficients



(b) Predictions using initial values of equilibrium coefficients

Fig. 5.6: Observed and predicted element volumes for Langstone Harbour using mean and initial (1955) relationships to calculate equilibrium volume

5.7 Chichester Harbour

ASMITA was applied to Chichester Harbour using a three element version of the model as described in 3.5.1. No trend for change in the equilibrium coefficients was observed and mean coefficients were similar to initial ones. Therefore, only one simulation, using mean equilibrium coefficients, was performed. The initial area and volume data, and equilibrium relationships, are given in table 5.17.

Sediment exchange coefficients were estimated as described in 3.5.2. Chichester Harbour has generally muddy sediments with a high proportion of silt and clay (Bray et al., 2004), so the vertical exchange coefficient (w_s) was set to 0.0002. The global equilibrium concentration was 0.00003, the same as neighbouring Langstone Harbour. The horizontal exchange coefficients (δ) were estimated using equation 3.14.

ASMITA predictions fell within the error estimates of the observed data for all three elements (Fig. 5.7). Observed volumes were variable, particularly for the intertidal flat element, but appear to vary around a mean value. A Brier's Skill Score comparing the skill of the ASMITA predictions with the baseline condition suggest that ASMITA predictions were no better than assuming the element volumes remained constant at their initial values for the flat and channel elements. ASMITA predictions for the ebb-tidal delta were better than the baseline condition. The relatively poor performance of ASMITA in this case is due to the lack of net change over time, meaning that the baseline assumption of no change describes the data fairly well.

Tab. 5.17: Initial volume and area data and equilibrium relationships used for Chichester Harbour simulations. A_n is the area of element n, V_n is its volume and V_{ne} is the elements equilibrium volume based on initial conditions.

	A_n (x10^6m^2)	V_n (x10^6m^3)	Equilibrium equation	V_{ne} (x10^6m^3)
Flat (f)	17.50	28.15	$0.23 * Ab * H$	28.49
Channel (c)	11.99	24.64	$0.26 * P$	24.88
Ebb-tidal delta (d)	15.31	17.19	$0.00258P^{1.23}$	16.39
Basin (b)	29.49			
Tidal Prism (P)		95.71		

Tab. 5.18: Sediment exchange coefficients used in the Chichester Harbour simulations

Exchange between	A (m^2)	L (m)	u (ms^{-1})	H (m)	w_s	D	δ
Flat, Channel	60000	2000	0.4	0.4	0.0002	31	941
Channel, Ebb-tidal delta	8000	4500	0.8	2	0.0002	563	1001
Ebb-tidal delta, Outside world	20000	4000	1	0.8	0.0002	400	2000

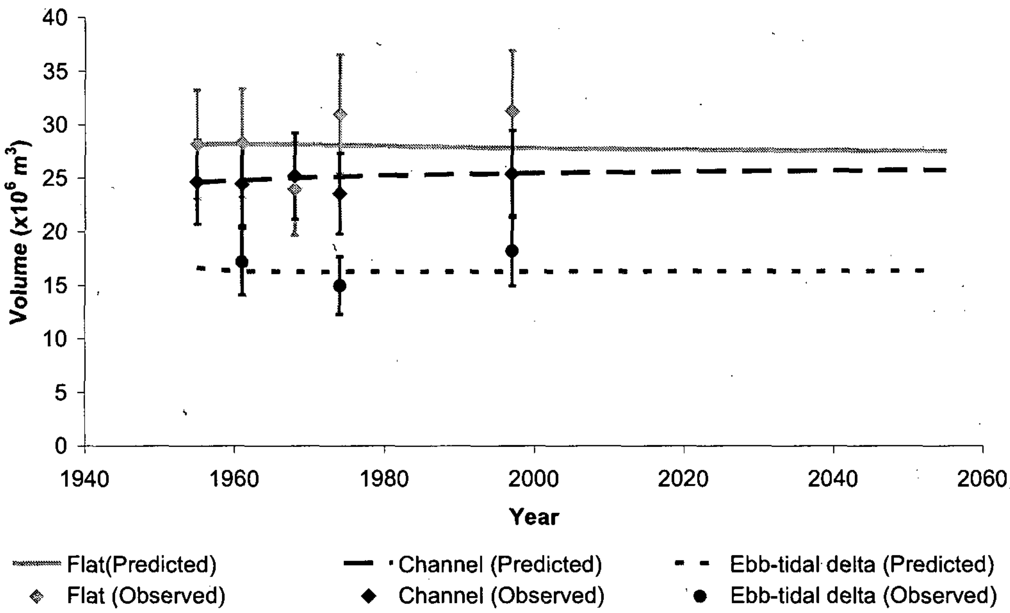


Fig. 5.7: Observed and predicted volumes in Chichester Harbour using mean values of the equilibrium coefficients

Tab. 5.19: Mean Square Error (MSE) between predicted and observed volumes in Chichester Harbour and Brier's Skill Score (BSS) comparing predictions based on mean equilibrium coefficients with the baseline condition (volumes remain constant at initial values)

	V_f (x10^{6}m^3)	V_c (x10^{6}m^3)	V_d (x10^{6}m^3)
MSE(Baseline)	1.18	0.29	5.84
MSE(Mean)	1.22	0.33	0.49
BSS (Baseline, Mean)	-0.04	-0.13	0.92

5.8 Thames Estuary

ASMITA was applied to the Thames Estuary using a six-element version of the model (Fig. 4.32). This reflects the different characteristics of three regions of the Thames Estuary and allows human interventions such as dredging to be specified for each region. Two simulations were carried out, using mean and initial values of the equilibrium coefficients. Initial areas, volumes and equilibrium volumes are shown in table 5.20. Volume and area corrections due to human disturbances (mainly dredging or dumping of sediment) are given in Appendix B.

Sediment exchange coefficients were estimated as described in 3.5.2. Maximum current velocities varied along the estuary and between channel and flat elements (HR Wallingford, 2006a). The vertical exchange coefficients (w_s) was 0.0006 in the inner and mid estuary, reflecting the muddy sediments found here and 0.003 in the sandier outer estuary. Horizontal exchange coefficinets were estimated using equation 3.14.

Predicted and observed volumes for the inner, mid and outer Thames using mean equilibrium coefficients are shown in figure 5.8. In all three regions, predicted intertidal flat volumes are close to observed volumes and little change is observed. Predictions for the channel element also tend to approach observed volumes. Channel predictions are mostly within the error estimates of the observed data, with the exception of some points in the mid estuary (Fig. 5.8b).

Tab. 5.20: Initial volume and area data and equilibrium relationships used for Thames Estuary simulations. A_n is the area of element n, V_n is its volume and V_{ne} is the elements equilibrium volume based on initial conditions.

	A_n (x10^6m^2)	V_n (x10^6m^3)		Equilibrium equation	V_{ne} (x10^6m^3)
Inner Channel	17.84	102.75	Mean	$0.92 * P$	99.71
			Initial	$0.95 * P$	102.96
Inner Flat	6.09	13.66	Mean/initial	$0.11 * AB * H$	13.42
Basin (b)	23.93				
Prism (P)		108.38			
Mid Channel	19.79	153.55	Mean	$0.68 * P$	153.95
			Initial	$0.64 * P$	144.89
Mid Flat	6.21	14.59	Mean/initial	$0.11 * AB * H$	14.59
Basin (b)	26.00				
Prism (P)		226.39			
Outer Channel	35.79	276.87	Mean	$0.51 * P$	258.55
			Initial	$0.55 * P$	278.83
Outer Flat	31.30	61.59	Mean/initial	$0.18 * Ab * H$	61.59
Basin (b)	67.09				
Prism (P)		506.96			

Tab. 5.21: Sediment exchange coefficients used in the Thames Estuary simulations

Exchange between	A (m^2)	L (m)	u (m s^{-1})	H (m)	w_s	D	δ
Inner Channel, Inner Flat	154000	18000	0.5	1.4	0.0006	58	499
Inner Channel, Mid Channel	7200	45000	1.1	8.19	0.0006	1652	264
Mid Channel, Mid flat	66300	2900	0.5	1.42	0.0006	59	1353
Mid Channel, Outer Channel	17379	15500	1.6	10.51	0.0006	4484	5028
Outer Channel, Outer Flat	76500	2500	0.7	1.66	0.003	27	830
Outer Channel, outside World	46350	25000	1.4	10.5	0.003	686	1272

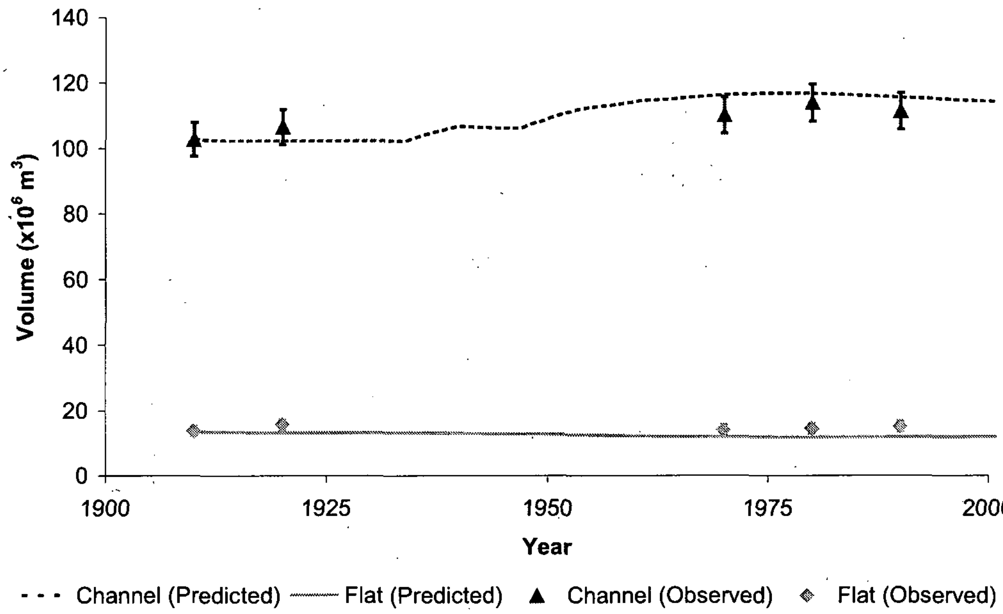
Tab. 5.22: Mean Square Error (MSE) between predicted and observed volumes in the Thames Estuary and Brier's Skill Score (BSS) comparing predictions based on mean equilibrium coefficients with the baseline condition (volumes remain constant at initial values)

	V_{c_o} x10^{6}m^3	V_{f_o} x10^{6}m^3	V_{c_m} x10^{6}m^3	V_{f_m} x10^{6}m^3	V_{c_i} x10^{6}m^3	V_{f_i} x10^{6}m^3
MSE(Baseline)	5.33	1.61	0.61	0.64	3.28	0.53
MSE(Mean)	1.65	1.52	3.38	0.73	1.81	1.10
MSE(Initial)	8.38	1.51	1.22	0.71	2.20	1.01
BSS (Baseline, Mean)	0.69	0.06	-4.54	-0.15	0.45	-1.08
BSS (Baseline, Initial)	-0.57	0.06	-0.99	-0.10	0.33	-0.91
BSS (Mean, Initial)	-4.06	0.00	0.64	0.04	-0.21	0.08

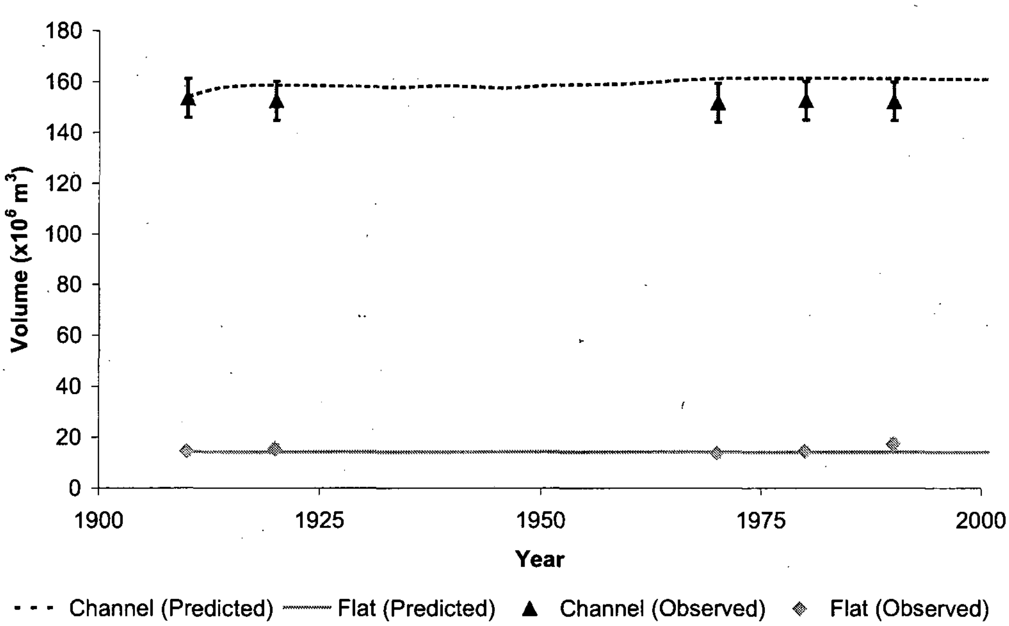
Predictions made using initial equilibrium coefficients are also close to observed volumes for the intertidal flat element in all three regions. Channel predictions for the mid estuary are closer to observed volumes than under the mean condition. Channel predictions for the inner and outer estuary tend to over estimate the observed volumes.

Brier's Skill Scores comparing the skill of ASMITA predictions with the baseline condition (volumes remain constant at initial values) indicates that using mean equilibrium coefficients ASMITA predictions were better than the baseline for the outer channel, outer flat and inner channel (Table 5.22), but similar to or worse than the baseline for the mid channel and flats and for the inner flats. Using initial equilibrium coefficients ASMITA predictions were better than the baseline for the outer flat and inner channel elements only.

Brier's Skill Scores were also used to compare the skill of the ASMITA predictions for the mean and initial equilibrium coefficients (Table 5.22). Predictions made using initial equilibrium coefficients were slightly better than those made using mean equilibrium coefficients in the outer flats, mid channel, mid flats and inner flats.

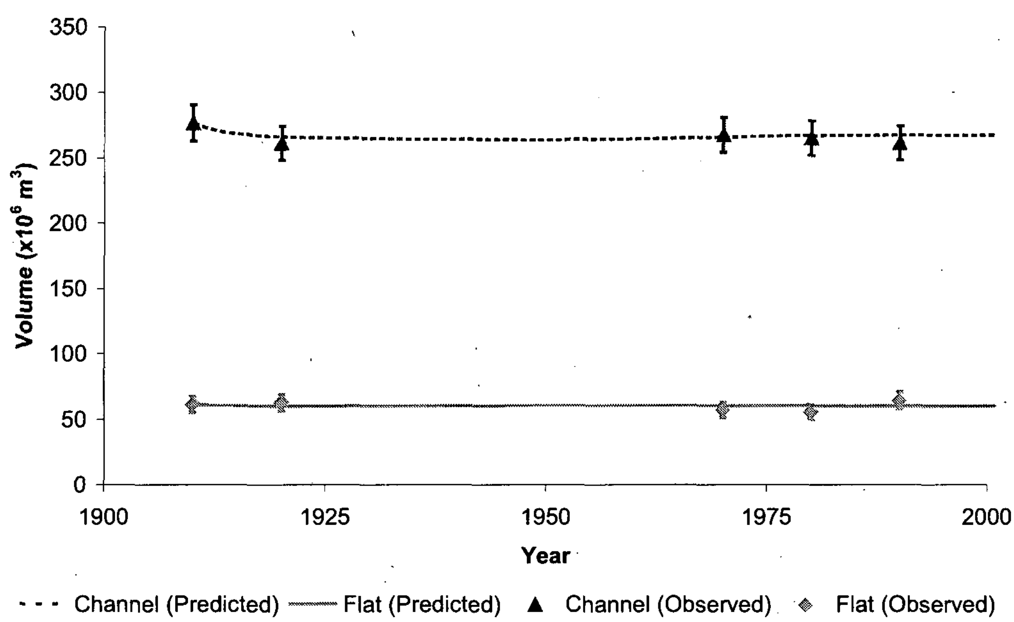


(a) Inner Thames



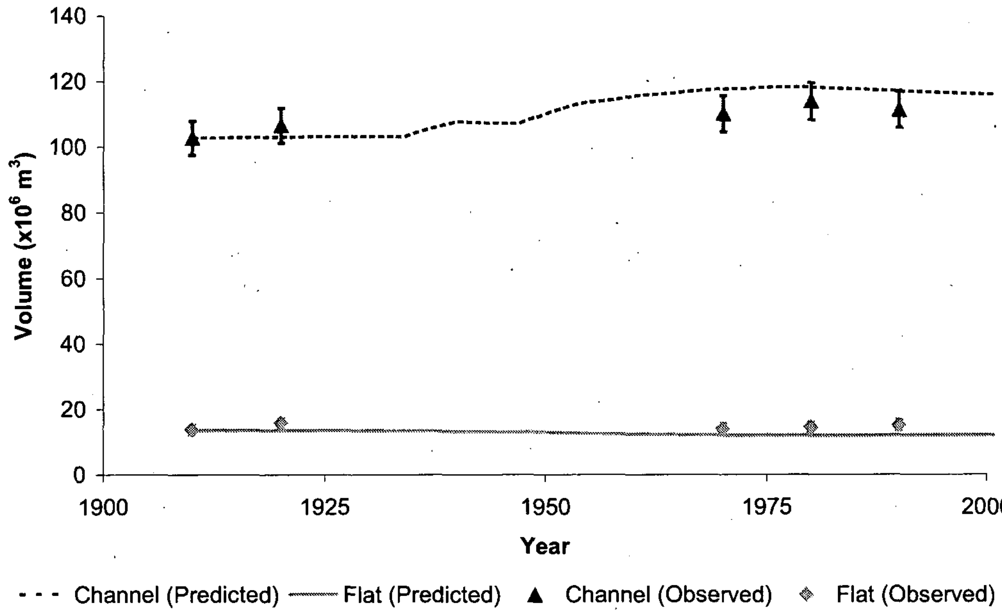
(b) Mid Thames

Fig. 5.8: Observed and predicted element volumes for the Thames Estuary using mean relationships to calculate equilibrium volume

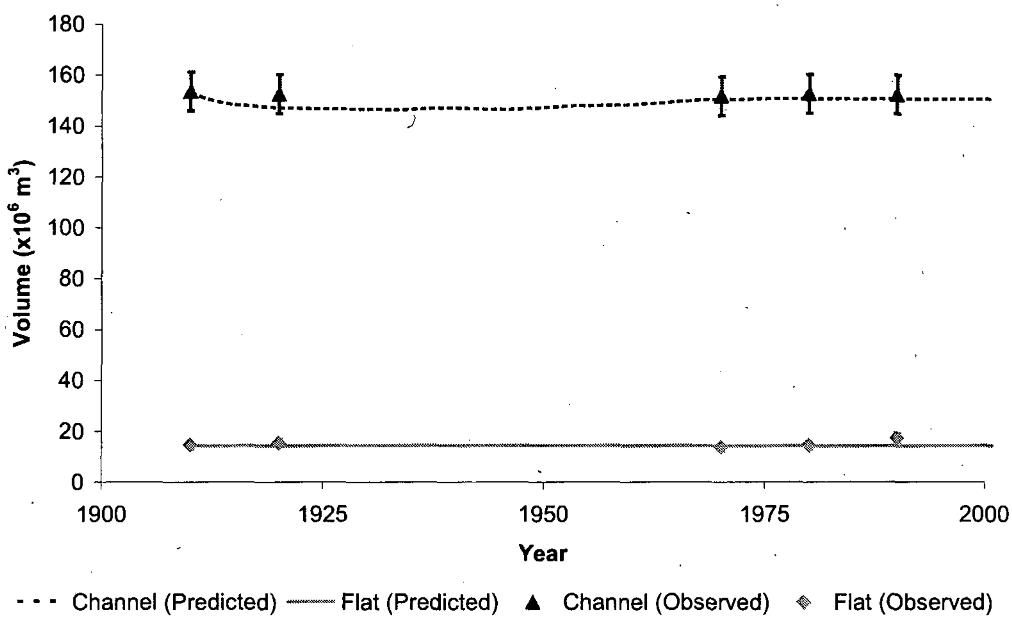


(c) Outer Thames

Fig. 5.8: Observed and predicted element volumes for the Thames Estuary using mean relationships to calculate equilibrium volume

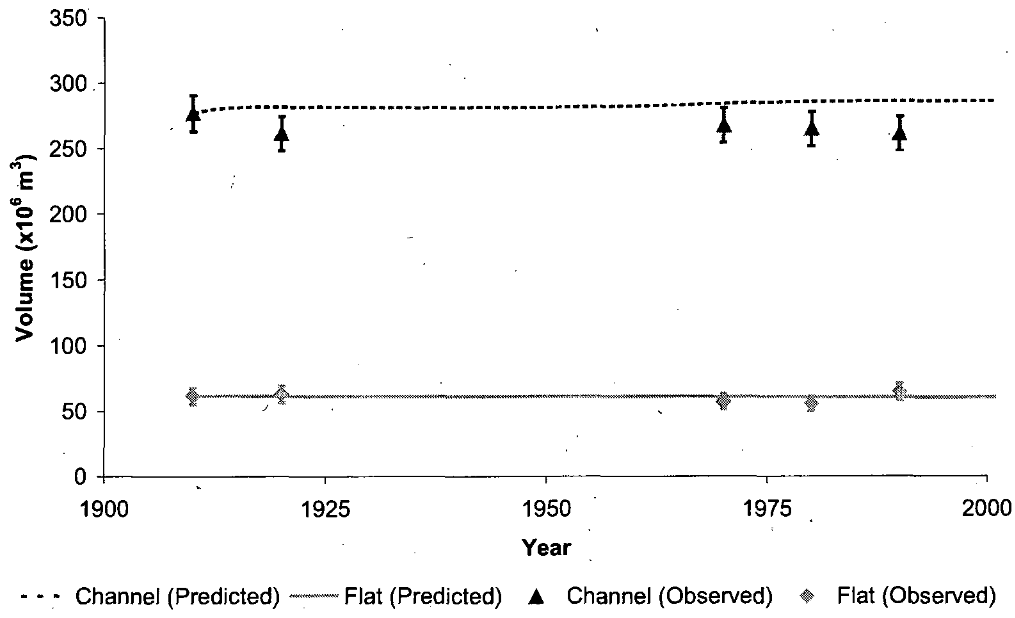


(a) Inner Thames



(b) Mid Thames

Fig. 5.9: Observed and predicted element volumes for the Thames Estuary using initial relationships to calculate equilibrium volume



(c) Outer Thames

Fig. 5.9: Observed and predicted element volumes for the Thames Estuary using initial relationships to calculate equilibrium volume

5.9 Humber Estuary

ASMITA was applied to the Humber Estuary using a two element version of the model containing intertidal flat and channel elements. No trend for change in the equilibrium coefficients was observed and mean coefficients were similar to initial ones (Table 4.13). Only one simulation, using mean equilibrium coefficients, was performed. The initial area and volume data, and equilibrium relationships, are given in table 5.23.

Sediment exchange coefficients were estimated as described in Chapter 3. The vertical exchange coefficient (w_s) was set to 0.0003, reflecting the dominantly muddy

Tab. 5.23: Initial volume and area data and equilibrium relationships used for Humber Estuary simulations. A_n is the area of element n, V_n is its volume and V_{ne} is the elements equilibrium volume based on initial conditions.

	A_n ($x10^6 m^2$)	V_n ($x10^6 m^3$)	Equilibrium equation	V_{ne} ($x10^6 m^3$)
Flat	105.82	292.21	$0.16 * Ab * H$	307.88
Channel	214.89	129.65	$0.8 * P$	130.56
Basin (b)	320.71			
Prism (P)		1632.05		

Tab. 5.24: Sediment exchange coefficients used in the Humber Estuary simulations

Exchange between	A (m^2)	w_{sn}	L (m)	D	δ
Flat, Channel	216000	6000	0.0003	45	1620
Channel, Outside World	103500	72000	0.0003	1000	1440

Tab. 5.25: Mean Square Error (MSE) between predicted and observed volumes in the Humber Estuary and Brier's Skill Score (BSS) comparing predictions based on mean equilibrium coefficients with the baseline condition (volumes remain constant at initial values)

	V_f (x10^6 m^3)	V_c (x10^6 m^3)
MSE(Baseline)	14.70736	14.41346
MSE(Mean)	7.370462	21.72519
BSS (Baseline, Mean)	0.498859	-0.50728

sediments found in the Humber. The global equilibrium concentration (C_E) was 0.0002, and reflects the relatively high sediment concentrations in the sea around the estuary mouth. The horizontal exchange coefficients (δ) were estimated using equation 3.14. The sediment exchange coefficient between the channel and flats was estimated to be slightly larger than between the channel and the outside world because the area available for exchange between the flats and channel is very large, and the length scale of diffusion is relatively small. In contrast, the area available for diffusion between the channel and the outside world is smaller and the length scale of exchange is much larger.

Figure 5.10 shows the observed and predicted element volumes for the Humber Estuary. There was little change in the observed volumes throughout the study period and the ASMITA predictions fall within the error estimates of the observed data. Brier's Skill Scores comparing the skill of the ASMITA predictions with the baseline condition, in which the element volumes are assumed to remain constant at there initial value, suggest that ASMITA was better than the baseline assumption for the intertidal flat element, but slightly worse for the channel element. As with Chichester Harbour, ASMITA predicts the lack of change which is observed from the data, suggesting the model is successfully predicting the behaviour of the estuary.

5.10 Evaluation of Initial Simulations

This section examines two aspects of these simulations: (1) the validity of the dynamic equilibrium relationships used for the study estuaries and (2) the usefulness of their application within ASMITA.

ASMITA performed well for the majority of estuaries, with the exception of some elements in specific estuaries where there has been a high degree of human interfer-

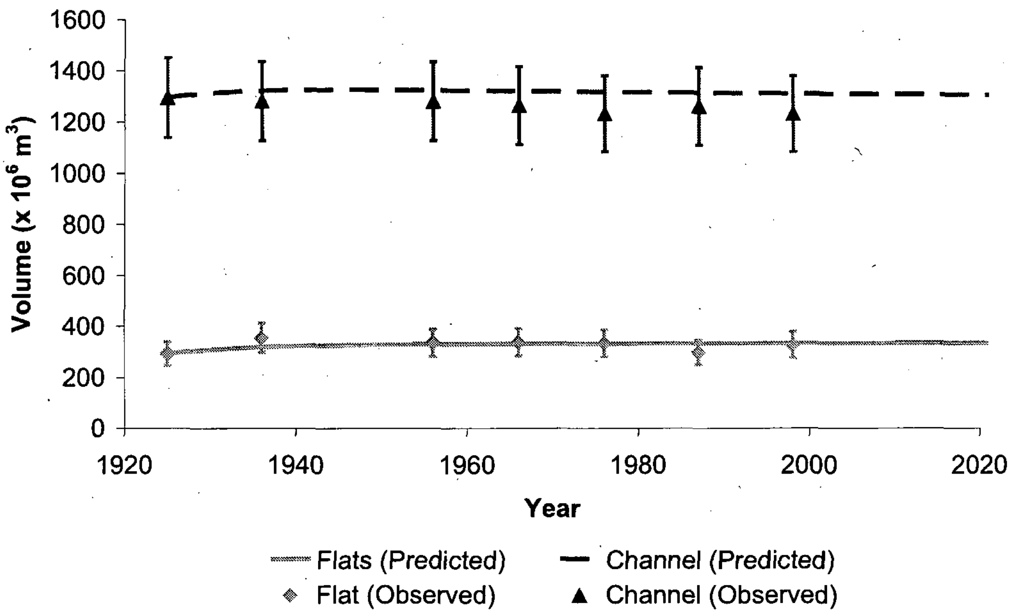


Fig. 5.10: Observed and predicted volumes in the Humber Estuary using mean equilibrium coefficients

ence. In a number of the study estuaries, including the Dart, Thames and Humber Estuaries, little change was observed in element volumes or forcing parameters over time, suggesting that the estuaries are close to dynamic equilibrium. In Langstone and Chichester Harbours, changes were observed but element volumes tended to vary around a mean value and net change was small. The ASMITA predictions based on the dynamic equilibrium relationship were similar to the baseline assumption that element volumes remain constant at their initial value. This reflects the lack of change over time and supports the suggestion that these estuaries are close to there equilibrium states, and therefore significant morphology changes should not be expected. The discussion now focuses on the more dynamic estuaries, where the application of ASMITA adds more to the understanding of the estuary behaviour.

The Ribble Estuary, Southampton Water and Portsmouth Harbour all showed significant changes, well outside uncertainty estimates of the data. For these estuaries, diverse patterns in equilibrium coefficients can be seen. In all three estuaries, ASMITA predictions using the initial equilibrium coefficient for the channel element gave the best fit to the observed data and the ASMITA predictions are better than the baseline assumption. In Southampton Water, the flat elements are also generally well represented by the initial value, except for 1998 when observed flat volumes are especially small (Table 4.8).

In the Ribble estuary, the lower flat element is also well represented by the initial/mean intertidal flat equilibrium coefficient but the upper flat is not. For the upper flat element neither mean nor initial values of the coefficient allow ASMITA to capture the increase in flat volume that was observed. This suggests that a single α_f is not sufficient to describe the flat behaviour over time and α_f varies in response to large human induced changes such as land reclamations and raises the possibility that the intertidal flats display meta-stable equilibrium behaviour (i.e large changes in forcing can cause evolution towards and new dynamic equilibrium relationship). It is also possible that the upper flat element in the Ribble Estuary is affected by waves and wind in ways that are not accounted for in the current equilibrium theory.

A similar pattern is observed in Portsmouth Harbour. The channel is well described using the initial equilibrium coefficient but the intertidal flat volume is not well described by either initial, mean or end-point values. Prior to the large reclamation (Horsea Island in 1972) the intertidal flat volume was best described by the initial equilibrium coefficients. After the reclamation, predictions based on the end-point coefficients are better. Again, this presents the possibility of meta-stable behaviour and supports the idea that α_f may need to change over time especially following large artificial forcing events such as reclamations.

Equilibrium coefficients varied between estuaries (Table 5.26). This indicates that the equilibrium morphology of estuaries will differ between sites and is likely to be influenced by factors not included in the current equilibrium relationship. For the channel element, small values of the equilibrium coefficient indicate that the channel will be small relative to the tidal prism, as observed in the Ribble Estuary. Larger channel equilibrium coefficients indicate larger channels relative to the tidal prism; for example the Dart Estuary has a channel volume that is greater than its prism volume. Similarly, large flat equilibrium coefficients suggest that the equilibrium flat volume will be large relative to tidal range and basin area. Hume and Herdendorf (1988) and Townend (2005) found that cross-section area – tidal prism relationships were improved when the estuaries were grouped with others of a similar morphological type. The study estuaries in the current work deliberately cover a variety of morphological types, with a maximum of three in any single category (Section 3.2). This means that the scope for comparing within categories is limited; however, similarities and differences between the study estuaries may give some insight into the the possibility of generic equilibrium relationships.

The most common morphological type in the study estuary sample is the symmetrical tidal inlet, represented by Portsmouth, Langstone and Chichester Harbours. Initial intertidal flat equilibrium coefficients (α_f) are similar for all three Harbours, ranging between 0.23 in Portsmouth Harbour to 0.26 in Chichester Harbour. Mean and end-point values of α_f were more variable, especially in Portsmouth Harbour, but this may reflect the larger degree of human interference. Channel equilibrium coefficients (α_c) were similar in Langstone and Chichester harbours, but were much larger in Portsmouth Harbour. Again this may reflect the degree of human interference; Portsmouth Harbour channels have undergone capital and maintenance dredging throughout the study period. However, it was observed that ASMITA predictions for Portsmouth Harbour, using initial channel equilibrium coefficients, provided a good fit with the observed data, suggesting that the equilibrium state is adequately described.

The two funnel shaped estuaries, the Ribble and the Thames, are very different and were given different schematisations for the ASMITA simulations. This makes a direct comparison of the equilibrium coefficients difficult. In general it is possible to say that the channel equilibrium coefficient for the Ribble is much smaller than the same coefficient for the Thames Estuary and intertidal flat equilibrium coefficients tend to be much larger in the Ribble than the Thames. Using the same equilibrium coefficients to describe both of these estuaries would not produce satisfactory results due to these large differences.

Southampton Water and the Humber Estuary are both classified as single spit-enclosed estuaries (Dyer, 2002). Again, direct comparison is complicated by the use of different schematisations, but in general the channel equilibrium coefficient is larger in the Humber Estuary than in Southampton Water. This is particularly true when looking at the initial values of the equilibrium coefficients for Southampton Water, which were shown to give the best fit to the observed volumes during the initial simulations. Intertidal flat equilibrium coefficients were similar for the outer part of Southampton Water and the Humber.

Some similarities were observed in equilibrium coefficients of estuaries with similar morphological types. Large differences were also observed, even within this small sample, and it is possible that generic equilibrium relationships based on morphological classification may not be suitable for use in ASMITA. The potential for generic relationships is investigated further in Chapter 6.

In addition to these general comments about the use of equilibrium theory, it is also necessary to evaluate issues specific to ASMITA. ASMITA was originally developed for modelling the interaction of tidal inlets and tidal basins with the adjacent coast, particularly in the Dutch Wadden Sea (Buijsman, 1997; Stive et al., 1998). While tidal inlets and estuaries have many similarities, the UK has a wide variety of estuarine morphologies which differ from tidal inlets.

The tidal basins of the Dutch Wadden Sea have numerous tidal inlets, with the flows through each inlet separated by a basin watershed. At the seaward boundary tidal basins are separated from the open sea by barrier islands or barrier beaches. UK estuaries tend to have single openings to the sea and include inlets with spits, headlands or directly into open water. The morphology of an estuary's connection to the open sea is likely to influence the equilibrium description of the whole estuary as it influences tidal flows, wave penetration and tidal exchange.

Sediment type varies extensively between (and within) UK estuaries depending on the local sediment sources and hydrodynamics. In the Dutch Wadden Sea, the sediment is mostly sandy with grain sizes of 125 to 500 μm. This may have significance for the application of ASMITA to muddy estuaries as the erosion and deposition of cohesive sediments is more complicated than the behaviour of sand. The possibility of different vertical exchange coefficients controlling the deposition and erosion of cohesive sediments was investigated as part of this PhD. This work is not reported here because the addition of extra sediment exchange parameters adds greater uncertainty to the parameter estimations and hence the modelling results.

UK estuaries differ from the basins of the Dutch Wadden Sea in the degree of fluvial influence. River flow into the Dutch Wadden Sea is small relative to tidal volume and has generally not been included in ASMITA simulations of the area (van Goor et al., 2003). In the UK, fluvial influence varies between estuaries, but in some cases (e.g. the Dart Estuary) may contribute significant volumes of water relative to the tidal prism. In some cases, fluvial sediment may also be important although generally this is thought to contribute less than 5% of the total sediment budget to UK estuaries (Morris, 2007). Fluvial flows and sediment supplies can be included in ASMITA and will be included in further model simulations where appropriate. Currently fluvial flows in ASMITA are capable of carrying sediment, but do not add to the tidal prism and therefore do not influence the equilibrium morphology of the estuary.

As observed by other authors (van Goor et al., 2003), a possible shortcoming of ASMITA is the assumption that the area of the elements and the basin as a whole is assumed to be constant throughout the simulation, unless it is altered through human interference. In a number of the study estuaries, element area is observed to vary over time and is not always a direct result of human interference. This raises the issue of whether an equilibrium area, as well as an equilibrium volume, can be specified in ASMITA and whether this improves the model predictions. In addition, information about area change may be more meaningful for estuary management than volume changes as it can be directly related to the issue of habitat loss. The possibility of equilibrium areas is investigated further in Chapter 6.

5.11 Concluding Thoughts

ASMITA performed well for the majority of the study estuaries. Five out of the eight estuaries appear to be close to dynamic equilibrium and have experienced little change over the study period (Dart, Thames, Humber) or have tended to vary around a mean value (Langstone Harbour and Chichester Harbour). The remaining three estuaries have been extensively modified by human interventions and showed considerable variations with respect to there equilibrium status. Even within these disturbed systems, the behaviour of the channel element was well described by ASMITA, suggesting equilibrium could be defined for the channels. The intertidal flat element however, appeared to be more sensitive to human interference and did not tend to evolve towards the same equilibrium relationship following disturbances,

Tab. 5.26: Summary of morphological type and equilibrium coefficients for the eight study estuaries

Estuary	Morphological type	Tidal Range	Element	Condition	Equilibrium coefficient
Ribble Estuary	Funnel Shaped	7.9	Channel		0.06
			Lower flat		0.19
			Upper flat	Initial	0.12
				Mean	0.2
				End-point	0.28
Dart Estuary	Ria	4	Channel	Initial	1.04
				Mean	0.95
				End-point	0.89
			Flat	Initial	0.026
				Mean	0.031
				End-point	0.039
Southampton Water	Single spit enclosed	4.05	Outer Channel	Initial	0.15
				Mean	0.16
			Outer Flat		0.09
			Inner Channel	Initial	0.41
				Mean	0.98
				End-point	1.46
			Inner Flat	Initial	0.28
				Mean	0.19
				End-point	0.03
Portsmouth Harbour	Tidal inlet	4.1	Channel	Initial	0.53
				Mean	0.57
				End-point	0.58
			Flat	Initial	0.23
				Mean	0.17
				End-point	0.14
Langstone Harbour	Tidal inlet	4.2	Channel	Initial	0.18
				Mean	0.22
			Flat	Initial	0.24
				Mean	0.23
Chichester Harbour	Tidal Inlet	4.2	Channel		0.23
			Flat		0.26
Thames Estuary	Funnel Shaped	5.1	Outer Channel	Initial	0.55
				Mean	0.51
			Outer Flat		0.18
			Mid Channel	Initial	0.64
				Mean	0.68
			Mid Flat		0.11
			Inner Channel	Initial	0.95
				Mean	0.92
			Inner Flat		0.11
			Channel	Initial	1.05
				Mean	1.02
			Flat		0.15
Humber Estuary	Single spit enclosed	6	Channel		0.8
			Flat		0.16

suggesting the possibility of meta-stable behaviour. Intertidal flats may require different equilibrium relationships to account for this.

There was considerable variation in the observed dynamic equilibrium relationships between different estuaries. This was true even when estuaries of the same morphological type were compared and may make it difficult to use generic equilibrium relationships within ASMITA.

6. EQUILIBRIUM ANALYSIS

Defining dynamic equilibrium relationships is fundamental to the ASMITA concept. Generic equilibrium relationships are needed to make ASMITA more widely useable, especially in areas with limited data. This section investigates the potential for generic relationships for a large sample of English and Welsh estuaries and compares these relationships with those derived for the study estuaries. In addition, the intertidal flat equilibrium coefficient is examined in detail in order to assess whether dynamic α_f values can be used, particularly following human induced disturbances.

6.1 Generic Relationships in UK Estuaries

In order to investigate possible generic dynamic equilibrium relationships a number of linear regression analyses were performed between pairs of estuary parameters for a sample of English and Welsh estuaries. The regressions performed are listed in table 6.1 along with comments on the reasons for the selection and earlier work using these relationships.

6.1.1 Data

The estuary sample uses data published in the Estuaries Database (EMPHASYS, 2000). The data in the Estuaries Database are subject to high error estimates. Townend (2005) compared nine estuaries in the Estuaries Database with higher quality data sets and found that the surface area at mean high water could differ between the two data sets by up to 113% . Surface area at low water and water volumes were found to be up to 35% different from higher quality data sets. Despite extremely high error potential, use of this data set is justified on the grounds that no other data set is available that contains the volume and area data needed to carry out this analysis.

The Estuaries Database sample was filtered to remove estuaries if the area differed significantly from area estimates published in other sources including FutureCoast (Dyer, 2002). Whilst this removes the most obvious discrepancies, it is important to remember that the error for the remaining estuaries may still be significant. The sample used for this analysis consisted of 53 estuaries and included all of the study estuaries in this thesis except the Humber, which the Estuaries Database reported to be more than double its area calculated from Ordnance Survey map data for the current study (Appendix C).

Tab. 6.1: Summary of dependent and independent variables examined using linear regression (A_b is basin area, H is tidal range and P is tidal prism)

	Dependent Variable	Independent Variable	Comments
1	Element area (A_n)	A_b	Relationships between element areas and basin area have been found by Renger and Partenscky (1974) for basins on the German North Sea coast. Non-linear relationships have been tested for UK estuaries by Townend (2005) (see Chapter 2.3.2).
2	Element volume (V_n)	A_b	Relationships between element volumes and basin area have been found by Renger and Partenscky (1974) for basins on the German North Sea coast. Non-linear relationships have been tested for UK estuaries by Townend (2005) (see Chapter 2.3.2).
3	Flat volume (V_f)	$A_b * H$	This is the relationship used to estimate the flat equilibrium coefficient (α_f) in ASMITA.
4	Element area (A_n)	P	Townend (2005) found a strong non-linear relationship between estuary area and tidal prism for UK estuaries.
5	Element volume (V_n)	P	The relationship between channel volume and tidal prism is used to estimate the channel equilibrium volume in ASMITA. Townend (2005) found a strong non-linear relationship between estuary volume and tidal prism for UK estuaries.
6	Element area (A_n)	P/H	
7	Element volume (V_n)	P/H	To examine whether the relationship between surface area at mean tide level and P/H (Townend, 2005) can be extended to volume.
8	Channel area (A_c)	$A_b^{1.5}$	Renger and Partenscky (1974) found that channel area was proportional to basin area$^{1.5}$ (Eq. 2.3).

6.1.2 Regression Analysis

For all parameters, both linear and power relationships were examined, however, only linear regressions are presented here. r^2 for power regressions were no better than for linear regressions and experiments with a random sub-sample of this data, containing 43 estuaries, indicate that power relationships are very sensitive to on the data used. This is supported by difference between power relationships found in this study, and those found by Townend (2005) using a larger sample from the same database (Chapter 2, Table 2.3). Linear relationships were therefore deemed to be preferable as they are more robust (less sensitive to the data set) than power law relationships.

Figures 6.1 to 6.5 show correlation plots and regressions lines for the relationships described in table 6.1. Regression coefficients and r^2 values are summarised in table 6.2. All relationships tested showed positive correlations but some were stronger then others. Pearson's r values were calculated for each correlation and are also given in table 6.1. All of the correlations are significant to 99% confidence level.

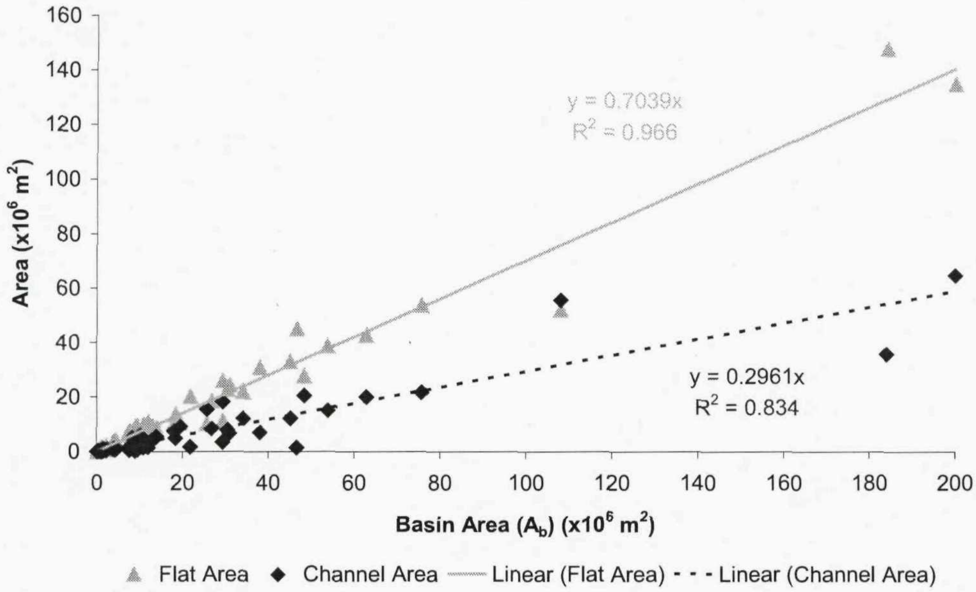
Basin area was found to be a strong predictor of intertidal flat area (Fig. 6.1a), with the data points clustered closely around the regression line (r^2=0.97). The data were less closely fitted to the regression line for channel area, channel volume and intertidal flat volume, but these variables still showed strong relationships with basin area. Intertidal flat volume showed a strong relationship with basin area times tidal range (Fig. 6.2) (r^2=0.95).

Relationships between dependent variables and tidal prism showed more scatter than relationships with basin area, although strong positive correlations were still observed. The weakest relationship was between channel volume and tidal prism. Relationships between dependent variables and tidal prism/tidal range were stronger than relationships with tidal prism alone, with the exception of intertidal flat volume. Tidal prism/tidal range was the strongest predictor of channel area of all the relationships tested.

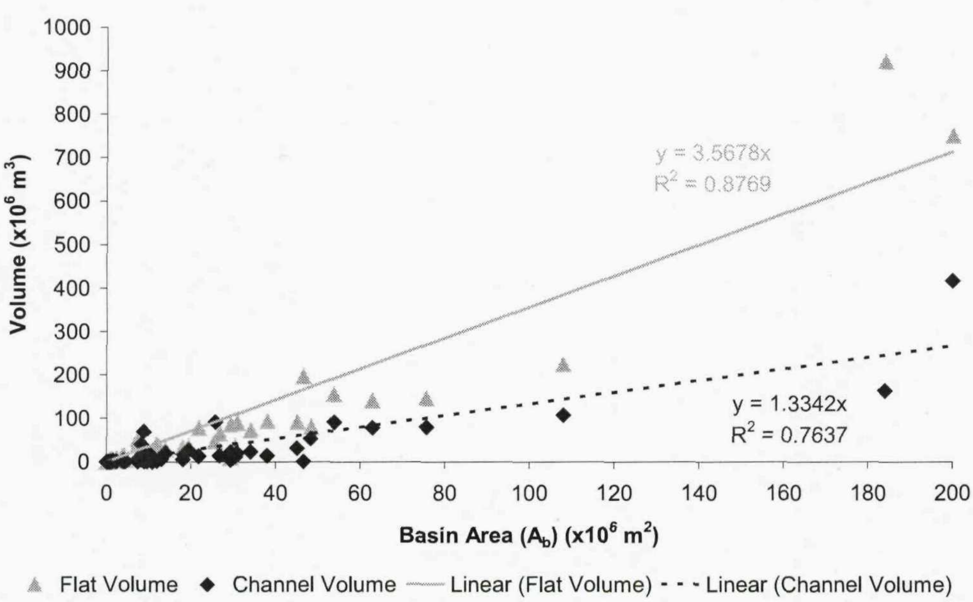
6.1.3 Rias and Spit-Enclosed Estuaries

Hume and Herdendorf (1988) and Townend (2005) found that cross-section area – tidal prism relationships were improved when the estuaries were grouped with others of a similar morphological type. This recognises fundamental differences in estuary morphology that could strongly influence dynamic equilibrium relationships. Using data from the Estuaries Database (EMPHASYS, 2000), only rias (type 3) and spit-enclosed estuaries (type 4) are present in sufficient numbers to be analysed separately (Table 6.3). The other types present, funnel shaped estuaries (type 5) and tidal inlets (type 7), contain too few estuaries for a meaningful regression to be carried out.

Regression coefficients and r^2 values for all sample estuaries, rias and spit-enclosed estuaries are summarised in table 6.4. In general the relationships for



(a) Element Area v Basin Area



(b) Element Volume v Basin Area

Fig. 6.1: Relationship between element area and volume and basin area for sample estuaries

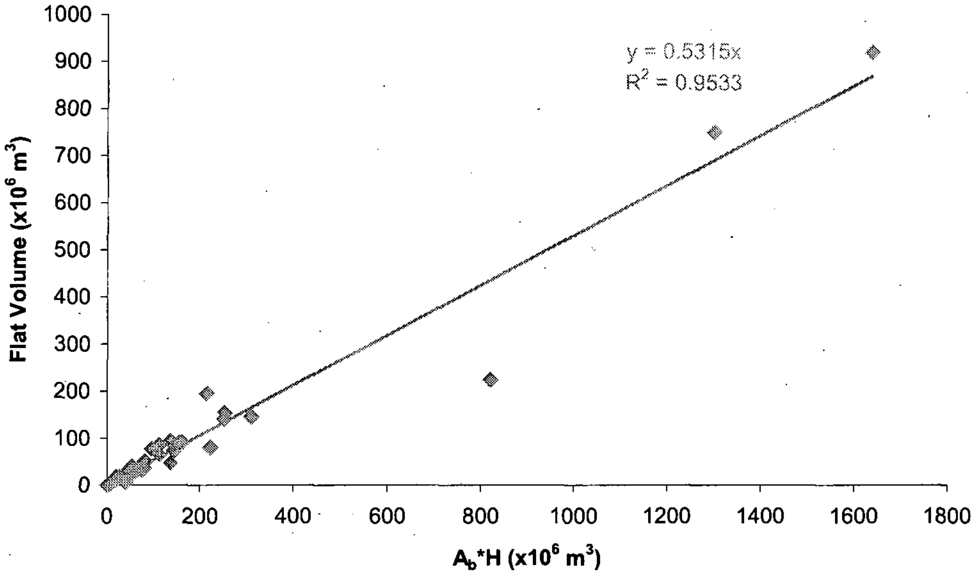
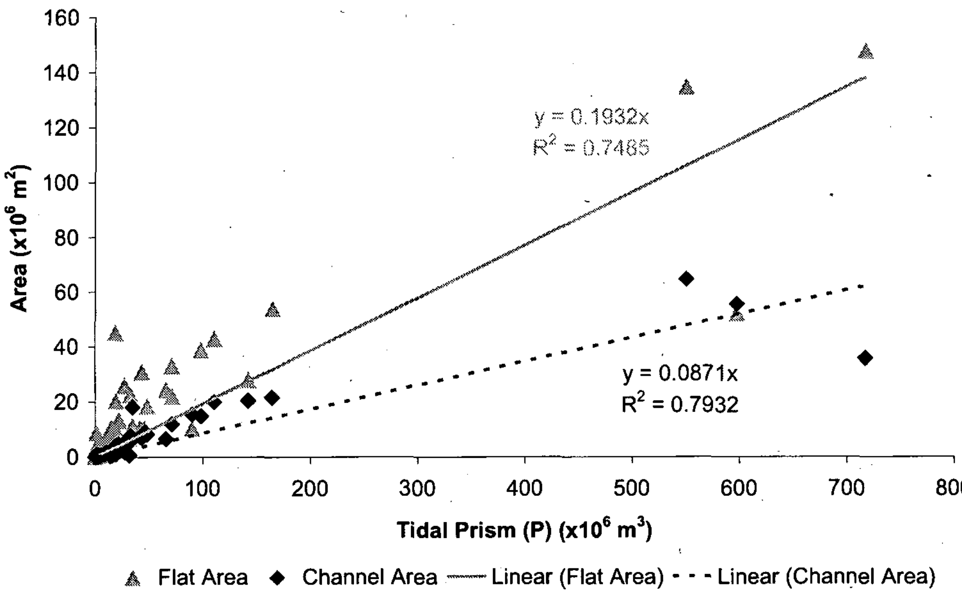


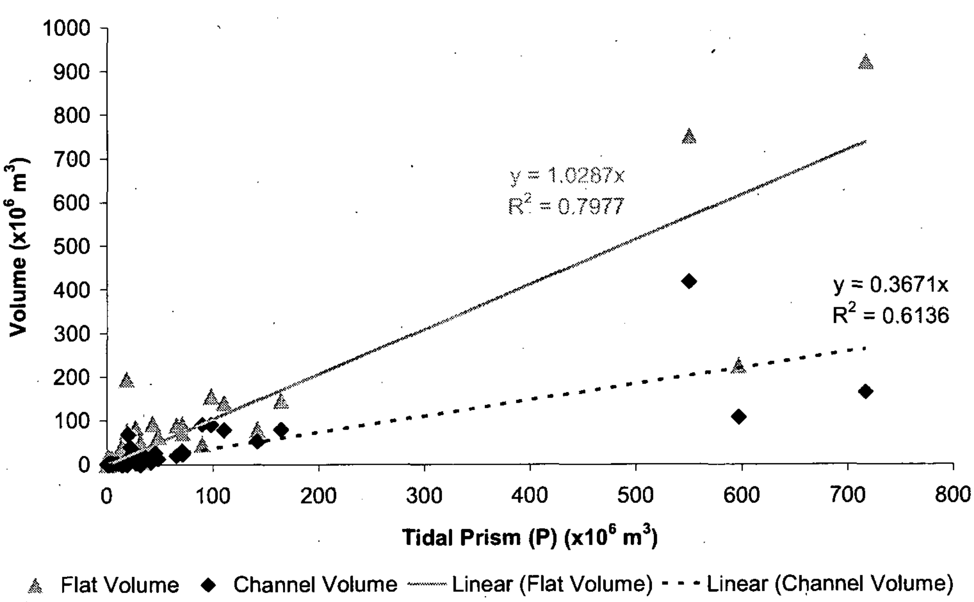
Fig. 6.2: Relationship between flat volume and basin area * tidal range for sample estuaries

Tab. 6.2: Summary of regression slopes and r^2 values for sample estuaries (where $y = mx$)

y	x	m	r^2	Pearson r
A_f	A_b	0.7	0.97	0.96
A_c	A_b	0.3	0.83	0.94
V_f	A_b	3.57	0.88	0.96
V_c	A_b	1.33	0.76	0.94
V_f	$A_b * H$	0.53	0.95	0.94
A_f	P	0.19	0.75	0.72
A_c	P	0.087	0.79	0.98
V_f	P	1.03	0.80	0.89
V_c	P	0.37	0.61	0.97
A_f	P/H	1.37	0.80	0.88
A_c	P/H	0.64	0.94	0.99
V_f	P/H	6.85	0.72	0.96
V_c	P/H	2.68	0.70	0.99
A_c	$A_b^{1.5}$	0.00005	0.72	0.99

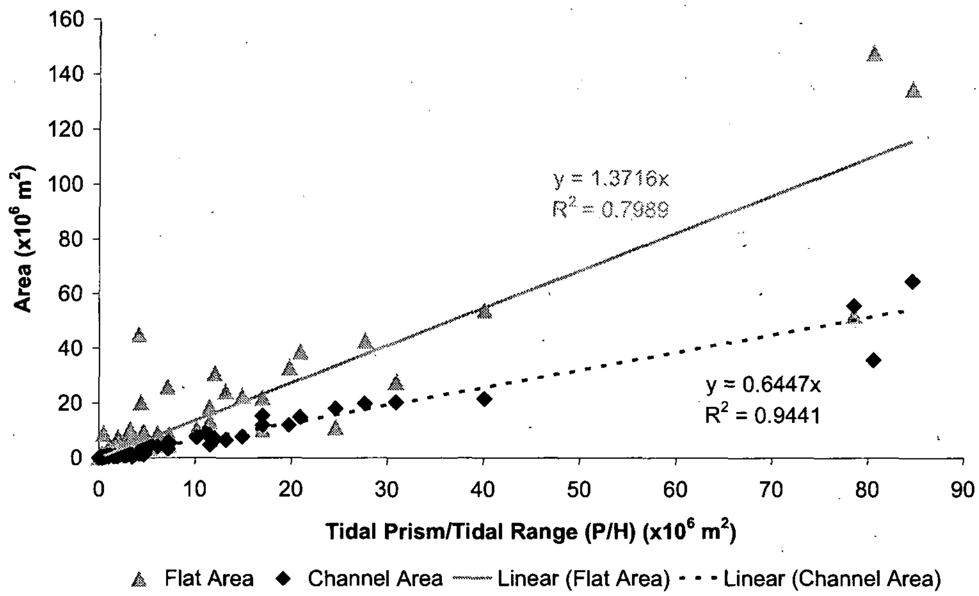


(a) Element Area v Tidal Prism

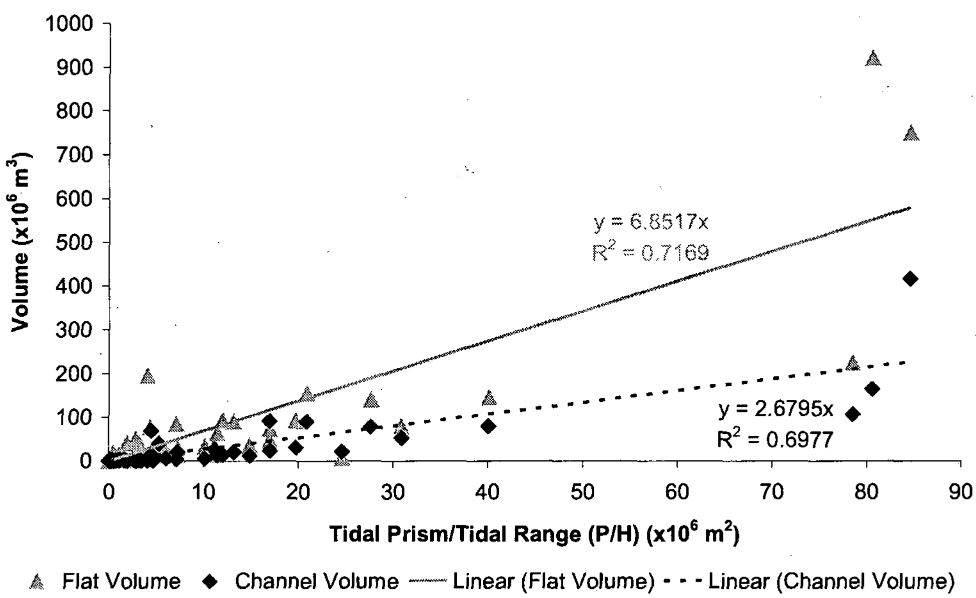


(b) Element Volume v Tidal Prism

Fig. 6.3: Relationship between element area and volume and tidal prism for sample estuaries



(a) Element Area v Tidal Prism/Tidal Range



(b) Element Volume v Tidal Prism/Tidal Range

Fig. 6.4: Relationship between element area and volume and tidal prism/tidal range for sample estuaries .

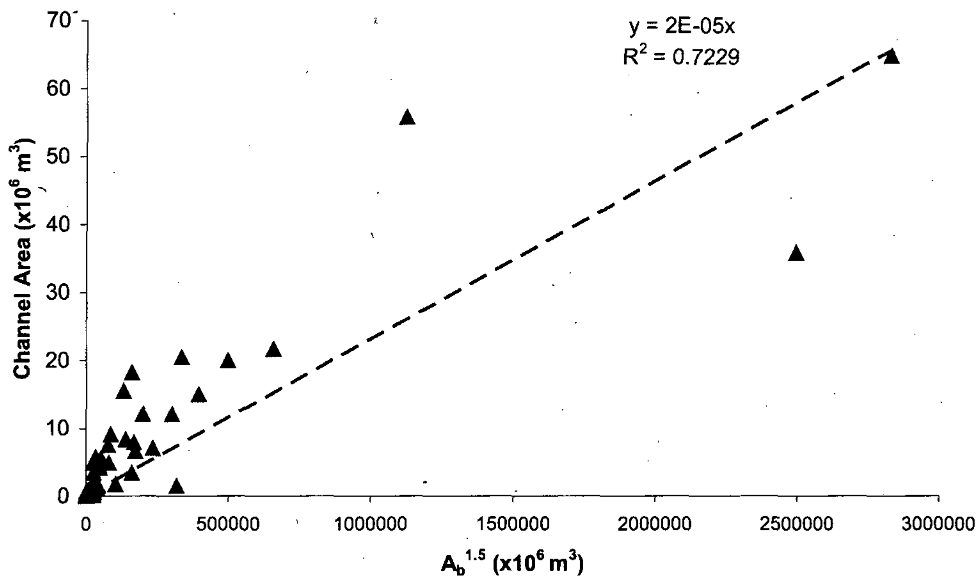


Fig. 6.5: Relationship between flat volume and basin area$^{1.5}$ tidal range for sample estuaries

Tab. 6.3: Distribution of morphological types in the sample of 55 English and Welsh estuaries taken from the Estuaries Database (EMPHASYS, 2000). The remaining 8 estuaries have not been classified in FutureCoast (Dyer, 2002) and are excluded from the following analysis.

Behavioural Type	Sub-type	Number
3. Ria	a. With spits	3
	b. Without spits	13
4. Spit-enclosed	a. Single spit	13
	b. Double spit	8
	c. Filled Valley	7
5. Funnel shaped		2
7. Tidal inlet	a. Symmetrical	3
	b. Asymmetrical	0

Tab. 6.4: Summary of regression slopes and r^2 values for sample estuaries (where $y = mx$)

Dependent Variable	Independent Variable	All Estuaries		Rias		Spit-Enclosed Estuaries	
y	x	m	r^2	m	r^2	m	r^2
A_f	A_b	0.70	0.97	0.79	0.99	0.64	0.90
A_c	A_b	0.30	0.83	0.21	0.89	0.36	0.79
V_f	A_b	3.57	0.88	4.75	0.97	2.16	0.84
V_c	A_b	1.33	0.76	1.00	0.81	0.89	0.78
V_f	$A_b * H$	0.53	0.95	0.56	0.998	0.37	0.72
A_f	P	0.19	0.75	0.21	0.98	0.13	0.13
A_c	P	0.087	0.79	0.05	0.82	0.1	0.88
V_f	P	1.03	0.80	1.28	0.99	0.48	0.34
V_c	P	0.37	0.61	0.25	0.71	0.23	0.64
A_f	P/H	1.37	0.80	1.78	0.97	0.95	0.47
A_c	P/H	0.64	0.94	0.48	0.93	0.67	0.98
V_f	P/H	6.85	0.72	10.67	0.95	3.21	0.48
V_c	P/H	2.68	0.70	2.31	0.85	1.56	0.84
A_c	$A_b^{1.5}$	0.00002	0.72	0.00002	0.76	0.00004	0.87

rias were stronger than the relationships for all estuary types. This was not true for spit-enclosed estuaries, where some relationships were weaker than those for all estuary types.

For rias, the best predictor of intertidal flat area was basin area (r^2=0.99). Intertidal flat volume was best predicted by basin area times tidal range (r^2=0.998). Channel area and channel volume both showed the strongest relationship with tidal prism / tidal range. For spit-enclosed estuaries, intertidal flat area and volume were best predicted by basin area and channel area and channel volume were best predicted by tidal prism / tidal range. Relationships between intertidal flat area and tidal prism and flat volume and tidal prism were particularly weak for spit-enclosed estuaries.

Overall, the best predictor of intertidal flat area was basin area. Intertidal flat volume was generally best predicted using basin area times tidal range, although this varied between estuary types. Tidal prism / tidal range was consistently the best predictor of channel area. Channel volume was the least well predicted variable, and showed the strongest relationships with basin area in the all estuaries case and with tidal prism / tidal range for both rias and spit-enclosed estuaries. This result is unexpected, as the predictor used to estimate channel equilibrium volume in ASMITA (tidal prism) gave relatively poor results.

Tab. 6.5: Comparing relationships of the form $A_f = \alpha A_b$, where A_f is flat area and A_b is basin area, for the study estuaries and for all estuary types, rias and spit-enclosed estuaries

Estuary	y	x	α
Ria	A_f	**Ab**	**0.79**
Dart	A_f	Ab	0.18
Spit-Enclosed	A_f	**Ab**	**0.64**
Humber	A_f	Ab	0.33
Southampton Water (inner)	A_f	Ab	0.39
Southampton Water (outer)	A_f	Ab	0.32
Southampton Water (total)	A_f	Ab	0.34
Genric	A_f	**Ab**	**0.7**
Ribble	A_f	Ab	0.77
Thames	A_f	Ab	0.39
Portsmouth Harbour	A_f	Ab	0.57
Langstone Harbour	A_f	Ab	0.62
Chichester harbour	A_f	Ab	0.59

6.2 Estuary Specific Relationships

The previous section suggested that the majority of variation in an element's area and volume can be predicted from variations in basin area, basin area times tidal range, tidal prism or tidal prism / tidal range. The strongest relationships are compared with the same measures for the study estuaries to test how closely the generic relationships match those for individual estuaries (Tables 6.5 to 6.11).

Individual relationships for the study estuaries varied between estuaries and rarely matched the generic relationships. Table 6.5 shows that the generic relationships over estimate the proportion of basin area occupied by intertidal flats for all estuaries except the Ribble. Intertidal flat volume is also over estimated using generic relationships between flat volume and basin area (Table 6.6) and using relationships between flat volume and basin area times tidal range (Table 6.7).

Estuary specific relationships between channel area and tidal prism / tidal range were variable and did not tend towards similar values to the generic relationships (Table 6.8). Relationships for the channel volume are similarly variable, and do not resemble the generic relationships derived in section 6.1 (Tables 6.9 to 6.11).

6.2.1 Implications

The generic equilibrium relationships derived for all sample estuaries, rias and spit-enclosed estuaries (section 6.1) did not perform well when compared with equilibrium coefficients for the eight study estuaries, despite high r^2 values and significant correlations for the generic relationships, indicating strong relationships. Estuaries fitting the generic relationship seem to be the exception rather than the rule, and the use

Tab. 6.6: Comparing relationships of the form $V_f = \alpha A_b$, where A_f is flat area and A_b is basin area, for the study estuaries and for all estuary types, rias and spit-enclosed estuaries

Estuary	y	x	α
Ria	V_f	**Ab**	**4.75**
Dart	V_f	Ab	0.12
Spit-Enclosed	V_f	**Ab**	**2.16**
Humber	V_f	Ab	0.97
Southampton Water (inner)	V_f	Ab	0.77
Southampton Water (outer)	V_f	Ab	0.36
Southampton Water (total)	V_f	Ab	0.47
Genric	V_f	**Ab**	**3.57**
Ribble	V_f	Ab	3.12
Thames	V_f	Ab	0.75
Portsmouth Harbour	V_f	Ab	0.76
Langstone Harbour	V_f	Ab	0.95
Chichester harbour	V_f	Ab	0.97

Tab. 6.7: Comparing relationships of the form $V_f = \alpha A_b * H$, where A_f is flat area and A_b is basin area, for the study estuaries and for all estuary types, rias and spit-enclosed estuaries

Estuary	y	x	α
Ria	V_f	$A_b * H$	**0.56**
Dart	V_f	$A_b * H$	0.03
Spit-Enclosed	V_f	$A_b * H$	**0.37**
Humber	V_f	$A_b * H$	0.17
Southampton Water (inner)	V_f	$A_b * H$	0.19
Southampton Water (outer)	V_f	$A_b * H$	0.09
Southampton Water (total)	V_f	$A_b * H$	0.12
Genric	V_f	$A_b * H$	**0.53**
Ribble	V_f	$A_b * H$	0.39
Thames	V_f	$A_b * H$	0.14
Portsmouth Harbour	V_f	$A_b * H$	0.19
Langstone Harbour	V_f	$A_b * H$	0.23
Chichester harbour	V_f	$A_b * H$	0.23

Tab. 6.8: Comparing relationships of the form $A_c = \alpha * P/H$, where A_f is flat area and A_b is basin area, for the study estuaries and for all estuary types, rias and spit-enclosed estuaries

Estuary	y	x	α
Ria	A_c	P/H	**0.48**
Dart	A_c	P/H	0.84
Spit-Enclosed	A_c	P/H	**0.67**
Humber	A_c	P/H	0.79
Southampton Water (inner)	A_c	P/H	0.75
Southampton Water (outer)	A_c	P/H	0.59
Southampton Water (total)	A_c	P/H	0.75
Genric	A_c	P/H	**0.64**
Ribble	A_c	P/H	0.37
Thames	A_c	P/H	0.71
Portsmouth Harbour	A_c	P/H	0.53
Langstone Harbour	A_c	P/H	0.49
Chichester harbour	A_c	P/H	0.53

Tab. 6.9: Comparing relationships of the form $V_c = \alpha A_b$, where A_f is flat area and A_b is basin area, for the study estuaries and for all estuary types, rias and spit-enclosed estuaries

Estuary	y	x	α
Ria	V_c	**Ab**	**1**
Dart	V_c	Ab	3.7
Spit-Enclosed	V_c	**Ab**	**0.89**
Humber	V_c	Ab	3.97
Southampton Water (inner)	V_c	Ab	3.04
Southampton Water (outer)	V_c	Ab	0.75
Southampton Water (total)	V_c	Ab	1.23
Genric	V_c	**Ab**	**1.33**
Ribble	V_c	Ab	0.29
Thames	V_c	Ab	4.42
Portsmouth Harbour	V_c	Ab	1.896
Langstone Harbour	V_c	Ab	0.69
Chichester harbour	V_c	Ab	0.84

Tab. 6.10: Comparing relationships of the form $V_c = \alpha * P$, where A_f is flat area and A_b is basin area, for the study estuaries and for all estuary types, rias and spit-enclosed estuaries

Estuary	y	x	α
Ria	V_c	P	**0.25**
Dart	V_c	P	0.95
Spit-Enclosed	V_c	**P**	**0.23**
Humber	V_c	P	0.8
Southampton Water (inner)	V_c	P	0.91
Southampton Water (outer)	V_c	P	0.16
Southampton Water (total)	V_c	P	0.35
Genric	V_c	P	**0.37**
Ribble	V_c	P	0.06
Thames	V_c	P	0.97
Portsmouth Harbour	V_c	P	0.56
Langstone Harbour	V_c	P	0.21
Chichester harbour	V_c	P	0.26

Tab. 6.11: Comparing relationships of the form $V_c = \alpha * P/H$, where A_f is flat area and A_b is basin area, for the study estuaries and for all estuary types, rias and spit-enclosed estuaries

Estuary	y	x	α
Ria	V_c	P/H	**2.31**
Dart	V_c	P/H	3.82
Spit-Enclosed	V_c	P/H	**1.56**
Humber	V_c	P/H	4.78
Southampton Water (inner)	V_c	P/H	3.63
Southampton Water (outer)	V_c	P/H	0.64
Southampton Water (total)	V_c	P/H	1.39
Genric	V_c	P/H	**2.68**
Ribble	V_c	P/H	0.48
Thames	V_c	P/H	5.16
Portsmouth Harbour	V_c	P/H	2.28
Langstone Harbour	V_c	P/H	0.89
Chichester harbour	V_c	P/H	1.09

of generic equilibrium relationships in numerical models such as ASMITA should be discouraged. Instead, data should be used to derive estuary specific relationships, as suggested by Wang et al. (1998). This implies that estuary equilibrium is more complex than the simple relationships tested here.

6.3 Model Development

6.3.1 Dynamic Equilibrium Relationships

In Chapter 5 it was noted that whilst ASMITA simulations made with equilibrium coefficients based on initial conditions tended to yield good results for the channel element, initial intertidal flat equilibrium coefficients were less reliable, particularly after major human disturbances, indicating meta-stable equilibrium behaviour. It is therefore desirable to be able to predict how α_f varies with time and how it is influenced by human induced changes in the estuary. This would allow new dynamic equilibrium relationships for intertidal flats to be predicted following disturbances above the threshold for stable behaviour.

Intertidal flat equilibrium volume (V_{fe}) is predicted using equation 6.1:

$$V_{fe} = \alpha_f * A_b * H \tag{6.1}$$

where A_b is basin area, H is tidal range and α_f can be split into two components, representing the relative flat height and relative flat area respectively (Eq. 6.2):

$$\alpha_f = \frac{H_f}{H} * \frac{A_f}{A_b} \tag{6.2}$$

where H_f is the average flat height (V_f/A_f), H is tidal range, A_f is the flat area and A_b is the basin area.

Renger and Partenscky (1974) suggested an empirical formula for $\frac{A_f}{A_b}$ based on observed relationships in the German Bight (eq. 6.3) (rearranged from Eq. 2.3) and Eysink and Biegel (1992) suggested that parameter $\frac{H_f}{H}$ was also related to the basin area (eq. 6.4).

$$\frac{A_f}{A_b} = 1 - 2.5e^{-5} * A_b^{0.5} \tag{6.3}$$

$$\frac{H_f}{H} = 0.41 - 0.24e^{-9} * A_b \tag{6.4}$$

Equation 6.3 can be rearranged, using $A_f = A_b - A_c$ to give equation 6.5:

$$A_c = c * A_b^{1.5} \tag{6.5}$$

where coefficient $c = 2.5 * 10^{-5}$.

Figure 6.5 shows the relationship between channel area and basin area$^{1.5}$ using data for English and Welsh estuaries ($c = 2e^{-5}$, $r^2 = 0.72$). Other independent variables, including tidal prism, tidal prism/tidal range and the linear relationship with basin area were better predictors of channel area (Table 6.2). In addition, no relationship was found between intertidal flat height/ tidal range and basin area for the sample estuaries. As has been shown previously, these generic relationships do not represent the observed relationships in the study estuaries and it was concluded that calculating the intertidal flat equilibrium coefficient based on generic relationships would not accurately describe the behaviour of specific estuaries.

It is possible that the intertidal flat equilibrium coefficient can be updated following changes in basin area caused by managed realignment or land reclamation using equation 6.6

$$\alpha_f = \frac{H_f}{H} * \frac{A_f + A_{change}}{A_b + A_{change}} \tag{6.6}$$

where A_{change} is the area change of the disturbance and is positive for managed realignment and negative for land reclamations.

Equation 6.6 assumes that the change in intertidal flat area is caused directly by the change in basin area (i.e. no other adjustment in areas takes place) and the the average flat height is constant and unaffected by the change in area. Of the three study estuaries undergoing large reclamations during the study period, only Southampton Water meets these assumptions. In the Ribble Estuary, upper flat area and average flat height are increasing over time. In Portsmouth Harbour, area changes caused by reclamations were accompanied by a strong trend of decreasing flat height. This suggest that other processes, not accounted for in the simple relationships used here, may also be operating on the intertidal flats.

Observed and predicted element volumes for Southampton Water using equation 6.6 to update the intertidal flat equilibrium coefficient following reclamations are shown in figure 6.6. ASMITA predictions match the observed volumes closely, including the 1998 flat volumes, which were previously over predicted by ASMITA (section 5.4). The skill of ASMITA predictions using equation 6.6 to update the intertidal flat equilibrium coefficient was compared with ASMITA predictions using initial equilibrium coefficients only (Table 6.12). Using equations 6.6 gave an improved fit between observed and predicted volume for the flat element, compared to using initial equilibrium coefficients alone. For the channel elements, predictions using the updating α_f were similar too, or slightly worse than, predictions based on initial coefficient values. Channel predictions were still within the error estimates of the observed data and it appears that, overall, using equation 6.6 improves ASMITA predictions for Southampton Water.

Tab. 6.12: Mean Square Error and Brier's Skill Scores between ASMITA simulations using initial equilibrium coefficients and using equation 6.6 to update the intertidal flat equilibrium coefficient following reclamations in Southampton Water

	$V_{c_{outer}}$ (x10^6m^3)	$V_{f_{outer}}$ (x10^6m^3)	$V_{c_{inner}}$ (x10^6m^3)	$V_{f_{inner}}$ (x10^6m^3)
MSE(Initial)	0.22	0.47	2.26	0.87
MSE(Corrected α_f)	0.34	0.31	2.37	0.36
BSS	-0.52	0.34	-0.05	0.59

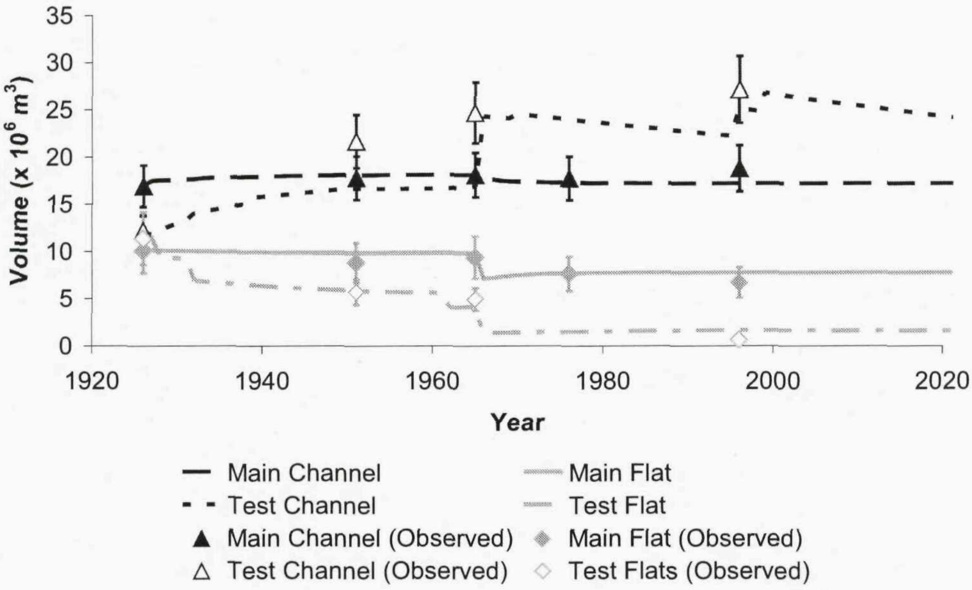
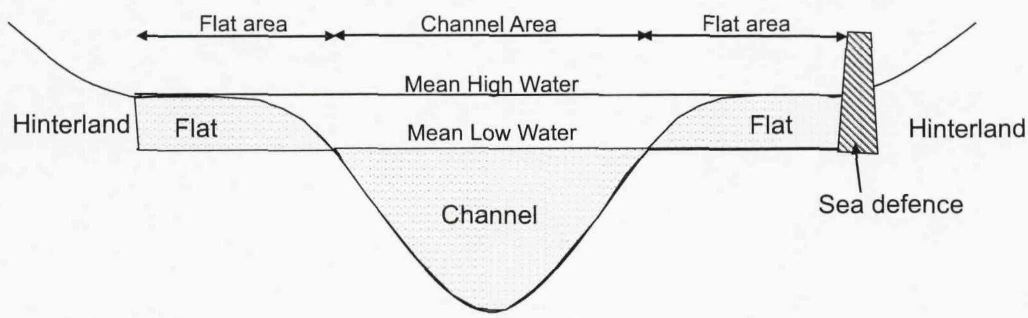
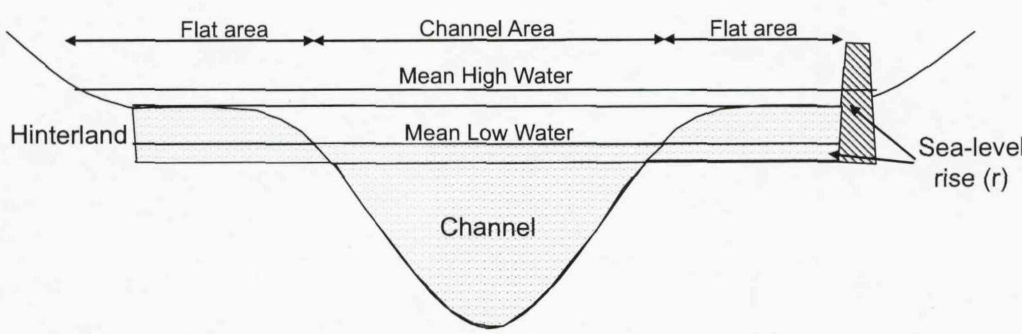


Fig. 6.6: Observed and predicted element volumes in Southampton Water using equation 6.6 to update the intertidal flat equilibrium coefficient following reclamations



(a) Element areas



(b) Element areas following sea-level rise

Fig. 6.7: Element areas before and after sea-level rise

6.3.2 Equilibrium Area

In ASMITA, the element areas and basin area are fixed at their initial areas unless they are altered by human interventions such as land reclamation. In other words, area in ASMITA is not dynamic, as it is in the real world. Figure 6.7 illustrates the area changes that might be expected as sea level rises. Channel area is enlarged by sea-level rise, with the area change depending on the rate of sea-level rise and the slope of the intertidal zone. Intertidal flat area may increase by retreating onto the hinterland and again, area change will depend on the slope. However, sea-defences or steep or cliffed coastline would prevent the intertidal flats retreating over the hinterland and flat area would decrease.

Possible changes in area become particularly significant at high rates of sea-level rise (Bijsterbosch, 2003). If element areas are allowed to change with sea-level rise, the SLR_{CRIT} (the rate at which all intertidal volume will be lost, also called "drowning") is increased. This suggests that area change (expansion) may be an important system response that slows intertidal loss in response to sea-level rise.

Generic relationships describing element area relative to basin area or tidal prism do not match the same values generated for individual estuaries. This suggests that any relationships describing element area for an individual estuary need to be specific to that estuary. Unfortunately, sufficient data are rarely available to analyse the behaviour of element areas and is unlikely to yield satisfactory relationships to allow equilibrium areas to be predicted.

Previous attempts at including variable element areas in ASMITA have assumed that the average flat height and average channel depth remain constant or can be predicted and element area is calculated using equation 6.7. Bijsterbosch (2003) used equation 6.4 to estimate the average flat height. Townend (2007) assumed that the average flat height was a constant value.

$$A_n = \frac{V_n}{H_n} \tag{6.7}$$

The current research has found no evidence to support the use of equation 6.4 to predict the average intertidal flat height in the sample estuaries and has shown that average flat height and channel depths vary in time. Carrying out simulations with variable area based on these assumptions cannot be justified at this time.

6.4 Discussion

Strong correlations were found, for a sample of 53 English and Welsh estuaries (EMPHASYS, 2000) (Appendix C), between various measures of estuary geometry and variables such as the total basin area and tidal prism. In particular, basin area was found to be a strong predictor of the intertidal flat area, with 97% of the variation in flat area explained by variations in basin area (r^2=0.97) (table 6.2). Intertidal flat volume was best predicted by basin area times tidal range (r^2=0.95), which is the same form as the relationship used in ASMITA.

Channel area was best predicted by tidal prism divided by tidal range (r^2=0.80). Channel volume was best predicted by basin area using this data set. Tidal prism, used to calculate the equilibrium channel volume in ASMITA, was found to be a relatively poor predictor of channel volume. This could be explained by the high number of estuaries that undergo dredging at some scale, making channel volumes more variable in relation to tidal prism.

In general, grouping the estuaries by type gave stronger relationships for rias, although not for spit-enclosed estuaries. This may be because, within the spit-enclosed category, there are subcategories with slightly different characteristics. There is insufficient data to analyse these sub categories independently.

Empirical generalisations from large data sets have a number of potential weaknesses. Firstly, the quality of the data set used may be unknown, or, as for the Estuaries Database (EMPHASYS, 2000), the error for individual estuaries may be large (Townend, 2005). The data used to generate the generic relationships does not include information on the equilibrium state of an estuary, or on factors that may effect this such as human disturbances including dredging, coastal defence and training walls. In particular, the presence of natural or man made constraints may influence dynamic equilibrium relationships in estuaries; O'Brien (1969) found coefficients linking the cross-sectional area of an inlet mouth with tidal prism varied for inlets with none, one or two jetties constraining the mouth width. This implies that, despite strong correlations, equilibrium relationships are influenced by additional factors that are ignored in the empirical generalisations used to derive the generic relationships and should therefore be used with caution.

The generic relationships found for the larger sample of estuaries in section 6.1 and 6.2 differed considerably from the estuary specific values found for the study estuaries (tables 6.1a to 6.4b). This may partially reflect the high uncertainty of the data set used for the generic relationships, but also reflects the high variability between the study estuaries. Using the data currently available it was not possible to derive generic relationships the adequately described equilibrium in specific estuaries and therefore it is concluded that estuary specific equilibrium relationships should be used in ASMITA.

In absence of reliable generic relationships, the development of ASMITA to include dynamic equilibrium relationships and dynamic element areas was severely limited. The intertidal flat equilibrium coefficient was modified using equation 6.6 to allow it to be updated following human induced area changes such as land reclamation or managed realignment. However, this correction assumes that area change is caused solely by human interventions and that the average flat height remains constant. These assumptions were found to be true for Southampton Water but not for the Ribble, where flat area and average flat height increased over time, or for Portsmouth Harbour, where flat height was observed to decrease.

Including dynamic element areas in ASMITA relies on the relationship between area, volume and average height (Bijsterbosch, 2003; Townend, 2007). The current research has found that average intertidal flat height is not constant and therefore cannot be used to accurately predict flat area from flat volume. No relationship has been found to predict the flat height from other basin properties and hence it is concluded that including variable area in ASMITA is not justified. Future work focusing on prediction of equilibrium flat heights could help to overcome this limitation.

7. APPLICATION OF ASMITA: RESPONSE TO SEA-LEVEL RISE

7.1 Introduction

ASMITA has previously been used to examine the effect of human interventions and climatic change on estuarine or tidal basin systems. Applications have included simulating dredging regimes for two basins of the Po Delta, Italy (Stive et al., 1997); investigating the response of Wadden Sea basins to closure (removal from the tidal basin) of large areas (Kragtwijk et al., 2004) and the effects of sea-level rise on a number of tidal inlets in the Wadden Sea (van Goor et al., 2003) and estuaries in the UK (Rossington et al., 2007).

Evidence presented in Chapters 5 and 6 suggest that, following human interventions causing area change, the flat element tends to evolve towards a new dynamic equilibrium that differs from its characteristic equilibrium relationship prior to the intervention. Methods for implementing a variable equilibrium relationship for the flat were investigated in Chapter 6 but the potential solution was not found to be suitable for all estuaries due to differences in morphological behaviour. For this reason, changes due to management scenarios involving area change, such as land reclamation and managed realignment are not presented in this thesis, as it is currently not possible to describe changes in the intertidal flat element with any confidence using ASMITA. General observations regarding these sorts of interventions are discussed in section 7.3 as they highlight some behaviours that may be worthy of further investigation in the future.

ASMITA has previously been applied to investigate the effects of sea-level rise (SLR) on tidal basins and estuarine systems (van Goor et al., 2003; Rossington et al., 2007). This work has focused on the critical rate of sea-level rise (SLR_{CRIT}), which is defined as the threshold rate of sea-level rise beyond which all intertidal volume will be lost (van Goor et al., 2003). Under conditions of rising sea levels, the morphological elements within ASMITA are moved away from their equilibrium state, causing the import of sediment. For a constant rate of sea-level rise a steady state may be reached, in which the elements tend to accrete at the same rate as sea-level rise but which is permanently removed from the equilibrium volume. At the SLR_{CRIT} threshold, the steady state volume of the intertidal flats is zero and the entire estuary volume is occupied by open water. In estuaries with complex schematisations, where more than one intertidal flat element is present, the critical rate of sea-level rise is defined as the threshold at which all intertidal will be lost for one of those intertidal elements.

Applying ASMITA to model the effects of sea-level rise in estuaries assumes the dynamic equilibrium relationships are not changed under conditions of rising sea level. No evidence is currently available to support or refute this assumption as all data currently available was collected under relatively modest rates of sea-level rise (1-2 mm/year). This is felt to be a reasonable assumption as sea-level rise represents a gradual change in forcing, rather than a sudden and dramatic change as seen in many human interventions. Within ASMITA, sea-level rise causes a difference between the element volume and its equilibrium volume. At a constant rate of sea-level rise, this results in a steady state volume that is permanently offset from dynamic equilibrium, although its evolution will still follow changes in dynamic equilibrium. This means that although sea-level rise alters the steady state volume of the element, the same dynamic equilibrium relationship can continue to be used. Simulations are presented for the eight study estuaries using the regional sea-level rise predictions suggested by DEFRA (2006a) for shoreline management and project appraisal purposes (Table 2.2). The critical rate of sea-level rise, and thresholds causing 25%, 50% and 75% intertidal loss, are also presented for each study estuary.

7.2 Sea-level rise

7.2.1 Evolution under DEFRA Sea-Level Rise Scenarios

ASMITA was applied to the study estuaries to simulate sea-level rise at the allowance rates predicted in Table 2.2 (DEFRA, 2006a). For each estuary, equilibrium coefficients best describing the observed behaviour were used and the sediment exchange parameters were the same as for the initial simulations described in Chapter 5.

Ribble Estuary

In the Ribble Estuary, mean equilibrium coefficients were used for the channel and lower flat elements, and trend equilibrium coefficients were used for the upper flats. The rates of sea-level rise predicted until 2115 had relatively little influence on the element volumes for the Ribble Estuary (Fig. 7.1 and Table 7.1). The upper flats are initially smaller than their predicted equilibrium volume and their evolution is dominated by this. The lower flat and channel elements are closer to equilibrium and are more affected by sea-level rise. Lower flat volume tends to decrease with increasing rates of sea-level rise, and channel volume tends to increase. The changes caused by sea-level rise are less than 1% of the element volumes.

Dart Estuary

The Dart Estuary was much more sensitive to sea-level rise at the rates predicted by DEFRA (Fig. 7.2 and Table 7.2). Simulations for the Dart Estuary used the mean

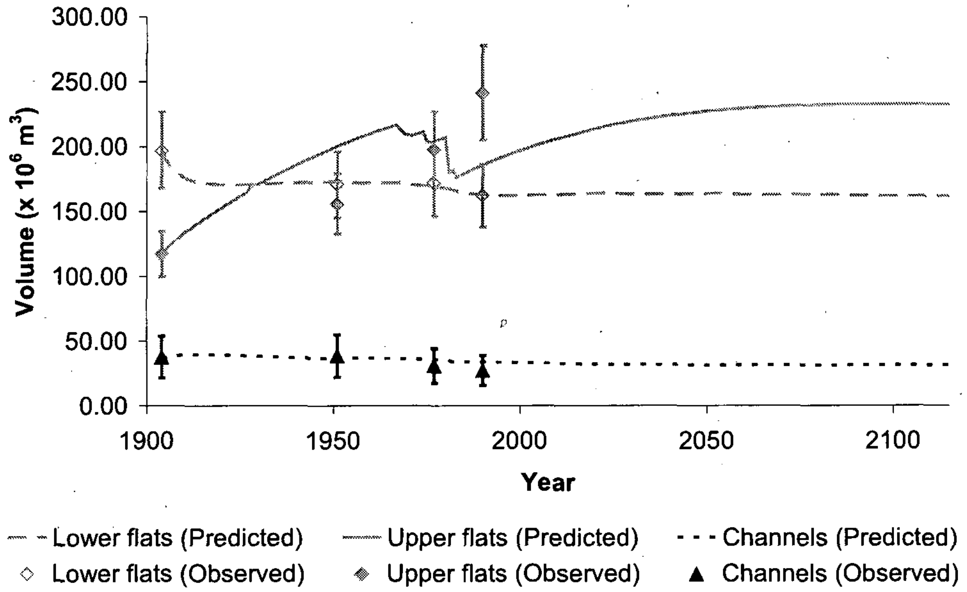


Fig. 7.1: Predicted volume changes in the Ribble Estuary under the DEFRA sea-level rise scenario until 2115

equilibrium coefficients. Channel volume was predicted to increase with increasing rates of sea-level rise and flat volume to decrease. ASMITA predicts, that under the DEFRA sea-level rise scenarios, all intertidal volume in the Dart Estuary will be lost by 2112. This reflects the very low sediment supply to the Dart Estuary from marine sources and these predictions may change if fluvial sediment supply could be quantified sufficiently for inclusion in the simulations.

Southampton Water

Southampton Water was predicted to be relatively resilient to the DEFRA sea-level rise scenario (Fig. 7.3 and Table 7.3). Southampton Water simulations were

Tab. 7.1: Predicted volume changes in the Ribble Estuary under the DEFRA sea-level rise scenario

	Rate of SLR	Volume change (x10^6 m^3)		
	(mm/year)	f_{lower}	f_{upper}	c
1990-2025	2	1.26	31.27	-2.11
2025-2055	7	-0.32	11.61	-0.57
2055-2085	10	-0.80	3.92	-0.03
2085-2115	13	-1.09	0.19	0.25
Total		-0.95	46.99	-2.47
%		-0.57	25.85	-7.27

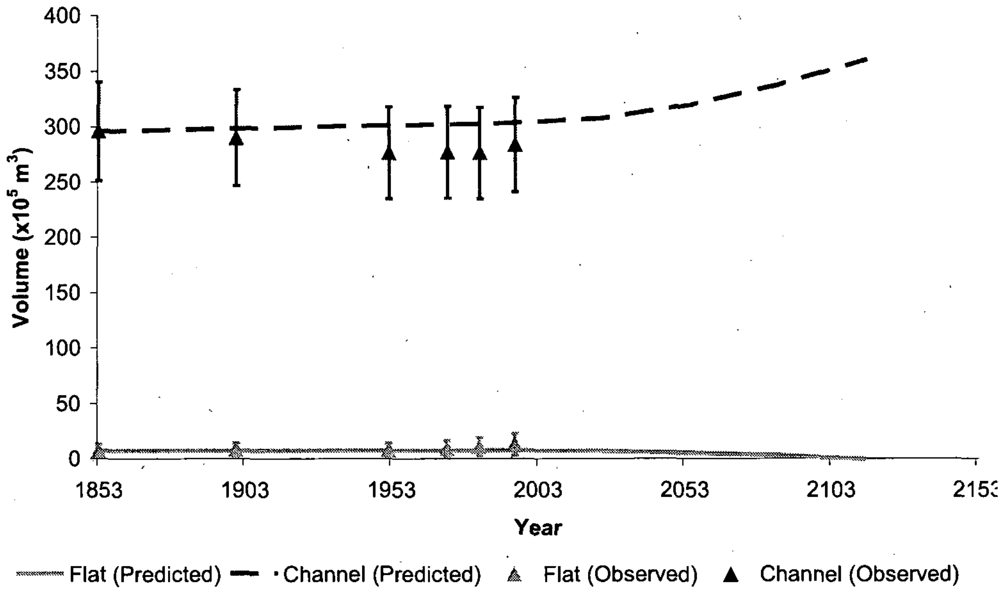


Fig. 7.2: Predicted volume changes in the Dart Estuary under the DEFRA sea-level rise scenario until 2115

Tab. 7.2: Predicted volume changes in the Dart Estuary under the DEFRA sea-level rise scenario

	Rate of SLR (mm/year)	Volume change ($x10^5$ m^3) f	c
1990-2025	3.5	-0.49	4.68
2025-2055	8	-1.63	11.98
2055-2085	11.5	-2.40	17.90
2085-2115	14.5	-3.29	22.80
Total		-7.81	57.36
%		-100	18.97

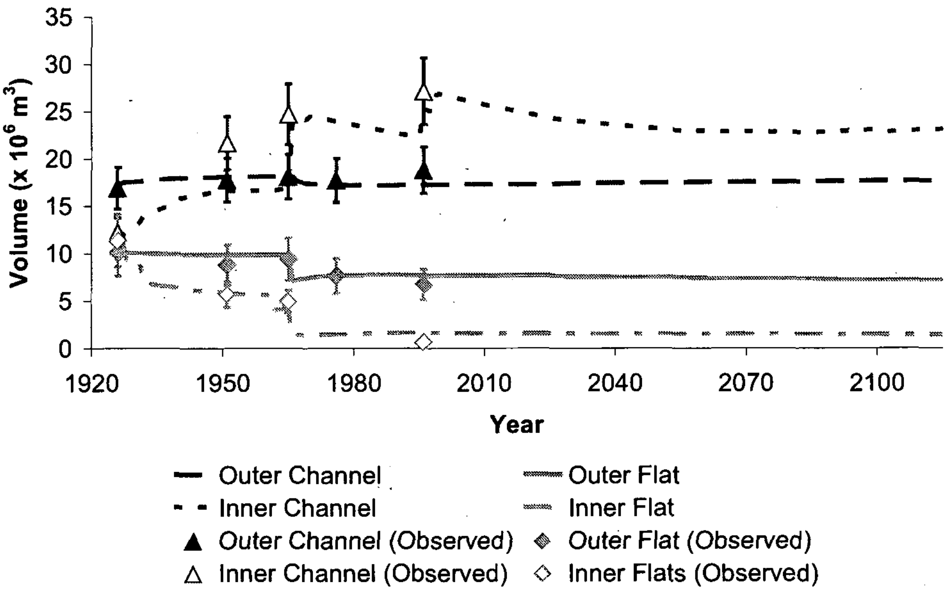


Fig. 7.3: Predicted volume changes in Southampton Water under the DEFRA sea-level rise scenario until 2115

performed using initial equilibrium coefficients and the flat equilibrium coefficient was corrected for human interferences as described in chapter 6. Channel volumes tended to increase with increasing rates of sea-level rise and flat volumes tended to decrease. The greatest change was in the inner flat volume, which was predicted to decrease by 12% between 1990 and 2115. This result suggests that Southampton Water is much more sensitive to human induced changes, including dredging, than it is to sea-level rise, as human interventions have resulted in much larger morphological changes over the 100 years. Simulations with ASMITA suggest that if dredging in Southampton Water were ceased, it would take between 80 and 100 years for the estuary to regain its natural equilibrium.

Tab. 7.3: Predicted volume changes in Southampton Water under the DEFRA sea-level rise scenario

	Rate of SLR	Volume change (x10^6 m^3)			
	(mm/year)	c_{outer}	f_{outer}	c_{inner}	f_{inner}
1990-2025	4	0.08	-0.08	1.66	-0.03916
2025-2055	8.5	0.15	-0.18	-1.39	-0.02261
2055-2085	12	0.13	-0.15	-0.22	-0.04273
2085-2115	15	0.12	-0.14	0.31	-0.07975
Total		0.48	-0.55	0.36	-0.18
%		2.79	-7.15	1.52	-11.87

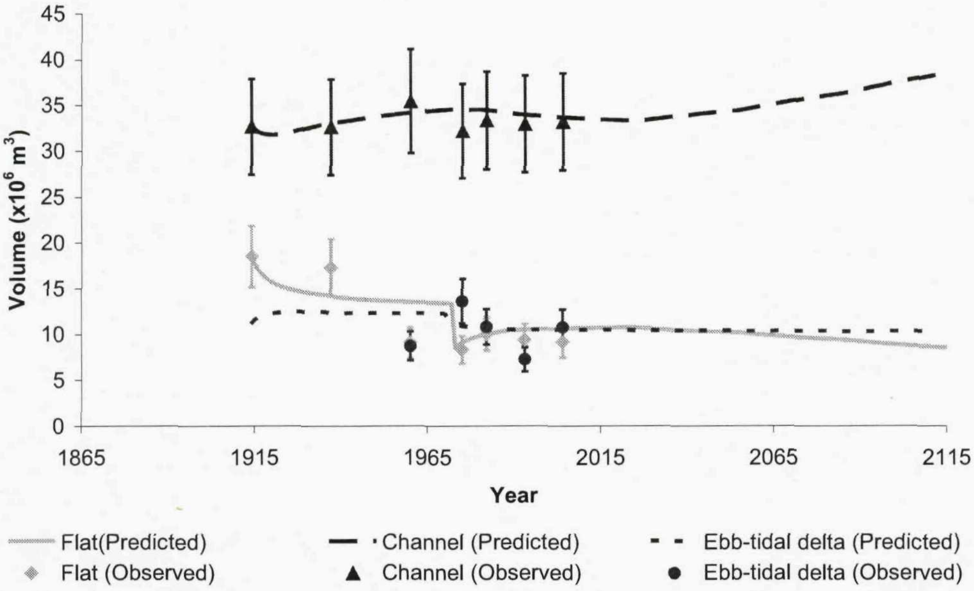


Fig. 7.4: Predicted volume changes in Portsmouth Harbour under the DEFRA sea-level rise scenario until 2115

Portsmouth Harbour

Portsmouth Harbour simulations were carried out using mean equilibrium values for the channel and ebb-tidal delta elements and trend coefficients for the intertidal flat element. This combination gives the best description of the observed behaviour and is therefore most suitable for making predictions about possible future behaviour. Channel volume tended to increase with increasing rates of sea-level rise and flat volume decreased (Fig. 7.4 and Table 7.4). Ebb-tidal delta volume showed little change in response to accelerated sea-level rise. Changes in element volume in Portsmouth Harbour were particularly noticeable after 2025, corresponding to an acceleration of sea-level rise from 4 mm/year to 8.5 mm/year. By 2115 it was predicted that the intertidal flat volume would be 20% less than in 1990 and channel volume would be 13% larger.

Tab. 7.4: Predicted volume changes in Portsmouth Harbour under the DEFRA sea-level rise scenario

	Rate of SLR (mm/year)	Volume change (x10^6 m^3) *f*	*c*	*d*
1990-2025	4	0.29	-0.76	-0.07
2025-2055	8.5	-0.56	1.17	-0.07
2055-2085	12	-0.77	1.86	-0.05
2085-2115	15	-0.87	2.18	-0.03
Total		-1.93	4.46	-0.22
%		-19.61	12.91	-2.04

Langstone Harbour

Langstone Harbour was relatively sensitive to accelerated sea-level rise. Even at relatively low rates (4 mm/year between 1990 and 2025) intertidal flat volumes were predicted to decrease and channel volumes to increase. As with Portsmouth Harbour, the ebb-tidal delta volume was not strongly influenced by accelerated sea-level rise. ASMITA predictions indicate that Langstone Harbour will lose 45% of its flat volume by 2115, compared to 1990 volumes. Channel volume was predicted to increase by 45% by 2115. If the rate of sea-level rise remained constant at 15 mm/year after 2115, it is predicted that the intertidal flat element would be lost completely by 2260.

Tab. 7.5: Predicted volume changes in Langstone Harbour under the DEFRA sea-level rise scenario

	Rate of SLR (mm/year)	Volume change ($x10^6$ m^3) *f*	*c*	*d*
1990-2025	4	-1.19	0.84	-0.24
2025-2055	8.5	-1.92	1.31	0.04
2055-2085	12	-2.40	1.66	0.12
2085-2115	15	-3.00	2.06	0.21
Total		-8.51	5.86	0.13
%		-44.83	44.67	1.16

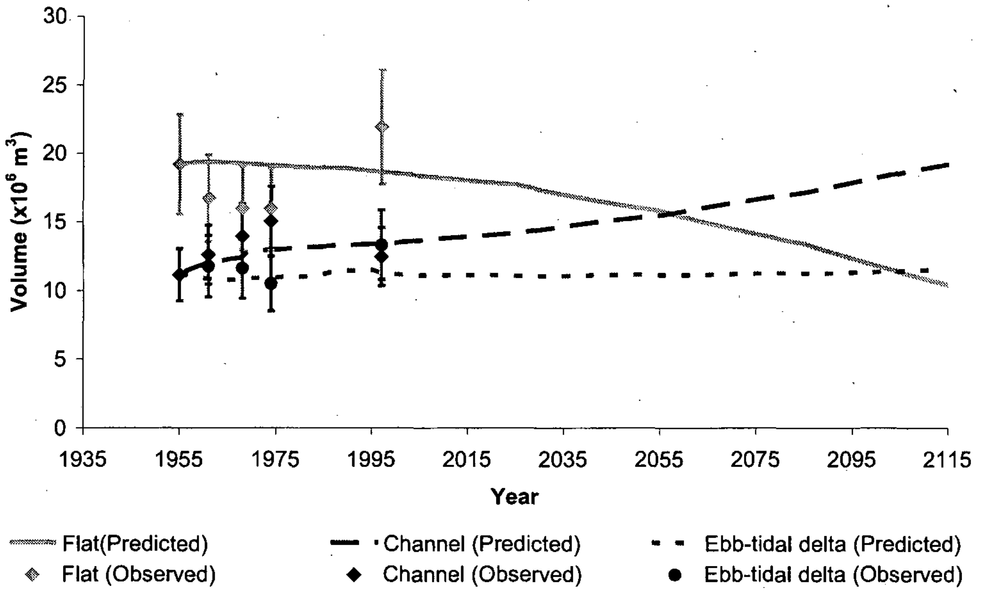


Fig. 7.5: Predicted volume changes in Langstone Harbour under the DEFRA sea-level rise scenario until 2115

Chichester Harbour

Chichester Harbour was also sensitive to the rate of sea-level rise. Intertidal flat volume decreased with increasing sea-level rise and channel volume increased. Ebb-tidal delta volume were not sensitive the the rate of sea-level rise. ASMITA predictions indicate that Chichester Harbour will lose 36% of its flat volume by 2115, compared to 1990 volumes. Channel volume was predicted to increase by 42% by 2115. If the rate of sea-level rise remained constant at 15 mm/year after 2115, it is predicted that the flat element would be lost completely by 2422.

Tab. 7.6: Predicted volume changes in Chichester Harbour under the DEFRA sea-level rise scenario

	Rate of SLR (mm/year)	Volume change (x10^6 m^3) *f*	*c*	*d*
1990-2025	4	-1.44	1.36	-0.04
2025-2055	8.5	-2.20	2.18	-0.08
2055-2085	12	-2.73	2.88	-0.01
2085-2115	15	-3.32	3.64	-0.05
Total		-9.70	10.05	-0.08
%		-35.77	41.50	-0.49

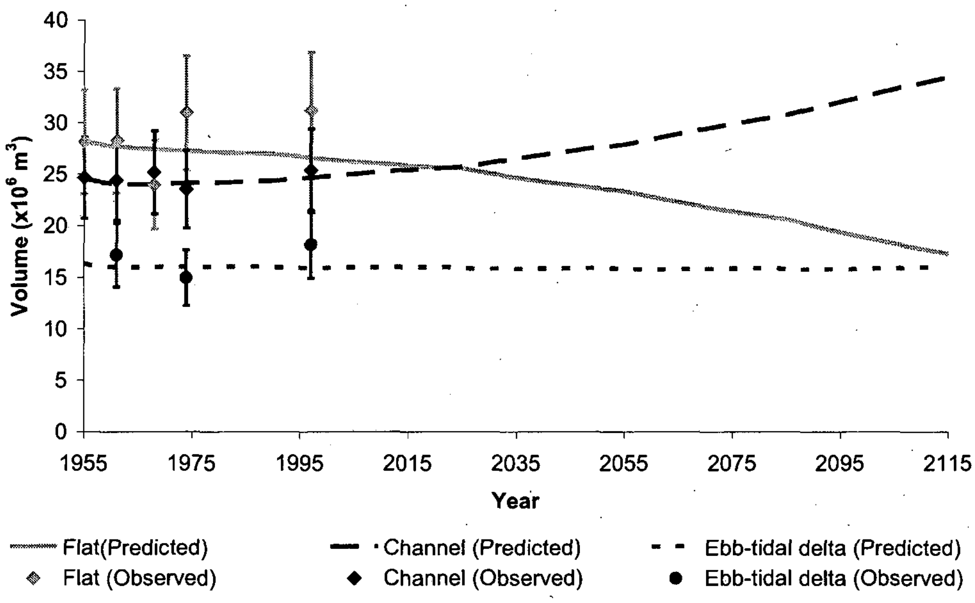


Fig. 7.6: Predicted volume changes in Chichester Harbour under the DEFRA sea-level rise scenario until 2115

Thames Estuary

The Thames Estuary was predicted to be relatively resilient to changes caused by sea-level rise at the predicted rates (Fig. 7.7 and Table 7.7). Channel volumes tended to increase with increasing rates of sea-level rise and intertidal flat volumes decreased. Intertidal flat loss was was predicted to be greatest in the outer estuary, with 16% of the 1990 volume being lost by 2115. If sea-level rise remained constant at 15 mm/year after 2115, the flat element would persist whilst sea-level rise remained constant. Although volume changes are not directly comparable with changes in area, intertidal loss predicted using ASMITA may be lower than suggested by other methods. For example the Regime-Shell model predicted a 5-10% intertidal area loss by 2030 (Huthnance et al., 2007).

Tab. 7.7: Predicted volume changes in the Thames Estuary under the DEFRA sea-level rise scenario

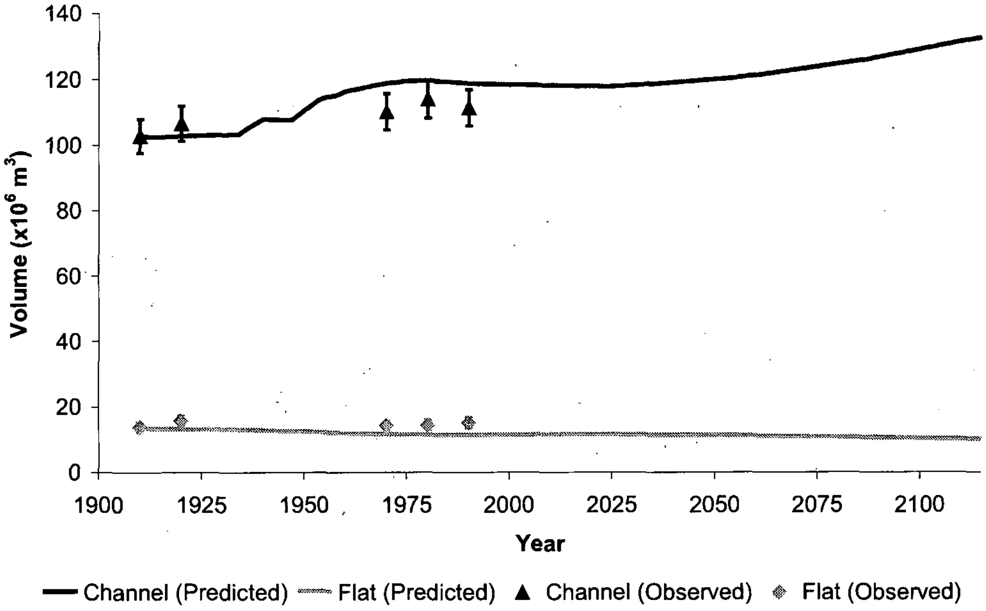
	Rate of SLR (mm/year)	Volume change (x10^6 m^3) c_{outer}	f_{outer}	c_{mid}	f_{mid}	c_{inner}	f_{inner}
1990-2025	4	3.27	-1.22	1.55	-0.14	-1.04	0.05
2025-2055	8.5	7.00	-2.43	3.88	-0.33	2.51	-0.32
2055-2085	12	9.27	-2.79	5.47	-0.41	5.03	-0.52
2085-2115	15	10.59	-3.00	6.43	-0.45	6.97	-0.65
Total		30.13	-9.44	17.33	-1.33	13.47	-1.44
%		11.09	-16.02	10.58	-9.62	11.26	-12.61

Humber Estuary

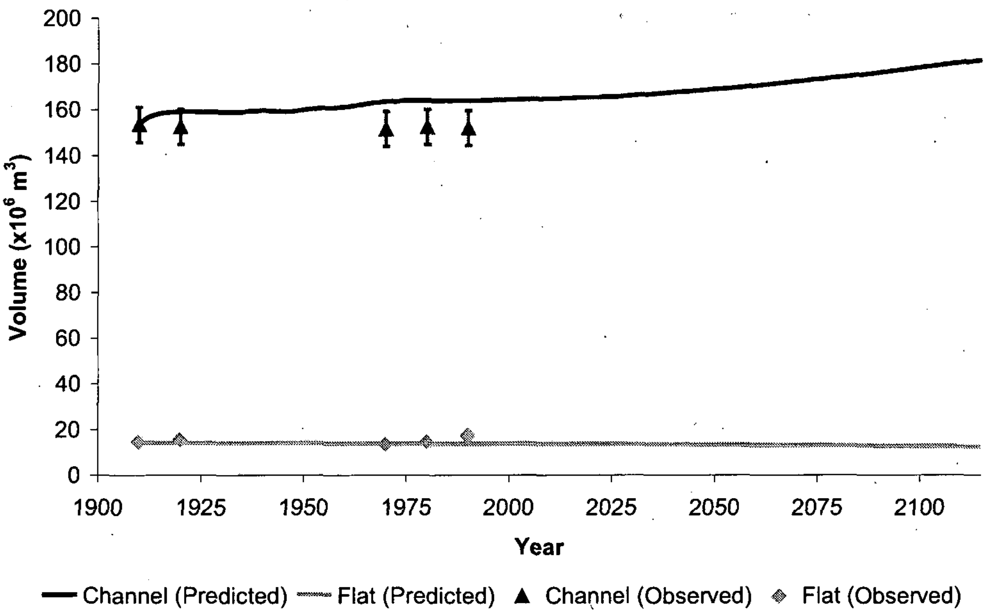
The Humber Estuary was also relatively resilient to changes caused by accelerated sea-level rise at the predicted rates. Intertidal flat volumes were predicted to decrease by 7% between 1990 and 2115. Channel volumes were predicted to increase by 13% over the same period.

Tab. 7.8: Predicted volume changes in the Humber Estuary under the DEFRA sea-level rise scenario

	Rate of SLR (mm/year)	Volume change (x10^6 m^3) f	c
1990-2025	2	-1.43	9.54
2025-2055	7	-6.55	39.39
2055-2085	10	-6.90	53.28
2085-2115	13	-7.63	65.14
Total		-22.51	167.34
%		-7.38	12.73

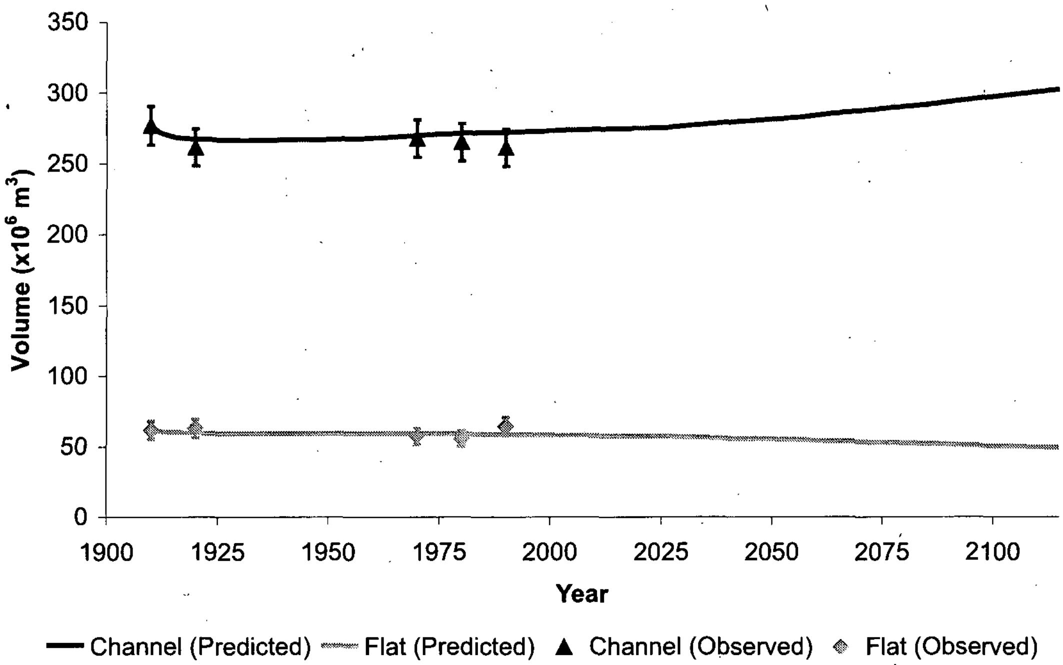


(a) Inner Thames



(b) Mid Thames

Fig. 7.7: Predicted volume changes in the Thames Estuary under DEFRA sea-level rise predictions until 2115



(c) Outer Thames

Fig. 7.7: Predicted volume changes in the Thames Estuary under the DEFRA sea-level rise scenario until 2115

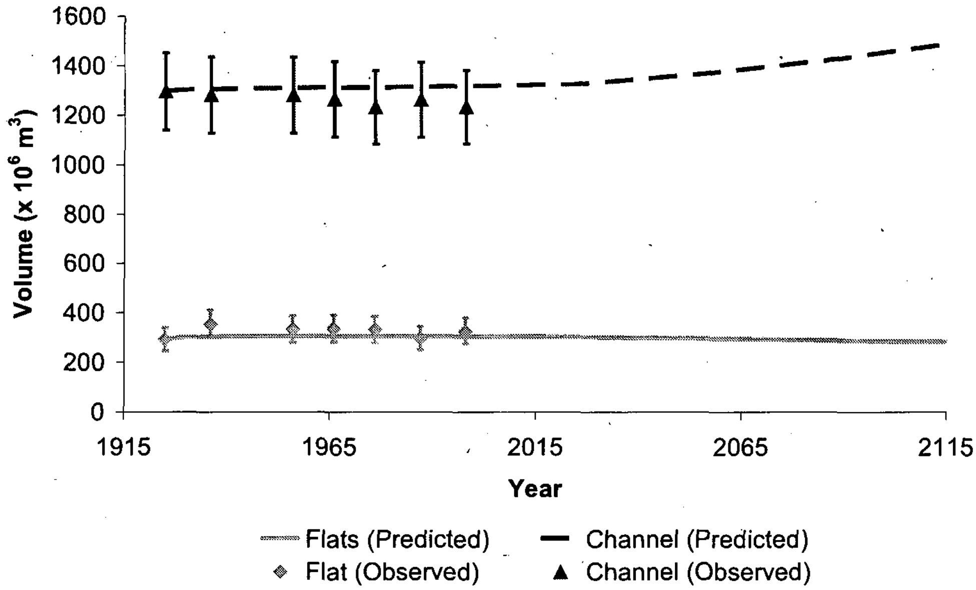


Fig. 7.8: Predicted volume changes in the Humber Estuary under the DEFRA sea-level rise scenario until 2115

Synthesis

Under accelerated sea-level rise predicted by DEFRA (2006a) all of the study estuaries were predicted to lose intertidal (flat) volume. The amount of loss varied widely between estuaries, with the Ribble predicted to lose less than 1% by 2115, and the Dart predicted to lose all intertidal volume by 2112 (Table. 7.9). Possible reasons for these differences are discussed in Section 7.3.

Tab. 7.9: Predicted percentage flat loss by 2115 under the DEFRA (2006a) scenario

Estuary	% flat loss
Ribble	<1%
Humber	7%
Southampton Water	12%
Thames	16%
Portsmouth Harbour	20%
Chichester Harbour	36%
Langstone Harbour	45%
Dart	100%

7.2.2 Critical Rates of Sea-Level Rise

This section focuses on sea-level rise thresholds causing 25%, 50%, 75% and 100% intertidal flat loss (SLR_{CRIT}) in the study estuaries. SLR_{CRIT} does not cause instantaneous intertidal loss, but if sea-level rise remains above the threshold for a period of time, then flat volume will eventually be lost completely.

Ribble Estuary

The Ribble Estuary is very resilient to accelerated rates of sea-level rise (Fig. 7.9). The upper flat is predicted to be the most sensitive element. The SLR_{CRIT} threshold is 80 mm/year for the upper flat, suggesting that very high rates of sea-level rise are needed to remove the inner flat element completely. Even then, the lower flat was predicted to remain, although with a reduced volume. 25% of the inner flat volume is predicted to be lost at 46 mm/year (fig. 7.17a). This rate is around three times greater than the allowances suggested by DEFRA for 2115, indicating that the inner flat of the Ribble Estuary is unlikely to suffer significant losses due to sea-level rise in the foreseeable future. Indeed, the highest estimates of sea-level rise rates are around 20-30 mm/year, suggesting that the critical rates of sea-level rise predicted for the Ribble are well above expected maximum rates (Church et al., 2007).

The Ribble's resilience to sea-level rise is likely to be caused by a very high sediment supply from the neighbouring shallow sea-bed in the eastern Irish Sea (van der Wal et al., 2002) which allows it to maintain intertidal areas despite high levels of sea-level rise. In addition, the high tidal range and flood-dominant characteristics of the Ribble Estuary favour sediment transport into the estuary. This is likely to be enhanced by sea-level rise, which will the sediment demand by moving the elements away from dynamic equilibrium.

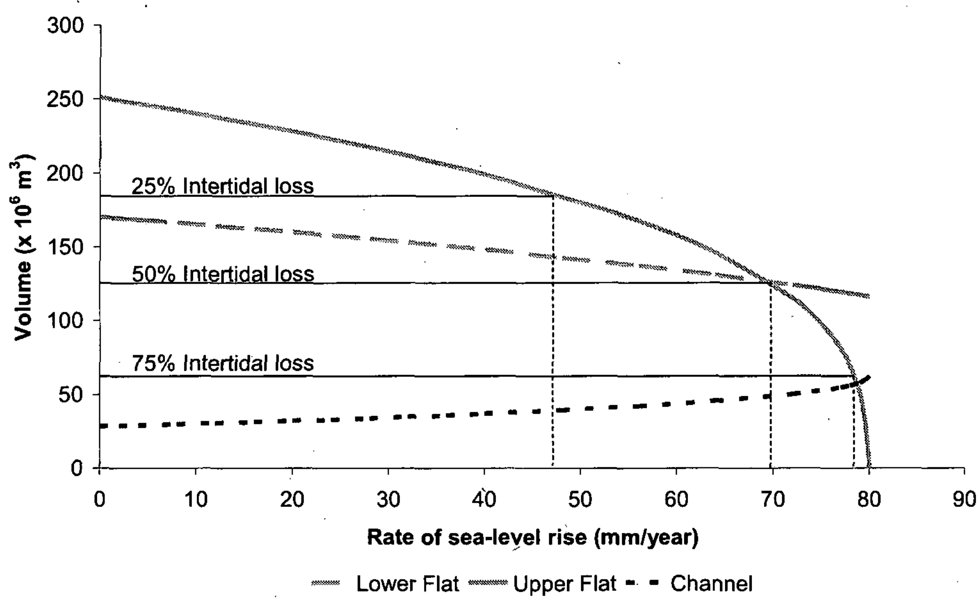


Fig. 7.9: Predicted steady state volume for the Ribble Estuary under different rates of sea-level rise

Dart Estuary

The Dart Estuary, in contrast, is predicted to be extremely sensitive to sea-level rise (Fig. 7.10). The critical rate of sea-level rise for the Dart was predicted to be just 4.8 mm/year, with 25% loss predicted to occur at rates of 2.5 mm/year (Fig. 7.17b). This suggests that intertidal loss should already be observable in the Dart Estuary. However, evidence presented in Chapter 4 suggested that the intertidal flat volume is currently increasing. The increase in intertidal volume is partly explained by a breach in the training wall at Sharpham Marshes, which added intertidal area and volume. There is also a high level of uncertainty for the Dart data set and it is possible that if a trend of decreasing intertidal flat volume is occurring, it may be missed because of this. The sensitivity of the Dart to sea-level rise is explained by the very low sediment supply from the outside world. It is possible that sediment supply from fluvial sources, which are not included in the model, also contributes significantly to the sediment budget of the Dart Estuary. If fluvial supply were found to be significant, this could increase the predicted critical rate of sea-level rise.

Model simulations were carried out to examine the sensitivity of the Dart estuary to fluvial sediment supply. Fluvial flow was set to a rate of 5 $m^3s{-}1$ and the fluvial sediment concentration (import concentration (C_I)) was varied. For C_I=C_E, the critical rate of sea-level rise increased to 5.9 mm/year. For $C_I = 2 * C_E$ SLR_{CRIT} was 11.9. The indicates that neglecting fluvial sediment supply may cause estuaries to appear more sensitive to sea-level rise than they are in reality. More data on rate of fluvial sediment supply to the Dart estuary is needed to improve estimates of SLR_{CRIT}.

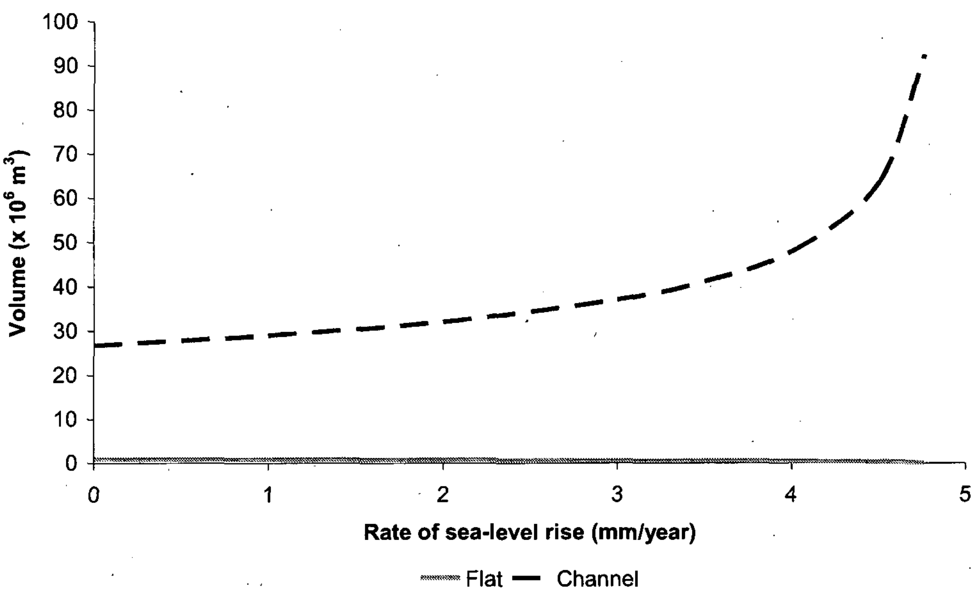


Fig. 7.10: Predicted steady state volume for the Dart Estuary under different rates of sea-level rise

Southampton Water

In Southampton Water the inner estuary was more sensitive to sea-level rise than the outer estuary. This difference is caused by the smaller horizontal diffusion coefficients for the inner estuary, meaning that the inner estuary cannot accumulate sediment at a sufficient rate to keep pace with accelerated sea-level rise, but the outer estuary can. The critical rate of sea-level rise for the inner flat was predicted to be 16.6 mm/year, with 25% loss predicted at 9.5 mm/year (Fig. 7.11 and Fig. 7.17b). Under the DEFRA sea-level rise scenarios, Southampton Water may lose most of its inner flat by 2115. The outer estuary however, was predicted to be much more resilient and showed only minor changes in response to sea-level rise.

Portsmouth Harbour

Portsmouth Harbour was also relatively resilient to intertidal loss caused by accelerated sea-level rise (Fig. 7.12). The critical rate of sea-level rise was similar to that

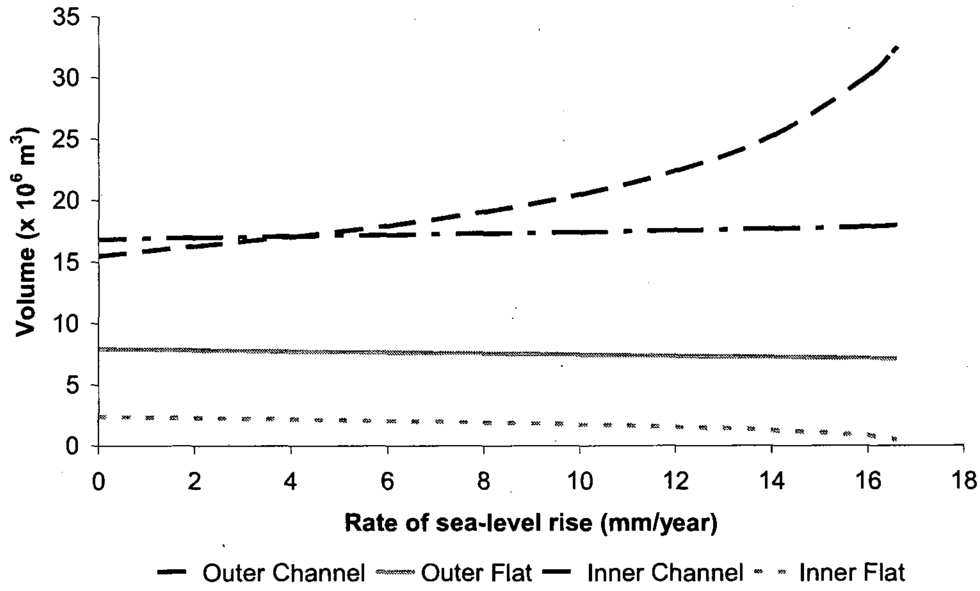


Fig. 7.11: Predicted steady state volume for Southampton Water under different rates of sea-level rise

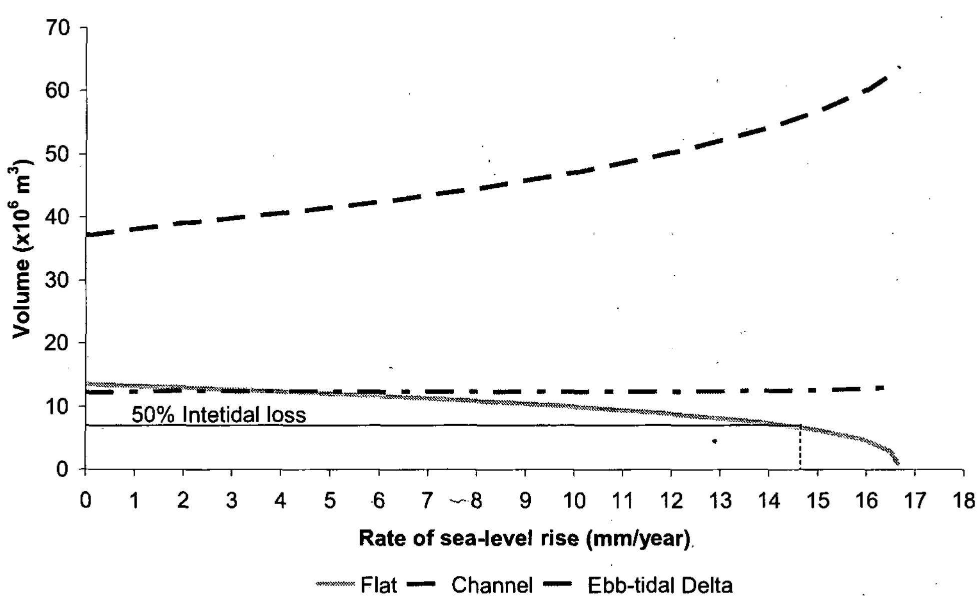


Fig. 7.12: Predicted steady state volume for Portsmouth Harbour under different rates of sea-level rise

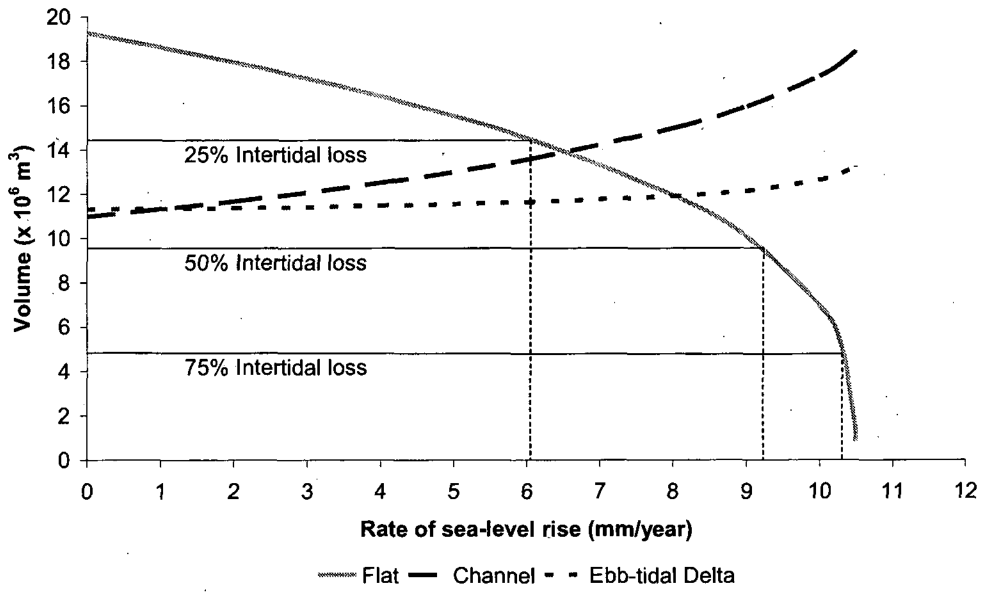


Fig. 7.13: Predicted steady state volume for Langstone Harbour under different rates of sea-level rise

for Southampton Water at 16.6 mm/year. 25% loss was predicted to occur at 9.8 mm/year, and 50% loss at 14.7 mm/year (Fig. 7.17b). This suggests that under the DEFRA sea-level rise allowances, Portsmouth Harbour would loss approximately 50% of its intertidal volume if sea-level rise continued at 15 mm/year following 2115.

Langstone and Chichester Harbours

Langstone and Chichester Harbours were both predicted to be sensitive to the rate of sea-level rise (Figs 7.13 and 7.14). The critical rate of sea-level rise for Langstone Harbour was 10.5 mm/year, with 25% loss and 50% loss at 6.1 mm/year and 9.2 mm/year respectively (fig. 7.17b). In Chichester Harbour SLR_{CRIT} was 12.5 mm/year and 25% and 50% were 7.3 mm/year and 10.8 mm/year respectively. As suggested in section 7.2.1, predictions for Langstone and Chichester Harbours indicate that they are likely to lose significant intertidal flat volumes by 2115 and the flat element will be lost completely if sea-level rise continues at 15 mm/year or accelerates further.

Thames and Humber Estuaries

The Thames Estuary and Humber Estuary were predicted to be relatively resilient to accelerated sea-level rise (Fig. 7.15 and 7.16). In the Thames Estuary, the outer flat element was most sensitive, with a critical rate of sea-level rise of 21.2 mm/year. 25% loss was predicted to occur at sea-level rise rates of 13.2 mm/year in the outer

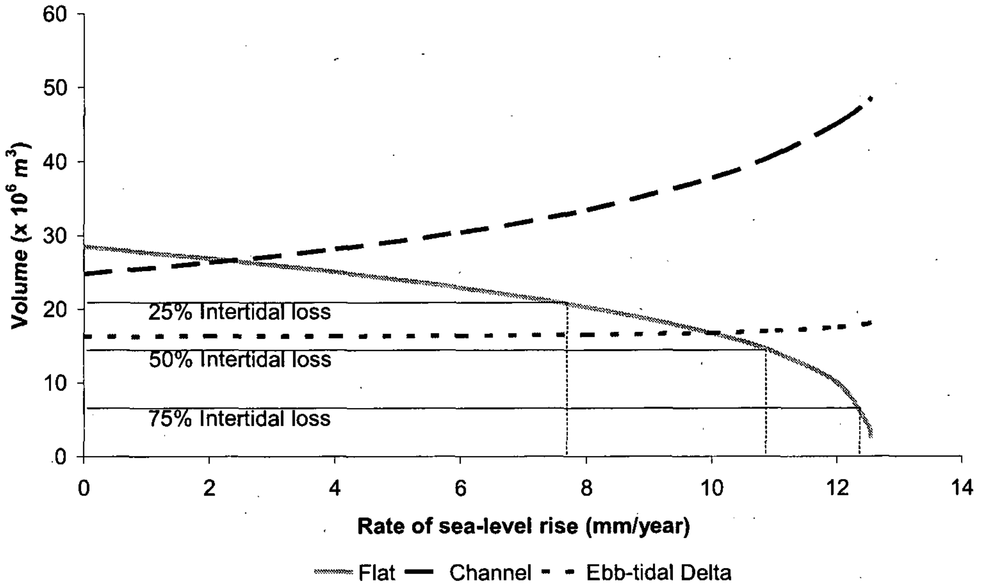


Fig. 7.14: Predicted steady state volume for Chichester Harbour under different rates of sea-level rise

Thames Estuary (Fig. 7.17b). In the Humber Estuary SLR_{CRIT} was predicted to be 21.6 mm/year, with 25% loss at 12.5 mm/year. This suggests that both the Thames and Humber Estuaries could lose up to a quarter of their respective intertidal volumes under the DEFRA sea-level rise predictions for 2215.

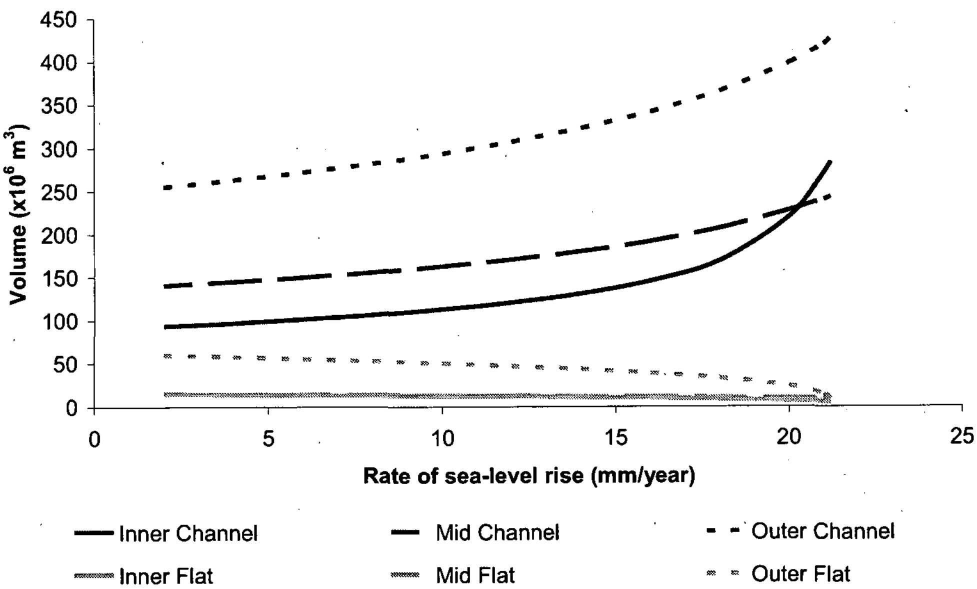


Fig. 7.15: Predicted steady state volume for the Thames Estuary under different rates of sea-level rise

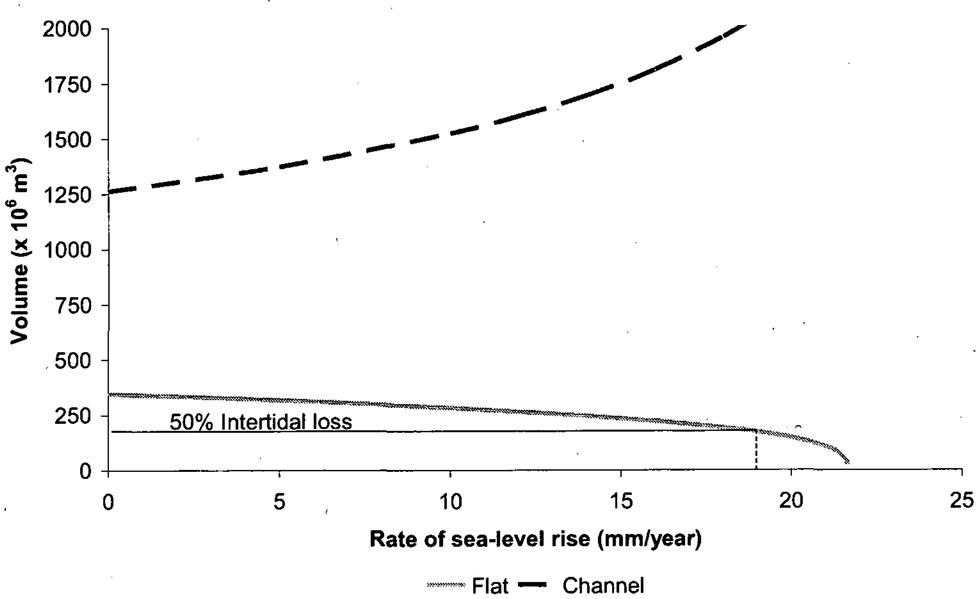


Fig. 7.16: Predicted steady state volume for the Humber Estuary under different rates of sea-level rise

7.2.3 Synthesis

The critical rates of sea-level rise, and thresholds predicted to cause 25%, 50% and 75% intertidal loss are summarised in figures 7.17a and 7.17b (which excludes the Ribble to allow the remaining estuaries to be viewed more clearly). The Ribble is predicted to be the most resilient estuary in the sample to sea-level rise. The Ribble Estuary has a very high sediment supply from the eastern Irish Sea (van der Wal et al., 2002) which would allow it to maintain intertidal areas despite high levels of sea-level rise. In addition, the high tidal range and flood-dominant characteristics of the Ribble Estuary favour sediment transport into the estuary. This is likely to be enhanced by sea-level rise, which will increase the sediment demand of the Ribble by moving the elements away from equilibrium.

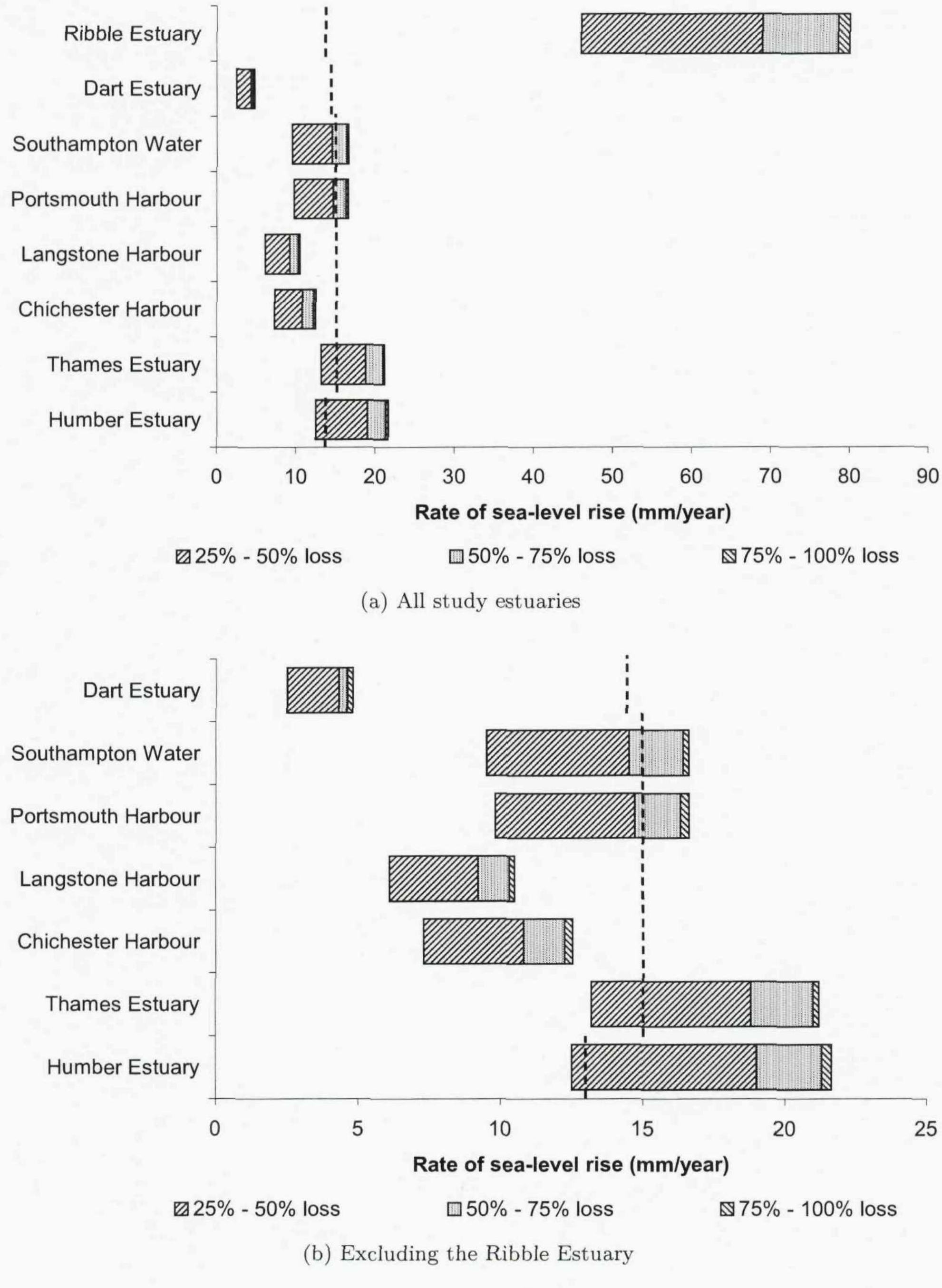
The Humber Estuary and Thames Estuary were predicted to have a similar resilience to sea-level rise, which although dramatically less that that predicted for the Ribble, suggests that they will not experience significant intertidal losses due to sea-level rise in the foreseeable future. The Humber Estuary is much larger than the Thames, creating a greater sediment demand, but also has a greater sediment supply available to meet this demand. In addition, the Thames Estuary may retain some small intertidal volumes in the inner and mid estuary even after the critical rate of sea-level rise for the outer flats has been reached.

Southampton Water and Portsmouth Harbour were predicted to have some resilience to sea-level rise. Significant intertidal losses may be seen with the highest predicted rates of sea-level rise, but they are likely to retain some intertidal volume unless the rate of sea-level rise exceeds 15 mm/year. In this case, Southampton Water may still retain some intertidal volume in the outer estuary, which was predicted to be less sensitive to sea-level rise. Langstone and Chichester Harbours were more sensitive and are predicted to lose all intertidal volume if sea-level rise continues at 15 mm/year or accelerates after 2115. The Dart Estuary is predicted to be extremely sensitive to accelerated rates of sea-level rise and it is predicted to lose all intertidal volume at rates of just 4.8 mm/year.

7.3 Discussion

The ASMITA predicted response to accelerating rates of sea-level rise was similar for all estuaries: channel volumes increased with increasing rates of sea-level rise and intertidal flat volumes decreased. The magnitude of the response varied dramatically between estuaries, with some estuaries, such as the Dart, predicted to be very sensitive to small increases in the rate of sealevel rise, whilst others, such as the Ribble, were predicted to be very resilient and did not show significant changes until very high rates of sea-level rise were simulated.

Predictions of intertidal loss are common results found using various methodologies used to predict the response of estuaries to sea-level rise. Gardiner et al. (2007)



(a) All study estuaries

(b) Excluding the Ribble Estuary

Fig. 7.17: Rates of sea-level rise leading to 25%, 50%, 75% and 100% intertidal loss for the study estuaries. Dashed lines indicate the maximum rate suggested by DEFRA (2006a) for each region

predicted intertidal loss at six UK sites under various sea-level rise scenarios using a GIS based approach. Huthnance et al. (2007) compared predictions from a variety of models predicting likely estuary morphology in 50 years time. These included the "Regime-Shell" model, which predicted losses in intertidal area in all estuaries modelled. ASMITA predictions are volumes and therefore cannot be directly compared with intertidal area loss; however, ASMITA predicts that intertidal sediment will be lost in response to sea-level rise in all of the studies modelled. As the element areas are constant in ASMITA, loss in intertidal volume represents lowering of the intertidal flats relative to low water, but in common with other methodologies the overall result is a decrease in the size of the intertidal zone. The magnitude of intertidal losses predicted by ASMITA may change if variable element areas, and therefore coastal squeeze, could be included in the model. Further work to extend ASMITA to include variable area is desirable to allow intertidal area change and the effects of coastal squeeze to be included.

The critical rates of sea-level rise for the eight study estuaries varied between 4.8 mm/year in the Dart and 80 mm/year in the Ribble. The Ribble Estuary is predicted to be exceptionally resilient to sea-level rise and may be considered as a special case. It is the only estuary in the sample which is flood dominant, has a very high sediment supply and a high capacity to redistribute the available sediment. For these reasons it is not typical of the study sample or UK estuaries in general. If the Ribble is excluded, the maximum SLR_{CRIT} is 21.6 mm/year for the Humber Estuary. For comparison, van Goor et al. (2003) found the SLR_{CRIT} for Amelander Zeegat and Eierlandse Gat in the Dutch Wadden sea to be 10.5 mm/year and 18 mm/year respectively. SLR_{CRIT} values predicted for Southampton Water, Portsmouth Harbour, Langstone Harbour, Chichester Harbour, the Thames Estuary and the Humber Estuary are within a similar range to those found for Dutch Wadden Sea inlets.

The response of an estuary to sea-level rise is strongly influenced by the basin area (and intertidal area), sediment availability and the capacity of sediment transport processes to distribute the available sediment within the system (van Goor et al., 2003). The basin area and rate of sea-level rise determine the sediment demand of the estuary. Large estuaries have a greater sediment demand than smaller ones and are therefore more vulnerable, all other factors being equal. Sediment availability and transport capacity determine the ability of marine and estuarine processes to meet this demand.

Basin areas, sediment availability (represented by the global equilibrium concentration, C_E) and sediment transport capacity (represented by the vertical and horizontal exchange coefficients) used in ASMITA simulations for the eight English study estuaries and two Dutch Wadden Sea basins (van Goor et al., 2003) are given in Table 7.10. The Ribble Estuary, Southampton Water and the Thames Estuary are estimated to have relatively high global equilibrium concentrations, with simi-

Tab. 7.10: Summary of estuary areas and sediment parameters used in this thesis for the ASMITA simulations and used in by van Goor et al. (2003) for Dutch Wadden Sea inlets (C_E is the global equilibrium concentration, w_s is the vertical sediment exchange coefficient and δ is the horizontal exchange coefficient between two elements)

	Basin Area ($x10^6$ m^3)	Flat Area ($x10^6$ m^3)	C_E	w_s	δ
Ribble Estuary	120.64	91.33	0.00012	0.0008	780-2372
Dart Estuary	7.274	1.22	0.00001	0.00002	500-750
Southampton Water	34.38	13.1	0.00015	0.0003	60-1228
Portsmouth Harbour	19.42	11.41	0.00003	0.0008	600-1650
Langstone Harbour	19.22	12.69	0.00003	0.0003	346-1201
Chichester Harbour	29.49	17.5	0.00003	0.0002	941-2000
Thames Estuary	117.02	43.6	0.000085	0.0006	264-5028
Humber Estuary	320.71	105.82	0.0002	0.0003	1440-1620
Amelander Zeegat	271.8	178.00	0.0002	0.00001-0.0001	1000-1500
Eierlandse Gat	157.70	105.00	0.0002	0.00001-0.0001	1000-1500

lar values to the Dutch Wadden Sea basins. The values of the horizontal exchange coefficients between elements are however much larger in the Ribble Estuary, due to its high tidal range and long boundary between the estuary mouth and the open coast, leading to a high SLR_{CRIT}. The Humber also has relatively high horizontal exchange coefficients, but the basin area is more than double that of the Ribble, meaning that the sediment demand required for accretion to keep pace with the same rate of sea-level rise is far greater. In Southampton Water, the horizontal exchange coefficients are smaller, suggesting that there is it lack of sediment transport capacity, rather than lack of sediment per se, that prevents further accretion. This is supported by Bray et al. (2004), who suggest that transport of coarser sediments into Southampton Water is very limited.

Portsmouth and Langstone Harbours have similar basin areas and therefore similar sediment demands. The global equilibrium concentration was the same for both Harbours. SLR_{CRIT} was predicted to be larger for Portsmouth Harbour. This difference arises from differences in the horizontal exchange coefficients, which tend to be larger in Portsmouth Harbour, allowing more sediment to be transported into the estuary. Chichester Harbour has a larger basin area and larger sediment demand than Langstone or Portsmouth Harbour. The global equilibrium coefficient was the same as Portsmouth and Langstone Harbours', but the horizontal exchange coefficients were larger, resulting in SLR_{CRIT} values similar to those predicted for Langstone Harbour.

The Dart Estuary was estimated to have the lowest global equilibrium coefficients, representing its extremely low marine sediment supply. Horizontal sediment exchange coefficients were also estimated to be very low and despite its small area, and therefore small sediment demand, the Dart was predicted to be very sensitive to sea-level rise.

The critical rate of sea-level rise for an estuary is influenced by basin area. Human interventions, such as land reclamation or managed realignment, which change the basin area therefore affect the critical rate of sea-level rise by altering the sediment demand of the basin. In Portsmouth Harbour, the reclamations described in Chapter 4 are predicted to increase the critical rate of sea-level rise by 2 mm/year as they reduce the sediment demand of the Harbour. In general it was observed that decreasing the basin area (i.e. land reclamation) increased the SLR_{CRIT} threshold, whilst increasing the basin area (i.e. realignment of flood defences) decreased SLR_{CRIT}. If this model result can be validated, it has implications for managed realignment and suggests that it will be very important to consider the additional sediment demand of potential managed realignment sites. However, problems estimating intertidal flat equilibrium volume following area changes mean this result should not be relied upon without further evidence (see section 6.3.2).

It was noted in Chapters 5 and 6 that the intertidal flat equilibrium coefficient was altered by human interventions which changed the basin area. To date, a suitable method for estimating the intertidal flat equilibrium coefficient has not been found and it is not currently possible to predict the new flat equilibrium volume following disturbances. For this reason, quantitative predictions of the effects of basin area change on SLR_{CRIT} have not been attempted in this thesis. Further work could focus on resolving this issue, as it is important to understand the influence of human interference on an estuaries ability to adapt to sea-level rise.

The model simulations presented in this chapter are based on the assumption that equilibrium relationships are not changed as the rate of sea-level rise increases. This assumption is currently untested as the majority of evidence for equilibrium relationships comes from estuaries which have historically experienced low rates of sea-level rise (1 - 2 mm/year). The assumption that equilibrium relationships are not changed by sea-level rise should be tested against sites which experience higher rates of sea-level rise, such as the Mississippi Delta and the east Texas coastline where sea-level rise rates may be up to 10 mm/year, to test whether equilibrium relationships remain valid.

8. DISCUSSION

The main aim of this thesis was to investigate the validity and limits of usefulness of equilibrium concepts in describing the large-scale morphodynamics of UK estuaries. This chapter summarises the main findings and discusses them in the context of the objectives detailed in Chapter 1. The strengths and limitations of using equilibrium theory to model estuary evolution are discussed, along with possible explanations for the weaknesses identified. Recommendations for further research are also provided.

8.1 Achievement of Objectives

8.1.1 Can estuary specific equilibrium relationships be defined to describe UK estuaries?

Historical analysis of morphological evolution of a sample of eight English estuaries with various morphological types showed that large-scale morphological behaviour varied significantly between estuaries (Chapter 4). The Humber, Thames and Dart estuaries showed only small variations over time and appear to be close to dynamic equilibrium. Langstone and Chichester Harbours showed larger variations, but no net change was observed, suggesting that element volumes vary around a dynamic equilibrium state. The Ribble Estuary, Southampton Water and Portsmouth Harbour have been significantly disturbed by human interventions and their equilibrium status is less obvious, and differed between elements.

In the Ribble estuary, the equilibrium coefficient for the channel was almost constant throughout the study period, despite the presence of training walls (built in the 1800s), dredging activities and changes in tidal prism resulting from reclamations. The lower flat element also appears to be close to dynamic equilibrium. The upper flat element however, does not appear to be close to equilibrium, and the intertidal flat equilibrium coefficient derived from the data increases by more than 100% over the study period.

In Southampton Water, the empirical coefficient for the channel derived from the data for the inner estuary increases from 0.41 to 1.46 between 1926 and 1996, due to dredging. The intertidal flat equilibrium coefficient for the inner estuary decreases dramatically over the same period, as a result of land reclamation and a decrease in average flat height. The same coefficients for the outer estuary are relatively constant, suggesting the outer estuary is close to dynamic equilibrium but the inner estuary is not, with dredging being the major cause.

In Portsmouth Harbour, the channel equilibrium coefficient derived from the data increased over time, whilst the intertidal flat equilibrium coefficient decreased. A possible interpretation, given in Chapter 4, was that Portsmouth Harbour was undergoing evolution towards a new equilibrium state following earlier human interventions over the preceding century. Application of ASMITA to the data suggests that this interpretation may apply to the flats, but that the channel element is closer to equilibrium than suggested by initial analysis of the data.

Despite large temporal variations in channel equilibrium coefficients derived from the data for Southampton Water and Portsmouth Harbour, the initial channel equilibrium coefficient, based on the earliest available data (i.e. before the disturbances or when disturbances were smaller), gave the best fit to the observed data when implemented in ASMITA, providing that the human interferences were accounted for in the model simulations (Chapter 5). This suggests that the development of these channels is still governed by the initial dynamic equilibrium relationship with tidal prism, but that this is masked when the data is examined without accounting for the volume changes caused by human interventions. In particular, it appears that ongoing dredging maintains the channels at volumes far removed from equilibrium. If dredging were to cease, it seems likely that the channels would eventually return to a state that fulfills their initial equilibrium relationship.

For all eight study estuaries, the evolution of the channel volume was well described by a single, estuary specific, coefficient linking the channel volume to tidal prism. This is taken as evidence that a dynamic equilibrium volume does exist in the channel element and can be defined as a function of tidal prism. Equilibrium volumes for intertidal flat elements were less easily defined, particularly in estuaries that have undergone large scale human interventions such as land reclamation. Intertidal flat equilibrium volumes can be defined for undisturbed estuaries, but were found to be sensitive to changes in basin or element area in ways that could not be predicted using the available data. It is possible that the intertidal flats display meta-stable equilibrium behaviour, with large disturbances causing them to evolve towards a new dynamic equilibrium.

Channel volume in a particular estuary seems to be adequately described by a linear relationship with tidal prism. The simplest explanation for this is feedback between the flow area, flow volume and flow velocity which tends to impart an equilibrium channel volume for a given tidal prism. This varies between estuaries depending factors such as the sediment type and sediment supply and may be constrained by the underlying geology. Flat equilibrium was described in ASMITA as a function of basin area and tidal range (Eq. 6.1). This was less reliable than the channel equilibrium relationships, especially following sudden changes in basin area. There are a number of possible explanations of why flat equilibrium was less consistent, including differences in forcing between flats and channels and the addition of biological factors on flats.

In addition to tidal forcing, other physical factors, such as waves and sediment supply, and biological influences, such as saltmarsh development, influence the equilibrium height and profile of the intertidal zone. Roberts et al. (2000) used a simple model to investigate the effects of tidal range, sediment supply and wave height on mud flat profiles. They found that the equilibrium slope of estuarine mudflats increased with increasing tidal range and sediment supply. Waves were found to modify the shape of the profile, generally making it less convex and more concave with increasing wave heights. van Dongeren and de Vriend (1994) suggested that tidal flats would try to maintain an overdepth below mean high water and explained this by suggesting that if the over depth increased, velocities would decrease and sediment would settle out of suspension, thus decreasing the overdepth. If the flat were too shallow with respect to mean high water, velocities would be increased and erosion would occur. However, van Dongeren and de Vriend (1994) did not suggest a method for defining the equilibrium height based on this mechanism.

French (1991) suggested that the equilibrium height of salt marshes in north Norfolk was approximately 0.8 m below highest astronomical tide (HAT), but this difference was predicted to increase with increasing rates of sea-level rise and is strongly related to sediment supply (French, 1993). Differences between marsh elevation and HAT elevation greater than 1.5 m lead to ecological drowning at this site: the marsh surface is too deep for salt marsh vegetation. This provides a critical sea-level rise threshold for saltmarshes, which is similar to that for intertidal flats in ASMITA, as the function of the intertidal morphology is fundamentally changed.

The intertidal flat element is more complex than the channel element, being affected by more forcing processes. More information is required to describe the equilibrium condition of flats than channels. In addition, it is less likely that all of the processes influencing the morphology of the intertidal flats will remain constant over time, so flats are less likely than channels to actually achieve steady state. Given the relative simplicity of processes influencing channels, it is unsurprising that channel equilibrium volume can be described more easily.

Sediment supply to intertidal flats has not been examined for the purposes of this study. It is however, likely that sediment supplies in Southampton Water and Portsmouth Harbour have decreased over time due to ongoing dredging of navigational channels. This could (at least partially) explain the decrease in the average flat height observed in Portsmouth Harbour and Southampton Water. Cox et al. (2003) suggested that capital dredging could cause changes in salt marsh extent by altering the tidal prism and allowing high tides to reach the marsh edge more frequently.

In the Ribble Estuary, sediment supply is large and does not appear to be limiting the growth of the upper intertidal areas. Reasons for the rapid accretion in the upper flat area are unclear, but may be a result of earlier human interference in the estuary. The construction of training walls modified tidal flows within the estuary and caused enhanced intertidal sedimentation (van der Wal et al., 2002). The sedimentation further reduced tidal prism, thus modifying tidal flows. This positive feedback appears to be continuing and it may be some time before a new equilibrium is reached. It seems likely that the flat equilibrium profile in the Ribble estuary is strongly influenced by the high tidal range, large sediment supply and moderate wave climate. The Ribble differs from other estuaries considered in this thesis in that it is flood dominant and has a very large sediment supply. The Ribble is likely to remain flood dominant as the ratio of tidal amplitude to channel depth (a/h) is very large (Friedrichs and Aubrey, 1988). This implies that the Ribble Estuary is likely to continue to accrete until available accommodation space is filled.

An additional factor that may influence the equilibrium flat volume in estuaries is the presence of vegetation, particularly saltmarsh macrophytes. Where salt marsh is present it will influence the stability and sediment trapping efficiency of the intertidal flat element, and is therefore likely to affect the equilibrium volume (Moller, 2006). Saltmarsh evolution is affected by factors such as vegetation dynamics and growth cycles, which are not included in ASMITA, but may influence the equilibrium state of the flat element. These include seasonal variations and longer term patterns such as the appearance, expansion and decline of *Spartina anglica* in the Solent over the last century (Havant Borough Council, 1997; Raybould et al., 2000). Temporal variations in saltmarsh cover could potentially account for variations in in flat volume. Further work is needed to asses the impact of vegetation on intertidal flat equilibrium.

8.1.2 Can equilibrium theory be implemented in a numerical model to predict evolution and behaviour of UK estuaries at engineering timescales and to model response to gradual changes, such as sea-level rise, and sudden changes, such as large scale land reclamation or managed realignment?

ASMITA (Stive et al., 1998) was applied to successfully hindcast the evolution of the majority of the study estuaries over time scales ranging from 42 years (Langstone and Chichester Harbours) to 142 years (Dart Estuary) (Chapter 5). This illustrates how equilibrium theory can be successfully implemented within a numerical model. Results of the initial simulations suggested that, whilst ASMITA performed well for the majority of estuaries, there are limitations to this approach. In particular, the equilibrium relationship for the intertidal flat element is altered by human interventions and the magnitude of this change cannot necessarily be predicted.

Reasons for the variability in intertidal flat equilibrium include changes in sediment supply, wave action and vegetation cover as discussed in section 8.1.1. It is possible that the reclamation or other human activities can influence these factors. For example, reclamation will often remove mostly saltmarsh, which has greater elevation, leaving the lower mud flats behind. This reduces the average height of the flat element and as saltmarsh are will recover only slowly, if at all, reduces the equilibrium height/volume of the flat element on medium to long timescales, depending on the time taken to reestablish equilibrium. Alternatively, human interference via dredging may increase intertidal slopes and reduce sediment supplies to intertidal areas.

Difficulties predicting the flat equilibrium volume following human interventions have implications for other models based on equilibrium concepts. For example ESTMORF (Wang et al., 1998) contains high and low intertidal flats, each defined by an equilibrium flat height. This study has found that this may be variable, particularly following large scale human interventions.

It has previously been assumed that equilibrium theory and ASMITA can be used to model human interventions including land reclamation and basin closure (Stive et al., 1997; Ubbink, 2003; Kragtwijk et al., 2004). This assumes that the equilibrium state of the altered estuary can be adequately defined. As described above, this proved to be problematic for the study estuaries. Previous applications of ASMITA have been to basins of the Dutch Wadden Sea, using equilibrium relationships based on a sample of basins with similar characteristics. This approach appears to be reasonable, and ASMITA was able to reproduce the observed behaviour following the disturbance (Kragtwijk et al., 2004). For the estuaries studied here, such generic relationships are not available and equilibrium relationships are based on data for the specific estuary at different times. This did not lead to reliable results following human interventions for the reasons discussed in Section 8.1.1.

8.1.3 Can generic relationships be used to adequately describe equilibrium in specific UK estuaries?

Empirical relationships, believed to describe the equilibrium state of an estuary or inlet, have traditionally been derived from data for a large number of similar inlets (O'Brien, 1969; Jarret, 1976). These have shown strong relationships between a number of parameters, including cross-sectional area at the inlet mouth and tidal prism (O'Brien, 1969; Jarret, 1976), water volume in the channels and basin area and surface area of the channels and basin area (Renger and Partenscky, 1974). Much of this work has been carried out for sand rich tidal inlets and basins on the US coast and the Dutch Wadden Sea. Strong relationships between mouth cross-section and tidal prism have also been observed for estuaries in New Zealand (Hume and Herdendorf, 1993) and the UK (Townend, 2005) grouped by morphological type.

In the current study, strong relationships were found between element areas, element volumes and basin area, tidal prism and tidal range (Chapter 6). In particular, flat area was strongly related to basin area and flat volume to basin area times tidal range. Channel area showed a strong relationship with tidal prism divided by tidal range, although given the strength of the relationship between flat area and basin area, channel area is best calculated as the difference between these two areas ($A_c = A_b - A_f$). Channel volume showed the weakest relationship with any of the independent variables, and tidal prism was found to be an unexpectedly poor predictor of channel volume. This may be caused by the relatively high error of the data set used (Townend, 2005). There are a number of limitations to using a large data set to make empirical generalisations, including poor data quality and a lack of information on potentially relevant factors, such as constraint on estuary behaviour (Section 6.4).

Despite the strong relationships observed for English estuaries, the generic relationships derived from linear regressions did not match the same relationships generated from data for the individual study estuaries (Chapter 6). Estuary specific equilibrium coefficients, based on a range of parameters, gave a wide range of values (Tables 6.5 to 6.11). It is unsurprising that generic relationships bear little resemblance to any specific estuary given this variability.

The high variability of estuary specific relationships could be caused by differences in littoral drift, sediment supply and wave action between estuaries (HR Wallingford et al., 2006). Several authors have reported that inlets with high littoral drift rates tend to have smaller cross-sectional areas relative to tidal prism than inlets with lower littoral drift (Kraus, 1998; HR Wallingford et al., 2006). In addition, Hughes (2002) suggested sediment properties were also important in determining the equilibrium cross-section area of an inlet mouth.

Generic relationships, based on currently available data, are not suitable for describing the equilibrium state of specific estuaries. It is possible that generic relationships could be improved by including additional terms to represent sediment supply, littoral drift, sediment characteristics and wave action. However, the contribution of these processes is not fully understood and it it outside the scope of this thesis to resolve these issues.

8.1.4 Can ASMITA be modified, based on generic relationships, to better represent UK estuaries?

Generic relationships were not found to describe the equilibrium state of specific estuaries satisfactorily (Chapter 6). In the absence of suitable generic relationships, equation 6.6 was proposed to correct the intertidal flat equilibrium coefficient follow human induced area changes. The ability of equation 6.6 to describe the equilibrium volume of a flat element following a disturbance relies on the assumptions that 1) the disturbance is the only cause of area change and no further adjustment takes place and 2) the average flat height remains constant or changes in flat height are small relative to changes in area. Of the three estuaries undergoing significant area changes, only Southampton Water met these assumptions. In the Ribble, upper flat area and average height were observed to increase despite large scale land reclamation. In Portsmouth Harbour, the average height of the flat element tended to decrease over time. This suggests that whilst equation 6.6 is useful in some circumstances, it is not generically applicable for all estuaries experiencing area change.

It is desirable to extend ASMITA to allow element areas to evolve during model simulations, as discussed in Chapter 6. This would allow more realistic simulations of the response to sea-level rise and the added benefit of being able to calculate loss of intertidal area as well as volume. Previous attempts to include dynamic element areas have made use of equation 6.7, assuming that area can be calculate from the element's volume and average height or depth. The method assumes that average height and depth are constant. In the current study average flat height and average channel depth were found to vary over time and no method was found for predicting this variation. It is therefore concluded that intertidal flat area cannot be deduced from element volume to sufficient accuracy, because the average height is not constant nor predictable from other parameters. Carrying out simulations with variable area based on these assumptions cannot be justified at this time.

8.1.5 Can numerical models based on equilibrium concepts be used to help estuary managers to predict and understand the likely responses of estuaries to sea-level rise and human interventions?

ASMITA was applied to the study estuaries to predict their evolution under accelerated sea-level rise. Scenarios involving human disturbances to the estuary were not modelled because of the limitations in predicting the flat equilibrium state following these types of disturbances, as discussed in section 8.1.4. The validity of applying ASMITA to sea-level rise scenarios should be investigated by applying the model to sites with a wide range of observed rates of relative sea-level rise and suitable historic data, such as the Mid Atlantic US coast (3 to 4 mm/year) and the Mississippi Delta, USA (up to 10 mm/year). For the purposes of this thesis, and earlier studies, it was assumed that equilibrium theory was able to describe the estuary satisfactorily under accelerated sea-level rise (van Goor et al., 2003; Rossington et al., 2007).

The predicted response to accelerating rates of sea-level rise was similar for all estuaries: channel volumes increased with increasing rates of sea-level rise and flat volumes decreased. The magnitude of the response varied dramatically between estuaries, with some estuaries, such as the Dart, being very sensitive to small increases in the rate of sealevel rise, whilst others, such as the Ribble, were very resilient and did not show significant changes under any plausible sea-level rise scenario.

The response of an estuary to sea-level rise is strongly influenced by the basin area (and intertidal area), sediment availability and the capacity of sediment transport processes to distribute the available sediment within the system (van Goor et al., 2003). The basin area and rate of sea-level rise determine the sediment demand of the estuary. Large estuaries have a greater sediment demand than smaller ones. Sediment availability and transport capacity determine the ability of marine and estuarine processes to meet this demand.

The critical rate of sea-level rise for an estuary appears to be influenced by basin area. Human interventions, such as land reclamation or managed realignment, which change the basin area therefore effect the critical rate of sea-level rise by altering the sediment demand of the basin. In general it was observed that decreasing the basin area (i.e. land reclamation) increased the SLR_{CRIT} threshold, whilst increasing the basin area (i.e. realignment of flood defences) decreased SLR_{CRIT}. This may have serious implications for the use of managed realignment, as it suggests it may have a negative impact on the ability of estuaries to respond to sea-level rise. Future work should focus on improving the prediction of the flat equilibrium volume following disturbances because there is potential to model not only the effects of human interventions but the interaction of these with sea-level rise.

At the current time, it seems that numerical models based on equilibrium concepts, such as ASMITA, may aid estuary managers in predicting the likely consequences of accelerated sea-level rise in a particular estuary. However, more work is needed before the effects of human interventions can be reliably predicted using equilibrium.

8.2 Recommendations for Future Work

This research has identified a number of issues that require further attention. Resolving these issues will improve the usefulness of equilibrium theory in large-scale estuarine modelling by allowing human interventions to be modelled with more confidence. In addition, the interactions between human interventions and climatic change could also be modelled using equilibrium concepts. Suggested further work includes:

1. **Improved estimation of the intertidal flat equilibrium volume:** The present research found that the intertidal flat equilibrium coefficient, relating flat equilibrium volume to basin area and tidal range, tended to change following interventions that affected the area of the estuary. This was partially due to the direct impact of the intervention which alters the area of the flats relative to the basin area. This change can be accounted for using equation 6.6. In addition to direct impacts, human interventions may also affect the flat volume by changing the average height of the flat, as observed in Southampton Water and Portsmouth Harbour. In the Ribble, human interventions appear to have affected tidal characteristics in such a way that the equilibrium volume of the intertidal flats is increasing, despite extensive reclamations. Changes in flat height and area that are not directly accounted for by the intervention also affect the equilibrium volume of the flats. Currently the effect of these changes on equilibrium volume cannot be predicted and are limiting the situ-

ations in which equilibrium theory can be used to model large-scale estuarine behaviour.

Future work should focus on developing an improved method for estimating the intertidal flat equilibrium volume following human interventions. In particular, a method for predicting the average flat height from forcing variables such as tidal range, sediment supply and wave impact is needed. If this can be resolved, models such as ASMITA will have a greater ability to predict changes in large-scale estuarine morphology caused by human interventions.

2. **Variable element area:** Previous work where variable element areas have been included in ASMITA has assumed that average flat height is constant or predictable. This research found that this was not true for several estuaries in the sample, and therefore suggests that further work is needed to improve the prediction of average flat heights in estuaries, and more generally, as indicated above, this will improve the power of ASMITA to predict large-scale estuarine behaviour.

3. **Generic relationships:** This study failed to identify any generic relationships that were suitable for predicting equilibrium in specific UK estuaries. Generic relationships are desirable as they allow equilibrium models to be applied where insufficient data is available to derive specific equilibrium relationships. It is likely that the simple relationships investigated in this research did not consider enough relevant processes to derive useful generic relationships. Future work should investigate whether the consideration of more parameters, such as sediment supply or relative wave impact, can provide generic relationships that describe specific cases sufficiently well to be used in equilibrium models.

4. **Impact of sea-level rise on equilibrium relationships:** The validity of applying ASMITA to sea-level rise scenarios should be investigated by applying the model to sites with a wide range of observed rates of relative sea-level rise and suitable historic data, such as the Mid Atlantic US coast (3 to 4 mm/year) and the Mississippi Delta, USA (up to 10 mm/year).

5. **Inclusion of differing sediment properties and biological factors** Two factors currently not included in ASMITA are differences between cohesive and non-cohesive sediments and the influence of biology on the morphology of the estuary. Sediment properties and biology may influence dynamic equilibrium relationships used to describe the estuary and may also change sediment erosion and deposition characteristics. Cohesive sediments may require different vertical exchange parameters to account for differences in the settling and erosion characteristics of muds. The inclusion of salt marsh vegetation, which could potentially be added as new element above the intertidal flats, may also require different settling and erosion rates to reflect the ability of

vegetation to trap and sediment and inhibit erosion. More work is needed to extend ASMITA to include the effects of different sediment type and biology.

9. CONCLUSIONS

This thesis has come to a number of important conclusions about the concept of equilibrium in estuaries. Empirical relationships were found to describe the dynamic equilibrium volume of the channel element in a number of English estuaries across a range of morphological types. Channel equilibrium volume can be described as a linear function of tidal prism. However, the coefficient (α_c) varied between estuaries, supporting the use of estuary specific equilibrium relationships as suggested by Wang et al. (1998).

Empirical relationships describing the intertidal flat volume as a function of basin area and tidal range were also observed for the eight study estuaries. However, unlike channel volume, they were sensitive to area changes caused by human interventions such as land reclamation and therefore only described the equilibrium volume of the intertidal flats in undisturbed estuaries. This suggest the possibility of meta-stable equilibrium behaviour on the intertidal flats, with large disturbances breaching some"threshold' and causing the intertidal flats to evolve towards a new dynamic equilibrium relationship. Further work is needed to allow the dynamic equilibrium of the intertidal flats to be predicted following large-scale human interventions.

Dynamic equilibrium relationships for specific UK estuaries were implemented in the numerical model ASMITA (Stive et al., 1998) to successfully reproduce the observed morphological evolution of the eight study estuaries over approximately 50 to 150 years. Brier's skill scores indicated that ASMITA predictions were better than assuming a baseline of no change, except in cases when the observed change was very small. The fit of the predictions to the observed data varied between estuaries and between elements. The most important improvement would be if intertidal flat equilibrium could be better defined following human interventions.

The ASMITA schematisations provide a structured framework for analysing data on historic morphological changes. This allows equilibrium to be analysed for individual elements and changes through time to be identified. This study has shown that new elements can be introduced and the basic schematisation extended to capture more complex morphological behaviour, without compromising the simplicity of the ASMITA model. This is an important extension as UK estuaries have a variety of differing morphologies and many do not conform to the simple channel–flat–ebb-tidal delta schematisation that has been used in many previous ASMITA studies (Stive et al., 1997; van Goor et al., 2003; Kragtwijk et al., 2004).

Generic relationships, based on a larger sample of 53 English and Welsh estuaries, were found to be unsuitable for describing the equilibrium state of specific estuaries, possibly due to differences in sediment supply and wave impact, which were not included in the relationships. It was felt that the derived generic relationships were not a suitable basis for improvements to ASMITA, due to their poor applicability to any of the study estuaries.

Equilibrium relationships were applied using ASMITA (Stive et al., 1998) to investigate the effects of different rates of relative sea-level rise in the study estuaries. Predictions suggest that estuaries vary largely in their ability to maintain intertidal areas with increasing rates of sea-level rise and this is influenced by the estuary area, sediment supply and sediment transport capacity. Of the study estuary sample, the Ribble was predicted to be extremely resilient to intertidal loss due to sea-level rise, whilst the Dart was predicted to be most sensitive to intertidal loss.

More work is needed to improve the estimation of the intertidal flat equilibrium volume, particularly following area changes, before ASMITA can be used to model the effects of human interventions in estuaries with confidence. However, if a reliable way of defining intertidal flat equilibrium can be found, ASMITA could be used to model human interventions in estuaries and the interaction of human interventions with sea-level rise. This would significantly increase its utility as a tool in estuarine management.

This thesis has contributed new insights regarding the use of equilibrium theory in the modelling of large scale-estuarine morphodynamics. In particular, this research has shown that:

- Channel dynamic equilibrium relationships, of the form $V_c = \alpha_c P$ can be defined for estuaries with a wide variety of morphological types.
- Empirical relationships defining the equilibrium volume of the intertidal flats can also be defined, but are sensitive to changes in estuary area and are hence less robust in estuaries subject to reclamation and, by implication, to managed realignment. This may suggest meta-stable equilibrium behaviour.
- The ASMITA estuary schematisation can be modified and extended to successfully represent the morphological behaviour of estuaries of different morphological types.
- Generic relationships, derived from a larger data sets (EMPHASYS, 2000), were not suitable for describing equilibrium in any of the study estuaries, and therefore estuary specific relationships are recommended for any equilibrium model.
- Equilibrium theory is useful in modelling the large-scale behaviour of estuaries and, if the problems defining intertidal flat equilibrium can be resolved, has the potential to be a useful tool for long-term estuary management.

APPENDICES

A. FUTURECOAST ESTUARY CLASSIFICATION

Tab. A.1: The relative importance of different physical processes in different types of estuary setting (Dyer, 2002)

Behavioural Type	**RELATIVE MAGNITUDE OF PROCESSES**									
	Tides		**Littoral Drift**		**Rock**		**River flow**		**Weather effects**	
	Large	**Small**	**Large**	**Small**	**Hard**	**Soft**	**High**	**Low**	**Large**	**Small**
1a. Fjord with spits		x	x		x			x		x
1b. Fjord, no spits	x			x	x		x			x
2a. Fjard with spits		x	x			x		x		x
2b. Fjard, no spits	x			x		x	x			x
3a. Ria with spits		x	x		x			x		x
3b. Ria, no spits	x			x	x		x			x
4a. Single spit-enclosed		x	x			x		x		x
4b. Double spit-enclosed		x	x			x		x		x
4c. Spit-enclosed, filled valley		x	x			x		x		x
5. Funnel shaped	x			x		x	x			x
6. Embayment	x			x		x		x	x	
7a. Symmetrical tidal inlet	x		x			x		x	x	
7b. Asymmetrical tidal inlet		x	x			x		x	x	

Tab. A.2: Geomorphological features present in different estuary types (Dyer, 2002)

	GEOMORPHOLOGICAL ELEMENTS											
Behavioural Type	Cliffs	Salt marsh	Sand flats	Rock platform	Mud flats	Linear banks	Low Water channel	Ebb/ flood channels	Spits	Ebb-tidal delta	Flood-tidal delta	Barrier beach
1a. Fjord with spits	x		x	x			x		x			
1b. Fjord, no spits	x			x			x					
2a. Fjard with spits		x	x		x		x		x			
2b. Fjard, no spits		x	x		x		x					
3a. Ria with spits	x	x		x	x		x		x			
3b. Ria, no spits	x	x		x	x		x					
4a. Single spit-enclosed	x	x	x		x		x	x	x	x	x	
4b. Double spit-enclosed		x	x		x		x	x	x	x	x	
4c. Spit-enclosed, filled valley		x			x				x	x		
5. Funnel shaped		x	x		x	x	x	x				
6. Embayment		x	x		x	x	x	x				
7a. Symmetrical tidal inlet		x	x		x		x	x	x	x	x	x
7b. Asymmetrical tidal inlet		x	x		x		x	x	x	x	x	x

B. ESTUARY DISTURBANCE DATA

Tab. B.1: Disturbance data used in ASMITA for the Ribble Estuary simulations

Year	V_{fl}	V_{fu}	V_v	A_{fl}	A_{fu}	V_c
1904	0	0	80900	0	0	0
1905	0	0	80900	0	0	0
1906	0	0	80900	0	0	0
1907	0	0	80900	0	0	0
1908	0	0	80900	0	0	0
1909	0	0	80900	0	0	0
1910	0	0	80900	0	0	0
1911	0	0	80900	0	0	0
1912	0	0	80900	0	0	0
1913	0	0	80900	0	0	0
1914	0	0	80900	0	0	0
1915	0	0	80900	0	0	0
1916	0	0	80900	0	0	0
1917	0	0	80900	0	0	0
1918	0	0	80900	0	0	0
1919	0	0	80900	0	0	0
1920	0	0	80900	0	0	0
1921	0	0	80900	0	0	0
1922	0	0	80900	0	0	0
1923	0	0	80900	0	0	0
1924	0	0	80900	0	0	0
1925	0	0	80900	0	0	0
1926	0	0	80900	0	0	0
1927	0	2717600	80900	0	344000	0
1928	0	0	80900	0	0	0
1929	0	-1414100	80900	0	-179000	0
1930	0	0	80900	0	0	0
1931	0	0	80900	0	0	0
1932	0	0	80900	0	0	0
1933	0	0	80900	0	0	0
1934	0	0	80900	0	0	0
1935	0	0	80900	0	0	0
1936	0	0	80900	0	0	0
1937	0	0	80900	0	0	0
1938	0	0	80900	0	0	0
1939	0	0	80900	0	0	0
1940	0	0	80900	0	0	0
1941	0	0	80900	0	0	0
1942	0	0	80900	0	0	0
1943	0	0	80900	0	0	0
1944	0	0	80900	0	0	0
1945	0	0	80900	0	0	0
1946	0	0	80900	0	0	0
1947	0	0	80900	0	0	0
1948	0	0	80900	0	0	0
1949	0	0	80900	0	0	0
1950	0	0	80900	0	0	0

Tab. B.1: Disturbance data used in ASMITA for the Ribble Estuary simulations

Year	V_{fl}	V_{fu}	V_v	A_{fl}	A_{fu}	V_c
1951	0	0	1070000	0	0	0
1952	0	0	1070000	0	0	0
1953	0	0	1070000	0	0	0
1954	0	0	1070000	0	0	0
1955	0	0	1070000	0	0	0
1956	0	0	1070000	0	0	0
1957	0	0	1070000	0	0	0
1958	0	0	1070000	0	0	0
1959	0	0	1070000	0	0	0
1960	-50000	0	1070000	0	0	0
1961	-50000	0	1070000	0	0	0
1962	-50000	0	1070000	0	0	0
1963	-50000	0	1070000	0	0	0
1964	-50000	0	1070000	0	0	0
1965	-50000	0	1070000	0	0	0
1966	-200000	0	1070000	0	0	0
1967	-200000	-4123800	1070000	0	-522000	0
1968	-200000	-4463506	1070000	0	-565000	0
1969	-200000	-1627400	1070000	0	-206000	0
1970	-200000	-1888100	1070000	0	-239000	0
1971	-200000	0	1070000	0	0	0
1972	-200000	0	1070000	0	0	0
1973	-200000	0	1070000	0	0	0
1974	-200000	-8713700	1070000	0	-1103000	0
1975	-200000	-1461500	1070000	0	-185000	0
1976	-200000	0	1070000	0	0	0
1977	-200000	0	1070000	0	0	0
1978	-200000	0	1070000	0	0	0
1979	-200000	0	1070000	0	0	0
1980	-200000	-2.8E+07	0	0	-3539000	0
1981	-200000	0	0	0	0	0
1982	-200000	-7062600	0	0	-894000	0
1983	-200000	0	0	0	0	0
1984	-200000	0	0	0	0	0
1985	-200000	0	0	0	0	0
1986	-200000	0	0	0	0	0
1987	-200000	0	0	0	0	0
1988	-200000	0	0	0	0	0
1989	-200000	0	0	0	0	0
1990	-200000	0	0	0	0	0
1991	-200000	0	0	0	0	0
1992	-200000	0	0	0	0	0
1993	-200000	0	0	0	0	0
1994	-200000	0	0	0	0	0
1995	-200000	0	0	0	0	0
1996	-200000	0	0	0	0	0
1997	-200000	0	0	0	0	0
1998	-200000	0	0	0	0	0
1999	-200000	0	0	0	0	0
2000	-200000	0	0	0	0	0

Tab. B.2: Disturbance data used in ASMITA for Southampton Water simulations

Year	V_{co}	V_{fo}	V_{ci}	V_{fi}	A_{co}	A_{fo}	A_{ci}	A_{fi}
1926	0	0	0	-420000	0	0	0	0
1927	0	0	420000	-2098785	0	0	0	-667500
1928	0	0	420000	0	0	0	0	0
1929	0	0	420000	0	0	0	0	0
1930	0	0	420000	0	0	0	0	0
1931	0	0	965050	-2305143	0	0	710743	-1147381
1932	0	0	420000	0	0	0	0	0
1933	0	0	420000	0	0	0	0	0
1934	0	0	420000	0	0	0	0	0
1935	0	0	420000	0	0	0	0	0
1936	0	0	420000	0	0	0	0	0
1937	0	0	420000	0	0	0	0	0
1938	0	0	920000	0	0	0	0	0
1939	0	0	370000	0	0	0	0	0
1940	0	0	370000	0	0	0	0	0
1941	0	0	370000	0	0	0	0	0
1942	0	0	370000	0	0	0	0	0
1943	0	0	370000	0	0	0	0	0
1944	0	0	370000	0	0	0	0	0
1945	0	0	370000	0	0	0	0	0
1946	0	0	370000	0	0	0	0	0
1947	0	0	370000	0	0	0	0	0
1948	0	0	370000	0	0	0	0	0
1949	0	0	370000	0	0	0	0	0
1950	0	0	270000	0	0	0	0	0
1951	0	0	270000	0	0	0	0	0
1952	0	0	270000	0	0	0	0	0
1953	0	0	270000	0	0	0	0	0
1954	0	0	270000	0	0	0	0	0
1955	0	0	270000	0	0	0	0	0
1956	0	0	270000	0	0	0	0	0
1957	0	0	270000	0	0	0	0	0
1958	0	0	270000	0	0	0	0	0
1959	0	0	270000	0	0	0	0	0
1960	0	0	280000	0	0	0	0	0
1961	0	0	280000	-1523786	0	0	0	-412500
1962	0	0	280000	0	0	0	0	0
1963	0	0	280000	0	0	0	0	0
1965	44506	-2695096	7636675	-2830178	48739	-1861535	343245	-1371379
1964	0	0	300000	0	0	0	0	0
1966	0	0	280000	0	0	0	0	0
1967	0	0	280000	0	0	0	0	0
1968	0	0	280000	0	0	0	0	0
1969	0	0	780000	0	0	0	0	0
1970	0	0	280000	0	0	0	0	0
1971	0	0	280000	0	0	0	0	0
1972	0	0	280000	0	0	0	0	0

Tab. B.2: Disturbance data used in ASMITA for Southampton Water simulations

Year	V_{co}	V_{fo}	V_{ci}	V_{fi}	A_{co}	A_{fo}	A_{ci}	A_{fi}
1973	0	0	280000	0	0	0	0	0
1974	0	0	280000	0	0	0	0	0
1975	0	0	280000	0	0	0	0	0
1976	0	0	280000	0	0	0	0	0
1977	0	0	280000	0	0	0	0	0
1978	0	0	280000	0	0	0	0	0
1979	0	0	280000	0	0	0	0	0
1980	0	0	280000	0	0	0	0	0
1981	0	0	280000	0	0	0	0	0
1982	0	0	280000	0	0	0	0	0
1983	0	0	280000	0	0	0	0	0
1984	0	0	280000	0	0	0	0	0
1985	0	0	280000	0	0	0	0	0
1986	0	0	280000	0	0	0	0	0
1987	0	0	280000	0	0	0	0	0
1988	0	0	280000	0	0	0	0	0
1989	0	0	280000	0	0	0	0	0
1990	0	0	280000	0	0	0	0	0
1991	0	0	280000	0	0	0	0	0
1992	0	0	280000	0	0	0	0	0
1993	0	0	280000	0	0	0	0	0
1994	0	0	280000	0	0	0	0	0
1995	0	0	3280000	0	0	0	0	0
1996	0	0	280000	0	0	0	0	0
1998	0	0	2280000	0	0	0	0	0
1997	0	0	280000	0	0	0	0	0
1999	0	0	280000	0	0	0	0	0
2000	0	0	280000	0	0	0	0	0
2001	0	0	280000	0	0	0	0	0
2002	0	0	280000	0	0	0	0	0
2003	0	0	280000	0	0	0	0	0
2004	0	0	280000	0	0	0	0	0
2005	0	0	280000	0	0	0	0	0
2006	0	0	280000	0	0	0	0	0
2007	0	0	280000	0	0	0	0	0
2008	0	0	280000	0	0	0	0	0
2009	0	0	280000	0	0	0	0	0
2010	0	0	280000	0	0	0	0	0

Tab. B.3: Disturbance data used in ASMITA for Portsmouth Harbour simulations

Year	V_f	V_c	V_d	A_f	A_c	A_d
1937	-112600	0	0	-112600	-74700	0
1972	-4685800	0	0	-2121800	-89500	0
1980	-5100	0	0	-5000	-32400	0

Tab. B.4: Disturbance data used in ASMITA for Langstone Harbour simulations

Year	V_f	V_c	V_d	A_f	A_c	A_d
1968	-9150	343700	0	-17500	250000	0
1976	-21400	0	0	-95000	0	0
1984	-44000	0	0	-115000	0	0
1987	0	0	-120000	0	0	0
1988	0	0	-120000	0	0	0
1989	0	0	-120000	0	0	0
1990	0	0	-120000	0	0	0
1991	0	0	-120000	0	0	0
1992	0	0	-120000	0	0	0
1993	0	0	-120000	0	0	0
1994	0	0	-120000	0	0	0
1995	0	0	-120000	0	0	0
1996	0	0	-120000	0	0	0
1997	0	0	-120000	0	0	0

Tab. B.5: Disturbance data used in ASMITA for the Thames Estuary simulations(volumes only)

	Disturbance volume (m3)					
	Inner Estuary		Mid Estuary		Outer Estuary	
Year	Channel	Flat	Channel	Flat	Channel	Flat
1910	0	0	0	0	0	0
1911	0	0	0	0	0	0
1912	0	0	0	0	0	0
1913	0	0	0	0	0	0
1914	0	0	0	0	0	0
1915	0	0	0	0	0	0
1916	0	0	0	0	0	0
1917	0	0	0	0	0	0
1918	0	0	0	0	0	0
1919	0	0	0	0	0	0
1920	0	0	0	0	0	0
1921	0	0	0	0	0	0
1922	0	0	0	0	0	0
1923	0	0	0	0	0	0
1924	0	0	0	0	0	0
1925	0	0	0	0	0	0
1926	0	0	0	0	0	0
1927	0	0	0	0	0	0
1928	0	0	0	0	0	0
1929	0	0	0	0	0	0
1930	0	0	0	0	0	0
1931	0	0	0	0	0	0
1932	0	0	0	0	0	0
1933	0	0	0	0	0	0
1934	908000	0	227000	0	0	0
1935	841333.3	0	210333.3	0	0	0
1936	852000	0	213000	0	0	0
1937	686666.7	0	171666.7	0	0	0
1938	877333.3	0	219333.3	0	0	0
1939	654666.7	0	163666.7	0	0	0
1940	0	0	-105000	0	0	0
1941	0	0	-105000	0	0	0
1942	0	0	-105000	0	0	0
1943	0	0	-105000	0	0	0
1944	0	0	-105000	0	0	0
1945	0	0	-105000	0	0	0
1946	198666.7	0	49666.67	0	0	0
1947	1081333	0	270333.3	0	0	0
1948	870666.7	0	217666.7	0	0	0
1949	1096000	0	274000	0	0	0
1950	1042667	0	260666.7	0	0	0
1951	912000	0	228000	0	0	0
1952	1200000	0	300000	0	0	0
1953	740000	0	185000	0	0	0
1954	601333.3	0	150333.3	0	0	0

Tab. B.5: Dredging volumes in the Thames Estuary between 1910 and 2000

	Disturbance volume (m3)					
	Inner Estuary		Mid Estuary		Outer Estuary	
Year	Channel	Flat	Channel	Flat	Channel	Flat
1955	474666.7	0	118666.7	0	0	0
1956	464000	0	116000	0	0	0
1957	541333.3	0	135333.3	0	0	0
1958	621333.3	0	155333.3	0	0	0
1959	685333.3	0	171333.3	0	0	0
1960	492000	0	307500	0	0	0
1961	317500	0	317500	0	0	0
1962	393333.3	0	393333.3	0	0	0
1963	315000	0	315000	0	0	0
1964	462500	0	462500	0	0	0
1965	420833.3	0	420833.3	0	0	0
1966	417500	0	417500	0	0	0
1967	340000	0	340000	0	0	0
1968	382500	0	382500	0	0	0
1969	358333.3	0	358333.3	0	0	0
1970	321666.7	0	321666.7	0	0	0
1971	197500	0	197500	0	0	0
1972	212500	0	212500	0	0	0
1973	453333.3	0	453333.3	0	0	0
1974	210833.3	0	210833.3	0	0	0
1975	200000	0	200000	0	0	0
1976	165000	0	165000	0	0	0
1977	170833.3	0	170833.3	0	0	0
1978	178333.3	0	178333.3	0	0	0
1979	160833.3	0	160833.3	0	0	0
1980	95833.33	0	95833.33	0	0	0
1981	51250	0	153750	0	0	0
1982	38750	0	116250	0	0	0
1983	25000	0	75000	0	0	0
1984	25000	0	75000	0	0	0
1985	25000	0	75000	0	0	0
1986	25000	0	75000	0	0	0
1987	25000	0	75000	0	0	0
1988	25000	0	75000	0	0	0
1989	25000	0	75000	0	0	0
1990	25000	0	75000	0	0	0
1991	25000	0	75000	0	0	0
1992	25000	0	75000	0	0	0
1993	25000	0	75000	0	0	0
1994	25000	0	75000	0	0	0
1995	25000	0	75000	0	0	0
1996	25000	0	75000	0	0	0
1997	25000	0	75000	0	0	0
1998	25000	0	75000	0	0	0
1999	25000	0	75000	0	0	0
2000	25000	0	75000	0	0	0

C. ESTUARIES DATABASE

Tab. C.1: Estuary characteristics from EMPHASYS (2000) and FutureCoast data

type	Name	A_b	A_c	H	V_b	V_c
	Tyninghame	8.8	3.44	4.5	89.4	69.2
3b	Tweed	0.762	0.343	4.1	2.3	0.299
4b	Aln	0.894	0.0366	3.3	0.725	0.0196
4a	Blyth NE	4.25	0.676	2.1	8.51	3.1
3b	Tyne	14	5.49	4.3	51.9	20.5
3a	Wear	4.24	0.44	4.4	5.85	1.08
4b	Tees	21.9	1.7	4.4	32.3	13.1
4a	Humber	648	193	6	2900	1160
4a	Blyth EA	8.95	0.0909	2.1	1.12	0.131
4a	Ore/Alde	30.5	7.87	2.2	44.2	11.4
4b	Deben	13.1	4.17	3.2	25.8	6.39
4b	Hamford	29.4	3.42	3.8	31	3.79
4a	Stour	45.1	12.1	3.6	102	30.9
	Orwell	38	7.08	3.6	57.9	14.5
4b	Colne	46.6	1.5	4.6	19.8	0.908
4a	Blackwater	48.3	20.5	4.6	195	52.8
4a	Crouch	31	6.63	5	86.7	20.7
5	Thames	200	64.9	6.5	967	417
4a	Medway	75.6	21.7	4.1	244	79.6
4a	Pegwell Bay	9.53	0.526	4.5	16.1	0.603
7a	Chichester Harbour	34.1	12.1	4.2	95	23.5
7a	Langstone Harbour	26.8	8.36	4.2	61.9	13.6
7a	Portsmouth	19.5	9.07	4.1	72.1	26.3
4a	Southampton Water	62.8	20	4	189	78.3
4a	Beaulieu	8.41	1.84	3.2	13.8	3.47
4b	Bembridge	2.19	0.383	3.1	5.55	0.569
4c	Wootton Creek	0.956	0.0633	3.8	0.627	0.0509
3b	Medina	2.43	0.729	4.2	4.72	1.42
4c	Newtown	1.57	0.801	2.9	6.01	2.79
4c	Yar	0.366	0.111	2.5	0.535	0.0953
4c	Lymington	2.38	0.486	2.5	2.45	0.6
3a	Christchurch	4.62	0.79	1.2	1.95	0.543
4b	Poole	29.4	18.2	1.4	56.5	22
	Fleet and Portland	18.4	4.84	1.9	38.5	16.6

Tab. C.1: Estuary characteristics from EMPHASYS (2000) and FutureCoast data

type	**Name**	A_b	A_c	H	V_b	V_c
4c	Axe	0.179	0.000521	3.7	0.111	0.0000872
4c	Otter	0.042	0.00962	4.1	0.0747	0.00556
4a	Exe	18.1	7.47	4.1	46.9	5.23
3b	Dart	10.2	5.74	4	49	20
	Salcombe	12	1.45	4.6	16.8	1.91
3b	Erme	1.23	0.298	4.7	2.6	0.193
3b	Yealm	3.81	0.757	4.7	6.71	1.54
3b	Plymouth	53.8	15	4.7	189	90.6
3b	Fowey	4.04	0.846	4.8	11	2.97
3b	Falmouth	25.7	15.5	5.3	181	91
4b	Hayle	1.49	0.144	5	3.87	2.32
3b	Gannel	1.19	0.0255	6.4	3.09	0.72
3b	Cammel	7.77	1.81	5.9	36.1	8.23
	Bridgewater	7.44	0.748	11.1	32.1	0.264
3b	Severn	617	363	12.3	7140	2000
4c	Teifi	8.36	4.91	4.1	62.1	40.2
	Dyfi	10.9	1.17	4.2	20.3	0.796
3a	Conwy	7.64	0.342	7.1	14.5	0.636
4a	Dee	108	55.8	7.6	704	107
3b	Mersey	184	35.9	8.9	881	164

Tab. C.2: Estuary characteristics derived from EMPHASYS (2000) data

Name	A_f	V_f	H_f	H_c	A_f/A_b	P	P/H	$A_b^{1.5}$	$A_b * H$
Tyninghame	5.36	19.4	3.62	20.12	0.61	20.20	4.49	26105.02	39.60
Tweed	0.419	1.1232	2.68	0.87	0.55	2.00	0.49	665.17	3.12
Aln	0.8574	2.2448	2.62	0.54	0.96	0.71	0.21	845.29	2.95
Blyth NE	3.574	3.515	0.98	4.59	0.84	5.41	2.58	8761.60	8.93
Tyne	8.51	28.8	3.38	3.73	0.61	31.40	7.30	52383.20	60.20
Wear	3.8	13.886	3.65	2.45	0.90	4.77	1.08	8730.69	18.66
Tees	20.2	77.16	3.82	7.71	0.92	19.20	4.36	102486.38	96.36
Humber	455	2148	4.72	6.01	0.70	1740.00	290.00	16495386.99	3888.00
Blyth EA	8.8591	17.806	2.01	1.44	0.99	0.99	0.47	26775.31	18.80
Ore/Alde	22.63	34.3	1.52	1.45	0.74	32.80	14.91	168441.76	67.10
Deben	8.93	22.51	2.52	1.53	0.68	19.41	6.07	47414.04	41.92
Hamford	25.98	84.51	3.25	1.11	0.88	27.21	7.16	159411.99	111.72
Stour	33	91.26	2.77	2.55	0.73	71.10	19.75	302875.97	162.36
Orwell	30.92	93.4	3.02	2.05	0.81	43.40	12.06	234247.73	136.80
Colne	45.1	195.468	4.33	0.61	0.97	18.89	4.11	318111.14	214.36
Blackwater	27.8	79.98	2.88	2.58	0.58	142.20	30.91	335676.31	222.18
Crouch	24.37	89	3.65	3.12	0.79	66.00	13.20	172600.70	155.00
Thames	135.1	750	5.55	6.43	0.68	550.00	84.62	2828427.12	1300.00
Medway	53.9	145.56	2.70	3.67	0.71	164.40	40.10	657328.85	309.96
Pegwell Bay	9.004	27.388	3.04	1.15	0.94	15.50	3.44	29419.78	42.89
Chichester Harbour	22	71.72	3.26	1.94	0.65	71.50	17.02	199127.65	143.22
Langstone Harbour	18.44	64.26	3.48	1.63	0.69	48.30	11.50	138740.16	112.56
Portsmouth	10.43	34.15	3.27	2.90	0.53	45.80	11.17	86109.67	79.95
Southampton Water	42.8	140.5	3.28	3.92	0.68	110.70	27.68	497667.71	251.20
Beaulieu	6.57	16.582	2.52	1.89	0.78	10.33	3.23	24389.00	26.91
Bembridge	1.807	1.808	1.00	1.49	0.83	4.98	1.61	3240.90	6.79

Tab. C.2: Estuary characteristics derived from EMPHASYS (2000) data

Name	A_f	V_f	H_f	H_c	A_f/A_b	P	P/H	$A_b^{1.5}$	$A_b * H$
Wootton Creek	0.8927	3.0567	3.42	0.80	0.93	0.58	0.15	934.73	3.63
Medina	1.701	6.906	4.06	1.95	0.70	3.30	0.79	3788.00	10.21
Newtown	0.769	1.333	1.73	3.48	0.49	3.22	1.11	1967.20	4.55
Yar	0.255	0.4753	1.86	0.86	0.70	0.44	0.18	221.42	0.92
Lymington	1.894	4.1	2.16	1.23	0.80	1.85	0.74	3671.69	5.95
Christchurch	3.83	4.137	1.08	0.69	0.83	1.41	1.17	9930.31	5.54
Poole	11.2	6.66	0.59	1.21	0.38	34.50	24.64	159411.99	41.16
Fleet and Portland	13.56	13.06	0.96	3.43	0.74	21.90	11.53	78927.21	34.96
Axe	0.18	0.55	3.09	0.17	1.00	0.11	0.03	75.73	0.66
Otter	0.03	0.10	3.18	0.58	0.77	0.07	0.02	8.61	0.17
Exe	10.63	32.54	3.06	0.70	0.59	42	10.16	77004	74.21
Dart	4.46	11.8	2.65	3.48	0.44	29.00	7.25	32576	40.80
Salcombe	10.55	40.31	3.82	1.32	0.88	14.9	3.24	41569	55.20
Erme	0.93	3.37	3.62	0.65	0.76	2.41	0.51	1364	5.78
Yealm	3.05	12.74	4.17	2.03	0.80	5.17	1.10	7436	17.91
Plymouth	38.8	154.46	3.98	6.04	0.72	98	20.94	394614	252.86
Fowey	3.19	11.36	3.56	3.51	0.79	8.03	1.67	8120	19.39
Falmouth	10.2	46.21	4.53	5.87	0.40	90	16.98	130280	136.21
Hayle	1.35	5.9	4.38	16.11	0.90	1.55	0.31	1818	7.45
Gannel	1.16	5.25	4.50	28.24	0.98	2.37	0.37	1298	7.62
Cammel	5.96	17.97	3.02	4.55	0.77	28	4.72	21658	45.84
Bridgewater	6.69	50.75	7.58	0.35	0.90	32	2.87	20293	82.58
Severn	254	2449.1	9.64	5.51	0.41	5140	417.89	15325962	7589.10
Teifi	3.45	12.38	3.59	8.19	0.41	21	5.34	24171	34.28
Dyfi	9.73	26.28	2.70	0.68	0.89	19	4.64	35986	45.78
Conwy	7.298	40.38	5.53	1.86	0.96	13	1.95	21117	54.24
Dee	52.2	223.8	4.29	1.92	0.48	597	78.55	1122368	820.80
Mersey	148.1	920.6	6.22	4.57	0.80	717	80.56	2495897	1637.60

GLOSSARY

behaviour-oriented modelling models representing the observed behaviour of a coastal system with a simple mathematical model that may or may not be related to underlying physical processes

capital dredging removal of sediment to create new berths or channels or to deepen and widen existing ones

coastal tract a framework proposed by Cowell et al. (2003a) to allow morphological models describing processes at different spatial and temporal scales to be integrated together

dynamic equilibrium the functional relationship describing the balance between the output (form) and inputs (forcing) (Ahnert, 1967; Howard, 1988)

engineering timescale tens to hundreds of years; the timescale over which coastal morphology and processes adjust to human interventions

equilibrium the tendency for morphologies to evolve to a profile which yields no further changes if forcing remains constant for a sufficiently long time

estuarine rollover landward and upward retreat of estuarine morphologies in response to sea-level rise

estuary "a semi-enclosed body of water having a free connection with the open sea and within which sea water is measurably diluted with fresh water derived from land drainage" (Cameron and Pritchard, 1963)

facies the appearance and characteristics of a sedimentary deposit especially as they reflect the conditions and environment of deposition and serve to distinguish the deposit from contiguous deposits

geological timescale thousands to hundreds of thousands of years

hypsometry the distribution of surface area or volume of an estuary relative to a horizontal plane

land reclamation conversion of intertidal areas into land by embanking and drainage *maintenance dredging* removal of sediment to maintain berths and shipping channels at a specified depth

managed realignment realignment of flood defences to allow new (previously reclaimed) areas to be inundated by tides

morphodynamics "the mutual co-adjustment of form and processes" (Woodroffe, 2002)

process-based modelling models based on physical understanding of small scale coastal behaviour over relatively short timescales

steady state the form associated with dynamic equilibrium if none of the inputs are changing over time

tidal inlet characterised by narrow mouth areas linking the sea with a tidal lagoon behind a barrier beach (Dyer, 2002)

tidal prism (P) The volume of water flowing through an inlet on a single tide

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