The application of historical data and computational methods for investigating causes of long-term morphological change in estuaries: a case study of the Mersey Estuary, UK

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THE APPLICATION OF HISTORICAL DATA AND COMPUTATIONAL METHODS FOR INVESTIGATING CAUSES OF LONG TERM MORPHOLOGICAL CHANGE IN ESTUARIES: A CASE STUDY OF THE MERSEY ESTUARY, UK

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ABSTRACT

Long-term morphological change in estuaries, of the order of 100 years, has developed into an area of significant research interest as a result of increased regulation and management of estuarine environments. The long-term behaviour of estuary morphology results from the net effects of perturbations induced by tidal, seasonal and episodic events, averaged over a longer period. Theoretically a dynamic equilibrium may exist between deposition and erosion when considered over a time period that is sufficiently long to encompass the cyclic variability that exists within an estuarine system. However the assemblage of physical processes required for a stable state to exist, and the causes of deviation from a stable state, are not well understood. The interaction of physical processes of tidal and wave action, and the influence of sea level rise and anthropogenic activity, with estuarine ecology and geology are largely responsible for the evolving state of an estuary. Although the physical processes of tidal movement and wave action are well known and documented, the interaction of these processes with factors controlling estuarine evolution over long time periods is less well understood.

This thesis evaluates approaches to analysing historical data and applying computational methods to examine the interaction between factors forcing long-term estuary morphology. Historical data is of considerable value to analysis of long-term morphological change in estuaries, and forms a pre-requisite for developing understanding of the nature and causes of the long-term evolution of estuary morphology. However few data sets exist which cover a period of sufficient duration with sufficient detail to identify the processes forcing morphological change, so recourse to computational methods is required for the purpose of developing understanding of estuary behaviour. Several techniques are employed, including analysis of bathymetric data, calculation of analytical parameters and computational hydrodynamic simulations, to develop a case study of processes causing morphological change in the Mersey estuary over the last century. A major requirement for the approach adopted in this thesis is the identification and reduction of uncertainty. Areas of uncertainty are identified, and the results arising from various computational techniques employing different assumptions are examined within a framework enabling evaluation of the uncertainty arising from analysis and assumptions upon which it is reliant.

Volumetric analysis demonstrates that morphological change is dominated by a trend of significant accretion between 1906-1977, with tidal volume reducing by approximately 10% (70Mm^3). Previous research has identified the construction of training walls, between 1906-36 to stabilise the position of the low water channel in Liverpool Bay outside the estuary, as a probable cause of perturbation. Changes to tidal flow and related sediment transport patterns outside the estuary resulting from training wall construction are examined with regard to the stability of the estuary system. The results from computational hydrodynamic models representing the years 1906, 1936 and 1977 quantifying potential changes in sediment transport pathways from outside the estuary indicate a significant increase in potential sediment supply to the mouth of the estuary during the period of peak accretion. However, these changes cannot be solely attributed to construction of the training walls, but result from the combined effect of training wall construction and dredging activity in the sea approach channels. Furthermore, it is not simply changes in tidal flow characteristics that cause sedimentation but also the existence of salinity induced gravitational circulation within the estuary and the wider Liverpool Bay system that acts as an important mechanism for importing sediment into the estuary. Evidence for evolution towards a stable estuary state is provided by derivation of a sediment budget demonstrating a negligible net flux of sediment into the estuary between 1977-1997. The establishment of a steady state is attributed to a reduction in the calculated transport of sediment, from west to east, across Liverpool Bay reducing the supply of sediment to the estuary mouth.

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DECLARATION

I wish to declare that, except for commonly understood and accepted ideas or where specific reference is made to the research of other authors, the contents of this thesis are my own original work. The work has not previously been submitted, in part or whole, to any University for any Degree, Diploma, or other qualification. The work was carried out in the Centre for Civil Engineering, School of Architecture, Oxford Brookes University, and at HR Wallingford Ltd. between October 1998 and September 2001.

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NOTATION

A	cross-section area
A	sea-surface height
a	tidal amplitude
A_{ss}	suspended sediment mobilization parameter
b	Rouse number (suspension parameter)
c	dimensionless coefficient
c	sediment concentration at height z above the bed
C	volume concentration of sediment
c_0	maximum volumetric bed load sediment concentration
c_a	reference concentration at height z=a above the bed
c_b	bed load sediment concentration
C_D	drag coefficient applicable to depth-averaged current
c_M	suspended sediment concentration or dry density (dry mass/volume)
C_z	Chezy friction coefficient
d	sieve diameter of grains
$D_* = \left[\frac{g(s-1)}{\nu^2}\right]^{\frac{1}{3}} d_{50}$	dimensionless grain size parameter
cos	cosine
d_{50}	median grain diameter
d_{90}	90 percentile grain size diameter
e	2.71 8281 828
$\exp(x) = e^x$	exponential function
f	Coriolis parameter
F	dimensionless shape factor (see van Rijn, 1984; Dyer and Soulsby, 1988; McLean, 1991)
f	frequency of occurrence
F_D	drag force
F_G	gravitational force
F_L	lift force
f_w	wave friction factor
g	acceleration due to gravity = 9.81ms^{-2}
h	average channel depth at mean sea level
H	height of water wave
h	water depth
H_ϕ	representative wave height
H_{HW}	mean depth over the estuary at high water
H_{LW}	mean depth over the estuary at low water
L	wavelength of water wave
ln	natural logarithm (to base e)
$\log_{10}$	logarithm to base 10
M	mass per unit area which is fluidized
m_e	erosion constant
P	tidal prism
q_b	volumetric bed load sediment transport rate
q_s	volumetric suspended load sediment transport rate
Q_{smud}	transport rate of suspended mud
q_t	total volumetric sediment transport rate
Re	grain Reynolds number
s	ratio of densities of grain and water
S_{HW}	wet surface area of the estuary at high water
sin	sine
sinh	hyperbolic sine

S_{LW}	wet surface area of the estuary at low water
t	time
T	wave period
$T = \frac{\tau - \tau_{cr}}{\tau}$	dimensionless bed shear stress parameter
tanh	hyperbolic tangent
$\bar{U}$	depth-averaged current speed
U	horizontal component of water velocity
$\hat{U}_\delta$	peak wave orbital velocity near the bed
$U_{(1m)}$	current speed at a height of 1 m above the bed
$\bar{U}_{cr}$	threshold depth-averaged current speed
U_{max}	maximum bottom wave orbital velocity
U_{rms}	root-mean-square wave orbital velocity at sea bed
μ_*	friction velocity
μ_{*cr}	threshold friction velocity
v	amplitude of tidal velocity
V	tidal velocity
V_c	volume of channels at mean sea level
V_S	intertidal storage in flats and marshes
w_s	settling velocity of sediment grains
z	height above bed level
Z'	suspension number
z_0	bed roughness length
z_a	reference height near the sea bed at which the reference concentration C_a is calculated
α	angle of dynamic friction
β	angle of sloping bed to the horizontal
δ_b	thickness of bed load layer
γ	Coriolis parameter
γ	Dronkers parameter
φ	latitude
κ	von Karmen's constant = 0.40
ν	kinematic viscosity of water
θ_{cr}	threshold Shields parameter
θ_s	skin friction Shields parameter
θ_t	sediment transport component of Shields parameter
ρ	density of water
ρ_s	density of sediment grains
τ	boundary shear stress
τ_o	total bed shear stress
τ_c	current only bed shear stress
τ_{cr}	critical shear stress
τ_d	critical shear stress for deposition
τ_e	critical shear stress for erosion
τ_{of}	form drag component of τ_0 due to bedforms
τ_{os}	bed shear stress due to skin friction
τ_{ot}	sediment transport contribution to shear stress
τ_w	amplitude of oscillatory bed shear stress due to waves
ω	tidal frequency
ω_e	angular velocity of the earths rotation
ξ	horizontal water particle excursion near the bed
ψ	potential vorticity

CHAPTER 1 INTRODUCTION

1.1 General aspects of the research

Significant changes in attitude, policy and practice have occurred in relation to UK estuaries over the last decade with three principal issues driving an increased requirement for management of estuarine resources and providing an impetus for improving understanding of estuary form and function. The first factor has been a growth in environmental concern, notably signalled as a high priority on the world's political agenda by the 1992 Rio Earth Summit, and endorsed in the UK by the subsequent government commitment to promoting sustainable development and biodiversity. The coastal zone (DETR, 1994a) and estuaries (DETR, 1994b) have been recognised as areas with significant environmental value that need to be conserved and protected. Secondly, the issue of flood defence in estuarine areas has precipitated concern which resulted in the announcement by the UK Government in May 1999 of interim high level targets for flood and coastal defence to secure delivery of flood and coastal defence aims and objectives. More comprehensive targets were subsequently announced in November 1999 (MAFF, 1999). Three key objectives were identified to achieve the flood defence policy aims: the use of adequate and cost effective flood warning systems; the provision of adequate, economically, technically and environmentally sound and sustainable flood and coastal defence measures; and discouragement of inappropriate development in areas at risk from flooding and coastal erosion. Thirdly, large-scale development, particularly port development and associated activity within estuaries, has aroused concern over impacts upon the estuary system. Contemporary development proposals in Southampton Water (port development at Dibden Bay), the Humber estuary (flood defence and port development scheme), the Stour/Orwell estuary (enlargement of container facilities), and the Thames estuary (development of a new container terminal at Shellhaven), have resulted in test cases of their impact upon the estuarine system. Due to the dynamic nature of estuaries, issues of concern cannot be treated separately and a key objective of studying long-term change in estuaries is to develop understanding of linkages between different aspects of the system to enable reliable assessment of impact significance to be made where conflicts of interest arise.

As a consequence of increased awareness of the resource value of UK estuaries and the need to manage the estuarine environment, voluntary programmes and a range of statutory legislation has been introduced imposing controls and designations from local, regional, national, European and international levels (Davidson *et al.*, 1991). Diverse user interests are regulated, including: conservation; fishing; mariculture; water quality and pollution control; flood and coastal defence; mineral extraction and agricultural practices (HR Wallingford, 1997a). To enable management decisions to be taken within a strategic framework a hierarchy of Plans and Appraisals is required (typically on the coast this hierarchy is well established: Coastal Zone Management Plans, Coastal Process Studies, Shoreline Management Plans, followed by Strategy Plans, followed by Scheme Appraisal). Strategic initiatives introduced to integrate management issues in estuaries include Shoreline Management Plans (MAFF, 1995; Leafe *et al.* 1998), and Estuary Management Plans (English Nature, 1993, 1995; Jemmett, 1998). In addition Coastal Habitat Management Plans (ChaMPs) are presently being compiled for a number of UK sites (with possible future extension to further sites), to provide a framework for managing sites located on or adjacent to dynamic coastlines and designated for protection under European regulations in circumstances where the conservation of all the existing interests within a site complex in situ is not possible.

At present, however, approaches to managing and regulating estuaries are in their infancy and are frequently disjointed and undeveloped. Only very high-level guiding principles have been established for most estuaries. Little practical guidance is provided, and management policies frequently only partially reflect the recognised need to manage on an estuary wide scale. Limitations upon effective management and decision-making processes are caused by the complexity of the legislative framework. Huggett (1995) suggests, for example, that before some of the tests of the Habitats Directive can be adequately passed, allowing decisions on development proposals, there is a need to reduce uncertainty over interpretation and advocation of the precautionary principle, which places an overriding importance on resource protection in the absence of complete knowledge of it's environmental value. Despite uncertainty regarding the precise interpretation of regulations and debate over the direction of future management strategies within estuaries, it is clear that an increased onus has been placed upon stakeholders to assess likely impacts of policies, plans and projects upon an estuary system.

Understanding the morphological functioning of an estuary system is a requirement for present day and future estuary management decisions, providing, in most circumstances, a tangible focus on which to base estuary management. Moreover, adopting morphology as a focus for decision-making provides a means to manage estuaries holistically, integrating the diverse interests and activities within estuaries and their potentially conflicting impacts. Estuarine morphology is one of six core estuary process areas identified in a scoping study for an Estuaries Research Programme (HR Wallingford, 1997a, 1997b), which directly or indirectly influences the other five areas of hydrodynamics, sediment dynamics, water quality, ecology and anthropogenic activity. Present scientific understanding of morphological linkages within an estuarine environment, and particularly linkages between large-scale estuary form and process is, however, undeveloped (Nordstrom and Roman, 1996). The physical components and controlling processes of an estuary encompass a range of temporal and spatial scales. Defining the constituents of estuary morphology and determining the processes responsible for shaping it are complex tasks. The complexity of form and process interaction in an estuary was emphasised in a seminal paper on estuarine channel development by Wright *et al.* in 1973, stating that:

> "Neither the channel morphology nor the tidal properties can be explained solely in terms of each other, though the two are mutually dependent. Simultaneous co-adjustment of both process and form has yielded an equilibrium situation in which further adjustment is non-advantageous."

The dynamic feedback between form and process continues to present a significant scientific challenge, notably because present day estuary morphology results from natural forcing and variability combined with the history of anthropogenic influence, which has played an increasingly significant role in many estuaries since the industrial revolution. The historical background of morphological change in an estuary is significant as governing processes caused by disturbance may be present in the system for an extended time-span and still reside in the system as further modifications are implemented. Thus the timing and magnitude of anthropogenic effects relative to previous modifications are important when trying to predict future estuary evolution.

Furthering understanding of long-term morphological behaviour of estuaries requires identification of the processes driving long-term evolution in estuaries. In order to assess current knowledge and gain a more complete understanding of the causes of long-term morphological change there is a need to develop case studies of estuaries where data exists to demonstrate the nature and the scale of the changes. Such case studies involve practical application of tools and methods for characterising morphological change and associated process behaviour. In addition to developing understanding of morphological functioning, the development of studies of long-term evolution fulfils an important role by providing case studies to calibrate and validate developments in long-term morphological modelling. A review of the state of understanding of estuary morphology funded by the Ministry for Agriculture for Fisheries and Food (MAFF), the Environment Agency (EA), Engineering and Physical Sciences Research Council (EPSRC), Natural Environment Research Council (NERC) and English Nature (EN) supported the case for an integrated research programme investigating estuary morphology including development of UK case studies (HR Wallingford, 1997a).

1.2 Scope of research

This thesis addresses the issue of long-term morphological change in estuaries, critically evaluating data requirements and the application of tools for analysing long-term evolution, through an investigation involving case study of the Mersey estuary. The approach adopted comprises three distinct parts, firstly analysis of changes in estuary form to establish the nature of morphological change, secondly employment of historical snapshots of estuary form with diagnostic modelling tools to simulate changes in estuary hydrodynamic regime, and thirdly use of hydrodynamic results as a basis for examining sediment behaviour. The approach of analysing historical snapshots of estuary form and physical process behaviour using diagnostic modelling tools has been employed in studies of the Stour/Orwell (Roberts *et al.*, 1998) and Humber (Associated British Ports [ABP] Research and Consultancy Limited, 1999) estuary systems. Further research conducted in the first phase of the Estuaries Research Programme completed in 2000 by members of the EMPHASYS consortium also presented research in this field providing guidance on techniques that may be applied to achieve understanding of estuary functioning (EMPHASYS consortium, 2000a, 2000b). The research for this thesis was undertaken in collaboration with HR Wallingford, a member of the EMPHASYS consortium, and develops some of the issues arising from the Estuaries Research Programme. The research presented was conducted in parallel with research undertaken by HR Wallingford for the Estuaries Research Programme but has been conducted independently except where specified.

The concept of morphological equilibrium is examined, investigating means of establishing the stability or otherwise of an estuary system. Stability is assessed by applying diagnostic modelling tools to identify key processes controlling estuary evolution with particular reference to the influence of internal estuarine processes and external forcing factors upon estuary behaviour. Physical processes of tidal movement and wave action are relatively well known and documented, but the interaction of these processes is less well defined, particularly in terms of their influence on sediment transport. Although the interaction of physical processes is complex, varying over a range of spatial and temporal scales and over a number of cyclic periods such as tidal cycles, an estuary can exhibit stability with a dynamic equilibrium between deposition and erosion where a net balance exists. The long-term stability of an estuary forms a key concept of morphological equilibrium reducing the complexity of analysing morphological change to the requirement for identifying physical process behaviour causing an estuary to deviate from a stable state and physical process responses to evolve towards a new theoretical equilibrium state. To achieve morphodynamic stability, Dronkers (1998) suggests that in response to perturbation, changes in system geometry alter physical processes, particularly tidal propagation, such that the average ebb and flood sediment fluxes become unbalanced and restore an equilibrium state. However, interaction between the estuary and the seaward environment also influences morphology by determining sediment supply to the system, which has been found to be significant, for example, in the Gironde estuary, France (Castaing and Allen, 1981).

The research undertaken investigates a case study of long-term morphological change in the Mersey estuary. The Mersey estuary was selected as historical data coverage is among the best available for UK estuaries, encompassing a period of morphological evolution with sufficient detail to permit examination of the processes responsible for change. Concepts relating to long-term estuary evolution in the Mersey have been examined through an investigation into the causes of morphological change between 1911-1957 undertaken by Price and Kendrick (1963), employing two physical models. The first model represented Liverpool Bay configured to bathymetries for 1911 and 1957 with freshwater flow only, and the second represented the Mersey estuary upstream of New Brighton including salinity effects. The physical model results demonstrated significant changes in hydrodynamic flow regime in Liverpool Bay following construction of a training wall between 1906-1936 to stabilise the position of the low water channel for navigation. This thesis examines the application of modern computational methods to accurately quantify changes in estuary form and cohesive and non-cohesive sediment transport processes to analyse morphological change in the Mersey. The advantage of applying computational models is their greater ability to resolve complex sediment transport phenomena and interactions between current and wave processes. However, current understanding of these phenomena is not complete and considerable uncertainty remains in investigating and interpreting analysis of these issues, which forms a focus for the investigation.

The first stage of the study comprises analysis of the nature of historic morphological trends in the estuary, investigated by converting bathymetric data into digital format where necessary and applying digital contour analysis tools to examine changes in estuary form. The historic period of estuary evolution and temporal intervals selected for examination were determined to a significant extent by the availability of historic data. A pre-requisite for analysing morphological change comprised historical bathymetric measurements of the Mersey estuary. Estuary wide surveys for the Mersey estuary have been recorded for the Mersey estuary over a historical timescale from 1861, although the frequency at which surveys were undertaken varied; surveys were quinquennial until 1951 when they were carried out annually until 1970, and then a survey in 1972 and 1977. A subsequent survey was commissioned in 1997. Bathymetric configurations for 1997, 1977, 1956 and 1936 were examined, maintaining a uniform interval of twenty years between surveys. The 1906 bathymetry was selected for examination as the closest compatible survey to a 1904 survey of Liverpool Bay employed in later investigation of the interaction between the estuary and Liverpool Bay; it also coincided with the initiation of training wall construction. 1871 was selected for examination as it represented the earliest survey available for the purposes of this study. In addition bathymetric surveys undertaken by the Mersey Dock and Harbour Company (MDHC), which was previously the Mersey Docks and Harbour Board, were employed for the Liverpool Bay area seaward of the estuary mouth for the years 1904 and 1933. An Admiralty chart including data from several surveys recorded in the 1970 and 1980's of different parts of Liverpool Bay was employed to derive the bathymetric configuration of Liverpool Bay for 1977.

The second stage of study, comprising analysis of historic changes in estuary hydrodynamics, employed computational modelling techniques to combine short-term field observations with one-dimensional (1D), two-dimensional (2D) and three-dimensional (3D) spatial scale modelling techniques. Estuary research has generally focused upon short-term data collection (less than 1 year), representing an accessible scale for the researcher. Little data on physical processes, other than tidal level records, has been collected over historical (>50 year) time-scales for the purpose of analysing estuary functioning due to the intensive effort required in collection. As a result a major shortcoming of the data resource for studying morphological change in the Mersey estuary is the limited data coverage of process changes over a historic time-scale. Employing historic bathymetries as temporal snapshots applied to models in a diagnostic analytical capacity therefore provides a suitable means to reproduce physical process behaviour where no historical data has been collected. However, diagnostic modelling tools represent different levels of compromise between reality and practicality. This study critically assesses the accuracy of hydrodynamic process simulation and the adequacy of tools to achieve satisfactory representation. Limits are imposed upon this element of study by the availability of tools and their computational requirements. Furthermore, analysis of relative changes requires that the approach is transferable to examine different bathymetric configurations.

The third component of study employs hydrodynamic flow results as a basis for computations of sediment transport processes. Short-term physical processes may be reproduced by careful application of diagnostic tools permitting representation of unmeasured parameters. However, data coverage of historical sediment transport processes and parameters is incomplete and in order to make use of it, assumptions have to be made about parameters that were not measured. Incomplete data coverage of sediment transport phenomena is exacerbated by limitations in current understanding of sediment transport processes. Calculations of sediment transport rate rely upon empirical formulae, as no analytical solutions are available. As a result considerable uncertainty exists in studying long-term changes in sediment transport phenomena. Constraints are imposed upon examination of sediment transport processes by the ability of available data and assumptions to support reliable representation of physical process behaviour.

The value of the research outcome is multifold. Firstly the results with regard to the Mersey estuary will provide an insight into the complexity of changes exhibited by the estuary. Secondly in a broader context the research findings have implications for examination of other estuaries and the suitability of techniques for investigating complex morphological change. Conclusions will be drawn about the complexity of physical processes determining morphological change, the use of computational methods to reproduce these, and the data requirements to support analysis of the nature and causes of long-term morphological change in estuaries.

1.3 Aims and objectives of research

1.3.1 Aims

The overall aim of this research is:

- To examine the extent to which existing historical data and available computational methods can produce a coherent, reliable analysis of the causes of historical morphological change in an estuary.

The objective of study raises several, more detailed issues, which have been adopted as research aims:

- To assess historical data and computational method requirements to investigate the behaviour of long term physical processes in estuaries.
- To examine the validity of a theoretical morphological equilibrium state and investigate the principal physical processes governing estuary behaviour.
- To examine whether schematising estuary process behaviour in computational models to represent differing levels of physical reality can have a significant effect upon the interpretation of causes of long-term morphological change.
- To examine whether the influence of anthropogenic activity upon morphological change in an estuary can be clearly identified and distinguished from natural estuary behaviour.

1.3.2 Objectives

To address these specified aims a case study of the Mersey estuary is examined. Long-term historical data is analysed to investigate changes in the form of the Mersey estuary and computational methods are employed to simulate changes in physical processes and resulting sediment related impacts. To achieve the aims of research the following objectives specific to a study of the Mersey estuary were adopted:

<u>Analysis of the nature of historical morphological change in the Mersey estuary</u>

- Collation of an estuary wide historical bathymetric data set for the Mersey estuary covering a period greater than 100 years, comprising conversion and formatting of data to provide a suitable digital form for analysis.
- Critical evaluation of historical bathymetric data variability in terms of spatial resolution of surveys, method of measurement and geographical coverage and associated implications for interpretation of historical change.

- Analysis of parameters representing the morphological behaviour of the estuary by interpolating bathymetric data into digital contour maps and assessment of trends in the estuary and its morphological sub-units.

Analysis of historical changes in the hydrodynamic regime in the Mersey estuary and Liverpool Bay

- Critical assessment of the ability of 1D and 2D models of the Mersey estuary and 2D and 3D models of Liverpool Bay and the Mersey estuary to reproduce historical changes in tidal propagation in the Mersey estuary, with particular regard to the Narrows.
- Investigation of estuary hydrodynamic response to anthropogenic activity in Liverpool Bay and implications for changes in net sediment transport processes

Analysis of historical changes in the sediment transport regime in the Mersey estuary and Liverpool Bay

- Investigation of the significance of process interaction between the offshore area and morphological change in the estuary by simulation of sediment transport patterns in the Mersey estuary and Liverpool Bay.
- Examination of historical changes in non–cohesive sediment transport patterns under tidal conditions and investigation of the relative effects of mean spring tide, highest astronomical tide (HAT) and mean neap tide conditions.
- Examination of the influence of wave stirring effects upon non-cohesive sediment transport patterns.
- Examination of potential changes in advection of cohesive material into the estuary.
- Examination of potential changes in historical deposition of cohesive sediment within the estuary.
- Critical assessment of means of parameterising and schematising sediment transport to represent features of sediment transport patterns where historical data is incomplete.

1.4 Thesis structure

This thesis comprises eight chapters. The aims and objectives for the study, defining the area of interest and the issues that will be addressed were set out in this chapter. Chapters 2 and 3 comprise reviews of existing literature and understanding. Chapter 2 sets an academic context for the study, reviewing understanding of factors controlling morphological evolution of estuaries. In Chapter 3 the Mersey estuary study area is introduced and long-term morphological change in the estuary evaluated. Analyses are undertaken in Chapters 4, 5 and 6. Chapter 4 consists of analysis of historical bathymetric data of the Mersey estuary to assess morphological trends in geometrical parameters and the reliability of trends extracted. In Chapter 5 changes in estuary hydrodynamics accompanying morphological evolution are examined. Changes in patterns of sediment transport related to changes in hydrodynamic flow patterns and wave activity are presented in Chapter 6. Chapter 7 comprises a discussion of the findings of the study. The conclusions arising from the research are presented in Chapter 8 together with suggestions for further work.

CHAPTER 2 LITERATURE REVIEW

2.1 Introduction

In general, literature on estuaries has concentrated upon detailed process studies with relatively little consideration given to understanding estuaries as holistic sedimentary environments (Nicholls and Biggs, 1985). It has been established in Section 1.1 however, that there is a strong requirement for understanding and predicting long-term changes in estuary wide sedimentary behaviour. This literature review outlines important concepts and tools that may be employed to examine the processes driving long-term morphological change in estuaries.

The first section of the literature review introduces estuary morphology, defining characteristic features and means of distinguishing between estuaries on the basis of morphology. The second section evaluates some of the concepts employed in modelling long-term estuary morphology highlighting their shortcomings and the need for developing understanding of processes driving long-term evolution. The third section appraises estuarine morphology in a context that illustrates the significance of physical processes and their interaction with morphological form to control evolution at an estuary wide scale. Finally, the fourth section discusses the data requirements and tools and methods that may be employed to assist evaluation of historical morphological change, and means of applying modelling tools to draw reliable conclusions where field data alone is insufficient to support a comprehensive study of the morphological behaviour of an estuary system.

2.2 Introduction to estuary morphology

Morphology is the form or structure of an object, relating to the form or structure of the earth's physical features in geological study. In the context of estuarine studies, morphology comprises the form or shape of an estuary, generally taken to cover the area between the estuary mouth and the tidal limit, below the level of the HAT. No definitive measure of estuary form exists, although various representative properties can be examined both qualitatively and quantitatively to describe aspects of morphology. At an estuary-wide scale the planshape is an obvious morphological property. Most UK estuaries are dominated by tidal activity and a useful division into morphological sub-units can be made according to the relation of different areas of the estuary to tidal activity; the subtidal area is permanently inundated by water, the intertidal area is periodically inundated and uncovered by water, and the supratidal area is permanently exposed to the atmosphere.

Subtidal, intertidal and supratidal divisions are of particular interest to ecological study of estuaries, as they comprise distinct habitat types. Other properties used to describe estuary morphology may include long profile and cross-sectional area, or meso-scale forms such as meandering channels and spits and bars. At a smaller micro-scale, bedforms such as ripples and dunes comprise components of the morphological system.

The form of an estuary is dynamically linked to physical process behaviour. McDowell and O'Connor (1977) consider the channel as modified by flow to represent a variable boundary influenced by a range of physical processes. Many estuaries exhibit a characteristic exponential decrease in width upstream, and various explanations have been proposed relating a characteristic "trumpet" estuary planshape to physical process behaviour. Langbein (1963) suggests that an exponential decrease in width produces a concentration of the energy of the tidal wave, increasing tidal range, balancing an increase in frictional resistance, and hence energy loss, due to the bed and banks of the estuary. Wright *et al.* (1973) note that a resonant tidal wave is created increasing tidal range landward in situations where tidal wave length is exactly four times greater than estuary length. Thus resonant macro-tidal estuaries exhibit pronounced funnel-shaped forms while estuaries experiencing no resonance exhibit almost parallel banks.

Certain properties may apply universally to estuaries, but other morphological characteristics can vary considerably, and several classification systems have been proposed on the basis of morphological features. An early approach viewed estuaries as a product of landscape evolution over a geological timescale, resulting from processes such as geology, glacial history and sea level incursions into former fluvial landforms. On the basis of these factors Pritchard (1952) distinguishes four main classes; bar-built estuaries; drowned river valleys; rias and fjords. The classification of Pritchard (1952), however, neglects present-day processes and an alternative approach proposed by Davies (1964) and Hayes (1975) comprises classifying estuaries according to tidal range, which frequently represents the most important control of estuarine processes. To emphasise the morphological basis for such a classification a series of characteristic morphological forms associated with estuaries or inlets within each class were identified. Estuaries are, however, dynamic environments, influenced by a variety of factors including geomorphological history, river discharge of water and sediment, tidal currents and waves and coastal processes. In order to reflect the interaction of this range of factors Dalrymple *et al.* (1992) considered morphological development as part of a more complex evolutionary sequence, determined by changes in the relative intensity of river, wave and tidal influences as represented by the diagram shown in Figure 2.1

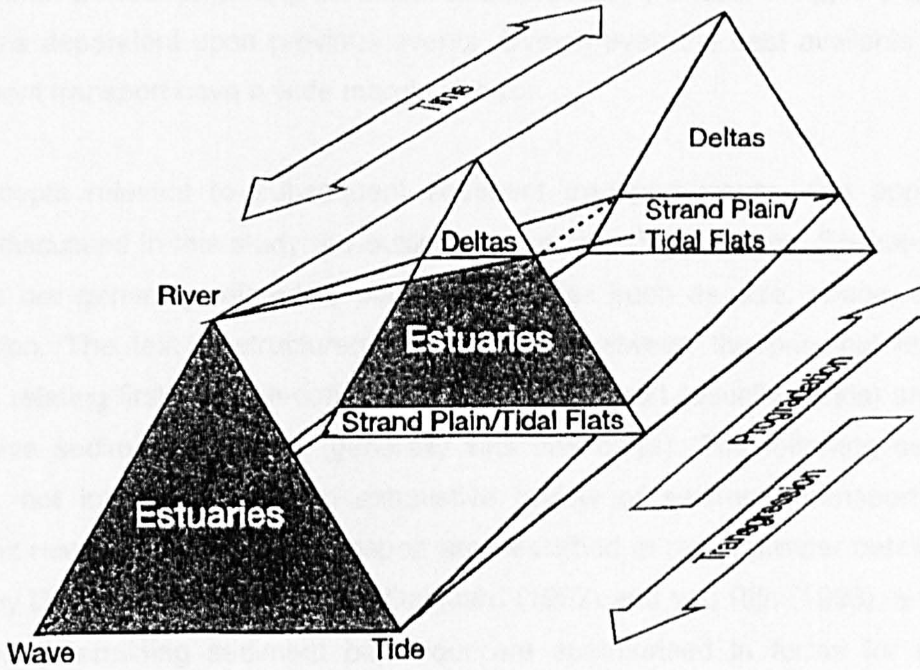


Figure 2.1 Evolutionary classification of coastal environments (after Dalrymple *et al.*, 1992).

2.3 Sediment processes

To develop understanding of processes driving long-term, estuary-wide evolution consideration has to be given to the smaller-scale, short-term processes controlling sediment transport within estuarine environments. In its most basic sense morphology is the result of the assemblage of individual sediment particles within an estuary. Erosion, transportation, deposition and consolidation of sediment act as the agents of morphological change. Horizontal sediment transport rate is of critical importance to prediction of sediment movement and redistribution and hence morphological change.

Although considerable work has been undertaken on sediment dynamics, it is still an inexact science (Soulsby, 1997) and no analytical solutions exist to predict sediment transport using general physics. The reason for this is that the momentum equations cannot be derived for sediment dynamics to relate the percentage of fluid flow energy used for transport; only the continuity equation (i.e. the x and y components of transport rate) can be defined. Furthermore, the dynamic nature of the coastal environment presents specific difficulties to measurement of sediment in order to develop understanding of sediment processes, with a degree of error always present in measurements (van Rijn, 1993). Developing understanding of sediment transport processes is further hindered by inadequate understanding of factors such as biological processes, the transport of sediment with a wide range of grain sizes, and time history effects of ripple and sandwave dimensions dependent upon previous events. Overall even the best available predictions for sediment transport have a wide margin of error.

Key concepts relevant to subsequent sediment transport issues and approaches to analysis discussed in this study are outlined in the following sections. Sediment transport dynamics are generally related to particle properties such as size, shape, density and composition. The text is structured to distinguish between the principal features and concepts relating firstly to non-cohesive sediment transport (usually sands) and secondly to cohesive sediment transport (generally silts and clays). The following sections are, however, not intended to be an exhaustive review of sediment transport dynamics. Processes relevant to sediment transport are described in much greater detail elsewhere in texts by Dyer (1986), Fredsøe and Deigaard (1992) and van Rijn (1993), and the main processes determining sediment behaviour are summarised in forms for use by the practising engineer in manuals by Soulsby (1997) and Whitehouse *et al.* (2000) which deal with non-cohesive sediment and cohesive sediment respectively. Many principles of sediment transport are derived from methods used in the fluvial environment and comprehensive explanations of the physics underlying sediment transport concepts are dealt with in books by Graf (1984) and Yalin (1977). In the wider context, more general principles of coastal sediment transport are covered by Muir Wood and Fleming (1981).

2.3.1 Non-cohesive sediment transport

Non-cohesive sediment transport may be divided into two principal transport processes, bed-load transport and suspended load transport. Bed-load is the mode of solids transport along the water sand-interface, comprising grains that are rolling, sliding or undergoing short hops (saltation), due to drag or traction. Suspended load grains travel with water when grains are entrained into suspension at a level above the saltation height of material transported as bed load and carried by currents, at the same velocity, supported by turbulence, a phenomenon noted as early as 1865 by Dupuit. Suspended load transport can be more significant than bed-load transport, particularly for finer sands (Soulsby, 1997). In marine environments the principle influences upon bed load and suspended load transport are tidal and wave induced currents. Estuaries are generally sheltered from open sea waves, except near the mouth. As a result tidal flows frequently exert the dominant influence upon transport within an estuary, particularly in subtidal channels where the influence of local wind generated waves is negligible. Wave effects can have a greater impact upon sediment transport processes outside the estuary, which can influence estuary morphology through estuary sediment exchange with coastal waters.

Erosion

Empirical study has demonstrated that as flow velocity increases, a point is reached where the intensity of the applied force is sufficiently large to cause sediment from the bed to move (Dyer, 1986). This stage, known as the threshold for movement, is difficult to define. If flow velocity is increased in small increments motion occurs first in a few particularly exposed grains but may be expected to demonstrate a subsequent reduction as dislodged grains occupy new equilibrium positions. Increases in velocity result in transportation becoming more widespread. These features of the initiation of sediment transport has resulted in observers using different numbers of grains moving per unit area per unit time as a threshold criterion.

From a theoretical perspective the main stabilising force for non-cohesive sediment is immersed particle weight. A simple model (Figure 2.2) developed by Chepil (1959) demonstrates the forces of motion acting upon a grain.

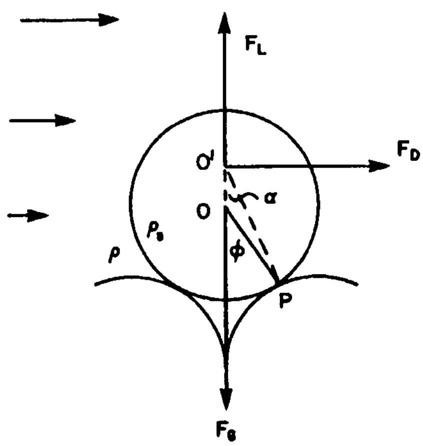


Figure 2.2 Forces acting on a static grain resting on a boundary grain (after Dyer, 1986)

An exposed grain sits on several others with their centres lying in the plane corresponding to direction of flow, and a gravitational force equal to its immersed weight acts upon the grain through its centre O. When exposed to a flowing fluid, sediment particles experience a drag force F_D. Much of sediment transport theory hinges on calculation or measurement of the drag on stationary or mobile grains at the bed. In addition the effect of a grain is to disturb flow, causing acceleration over the top of the grain, which according to Bernoulli's equation causes a lowering in pressure. The difference in pressure vertically across a grain causes a lift force F_L that opposes the gravitational force acting on the particle. When on the point of movement the resultant forces must act through the point of contact P between the grains, and along the line O'P where

$$F_D = (F_G - F_L)\tan\alpha \qquad \text{Eq. 2.1}$$

The threshold of grain movement may be represented as an equivalent critical or threshold shear stress expressed as frictional shear stress exerted by the flow per unit area of bed. Sediment movement is induced as the boundary shear stress, τ, acting on the sediment grains reaches a threshold or critical shear stress, τ_{cr}, equal to the shear strength holding the sediment to the bed.

Total shear stress acting on the bed comprises the effects of shear stress due to skin friction (τ_{os}) produced by the sediment grains, form drag (τ_{of}) produced by the pressure field, and a sediment transport contribution (τ_{ot}) caused by momentum transfer to mobilise grains. The three components added together produce total shear stress. However, only the skin-friction component acts directly upon sediment grains (Soulsby, 1997) and is used to calculate the threshold of motion. Skin-friction is not uniformly distributed along a sand-wave but varies from zero in the trough to a maximum value at the crest corresponding to the fact that local bed load transport is proportionate to the local height of the sand wave (Engelund and Hansen, 1972). The average bed load transport is usually related to an average value of skin shear stress along the sand wave according to Einstein (1950).

In turbulent flow consisting of random movements of small eddies within the fluid, the only means of observing coherence is through time-averaged velocity. Eddying movements around the average streamline are much larger than molecular ones so momentum exchanges and shear stresses are larger. The resulting turbulent shear stress has been experimentally observed to be proportional to the square of the time averaged velocity (Dyer, 1986) defined through the relationship:

$$\tau_o = \rho\mu_*^2 \qquad \text{Eq. 2.2}$$

where, τ_o is total bed shear stress, u_* is friction velocity, and ρ is water density (1027kg/m^3). The friction velocity u_* does not correspond to a real velocity in the flow although it can be related to turbulent fluctuations in the real velocity components. Assuming that within the bottom few metres above the bed current velocity U varies with height above the bed according to a logarithmic profile, u_* may be defined as:

$$u_* = \frac{U(z)}{\kappa}\ln\left(\frac{z}{z_0}\right) \qquad \text{Eq. 2.3}$$

where,u_* is friction velocity, z_0 is bed roughness length, and κ is von Karman's constant (0.40). Equation 2.4 is valid for a range of heights from a few centimetres above the bed up to about 20-30% of the water-depth in shallow water (approximately z = 2-3m), or 20-30% of the boundary layer thickness in deep water (approximately z = 20-30m).

The most commonly used measure of the current speed at a particular time and place is the depth averaged current speed, $\bar{U}$, which may be related to bed shear stress, τ_o, through the drag coefficient C_D, where ρ is water density (1027kg/m^3) by the quadratic friction law:

$$\tau_o = \rho C_D \bar{U}^2 \qquad \text{Eq. 2.4}$$

The first research using bed shear stress as a measure of threshold of motion was developed by Shields (1936), in terms of the ratio of force exerted by the bed shear stress acting to move a grain on the bed to the counteracting force of the submerged weight of the grain. Shields (1936) related dimensionless shear stress, ϑ_t, to grain Reynolds number, *Re*. The critical shear stress for erosion of non-cohesive sediment is commonly obtained from a refinement of data from Shields (1936) diagram (Miller *et al.*, 1977). For very fine grain sizes, however, Shields' curve over predicts threshold shear stress, and force considerations by Bagnold (1956) have shown that ϑ_{cr} cannot exceed a value of approximately 0.30, because this exerts sufficient force upon grains to overcome the weight of every grain in the topmost layer of the bed. In addition the curve does not account for boundary conditions e.g. bedforms, slope, and non-uniform grain size distributions, and the presence of fecal pellets and microbially colonised beads that alter the resistance to erosion (Nicholls and Biggs, 1985). Moreover, Miller *et al.* (1977) and Soulsby (1997) suggest that Shields curve is inconvenient to use because the unknown u_{*cr} appears on both axes, and propose a transformation to a plot of ϑ_{cr} versus dimensionless grain size as being useful. An algebraic expression found to fit Shield's curve was proposed by Soulsby (1997) for use in practical applications:

$$\vartheta_{cr} = \frac{0.24}{D_*} + 0.055[1 - \exp(-0.020D_*)] \qquad \text{Eq. 2.5}$$

where D_* is a dimensionless grain size parameter. The threshold Shields parameter ϑ_{cr} is related to threshold shear stress, τ_{cr}, through:

$$\tau_{cr} = \vartheta_{cr} g(\rho_s - \rho)d \qquad \text{Eq. 2.6}$$

in which g is acceleration due to gravity ($9.81 ms^{-2}$), ρ_s is density of sediment grains, ρ is density of water and d is sieve diameter of grains.

Deposition

Deposition occurs when the force exerted upon grains is no longer sufficient to maintain transport and grains come to rest. Entrainment of sediment and settling of other sediment may occur simultaneously. In the case of non-cohesive sediment deposition occurs for particles being transported when fluid lift and drag forces produced by turbulence no longer overcome stabilising forces of the sediment. Thus shear stress, τ, no longer reaches the threshold shear stress, τ_{cr}, equal to the shear strength holding the sediment to the bed. Non-cohesive sediment carried in suspension is deposited when the force of gravity overcomes the forces holding the sediment in suspension. Deposition of non-cohesive sediment is affected directly by hydrodynamics and thus responds relatively quickly to changes in hydrodynamic currents.

2.3.2 Non-cohesive sediment transport rate

Methods developed to calculate sediment transport rate generally rely on theoretical physical principles combined with empirical field results to produce semi-empirical formulae. The relationship between sediment transport rate and flow is complex as grain movement develops from saltation dominated to suspension dominated with increasing transport stage. The concentration of sediment and the velocity of movement are functions of excess shear stress, and bedforms may be generated producing form drag, further complicating calculations of sediment transport rate (Dyer, 1986). Many sediment transport formulae have been proposed, and Dyer (1986) proposes three classifications; experimental, relying on flume results e.g. Meyer-Peter and Muller (1948), theoretical employing basic physics as a starting point but using empirical studies for calibration e.g. Bagnold (1956,1966) and dimensionless analysis determining constants and coefficients with flume results e.g. Yalin (1963). Some formulae apply to bed load only whilst other include suspended load to predict total load. All formulae depend on calibration with empirical data resulting in restrictions in range and significant instability when applied to long-term sediment transport patterns. Nevertheless, Dyer (1986) notes there is a degree of conformity between most formulae with sediment transport rate being proportional to u_*^3 over some part of the range.

Bed-load transport rate

The earliest approach to bed-load transport was proposed by DuBoys in 1879, employing the assumption that sediment particles are moving along the bottom in layers of progressively decreasing velocities in a vertical downward direction. Since then various other approaches have been developed. One of the most rigorous was developed by van Rijn (1984), where bed-load transport rate was defined as the product of the thickness of the bed load layer, the velocity of the sediment particles and the concentration of the bed-load in the bed-load layer.

$$q_b = \delta_b u_b c_b \qquad \text{Eq. 2.7}$$

where, q_b is volumetric bed load transport rate (m^2/s), δ_b is thickness of the bed load layer, u_b is particle velocity (m/s) and c_b is volumetric concentration. It may be assumed that the thickness of the bed layer is defined by the maximum saltation height of the transported sediment particles. By investigating all the forces acting on an individual particle, van Rijn (1993) developed a theoretical model of the dynamics of entrained particles to compute the saltation trajectories, and using this model formulated a dimensionless relationship between the saltation height and the sediment fluid and flow characteristics expressed as:

$$\delta_b = d_{50} 0.3 D_*^{0.7} \mathrm{T}^{0.5} \qquad \text{Eq. 2.8}$$

where, $$\mathrm{T} = \frac{\tau - \tau_{cr}}{\tau} \qquad \text{Eq. 2.9}$$

in which, d_{50} is median particle diameter, D_* is a dimensionless particle diameter, and T is a dimensionless bed shear stress. The bed-load concentration was computed from measurements taken from flume experiments as:

$$c_b = c_o 0.18 \frac{\mathrm{T}}{D_*} \qquad \text{Eq. 2.10}$$

where, c_b is volumetric bed load concentration, c_o is a maximum volumetric concentration D_* is a dimensionless particle diameter, and T is a dimensionless bed shear stress. Van Rijn (1993) assumed a reasonable average value for $u_b = 7u_{*,c}$, to produce the following bed-load formula:

$$q_b = 0.25 d_{50} u_* D_*^{-0.3} \mathrm{T}^{1.5} \qquad \text{Eq. 2.11}$$

In which, q_b is volumetric bed load transport rate (m^2/s), d_{50} is median particle diameter, u_* is friction velocity, D_* is a dimensionless particle diameter, and T is a dimensionless bed shear stress. Due to the effects of stratification, the near bed shear stress is the most important for the calculation of sediment transport rates.

<u>**Suspended load transport rate**</u>

When the value of the bed shear velocity exceeds the particle fall velocity, the particles can be lifted to a level at which the upward turbulent forces will be comparable to or higher than the submerged particle weight. The particle velocity in the longitudinal direction is almost equal to the fluid velocity. Depth integrated suspended load transport may thus be defined as the integration of the product velocity (u) and concentration (c) from the edge of the bed layer (z=a) to the water surface (z=h), yielding:

$$q_s = \int_a^h uc \cdot dz \qquad \text{Eq. 2.12}$$

or,

$$q_s = c_a \overline{U} h \frac{1}{h} \int_a^h \frac{u}{\overline{U}} \frac{c}{c_a} dz = c_a \overline{U} h F \qquad \text{Eq. 2.13}$$

in which q_s is volumetric suspended load transport (m^2/s), u is fluid velocity at height z above the bed, c is a sediment concentration (volume) at height z above the bed, c_a is a reference concentration at height z=a above the bed, h is water depth, and F is a dimensionless shape factor (see van Rijn, 1984, Dyer and Soulsby, 1988 and McLean, 1991). The shape factor F cannot be integrated analytically. As an alternative to the full approach van Rijn (1984) derived a simplified method based on computations with a roughness predictor. Using regression analysis, the computational results for a depth range of 1-20m, a velocity range of 0.5-2.5 m/s and a particle range of 100-2000 μm were represented by the following simple power function:

$$q_s = 0.012\overline{U}h\left(\frac{\overline{U}-\overline{U}_{cr}}{((s-1)gd_{50})^{0.5}}\right)^{2.4}\left(\frac{d_{50}}{h}\right)\left(\frac{1}{D_*}\right)^{0.6}$$ Eq. 2.14

with, $$\overline{U}_{cr} = 0.19(d_{50})^{0.1}\log_{10}\left(\frac{4h}{d_{90}}\right)$$ for $100 \le d50 \le 500\mu m$ Eq. 2.15

where $\bar{U}$ is depth averaged velocity, $\bar{U}_{cr}$ is threshold depth-averaged current speed h is water depth, s is the ratio of densities of grain and water (2.65), g is gravitational acceleration ($9.81 m/s^2$), d_{50} is median grain diameter, d_{90} is a 90 percentile characteristic sediment diameter and D_* is a dimensionless grain size parameter.

2.3.3 Cohesive sediment

Sediment varies in terms of chemical composition and grain size. In general finer sediment grains are more mobile than coarse ones, but relating grain size distributions to fluid flow depends on definition of the means of transport of sediment grains (Dyer, 1986). Cohesive properties may be exhibited by sediments containing more than about 10% by mass of fine sediment, i.e. sieved material less than 63μm. Cohesion, causing the formation of flocculates, is promoted in sediment with a large surface area relative to mass when repulsive surface charges are suppressed in a weak electrolyte such as seawater, and may be reinforced by organic cohesion.

Erosion

To remove a floc of cohesive sediment by flowing water requires a bed shear stress τ_0 sufficient to overcome the attractive forces induced by interparticle adhesion and organic binding. The critical erosion shear stress τ_e of a cohesive sediment surface is defined as the shear stress required to be exerted by flowing water to cause erosion of flocs. Considering a flow beginning with a velocity of 0, as velocity over the bed increases erosion of the topmost sediment eventually occurs (Dyer, 1986). As velocity is increased in small increments erosion is manifest as an increase in sediment concentration. Initially concentration increases rapidly but gradually levels off to a constant value as sediment is eroded down to a level where the sediment is able to resist shear. A further increase in velocity causes a further increase in concentration as shear stress exceeds the higher critical erosion shear stress of consolidated mud found in lower layers. These processes result in differences in erosional characteristics between newly deposited muds and those that have undergone a degree of consolidation (Mehta *et al.*, 1982).

Based upon experiments on Avonmouth mud, Owen (1975) found that the rate of erosion dm/dt expressed as dry mud per unit area per unit time is related to the magnitude of the excess shear stress by the dimensional coefficient m_e known as the erosion constant:

$$\frac{dm}{dt} = m_e(\tau_0 - \tau_e) \qquad \text{for } \tau_0 > \tau_e \qquad \text{Eq. 2.16}$$

$$\frac{dm}{dt} = 0 \qquad \text{for } \tau_0 \leq \tau_e \qquad \text{Eq. 2.17}$$

However, there is considerable variation in the erosive properties of cohesive sediments from different sites (Delo and Ockenden, 1992) and at shear stresses greatly exceeding critical shear stress, a cohesive bed may experience mass erosion comprising detachment of lumps of sediment from the bed. Furthermore, at present no satisfactory way exists to predict critical shear stress or erosion rates as a function of erosion resistance for a range of flow conditions, although bed shear strength has been found to be related to the dry density of the bed (Thorn and Parsons, 1980).

<u>Deposition</u>

In the simplest case involving settling in still water the rate of deposition, R_d, is predicted by the product of the suspended concentration, C_b, and its settling velocity, w_s. In a weak current sediment continues to settle but can only deposit if the shear stress exerted on the bed by the current, τ, is lower than the initial bonding strength of the particles to the bed. The shear stress below which deposition can proceed is the limiting shear stress for deposition, τ_d (Owen, 1977). Deposition of fine sediment occurs when the limiting shear stress for deposition falls below a certain value at a rate proportional to the ratio $(1- \tau/\tau_d)$. Thus neglecting factors such as waves, bed roughness, and the influence of organic activity the rate of deposition is given by:

$$\frac{dm}{dt} = Cw_s\left(1 - \frac{\tau_0}{\tau_d}\right) \qquad \text{for } \tau_0 < \tau_d \qquad \text{Eq. 2.18}$$

$$\frac{dm}{dt} = 0 \qquad \text{for } \tau_0 \geq \tau_d \qquad \text{Eq. 2.19}$$

Accumulation of cohesive sediment upon the bed is followed by consolidation as pore water escapes. Experiments (e.g. Migniot, 1968; Owen, 1970) indicate four temporal phases of settling and consolidation: (1) 0.1-1 hour: flocculation and rapid settling of flocs forming an upper "fluffy" mud layer of high concentrations 2-10 g/l, and a lower fluid mud layer greater than 10g/l with hindered settling as the abundance of water slows the upflow of displaced water (Krone, 1962). (2) 1-10 hours floc structure collapses and pore water escapes. (3) 10-500 hours pore water escapes slowly through drainage wells. (4) more than 800 hours consolidation proceeds slowly as the weight of overlying sediment forces out remaining water. In estuaries with high suspended concentrations, the rate of deposition is too fast to permit a normal self-weight consolidated mud to form. As a result over many tidal cycles layers of dense suspensions called fluid mud accumulate, consolidating as they become static. Under the influence of accelerating tidal currents upper layers of the fluid mud redisperse or flow slowly along the bed (Kirby and Parker, 1983). Consolidation of cohesive sediments introduces additional complications to studies of long-term morphological change and the development of long-term morphological modelling tools as it introduces another, quite variable time scale and a hysteresis effect which places more emphasis upon the chronology of inputs (Villaret and Latteux, 1992).

2.3.4 Cohesive sediment transport rate

Transport mechanisms for fine grained (cohesive) sediments are more complicated than for non-cohesive sediment, because more parameters including particle settling velocity, tidal resuspension and water depth (and cross-sectional area) are involved in calculation of transport rate. The transport rate of mud is defined as the mass of sediment crossing a unit width of bed in unit time obtained from the product of the concentration profile and the velocity profile integrated over the water depth:

$$Q_{smud} = \int_0^h C_M(z)U(z)dz \qquad \text{Eq. 2.20}$$

2.3.5 Wave effects and sediment transport

Waves can exert a significant influence upon sediment transport, stirring up sediment from the bed and giving rise to steady current motions such as longshore currents, undertow and mass-transport (or streaming velocities) which transport sediment. The most significant parameter expressing wave bottom effects is the maximum bottom orbital velocity U_{max}, expressed as:

$$U_{max} = \frac{H\pi}{T \sinh(2\pi h / L)} \qquad \text{Eq. 2.21}$$

where H is wave height, T the wave period, L the wavelength, and h the water depth (Komar and Miller, 1973). As 1/(sin h 2πh/L) falls rapidly with depth, and its square falls even faster, it is evident that the maximum bed shear stress is very sensitive to water depth. Grant and Madsen (1979) suggested that even though wave orbital velocity may be of the same order of magnitude as the stronger tidal currents at the seabed, wave residual shear stress can be an order of magnitude larger. However, there is generally no net sediment transport associated with the wave motion over a complete wave period (Grant and Madsen, 1979). Waves act primarily to suspend sediment making it available for transport by the tide. The effect of turbulence caused by wave orbital velocity results in a much smaller tidal current being required to produce erosion (Mehta, 1988).

As with currents the most important hydrodynamic property of waves for sediment transport purposes is the bed shear stress produced. This is oscillatory in the case of waves, having an amplitude τ_w. It is usually obtained from the bottom orbital velocity of waves via the wave friction factor f_w, defined by:

$$\tau_w = \frac{1}{2}\rho f_w \left(\hat{U}_\delta\right)^2 \qquad \text{Eq. 2.22}$$

The time averaged (over half a wave cycle) bed shear stress is:

$$\tau_w = \frac{1}{4}\rho f_w \left(\hat{U}_\delta\right)^2 \qquad \text{Eq. 2.23}$$

and where ξ is given by Swart (1974)

$$\xi = C_z \left(\frac{f_w}{2g}\right)^{\frac{1}{2}} \qquad \text{Eq. 2.24}$$

in which, f_w is the bottom friction coefficient and C_z is the Chezy coefficient

Wave effects and non-cohesive sediment transport

Van Rijn (1993) derived an expression for non-cohesive bed load transport of the form:

$$q_b = 0.25\alpha d_{50} D_*^{-0.3} \left[\frac{\tau_w}{\rho}\right]^{0.5} \left[\frac{(\tau_w - \tau_{cr})}{\tau_{cr}}\right]^{1.5} \qquad \text{Eq. 2.25}$$

Equation 2.24 is of a similar form to equation 2.9, except it employs a formulation to calculate excess shear stress responsible for mobilising sediment comprising the addition of current stress and wave orbital stress terms.

Soulsby (1997), derived a term for non-cohesive suspended load transport based upon a parameterisation of Van Rijn's work (1993) comprising a time-averaged approach to compute suspended load transport:

$$q_s = A_{ss}\overline{U}\left[\left(\overline{U} + \frac{0.018}{C_D}U^2{}_{rms}\right)^{0.5} - \overline{U}_{cr}\right]^{2.4} (1 - 1.6\tan\beta) \qquad \text{Eq. 2.26}$$

where, $$A_{ss} = \frac{0.012 d_{50} D_*^{-0.6}}{[(s-1)g d_{50}]^{1.2}} \qquad \text{Eq. 2.27}$$

in which, $\bar{U}$ is depth averaged velocity, $\bar{U}_{cr}$ is threshold depth-averaged current speed (derived from equation 6.3), h is water depth, s is the ratio of densities of grain and water (2.65), g is gravitational acceleration (9.81m/s^2), d_{50} is median grain diameter and D_* is a dimensionless grain size parameter.

Wave effects and cohesive sediment transport

The action of waves may be sufficient to cause surface erosion, with material passing directly into suspension. Experiments with a natural mud bed have shown that wave action erodes mud of a given dry density at about the same peak shear stress as that required with uni-directional flow, and the erosion rate of a mud bed with a bulk density of 1280kg/m^{-3} was similar to the proportional excess shear-stress relationship for current erosion given in equation 2.16 (Diserens and Delo, 1988). Hence to calculate the mean erosion rate of a mud bed by waves the steady current bed shear stress is replaced by the maximum bed shear stress during a wave-cycle, τ_w.

Deposition of mud under waves occurs if the peak bed shear-stress, τ_w ,exerted by the waves falls below the threshold vale for deposition, τ_d. The rate of deposition follows an empirical equation similar to equation 2.18, but with the current-induced bed shear-stress replaced by the maximum bed shear stress during a wave-cycle, τ_w.

If waves are present, then the transport rate at any instant in the wave cycle is given by equation 2.20 with C(z) and U(z) being instantaneous concentration and velocity profiles. The net transport rate is then given by taking a time average of equation 2.20. However, understanding of mud suspension under waves is not yet sufficiently advanced to include this refinement, and for practical purposes it is usual to apply equation 2.20 with C(z) and U(z) taken as the time averaged concentration and velocity profiles (Whitehouse *et al.*, 2000).

2.4 Estuarine sedimentation

In many estuaries tides are the major energy source for moving sediment, particularly in UK estuaries, which can exhibit large tidal ranges. Tides exhibit dynamic interaction with the bathymetric form of estuaries, acting as a significant influence upon morphology. This thesis concentrates upon the effect of tides as the dominant influence upon estuary morphology, although the role of other processes, particularly wave activity, is also recognised and discussed. In addition to tidal flows, the principal processes affecting the morphology of coastal environments such as estuaries include freshwater flow, waves and Coriolis force (Muir Wood and Fleming, 1981).

De Vriend *et al.* (1993) suggest in a review of approaches to long-term coastal morphology modelling that uncertainty regarding interaction of flow and sediment transport resulting from non-linear behaviour of estuarine systems means small-scale process based models may not provide the best method of representing long-term estuarine behaviour. This implies that benefits may be derived from examining estuarine processes at a scale greater than that associated with the sediment dynamics. It is suggested that there is a requirement for data reduction, to identify and separate representative processes from 'noise' associated with process operating at smaller time-scales.

2.4.1 Tidal effects and estuary morphology

In many estuaries tides represent the major energy source for transporting sediment seaward or landward. Tides in the ocean are controlled by the gravitational effects of the sun and moon, and the centrifugal effects of the earth's rotation. In the deep oceans tides have a characteristic sinusoidal form. As tides approach shallow areas such as estuaries, however, they can exhibit considerable distortion. Whilst tides are linked to astronomical forces they are predominantly shaped by geometry in estuarine areas.

Airy (1842) was one of the earliest researchers to analyse tidal phenomena and their distortion from sinusoidal forms, examining the generation of overtides and the distortion of tidal waves as they propagate into shallow water. Based upon study of propagation of a shallow water wave in a frictionless estuary at a velocity $c=\sqrt{gh}$, it was noted that water depth is greater at the tide crest than at the trough. Thus the crest may travel more quickly than the trough, resulting in a shorter flood and longer ebb tide. The effect noted by Airy (1842), however, neglects the greatly increased importance of friction in shallow water. The role of friction was first considered by Young (1813) and developed by Ferrel (1874) to demonstrate the effect of frictional resistance in the opposite direction to wave propagation. Proudman (1923) employed Fourier analysis to demonstrate that the frictional mechanism can produce new harmonic constituents at frequencies other than those present in compound tides.

With the development of computers enabling numerical examination of more precise relationships between compound tides LeBlond (1978) demonstrated the dominant role of friction in shallow estuaries using scaling analysis to demonstrate that the friction term was greater and often more important than the acceleration term in the axial motion equation. On the basis of this analysis it was suggested that pressure gradient and friction predominantly control the momentum balance in shallow estuaries. Brown and Trask (1980) analysed the individual terms in the one dimensional momentum equation, and showed that empirical estimates of the terms were consistent with the dominance of pressure gradients and friction terms. The effects of friction upon tidal distortion were emphasised by Parker (1991) who demonstrated that non-linear harmonic components can be represented by a shallow water term, convective term and frictional term, with first order effects of friction causing a decrease in wave propagation velocity and attenuating wave amplitude. Salomon and Allen (1983) recognise three distinct processes of tidal wave deformation as it advances into an estuary: (1) frictional damping on the bottom, (2) landward constriction or convergence in the channel, and (3) reflections on shoals or from the estuary head.

The deformation of a tidal wave in shallow systems with a regular or complex geometry can have a significant influence upon the residual sediment flux, which is investigated extensively in Dronkers (1986), based upon the concepts of Postma (1967). In general the two principal features of tidal wave deformation relevant to residual sediment transport are:

- The difference between the maximum tidal currents during ebb and flood, which particularly affects the residual flux of the coarse suspended fraction.
- The difference between the slack water periods preceding ebb and flood, which particularly influences the residual flux of the fine suspended fraction.
- The relation of these processes to net estuary morphological behaviour is discussed in the following two sub-sections.

Tidal velocity asymmetry

In estuaries where tidal effects play a dominant role in sediment transport, a state of equilibrium requires that as much sediment is transported landwards on the flood tide as is carried seawards on the ebb tide. Assuming the volume of water transported by flood and ebb tides is equal, the duration of flood and ebb must also be equal in order that tidal velocities, and therefore potential to transport sediment are the same. Postma (1967) has noted, however, that tidal curves often deviate from a simple symmetrical shape. 'Flood dominant' estuaries have shorter duration, higher velocity floods and tend to infill their channels with coarse sediment, whilst 'ebb dominant' systems have shorter, higher velocity ebbs, flushing bed load sediment seaward. Hypotheses put forward to qualitatively explain flood and ebb dominance have focussed on the distortion of a sinusoidal tidal curve.

A progressive tidal wave occurs where the energy of the tidal wave is completely dissipated by friction before reflection, or if the channel is infinitely long. The amplitude of the tide and the magnitude of the tidal currents diminish towards the head of the estuary and there is a progression in the times of high and low water and the turn of the current along the estuary. A standing wave is the opposite of a progressive wave, and is created if there is no friction, and the tidal wave is reflected at the head of the estuary so it meets the wave just entering from the sea. An antinode is then created at the head where there is a maximum in the tidal range, and a node is created at a distance down the estuary equal to

1/4 the wavelength of the wave, with no variation of depth, but with a maximum in the horizontal currents (McDowell and O'Connor, 1977). High and low waters would be simultaneous throughout the estuary and would coincide with the time of turn of the current. Tidal propagation in many small estuaries (where length of estuary<<tidal wavelength) is complicated by co-oscillation due to tidal wavelength reflection from the head of the embayment (Dronkers, 1986).

Tidal velocity asymmetry does not determine the residual flux of all sediment types, but according to Dronkers (1986), especially affects the residual transport of the coarse fraction of the suspended load of grains larger than 63μm. The asymmetry of tidal current velocity strongly influences the residual suspended load transport of coarse sediment, as it is characterised by a sediment load saturation limit, which is rapidly reached and is non-linearly related to increases in current velocity. The velocity of coarse bed load sediment transport of grains larger than 200μm is much smaller than the current speed, theoretically enabling ebb or flood dominance to determine residual bed load flux. However, sandy bays and estuaries are frequently characterised by alternating flood and ebb channels with slow moving grains transported by traction trapped in the channel systems, with the result that ebb-flood asymmetry often does not greatly affect residual flux. Suspended coarse grains move with sufficient velocity to bypass localised areas of the channel where the residual current is opposed. Bed load transport of fine sediment grains smaller than 63μm known as "fluid mud" or "high concentration near bed suspensions" occurs where a turbidity maximum exists, with ebb-flood asymmetry dominated by estuarine gravitational circulation in these areas. Suspended load transport of fine sediment grains smaller than 63μm differs from coarse sediment because even at rather small current velocities, an important load of fine sediment can be maintained in suspension, with deposition dependent upon the settling velocity of the sediment and saturation rarely occurring.

Peak velocities on flood and ebb are used as a first indicator of the preferred direction of movement for the coarse sediment fraction, as sediment transport is generally related to peak flows through a non-linear relationship approximating u^3 (Dyer, 1986). However, this measure takes no account of the duration of such peak velocities. It is possible that a slightly lower velocity on one stage may prevail for longer than the higher peak on the opposing stage. This effect may be accounted for by calculating net tidal excursion, representing the difference under the curves for flood and ebb tides. To provide an accurate indication of sediment movement it may be necessary to introduce a velocity threshold.

The distortion of the tide as it propagates from the open ocean into the shallower water of an estuary can be represented more accurately by the non-linear growth of compound constituents and harmonics of the principal astronomical tidal components (Dronkers, 1964; Uncles, 1981; Aubrey and Speer, 1985). For the majority of estuaries the dominant astronomical constituent is the semi-diurnal lunar tide M_2. The first harmonic and hence most significant overtide of M_2 is M_4. Speer *et al.* (1991) proposed the ratio of M_4 to M_2 tidal harmonic amplitudes in both sea surface elevation and velocity as a representation of the degree of tidal asymmetry in an estuary. The relative phase, defined as twice the phase of M_2 minus the phase of M_4, determines the direction of tidal asymmetry (ebb or flood dominant). Relative sea surface phases between 0° and 180° indicate a tendency towards flood dominance and ebb dominance is indicated by a relative sea surface phase between 180° and 360°.

<u>Settling and scour lag effects</u>

The residual transport of the fine fraction of the suspended load (grains smaller than 63μm), is affected more by differences in the duration of slack water periods between ebb and flood than the relative magnitude of peak and ebb and flood tidal velocities according to Dronkers (1986). The cohesive properties of this sediment cause time lag effects in responding to changes in tidal current velocity. The concentration of fine suspended sediment is limited by the availability of erodible bottom material, with weakly consolidated material resuspended when the current velocity reaches a critical level, and subsequent, increasingly consolidated, layers brought into suspension as current velocity increases further. The relative duration of the slack water periods before ebb and flood tide influence the quantities of sediment deposited at each end of the tidal excursion, determining the residual transport of sediment. In irregularly shaped estuaries tidal current variation is heavily influenced by channel geometry. Dronkers (1986) distinguished two types of channel geometry; shallow channels decreasing in depth landwards with tidal flats below mean sea level, and deep channels throughout with tidal flats above mean sea level. In the former case the slack water period before ebb exceeds the slack water period before flood favouring a residual import of sediment, whilst in the latter case the inverse situation occurs.

Observations in the Dutch Wadden Sea have revealed high suspended sediment concentrations in landward reaches despite tidal flow favouring transport to the sea. Mineralogical and petrographical analyses have shown that the source of the sediment is the North Sea (Van Straaten and Keunen, 1957). Postma (1961,1967) explains this phenomenon in terms of a settling lag and scour lag effect, which results in an imbalance between critical shear stress for erosion and critical shear stress for deposition. Settling lag is the time taken for a sediment particle to reach the bed after tidal velocity has diminished to a point where it can no longer support the sediment in suspension, resulting in a delay between slack water and minimum suspended sediment concentration. As a result sediment is carried landward beyond the point where it begins to sink, and is deposited in an area where successive ebb currents are weaker than the initial flood current. Therefore the returning water mass carries less sediment than the incoming water mass. Scour lag is the additional velocity required to move or suspend a particle in excess of the velocity at which the sediment settled. The deposited sediment will not be resuspended until the currents have attained a higher velocity than when the sediment was originally deposited. The constant shifting of sediment from a flood water mass to an ebb water mass with settling and scour lag and a landward diminishing velocity trend, results in a distance-velocity asymmetry whereby sediment has a net landward transport with each cycle. However, the effects of waves on intertidal areas discussed in Section 2.4.2 can suspend sediment at low current velocities and reverse the effects described above.

The effects of consolidation induced by the biological and physical changes that occur in a sediment once deposited can enhance the effect of sediment settling and scour lag e.g. Paterson *et al.* (1990). Once deposited, consolidation of the sediment results in an increased critical erosion stress, and the difference between critical shear stress for erosion and critical shear stress for deposition is magnified increasing landward sediment transport.

2.4.2 Wave effects and estuary morphology

Essentially two genetic types of surface wave can affect estuary sediment processes: (1) those generated externally in the ocean and penetrate estuary mouths, and (2) those generated internally (Nicholls and Biggs, 1985). Deepwater ocean waves have lengths of approximately 40-60m, and become distorted from a circular motion to a more elliptical and asymmetrical motion where water depth becomes less than one-fourth the wavelength. When the resulting motions impinge on the bed and produce sufficient shear velocity, a measure of bottom shear stress (Imman, 1949), sediment transport is initiated. Sediment transport is generally shoreward as shoaling waves become asymmetrical, although due to irregular bottom topography transport may also be affected by wave refraction. Ocean waves may also provide a supply of sediment for transportation into the estuary by eroding sediment along the shoreline or shoaling wave zone, and move it via drift currents to the estuary entrance. Estuary waves are shorter and less regular than ocean waves with lengths of 5m to 15m. Wave size and character is determined by water depth, and the direction strength and duration of winds blowing over the estuary. The waves are termed fetch limited, as there is a finite distance over which winds can influence estuary wave conditions and hence a finite size of wave which may be generated. The largest waves are usually associated with winds blowing from an orientation parallel to the longest axis of the estuary. In a meso-tidal estuary fetch lengths at high water may be considerably greater than at low water with the effect of wave stirring being greatest around high water.

Of significant interest to the study of historical morphological change are long-term changes in surface waves propagating towards estuaries. This may be induced by two factors; changes in bed topography in the nearshore zone altering patterns of wave refraction and diffraction, and changes in meteorological conditions resulting in changes in offshore wave climate. Jelliman *et al.* (1991) reported an investigation of wave climate trends for the UK coast. The findings indicated an increase in mean wave heights of 1-2% for each year for the past thirty years although extreme wave heights have risen more slowly. More recent results by Samuels (1996) have shown that median wave heights in the North-East Atlantic have increased by up to 23cm per year over the same period. However, considerable variations may have occurred in nearshore areas where localised changes in bathymetry have caused changes in wave propagation.

Dronkers (1986) suggests that wave effects within an estuary system can influence the residual transport of sediment. Wave energy dissipation is concentrated in shallow areas where water depth is a few meters or less, and the dominant influence of wind waves in estuaries is to transport sediment seawards. In estuaries where depth decreases landwards sediment deposited during the slack water period before the ebb tide is more strongly affected by wave action than the amount deposited during the slack water period before the flood tide. The seaward flux due to wind waves can be particularly important in estuaries with high tidal flats, as the fine sediment eroded from the tidal flats by waves around high water can remain in suspension for a long period during the ebb tide and can therefore be transported seawards. Waves can also cause a net seaward transport of coarse sediment, by bringing it into suspension from intertidal areas at high water. Although coarse sediment is deposited more readily than fine sediment and is therefore not carried as far by the ebb tide, coarse sediment is not so easily resuspended by the flood current. Wind waves, therefore, can serve to counteract a landward residual transport of both fine and coarse sediment by tidal currents.

2.4.3 Freshwater flow and estuary morphology

The magnitude of river discharge into an estuary has a significant effect upon important estuary processes affecting morphology, and can affect morphology directly by supplying sediment to an estuary and indirectly by influencing flow conditions and hence sediment transport patterns.

Freshwater discharge has a significant impact upon the salinity regime and stratification in an estuary, although vertical mixing is also affected by factors such as tides (Prandle, 1991), bathymetry (Prandle, 1981) and wave climate (Olson, 1986). The distance a river is capable of thrusting freshwater and sediment into an estuary is quantifiable in terms of "flushing velocity" (Gibbs, 1977) by dividing mean annual river discharge by cross-sectional area at the freshwater-saltwater transition taken as 1ppt at the surface. Landward of the freshwater-saltwater transition, river flow is restricted to channels in which velocities and turbulence are relatively high. Fine sediment (<16μm) is transported throughout the flow while sand (63-250μm) is transported in near bottom water, and coarser sediment is transported as bed load. As the river channel widens and cross-sectional area increases seaward, velocities fall causing bed load and coarse sediment held in suspension to drop out. Bi-directional tidal currents that penetrate landward from the freshwater-saltwater transition and superimpose on river flow, can mix river-borne flow. At the bed, flow velocity approaches zero where river flow converges with landward flowing estuarine flow, stopping seaward transport of bed load. Suspended load in near surface water, however, can pass further seaward as lighter freshwater flows over denser saline water.

River discharge can also have a significant effect on distorting the tidal wave in an estuary, with associated implications for sediment transport particularly in the upper estuary, due to frictional momentum loss from the tide increasing as the ratio of tidal current velocity to river current velocity increases (Parker, 1991) dampening the tidal impact. Godin (1985) examined this effect, producing theoretical calculations using tidal gauge and river discharge observations for the Fraser, St. Lawrence, and St. John rivers (Canada). Estuaries were divided into three reaches and calculations scaled accordingly for the effects of tidal and freshwater discharge. The results demonstrated that the effects of freshwater discharge were most pronounced upstream where tidal range was reduced by an increased discharge; the time of arrival of low water was accelerated, and high water was retarded, with higher low water and high water levels. Downstream the effect of increased freshwater discharge was the converse of upstream, retarding low water and accelerating high water due to damping of low water, but reducing the effect of friction of high water.

2.4.4 Coriolis force and estuary morphology

The earth's rotation causes gases or fluids with momentum to be deflected by the Coriolis force. The Coriolis parameter (γ) is dependent upon latitude and is calculated by $\gamma = 2\omega_e \sin\varphi$, where ω_e is the angular velocity of the earth's rotation and φ is the latitude. In open water in the northern hemisphere, the Coriolis force creates Rossby waves with an anticlockwise rotation. This motion is governed by the conservation of potential vorticity, and becomes increasingly important in shallow waters. If there is a change in either the Coriolis force or water depth, then the conservation of potential vorticity requires a change in the relative vorticity about an a vertical axis causing deflection (Pond and Pickard, 1983). In the northern hemisphere the Coriolis force causes a generally clockwise rotation of the semi-diurnal equilibrium tide. Where tidal currents are approximately in phase with the tidal wave, i.e. maximum currents occur in opposed directions near the time of high and low water, a tide confined to a channel will be found to have a different range along the two sides of the channel (Muir Wood and Fleming, 1981), and ebb and flood dominant channels may be formed.

2.4.5 Estuary-nearshore sediment exchange

The exchange of sediment between an estuary and the seaward environment can exert a significant influence upon the long-term morphological behaviour of the estuary. In the zone where estuaries meet the sea, transport of sediment is modulated by river flow, tidal currents, coastal drift and wave processes (Nicholls and Biggs, 1985). These processes can dominate the supply of sediment to the mouth of the estuary, influencing sedimentation in situations where the estuary is acting as a sediment sink, with physical processes acting to convey sediment into the estuary. In contrast seaward escape of sediment from the estuary has been found to occur where river flow forces the turbidity maximum near the mouth of the estuary, and there is significant resuspension of sediments during spring tides (Castaing and Allen, 1981). During these periods, the increased seaward surface density flow supplies large quantities of suspended sediment to the shelf.

2.5 Approaches to modelling long-term morphological change in estuaries

Ultimately decisions on the long-term behaviour of estuary morphology and the impacts of proposed developments require long-term predictive tools. The objectives of long-term predictive tools, as defined in a review of estuary research and user needs (HR Wallingford, 1997a), comprise predicting future evolution of estuary shape, predicting impacts of modifications to process or shape, predicting impacts on water quality and ecology and ultimately designing a self-sustaining estuary morphology. Several researchers have explored approaches to long-term morphological modelling of estuarine systems and tidal inlets based upon extrapolating from short-term process modelling, applying form-function relationships or a combination of the two (Wang *et al.*, 1998; Spearman *et al.*, 1998; Van Dongeren and de Vriend, 1994; Stive *et al.*, 1998).

Modelling long-term morphological change in estuaries requires a predictive approach that represents iterative changes in estuary morphology from initial conditions accounting for dynamic feedback between estuary form and process as a continuous sequence. A distinction may be made between the diagnostic analytical role of models and their predictive role. Van Rijn (1993) divides these two functions into initial models and dynamic models (see Figure 2.3). Initial models are employed to determine hydraulic conditions under fixed model input conditions resulting in short term prediction. Existing hydrodynamic models are not generally designed to incorporate complex large-scale estuary feedback mechanisms as morphology is regarded as an independent variable. Although processes such as erosion and deposition may be represented, they cannot presently be extrapolated very far into the future since the changing morphology alters the current distribution and the model becomes unstable.

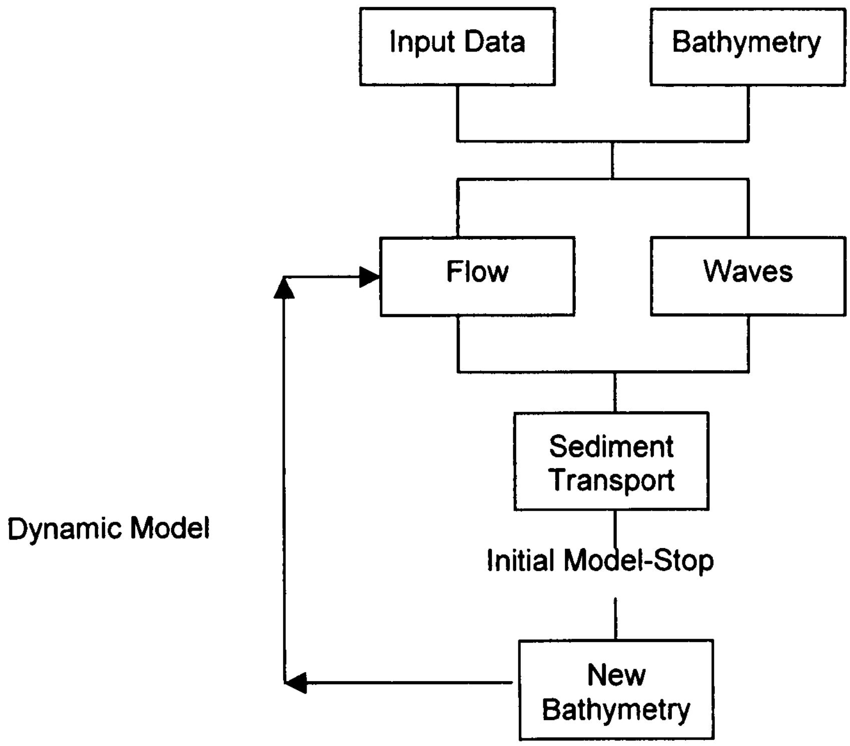


Figure 2.3 Structure of Initial and Dynamic estuary models after van Rijn (1993)

Long-term morphological models have been developed (e.g. Spearman *et al.*, 1998; Wang *et al.*, 1998; Van Dongeren and de Vriend, 1994) although it is emphasised that these are in their infancy. The two main approaches identified within the development of long-term modelling tools are a "bottom up" approach reliant on representing detailed micro-scale processes and a "top down" approach employing the concept of a system response to attain a specified energy balance between inputs and outputs. A third "hybrid" approach combines conceptual elements of the "top down" method with the more quantitative small scale elements of a "bottom up" technique.

2.5.1 Estuary stability

An important body of work on long-term morphological evolution of estuaries concerns the equilibrium state of the system given the extrinsic conditions, a concept employed in "top down" approaches. The dynamics underlying estuary morphology have been analysed using empirical form-function relationships allied to conceptual models of morphological adjustment to perturbations about a hypothetical equilibrium state (e.g. Pethick, 1994; 1998). This approach defines the steady state response of an estuary utilising observed relationships between geometrical and process parameters as a basis for examining interaction between process and form. Over time there may be changes in estuary conditions causing the creation of a non-equilibrium state. A concept of estuary stability implies that changing the input conditions of an estuary (primarily hydrodynamics or morphology) results in feedback effects altering the estuary to create a new equilibrium state. Estuary stability has been defined by Gerritsen (1990) as the ability of an estuary "to resist changes of size and form under stable environmental conditions". In essence equilibrium is a state of theoretical balance in the estuary system, and estuary stability is a measure of the degree to which a theoretical balance exists in the system.

A simple approach to defining estuary stability is estuary regime which asserts that an estuary, under constant forcing, will reach an equilibrium form which may be described by relationships between estuary parameters, usually relating to channel geometry and key features of hydrodynamics following the work of O'Brien (1931) and Leopold and Langbein (1962). Functions that are typically empirically based are employed in a static stress-strain relationship to relate some measure of estuary form to process. Early examples of such approaches are the work on tidal inlets of O'Brien (1931) relating cross-sectional area and tidal prism and Escoffier (1940). This type of relationship was developed further by O'Brien (1969) and has been studied by many authors including; Nayak (1971); Moore (1972); Jarrett (1976); and Byrne *et al.* (1975), who found similar relationships varying for different conditions. Alternative regime relationships employing different process or geometric parameters have also been proposed (e.g. Bruun and Gerritsen, 1960; Myrick and Leopold, 1963; Chantler, 1974; de Jong and Gerritsen, 1984; Eysink, 1991).

Developments in regime theory have also taken account of the dependence of relationships on sediment transport. Kondo (1990) for example developed a relationship quantifying the effect of littoral drift on cross-sectional area stating that an increase in sediment supplied by littoral drift and an increase in tidal prism to carry this sediment into the estuary, results in decrease in cross-sectional area. Dyer (1997) notes that the value attained by O'Brien (1969) as a constant (c) in a power law relationship between cross-sectional area (A) and tidal prism (P):

$$A = cP^n \qquad \text{Eq. 2.28}$$

is equivalent to 0.67m^{s-1}, the threshold for movement of coarse sand. According to Dyer (1997) the relationship thus specifies that an increasing tidal prism leads to an increase in velocity at the mouth, causing sand to move and cross-sectional area to increase until velocity diminishes until the threshold value, and conversely a decreasing tidal prism leads to a reduction in cross-sectional area until the threshold value for sediment movement is attained. Further research by Gao and Collins (1994) also highlights the significance of sediment transport, suggesting that deviations in the relationship can be explained in terms of different sediment types, which have different thresholds for movement, or the existence of non-equilibrium conditions.

Further consideration of the concept of estuary stability, extremal hypotheses developed in river channel studies have been adapted for estuarine situations. They attempt to explain some of the factors controlling sediment transport dynamics by making assumptions about characteristics that channels seek in order to achieve an equilibrium form. For a given water and sediment discharge, the corresponding alluvial unidirectional channel can be described by its width, depth and slope. The system therefore has three unknowns that mathematically require three equations to solve, the equations available are the sediment transport equation, and a friction equation, a third is needed and the assumptions made according to extremal hypothesis are employed to produce this. A number of controlling factors have been put forward; the three main ones are maximum sediment transport hypothesis, minimum stream power hypothesis, and minimum unit stream power hypothesis (White *et al.*, 1987). Despite the differences between fluvial and estuarine environments, coastal engineers have attempted to adapt fluvial expressions to relate to estuarine hydrodynamics and morphology. Langbein (1963) solved a system of four unknowns to determine the solution for an ideal estuary with an exponentially decaying upstream width and depth. The theoretical results produced by Langbein (1963) correlate well with empirical results of Myrick and Leopold (1963), lending support to the assumption employed by Langbein that an ideal estuary channel seeks to minimise power dissipation and distributes power expenditure evenly over the bed of an estuary.

"Top down" stability based approaches attempt to consider estuarial behaviour on a scale greater than sediment dynamics, a case for which was implied in Section 2.4. Despite the attractions of stability based approaches, several researchers have identified shortcomings as a basis for developing geomorphological understanding (de Vriend *et al.*, 1993; HR Wallingford, 1997a; French and Clifford, 2000; Cayocca, 2001). Firstly, the link between form and process is poorly specified due to limited process knowledge and the large spatial scale covered. Although empirical and conceptual models have increased understanding of the overall mechanisms driving the behaviour of tidal inlets, they cannot account for the respective roles of processes such as tides and waves in reshaping an inlet. Secondly, the validity of supporting empirical relationships may be questioned (Gao and Collins, 1994) and may rely upon concepts such as hydraulic geometry not devised for tidal situations. Implicit in these relationships is the assumption that the selected relationship describes a dominant influence on estuary morphology that is intrinsic to the estuary system, ignoring the possible impact of changes outside the immediate estuary system, i.e. changes in the fluvial or offshore regimes. Thirdly, such an approach does not predict the rate of change and hence interactions with timescales of disturbing events. It is an oversimplification to assume that the transition from an initial state to an equilibrium state is always described by an exponential decay of the difference. Fourthly, many estuaries especially in the UK have experienced anthropogenic interference disturbing the natural balance between form and process.

2.5.2 Probabilistic approach to long term modelling

Research has recently focused upon procedures for simplifying process modelling computations by modelling the most important processes driving morphology. A probabilistic approach has facilitated representations of time-averaged conditions operating over longer timescales. A fundamental feature of probabilistic approaches has been the issue of data reduction (de Vriend *et al.*, 1993), to separate relevant information from "noise" and to map this onto a manageable number of parameters. The reduction of inputs to process models relies on the assumption that long-term residual effects can be described with models if suitable representative inputs are devised to drive them. Furthermore, one of the major hurdles for long-term morphological modelling is that the reduction of inputs relies on the assumption that non-linear effects are not significant, particularly with respect to processes not included in the model.

Natural tidal conditions, for example, exhibit significant long-term modulation cycles (spring/neap, equinoxial, nodal cycle), which although deterministic and predictable lead to prohibitively time consuming computational requirements. Pragmatic techniques to reduce the computational cost and the number of natural tidal situations to be simulated have been devised by Latteux (1995) to represent time averaged field conditions. Using measured current data from three French sites in conjunction with sediment transport formulae, residual transport was computed for different classes of tidal range that were then combined according to frequency of occurrence to yield reference values for yearly averaged sediment transport. By comparing the yearly averaged sediment transport values with those derived from representative tides, a representative "morphological" tide was proposed of 7% to 20% higher than mean tide range depending on the ratio of maximum velocity to critical velocity and on the choice of sediment transport formula. In simple cases of bed and coast topography, where the tidal condition was approximately uniform over the investigated area, a single representative tide was found to be sufficient. In a more complex case where topography leads to irregular variation of the currents it was necessary to discretize the tidal cycle using several classes of representative tidal conditions.

Wave conditions in coastal areas, unlike tidal conditions, are not deterministic and cannot be accurately predicted in terms of magnitude and time evolution. Recourse therefore has to be made to past records of wave conditions to represent the probability of different wave conditions occurring for input as boundary conditions. Schematisations of wave randomness can take two forms; the multiple representative wave (MRW) approach and the single representative wave (SRW) approach. The MRW-approach is described extensively in Steijn (1989,1992), and reduces measured wave heights and directions to a limited number of combinations of wave heights and direction inputs at the model boundary plus a weighting factor to be applied to results for each set of results in calculation of long term mean transport. The SRW-approach described by Chesher and Miles (1992) combines the computations for a number of sectors to yield a single set of representative of wave parameters to be applied to sediment transport computations.

Devising representative input conditions clearly depends upon a number of assumptions. Applying a representative tidal input for example assumes that tidal range and shape are the most important properties of the tide from a morphological point of view enabling the representative tide to reproduce both intensity and direction of long-term mean transport. Furthermore, it is implicitly assumed that the representative quantity of sediment transport characterises all morphologically important properties of the tide and that tidal currents are the only cause of sediment transport or may be treated separately to wave climate schematisations if these are important. Automatic procedures for tidal input filtering are not yet available and the derivation of a representative tidal condition depends heavily on the specific properties of the tide in the area of interest. Limitations are also apparent in the application of representative wave conditions for long-term sediment transport predictions. The SRW-approach rests exclusively upon the stirring effect of waves so it is not applicable to situations with strong wave driven currents. The MRW-approach has been shown by Steijn (1992) to neglect transport occurring under extreme conditions e.g. in the deeper parts of the model domain. The overall inherent limitation of probabilistic based approaches to process modelling is the issue of validity for representing conditions throughout the model domain. If the schematisation of applying representative conditions is correct for one point or one transport mechanism it is not necessarily so for all others. Omission of small but persistent effects from modelling approaches or the misrepresentation of processes can cause large errors in long-term predictions as a result of extrapolation. To achieve a more general applicability it may be necessary to discretize representative conditions although this generates an additional element of complexity and increases the data requirements for study, thus hindering the initial aim of the exercise.

2.6 Data requirements for studying historic morphological change in estuaries

The overriding limitation on present predictive long-term morphodynamic models is a lack of understanding of the processes driving long-term change in estuaries and the ability of modelling tools to represent these (HR Wallingford, 1997a). There is an identifiable requirement for improved understanding of the behaviour of estuaries as a basis for developing a capacity to predict future changes. A core element of the development of tools and techniques to study and predict long-term morphological change in estuaries is the use of relevant data as the basis of predictions and for validation of predictions. Data often has additional value beyond its original purposes; this value lies in its contribution to enabling decision-makers and managers to reach decisions i.e. the supply to an end user of information extrapolated from raw data. The re-use of existing data requires the re-interpretation of a raw data set in order to extract new information, which meets a different end user demand.

In the context of long-term change in estuaries, data availability is crucial for developing conceptual understanding of estuarine behaviour. Data plays a fundamental role in study of long-term morphological change. Observational data are a prerequisite to enable formulation of the concepts and hypotheses underlying morphological change. In terms of developing modelling tools, data is then required to enable validation of the concepts and hypotheses, which may be achieved through devising model representations. Application of the modelling tool will require additional data for calibration and verification, and ongoing development of the model capabilities will require assimilation of new data. In a broader context the requirement for comprehensive observational data sets to enable development of predictive modelling tools has been universally recognised (Lane *et al.* 2000). Existing data sets covering a sufficiently long period to examine morphological evolution do not have complete data coverage of changes in estuary form and process necessary to examine morphological evolution. Thus of primary importance to studies of long-term morphological change is elucidation of the constituents of an adequate data set for examination of the principal changes in estuary form and associated changes in physical process behaviour driving evolution.

Assigning a minimum requirement for the length and content required of a data set is difficult, and clearly longer and improved quality data sets should lead to more reliable predictions although excessively long data sets can create difficulties of data handling. As a general principle, O'Connor (1987) proposes that the temporal range of data employed to study long-term morphological change should cover all possible time scales of components contributing to changes in estuary geometry. A period of 100 years is suggested as sufficient since it encompasses long-term tidal periodicities of 19 years, and identified long-term variations in weather patterns of 10-85 years. However, perturbations may be induced by factors other than the natural processes as considered by O'Connor (1987) and may thus reside in the system for a longer period.

Historical bathymetric data are of fundamental importance to establish trends in the physical morphology of an estuary and enable analysis of changes in estuary processes. Estuary wide bathymetric coverage is a minimum requirement for studying long-term morphological evolution. It is imperative that the estuary system can be considered holistically as the morphological forms constituting the estuary system i.e. subtidal, intertidal, and tidal foreshore areas have a complex inter-relationship which represent a critical factor for examination. Ideally the data should cover a period of relative stability, followed by a disturbance event in order to assess the magnitude of perturbation in relation to natural fluctuations. In practice, however, the expense of surveying has resulted in few estuaries having been surveyed regularly, limiting available data for analysis. Furthermore, those estuaries which have been surveyed are often monitored due to commercial interests such as shipping and these estuaries often experience greatest anthropogenic activity with complex interaction between a diverse range of impacts, making it difficult to define the precise effect of perturbations which are superimposed upon each other as well as natural fluctuation. Additionally surveys may concentrate on areas of greatest interest, such as navigation routes rather than an estuary wide coverage.

The application of computational models combined with data resources permits simulation of physical process behaviour over wider spatial and temporal scales than permitted by analysis alone (Smallman *et al.*, 1995; Roberts *et al.*, 1998). However, quantitative data input into models to permit manipulation must be reliable and consistent. It may be necessary to calibrate data sets in order to achieve internal consistency as measuring equipment has changed, or units of measurement have altered (i.e. from imperial to metric units), and also to format data sets digitally in order that they may be manipulated as required. The manipulation of data to a stage where it may be applied to predictive models is time consuming and should not be underestimated even where reliable long-term data sets exist.

The stochastic nature of estuarial processes, involving a wide range of space and time scales, creates significant difficulties for studies of long-term morphology. Comprehensive data coverage of all physical processes covering all spatial and temporal scales is never available and even if it were available the data resource would be unmanageable. Instead it is necessary to synthesise the principal trends and features exhibited by data where it is available and employ tools to reproduce features of physical processes where it is not. Estuary morphology may change in response to a large number of forcing factors, such as tides, which vary on a scale ranging from a single flood and ebb cycle, to a spring-neap cycle to a 19-year periodicity. Temporal scale is therefore an important consideration in approaches to studying estuary morphology. In general it may be considered that as scales of spatial or temporal resolution are increased, levels of complexity are also increased as smaller scales of variation are compounded within larger scale variation.

The number of variables influencing long-term morphology is considerable, and a high priority is attached to reducing the data to manageable levels. Parameterisation i.e. the reduction of variables considered, is an effective means by which information may be reduced, most commonly at the input stage. In the case of long-term estuary morphology where process details are not well understood, it is particularly important at a simple level since uncertainty is amplified as the number of variables and dimensions increase, as illustrated in Figure 2.4. This has significant implications for approaches to long-term modelling, and their data requirements for operation.

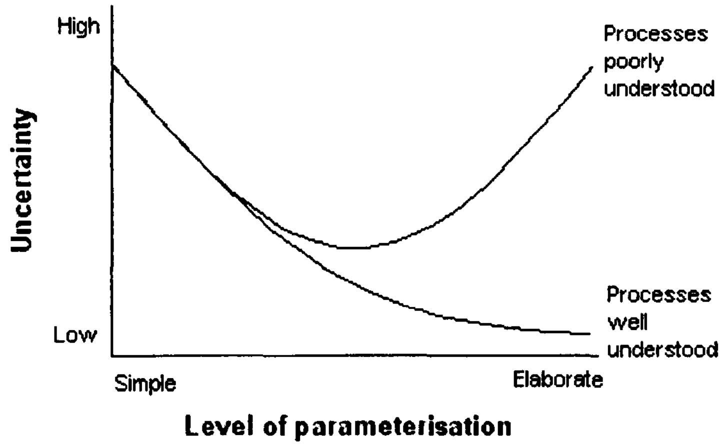


Figure 2.4 Levels of uncertainty in morphological modelling (after Cowell *et al.*, 1995)

2.6.1 Studies of historical morphological change in estuaries and inlets

Several studies have been undertaken of historical morphological change in estuaries, and useful information can be derived from them concerning techniques for analysing morphological evolution. In this study the scope of interest is generally confined to developing conceptual understanding of the nature and causes of morphological change over an historical time period of the order of one hundred years, and previous studies of historical morphological change are discussed reflecting this. One of the most basic approaches to analysing morphological change involves comparing surveyed depths between a series of historical charts. For example, Bryant (1980) examined changes in depths over the period 1868-1974 in 3 estuaries in New South Wales, Australia by constructing grids and comparing values at common intersects to draw depth change contours. More recently the development of computing software has provided new approaches to studying bathymetric change through Digital Elevation Models (DEMs), enabling irregularly spaced data and non-overlaying historical data to be compared by interpolating depths onto a regularly spaced grid system (Schroeder *et al.*, 1995).

A more integrated approach to studying the morphological evolution of estuaries comprises examining detailed bathymetric data combined with physical process data. Mulder and Louters (1994) examined changes in basin geomorphology in the Oosterschelde (Netherlands) following a series of civil engineering projects to protect the Delta area from flooding. Bathymetric changes were examined by calculating geometric properties from bathymetries interpolated from surveyed depths. The resulting calculations of estuary volume were analysed, and found to exhibit a decline in estuary volume of 160Mm^3 (120Mm^3 attributed to dredging and 40Mm^3 attributed to natural processes), reversing a long-term trend of erosion in the estuary. More detailed examination of bathymetric data demonstrated that between 1960-1987 the intertidal area had increased in height, whilst tidal channels had deepened and widened. Analysis of hydrodynamic data observed in the estuary demonstrated that following closure of dams in the estuary, tidal volume and tidal velocities were reduced by 70%, and tidal range was reduced by 87%; these were proposed as the likely cause of geomorphological change within the estuary.

To develop a more detailed analysis of the behaviour of an estuary system, modelling techniques may be combined with bathymetric and physical process data. Physical models of estuary systems were predominantly employed in studies of estuary systems conducted before the 1980's, but computational models are now more frequently used. For example, Sherwood *et al.* (1990) examined bathymetric changes by calculating geometric properties of the Columbia river estuary (USA) from bathymetries interpolated from surveyed depths, and employed numerical modelling techniques to examine changes in estuary processes. Comparison of hydrographic surveys conducted in the periods 1868-75, 1926-37 and 1949-58 demonstrated a coincidence of morphologic change with navigational improvements, with lesser changes attributed to natural shoaling and erosion. The principal changes in geometric properties of the estuary were a decrease of approximately 15% in tidal prism, and ignoring erosion at the entrance, a net accumulation of sediment in the estuary at a rate of 0.5cm y^{-1}. Based on the results from a laterally averaged, multiple-channel, two-dimensional numerical flow model, it was proposed that the changes in morphology and river flow had reduced mixing, increased stratification, and decreased the salinity intrusion length and hence transport of salt into the estuary. The net effect of these changes was a decrease in sediment supply to the estuary, and increased trapping of sediment within the estuary system.

A detailed analysis of historical changes in the Humber estuary between 1851-1998 was undertaken by ABP Research and Consultancy (1999). The analysis combined historic bathymetric data, physical process data and computational modelling. Detailed analysis of volume change based on bathymetric data combined with assessment of water levels along the estuary found changes were small in relation to the scale of the system as a whole. Based upon analysis of a 1D model of estuary hydrodynamics, it was suggested that water levels in the estuary have oscillated around a point of critical damping in response to changes in mean sea level.

More complex analyses of estuarine systems may be undertaken by measuring and modelling sediment behaviour. Although this may provide a clearer representation of sediment behaviour, sediment processes are complex and introduce a considerable element of uncertainty to analysis. Studies for the Stour-Orwell estuaries undertaken by HR Wallingford (1997c), examined both the historical impact of engineering works and the natural variability of the system using numerical hydraulic models to provide information on changes in estuary processes. Morphological change in the estuaries was initially examined by calculating geometric properties from bathymetries interpolated from surveyed depths, and comparing volumetric change occurring on the intertidal areas only as there has been considerable dredging activity, which has concealed any natural morphological response. Volumetric analysis demonstrated that the period 1965-1994 was characterised by overall erosion, although within this period there are distinct differences between sub-periods. 1965-78 for example was characterised by accretion at the edges of the low water channel, with some erosion of intertidal areas. 1978-82 showed relatively little volumetric change. 1982-94 conversely was characterised by substantial erosion of intertidal flats. Computational modelling was employed to examine the causes of morphological change for the purposes of developing an understanding of the behaviour of the system on the basis of available physical process data. Based on this analysis, HR Wallingford (1997c) suggested that bathymetric changes in the Stour/Orwell system could have resulted from past aggregate dredging causing disturbance of (muddy) overburden from the estuary bed, which may have settled on the intertidal areas adjacent to the navigation channel.

Appraisal of previous studies of morphological change indicates that estuaries are complex environments and a structured approach is required to examine a clearly defined set of issues when dealing with morphological change. Significant differences have existed in the availability of data and the application of analysis techniques, which has enabled differing degrees of analysis to be undertaken. It is evident also that the nature and causes of morphological change can differ significantly between and within estuarine areas, and thus different analysis techniques may be appropriate for addressing different issues. The quantity and type of data required for analysis of morphological change varies according to the technique employed. Bathymetric data have been a fundamental requirement for all studies to establish the nature of morphological change. While much is known about the mechanics of sediment movement, sediment transport rates cannot be accurately predicted on a purely theoretical basis, so a significant requirement for field data exists. Physical process data and modelling techniques are therefore required to examine the causes of morphological change by extrapolating from small-scale process behaviour.

2.7 Modelling estuary processes

As a result of improvements in hardware and algorithms, numerical simulation has become an increasingly significant research area in coastal and estuarial studies. Rising environment-related problems in these domains have also raised more complex interdisciplinary questions placing pressure on tool developers to produce means of integrating methods of representing different physical process behaviour. This has led to evolution towards an approach to study that has been termed hydroinformatics (Abbott *et al.*, 1991), representing the development of suites of environmental simulation software based upon a common platform. These systems enable commercial studies and multidisciplinary research in conventional fields and new applications. Hervouet and Bates (2000) suggest that model development and application is being increasingly undertaken in the commercial sector outside traditional academic channels with the net result of a shift from a pure science to an environmental design objective.

The selection and application of estuary models are strongly related to the type and scale of the problem to be studied. Models may reproduce the estuarine environment as a scale physical model or solve numerical computations to resolve hydraulic conditions. This study concentrates upon the role of computational models that have commonly been divided into different classes according to the dimensionality of the phenomena involved. According to van Rijn (1993) some of the selection criteria for a model are:

- Available data input
- Available calibration data
- Degree of physical schematisation
- Scale of the problem
- Required accuracy
- Available budget

Models are fundamentally employed to provide a more complete understanding of the processes occurring in an estuary system, and an initial requirement for most modelling studies is to represent estuary hydrodynamics. The following sections therefore examine means of representing estuary hydrodynamics, before discussing briefly the principal features of sediment transport models.

2.7.1 Hydrodynamic modelling

Both Eulerian and Lagrangian models have been developed to predict estuarine hydrodynamics and dispersion in 1D (Dronkers, 1982; Wallis and Knight, 1984), 2D (Falconer and Owens, 1990), and 3D (Davies, 1991; Noye, 1987). An Eulerian model records speed and direction through time at a point fixed in relation to external co-ordinates whilst a Lagrangian model follows a particle trajectory providing speed and trajectory at a given time, but varying in position over time with respect to external reference. Most of the models developed are based upon solving equations of fluid motion and continuity employing certain assumptions. The nature of the assumptions depends upon the purpose and use of the model. It is therefore of significant importance that the type of model used should reflect the type of observed data to be simulated so that the model can be calibrated and then be successively validated by additional data.

Most estuaries exhibit features of three-dimensional flow and density structure (Leendertse *et al.*, 1973), and ideally should be represented as such. Three-dimensional models have the ability to simulate the most complex aspects of variability encountered in observed situations, although representation of the estuarine environment is heavily dependent upon application of the model particularly with regard to spatial and temporal resolution employed. Selecting temporal and spatial resolution is a balance between the degree of detail required and computational time expended in calculations as time is non-linearly proportional to the number of computational points incorporated in the model (Usseglio-Palatera and Sauvaget, 1987). However, modelling estuaries in three dimensions is not always practical, as considerable computer resources are required for the simulation. Representing estuaries in 1 or 2 dimensions reduces the complexity of simulation, which is traded off against a more extensive process of schematisation and parameterisation.

User input is a substantial element in producing robust tidal hydrodynamic predictions, due to the dependence of results upon parameters used. Different dimensional schematisations of estuaries can also produce different computations; Davies (1985) suggests, for example, that significant differences in surface elevation are apparent at modest wind speeds when the ratio of wind to tide induced currents is low. However, multi-dimensional models are not cost effective in treating simple channel flow and over simplified models should not be employed to simulate fine details in multi-dimensional time dependent processes (Cheng *et al.*, 1991). A fundamental requirement for all modelling approaches is accurate bathymetric representation, which is one of the most important requirements in successful modelling (Cheng *et al.*, 1991), especially with regard to shallow estuaries.

One–dimensional modelling

One-dimensional simulations are of interest in situations where the flow field shows little variation over the cross-section. The models employ an approximation of the two-dimensional equations, using cross-sectionally averaged variables of depth, elevation, velocity and salinity, based upon the assumption that the flow is well mixed vertically and horizontally and is represented adequately as homogenous averaged currents. As a result, one-dimensional models have been applied in conjunction with two-dimensional modelling to provide a continuation of dynamic conditions up river, in situations where two-dimensional modelling is inefficient or inappropriate (Prandle, 1974). Bathymetry employed in one-dimensional models may be simplified to representative boxed or v-shaped cross-sectional forms, but more complex bathymetry can be employed for channels with extensive mudflats (Dronkers, 1982; Wallis and Knight, 1984).

Results from one-dimensional models are cross-sectionally averaged and are therefore sensitive to parameter variations and boundary conditions such as river flow hydrography (West and Lin, 1983). However, when applied to well mixed areas, flow calculations can show reasonable agreement with observed data (e.g. Nassehi and Williams, 1986). Furthermore, utilising system geometry and elevation data, one-dimensional models have been employed to predict velocity trends, providing a link between tidal asymmetry and cross-section channel geometry (Aubrey and Friedrichs, 1988).

Two-dimensional modelling

Two-dimensional models have been termed the workhorses of tidal-flow modelling by Abbott (1997) and may represent flow fields as 2-Dimensional depth averaged or 2-Dimensional laterally averaged simulations. 2-Dimensional depth averaged flow (2DH) simulations are of particular interest in situations where the flow field shows no significant variation in vertical direction and where fluid density is constant. Conversely 2-Dimensional simulations in the vertical plane (2DV) simulations are of interest in situations where flow is uniform in one horizontal (lateral direction), but with significant variations in vertical direction. The models are particularly suited to hydrodynamic and dispersion predictions of salinity and suspended particulate matter in shallow water estuaries where there is no significant stratification.

Abbott (1997) identifies three approaches to the schematisation of the computational domain that are widely used in two-dimensional depth averaged modelling. The first schematisation is a rectangular grid with multi-scale nesting systems, the second is a curvilinear grid, and the third is an "unstructured mesh". In the first two cases the numerical schemes are generated using a finite-difference approach, while the third employs a finite-element methodology (Viera *et al.*, 1994; Hervouet *et al.*, 1994; Rodenhuis, 1994). Abbott (1997) notes that although the unstructured grid appears to offer the best resolution for a given number of computational points, with the second and first approaches following behind, this advantage becomes less significant as further application components are superimposed. For example, considerable difficulties can arise when applying an unstructured grid to both hydrodynamic models and short-period-wave models, as a result of differences in resolution requirements for different areas of the model domain, to enable both processes to be resolved accurately.

Three–dimensional modelling

3-Dimensional models are of particular interest in situations where the flow field shows significant variation in vertical distribution e.g. salt intrusion in estuaries, wind driven circulation and flow around structures. Models employ the same schematisation of the computational domain as two-dimensional depth averaged modelling, but also resolve variations in flow with height, and are therefore able to reproduce much of the variability encountered in observed estuarine situations.

The use of an untransformed vertical co-ordinate system (z-models) has been replaced in recent three-dimensional models by sigma systems (Bode and Hardy, 1997). The z-models (e.g. Leenderste and Liu, 1976; Dietrich and Ko, 1994) represent ocean depth in a "staircase" fashion. Representation of bathymetry as Cartesian co-ordinates is often inappropriate in the vertical axis for estuaries with a large depth variation because in shallow areas where shears become increasingly important only a reduced number of grids are available for calculations. Sigma systems in contrast map the local depth of the water column onto a convenient interval by defining a new co-ordinate system. The number of computational layers is constant over the entire computational domain, providing smooth representation of bathymetry on a sloping bed.

2.7.2 Modelling sediment dynamics

Hydrodynamic models described in Section 2.7.1 may be employed as platforms for a number of applications, so that the specifications of tidal-flow models are to some extent determined by the requirements of these applications (Abbott, 1997). Computational modelling of sediment transport processes is, however, a large and complex research field, which is evolving continuously. In the following section approaches to modelling sediment transport for some of the different types of estuarial problems are briefly outlined. The synopsis is not exhaustive or generic, and its purpose is to identify some of the important issues for consideration, particularly that it is the specific problem to be solved that determines the approach to be adopted. The intricacies of modelling sediment transport dynamics is covered in greater depth elsewhere, and a sound basis for investigating the detail of principles underlying sediment transport modelling is provided by Abbott and Price (1994).

Sediment transport models can be classified like flow models according to dimensionality, for example:

- 3D
- 2DH
- 2DV
- 2D 2 layer
- 1D
- Point models
- Particle (Lagrangian) models

Common to most applications is the need for an accurate modelling of transport processes, which may be divided into advection and diffusion sub-processes. Many investigations have demonstrated the need to combine tidally and short wave induced motion when considering sediment processes. A further division is commonly made in the description of processes reviewed in Sections 2.3-2.3.4 between almost cohesionless materials such as sand, and more cohesive materials such as mud, with different modelling approaches developed accordingly (Fredsøe, 1984; Hamm and Migniot, 1994). The resulting two classes of sediment models also tend to have different areas of application. The non-cohesive sediment models are widely used to study the influence of engineering works on sedimentation and erosion processes in connection with design of coastal structures, dredging operations, beach protection and reclamation schemes. Cohesive sediment models are more commonly used for determining siltation in harbours, and for determining the fate of dredged spoils (Johnson *et al.*, 1994).

Bed load transport in non-uniform and non-steady conditions can be modelled by a formula-type approach because the adjustment of the transport process to the new hydraulic conditions proceeds rapidly (van Rijn, 1993). Based on this a 1-Dimensional or 2-Dimensional approach may be the most efficient, provided that magnitude and direction of bed-shear stress can be predicted with sufficient accuracy. 3-Dimensional models may be required to compute bed-shear stress in complicated situations such as flow in bends and tide, wind and wave induced flows in coastal seas.

Suspended load transport does not adjust as rapidly as bed load transport to new hydraulic conditions due to the time and space necessary to transport particles upward and downward over the depth, thus making it necessary to include convective and diffusive processes (van Rijn, 1993). These types of models are also called continuum models. Modelling the small-scale short-term processes requires a 3-Dimensional or 2-Dimensional approach; although 1-Dimensional and 2-Dimensional horizontal depth integrated models can be used for large-scale and long-term modelling of transport in rivers and shallow tidal waters.

2.8 Chapter summary

This chapter has reviewed many of the primary points of interest in the study of long-term morphological change in estuaries. It is clear that the morphological behaviour of estuaries is a complex issue resulting from the influence of several interrelated physical elements. Each estuary adapts to a unique combination of physical processes by altering its form until it achieves a state of quasi-stability (Carter, 1988). Erosion, transport and deposition of sediment enable morphological change to occur. Despite the devotion of considerable research effort to developing understanding of sediment dynamic processes and to establishing reliable theoretical concepts, full analytical solutions to sediment transport problems are not available due to the non-conservative behaviour of sediment. Considerable uncertainty remains in methods of representing sediment transport rate, which is central to the issue of morphological change.

Attempts have been made to model and predict long-term morphological change using approaches that reduce the need for detailed process information. Previous methods which have been employed include the use of probabilistic methods to examine the principal processes driving morphology, the use of a stability based approach examining energy balance between inputs and outputs or a combination of these two approaches. These methodologies are at relatively early stages of development and have not been demonstrated to be robust tools and no case made has been made for their universal applicability. Furthermore, both methodologies exhibit significant theoretical limitations and there is an identifiable need to develop understanding of the nature of long-term morphological change in estuaries and processes driving it.

Developing an understanding of historical morphological change in estuaries is largely limited by data availability. As a minimum requirement, bathymetric data of sufficient spatial extent covering a historic period of the order of 100 years in adequate detail is needed to assess the nature of morphological change. Historic data coverage of physical process behaviour is unlikely to be sufficient to analyse the key changes driving evolution. Resort can be made to simulation of historic changes in physical processes by applying computational methods in a diagnostic analytical capacity. Several issues arise concerning the application of modelling tools to represent physical processes in an estuary. Simulations are dependent upon the controlling parameters chosen. Model type also influences the accuracy and outcome of simulations and the type of physical processes existing within the estuary must be taken into account when considering the type of model to be used. Model simulations represent a compromise between accuracy of simulation and computational expense. This requires decisions to be made concerning the spatial extent of the model domain, the type of model employed and model discretization of the area examined each of which can affect the outcome.

CHAPTER 3 REVIEW OF PREVIOUS RESEARCH ON MORPHOLOGICAL CHANGE IN THE MERSEY ESTUARY

3.1 Introduction

The Mersey (Figure 3.1) is a strongly tidal estuary located on the Northwest coast of the UK between the estuaries of the Dee and Ribble. The "inner estuary", is defined as the area landward of the estuary mouth at New Brighton, and the area seaward of New Brighton shown in Figure 3.1 is referred to as Liverpool Bay. The inner estuary consists of a wide tidal basin, approximately 42km long with a maximum width of 5.5km, and the Narrows, a 10km long, 1km wide inerodible channel with maximum depths in excess of 20m which connects the inner estuary to Liverpool Bay.

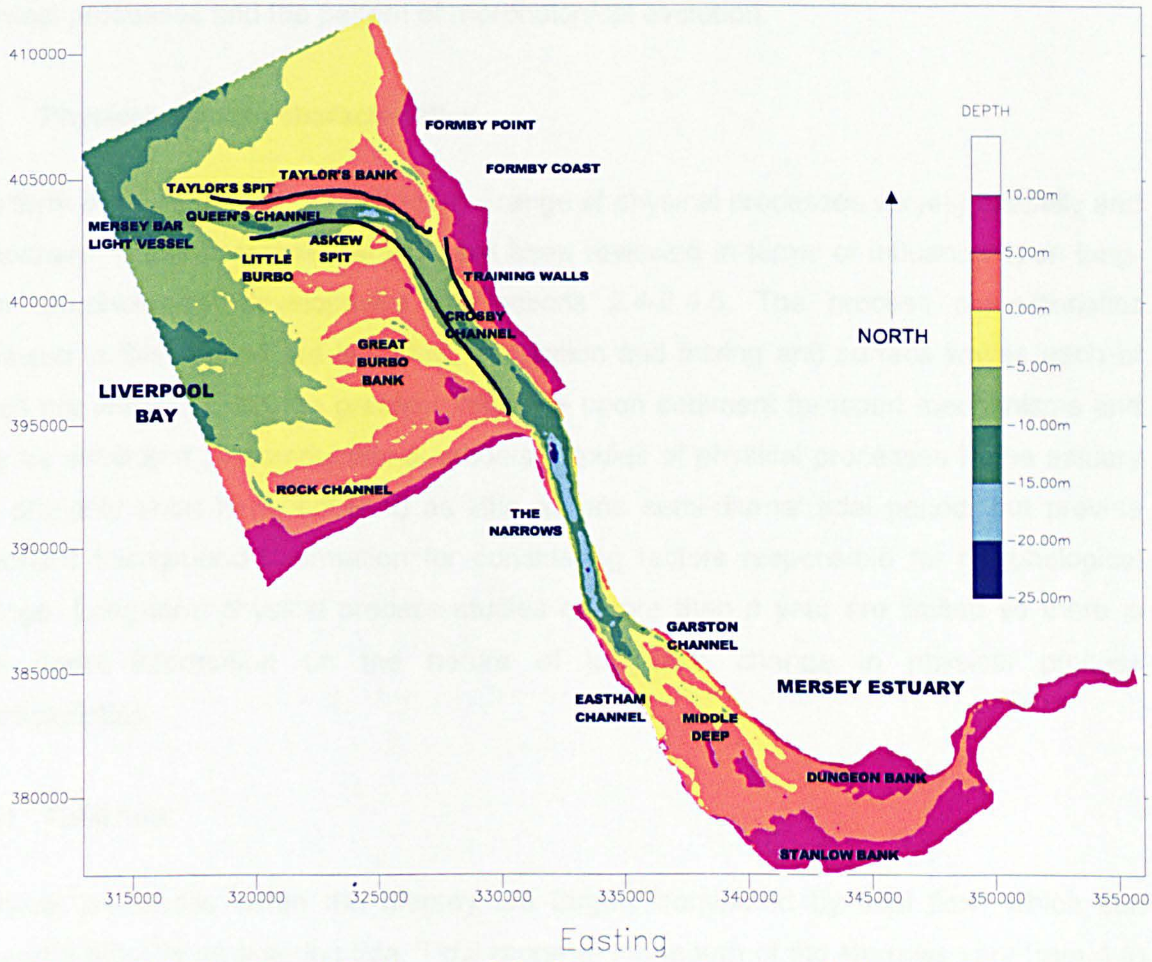


Figure 3.1 Significant features of the Mersey estuary and Liverpool Bay

The estuary has experienced significant morphological change over the course of the last hundred years. Throughout this period there has been extensive anthropogenic activity, most notably navigation improvements, resulting in several impacts with a potentially significant effect upon the morphology of the estuary. Due to the role of the estuary as an important centre for shipping, historical changes in the estuary have been relatively well documented in comparison with most other UK estuaries.

The purpose of this chapter is to review the physical process characteristics of the estuary and identify issues requiring consideration in a study of long-term morphological change. The history of morphological change is appraised, drawing attention to the history of anthropogenic activity coincident with the period of morphological change. Possible causes of morphological change are discussed in the context of existing knowledge of physical processes and the pattern of morphological evolution.

3.2 Physical process characteristics

The form of an estuary is influenced by a range of physical processes varying spatially and temporally. These processes which have been reviewed in terms of influence upon long-term morphological development in Sections 2.4-2.4.5. The process characteristics reviewed in this section are tidal flow, circulation and mixing and surface waves each of which are likely to exert the greatest influence upon sediment transport mechanisms and may be simulated by computational models. Studies of physical processes in the estuary are primarily short term, covering as little as one semi-diurnal tidal period, but provide important background information for considering factors responsible for morphological change. Long-term physical process studies of more than a year are limited so there is little direct information on the nature of long-term change in physical process characteristics.

3.2.1 Tidal flow

Physical processes within the Mersey are largely dominated by tidal flow, which can exceed $3000m^3/s$ on a spring tide. Tidal range at the mouth of the Narrows vary from 4 to 10m over the extremes of the Neap-Spring cycle and tidal currents through the Narrows can exceed 2m/s. Prandle *et al.* (1990) calculated the tidal harmonics within the Mersey Narrows and summarised the four main constituents shown in Table 3.1 for two sets of elevation data at Liverpool of 21 years and 29 days respectively. The M_2 constituent is the principal tidal component, followed by S_2 and N_2, having ratios of 1:0.33:0.2. The M_2 phase difference between current and elevation is 98° indicating a near standing wave progression up the Narrows (Prandle *et al.*, 1990), a standing wave occurs with a phase of approximately 90°. The phase difference between surface and mid-depth currents reflects the variations in current profile; the lower boundary currents lag the surface by up to ten minutes. The slight flood dominance of the tidal curve at the mouth of the estuary was noted as long ago as 1837 by Denham and is due to the frictional effect of the bed on tides entering Liverpool Bay which acts as a shallow water system for tides propagating from the Irish Sea.

Tidal Harmonic	Amplitude (m) 29 days	Amplitude (m) 21 years	Phase (°) 29 days	Phase (°) 21 years
M_2	3.07	3.12	322	324
S_2	1.00	1.01	6	8
M_4	0.21	0.22	322	324
Z_0	5.01	-	-	-

Table 3.1 Principal tidal constituents for the Mersey estuary (after Prandle *et al.*, 1990)

The form of the estuary has a significant influence upon the propagation of the tide, and the sinusoidal tidal curve is rapidly distorted landwards of the Narrows (see Figure 3.2). Tidal propagation landwards becomes increasingly flood dominant, the duration of the flood tide being shorter than the ebb tide, with associated higher velocities, and a greater capacity to transport sediment. This is attributed to the friction effect of the estuary bed as the flood tidal wave enters the shallow water of the estuary. The steep bed slope of the inner estuary enhances the friction effect of the bed resulting in increased tidal asymmetry and the significant distortion of the tidal curve. Beyond 11km landwards, the flow near the low tide level is confined to relatively narrow channels between shoals. This has the effect of increasing the duration of ebb tidal flows, as an initial rapid drainage of water from the narrow channels between alluvial shoals is followed by slow drainage from the shoals themselves (McDowell and O'Connor, 1977).

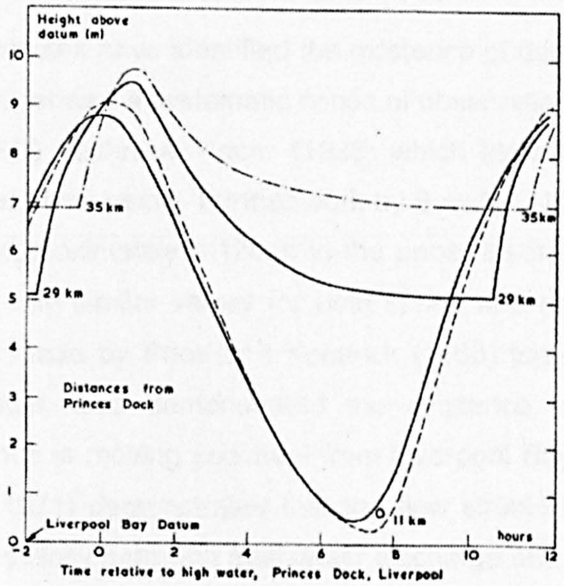


Figure 3.2 Spring tide distortion with progression along the estuary (after West, 1980)

Tidal processes play a significant role in sediment transport. Non-linear tidal effects in particular exert a considerable influence upon bed load transport of non-cohesive sediment. A general trend of flood dominance in tidal propagation through the Narrows and the inner estuary indicates potential for landward transport of sediment. However, flow patterns in the estuary are complex, and both ebb and flood dominated channels have been observed (McDowell and O'Connor, 1977). With regard to sediment transport Norton *et al.* (1984) and Crickmore (1972) conclude that in general, under neap tide conditions alone, net sand movement is approximately zero and undisturbed fine particle accumulation occurs; during spring tides, however, considerable reworking and dispersion of sand and mud deposits may take place.

3.2.2 Circulation and mixing

The term “circulation” is taken to cover the pattern of currents remaining when tidal streams and transient flows associated with storm surges are eliminated, and is caused primarily by residual flow arising from density driven currents. Although fluvial flow in the estuary is in general considerably lower than tidal flow, it is sufficient to induce characteristics of a partially mixed estuary in the Narrows. Differences between extreme longitudinal variations in salinity at high and low water in any position in the Narrows during a tidal cycle are approximately 4g/l for low river discharge, and 11g/l for high river discharge, and even during periods of low river flow, observations have demonstrated that a vertical salinity stratification is created (Dyer, 1997).

Several observational studies have identified the existence of density currents in the inner estuary. One of the earliest was a systematic series of observations by the Water Pollution Research Board (WPRB) Technical Paper (1938) which identified seaward flow in the upper layer and landward flow below. Further work by Bowden (1960) recorded a seaward residual circulation of approximately 0.12m/s in the upper layer and a 0.10m/s landward flow in the lower layer with similar values for both spring and neap tides. The results of current measurements made by Price and Kendrick (1963) together with results from a physical hydraulic model, also demonstrated the existence of density currents and identified their importance in moving sediment from Liverpool Bay into the upper estuary. Bowden and Gilligan (1971) demonstrated that the flow structure was density driven by correlating current and salinity data with freshwater discharge and tidal range. The findings of Bowden and Gilligan (1971) demonstrated that density circulation was most highly developed in the central stretch of the Narrows, where the advective mode accounts for approximately 75% of upstream salt transport. Towards the upstream and downstream ends of the Narrows, the advective transfer becomes less important than the diffusive process.

A survey of the physical oceanography of the Irish Sea by Bowden (1955) found vertical mixing to be fairly complete with only slight differences in temperature and salinity through the vertical profile, attributed to strong tidal currents that also promote horizontal mixing. However, a decrease in salinity towards the coast, caused by the influx of river water, was identified by Bowden and Sharaf El Din (1966), and although mixing by tidal currents in Liverpool Bay is strong, appreciable vertical gradients of salinity and density were evident in data reported by Bowden and Sharaf El Din (1966) and Ramster (1971). The influence of these salinity and density gradients can be observed in current measurements reported by Price and Kendrick (1963) at the entrance to Gresswell in Liverpool Bay where measurements demonstrated a seaward flow near the surface and landward flow near the bed. Current meter measurements at several locations in Liverpool Bay reported by Bowden and Sharaf El Din (1966), also found evidence that residual currents existed, the strongest being near Mersey Bar light vessel where surface flow was to the north-west and flow at the bed was south-east. Bowden and Sharaf El Din (1966) concluded that an estuarine type circulation existed extending into Liverpool Bay at least 12 miles from the Mersey estuary.

Evidence of a density driven residual circulation extending into Liverpool Bay was reinforced by Czitrom (1986) who found that horizontal density gradients drive an estuarine like residual circulation shoreward near the bed, although stratification disappeared during periods of increased wind or tidal stirring. Bowden and Sharaf El Din (1966) and Khan and Williamson (1970) reported a clockwise residual circulation, whilst Ramster and Hill (1969) reported an anti-clockwise circulation. Simpson and Nunes (1981) found that the only significant drift was found to be perpendicular to the coast in an offshore direction, and suggested that previous studies had identified patterns of circulation resulting from tidal effects.

The patterns of circulation identified have a potentially significant effect upon sediment transport and important role in morphological change. Observed patterns of density induced residual circulation result in stronger landward currents at the bed which are of particular importance to bed load transport of sediment. Observations by Sharples and Simpson (1995) identified a marked difference in phase advance of near bottom currents for low water to high water. During the change from flood to ebb, the near bottom density current acts against phase advance, conversely during the change from ebb to flood the density currents act with phase change. This should result in a shorter flood duration at the bed, and hence an increased flood dominance in the lower layers of flow. Several authors have demonstrated that the residual transport of sand on the bed of Liverpool Bay is eastwards (Harvey, 1966; Belderson and Stride, 1969; Williams *et al.*, 1981), compatible with the net effect of observed density driven residual currents extending seaward of the mouth of the estuary.

3.2.3 Surface waves

In the case of the Mersey estuary a relatively clear division can be made between internal and external wave conditions due to the restricted mouth of the estuary, creating two distinct wave environments. Both regimes are fetch limited; external wave conditions are determined by the fetch across the Irish Sea, whilst internal wave conditions are determined by the estuary boundary. Wave conditions can play an important role in sediment transport as described in Section 2.3.5, and Halliwell and O'Connor (1975) note the importance of quantifying the effects of wave action upon sediment transport in the tidal environments of Liverpool Bay and the estuary.

Maximum wave size and degree of impact is dependent upon the wind direction and duration and fetch length. In addition, the effective internal fetch within an estuary is influenced by estuary width (Ippen, 1966). Based upon values calculated by Saville (1954), McArthur (1996) demonstrated that the wind associated with the maximum fetch is of limited effectiveness in the Narrows. Model simulations by McArthur (1996) of the effect of a 20m/s wind which would be experienced in a severe storm, demonstrated that only north/south winds make a substantial difference to net sediment fluxes in the Mersey. East/west winds enhance mixing and dispersion by the creation of seiches and gyres in the main basin, but their overall effects reduce rapidly in sediment fluxes for following tides.

Wave data for Liverpool Bay is available from previous studies (Sly, 1966; Draper and Blakey, 1969; Bell *et al.*, 1975) was analysed by Pye and Neal (1994). Their study indicated that the largest waves in the eastern Irish Sea come from a dominant wave approach angle of approximately 277° corresponding to the direction of the maximum fetch length of over 200km. Frequent south-westerly winds are experienced but are limited by a fetch length of 80km. McArthur (1996) calculated significant wave heights of 2.1m and 2.4m for a wind of 10m/s and 5.2m and 5.5m for a wind of 20m/s according to Ippen (1966) method of calculation for winds from 270° and 300° respectively. Data collected at the Mersey Bar light vessel between September 1965 and September 1966 indicated that a significant wave height of in excess of 2m had an exceedance of approximately 10% in winter and autumn and approximately 2% in spring and summer (Draper and Blakey, 1969).

Norton *et al.* (1984) and Crickmore (1972) suggest that strong wave activity can promote significant reworking and dispersion of sand and mud deposits in Liverpool Bay. Wave activity can have a particularly significant effect under neap tide conditions, where net sand movement under tidal forcing alone is zero and undisturbed fine particle accumulation occurs. Thus the general patterns of sediment transport and accumulation may be significantly altered when neap tidal processes are combined with wave activity causing sediment transport to occur. During spring tidal conditions, tidal forcing is sufficient for sediment transport to occur and wave activity provides a higher concentration of sediment to be transported enhancing the general patterns of sediment movement.

3.3 Sediment distribution

Knowledge of sediment properties is important for understanding morphological change due to the important distinctions between transport processes for different sediment types as described in Sections 2.3-2.3.4 and elsewhere. Sediment properties can be a useful indicator of processes underlying morphological change, indicating possible sources of sediment in cases of accretion. Sediment with a high sand content for example is likely to originate from a marine source. Furthermore, information on sediment properties is important to parameterisation of theoretical sediment transport calculations that can be employed to examine in greater depth the potential causes of morphological change.

Sediment found within an estuary may be derived from fluvial, marine and littoral sources. Peirce *et al.* (1970) studied physical characteristics of deposits from the middle and upper reaches of the Mersey identifying characteristic properties shown in Table 3.2 below.

Physical Characteristic	Value at Bromborough Bar (Mersey estuary)
Specific Gravity	2.39±0.02
Organic Content (%)	2.08
% Clay	10
% Silt	40
% Sand	50
Critical erosion stress, τ_{cr} (N/m^2)	1.6

Table 3.2 Physical characteristics of Mersey estuary sediment (from Peirce *et al.*, 1970)

The values produced by Peirce at al (1970) are from a single point in the estuary, and sediment properties from another study (HR Wallingford, 1989) have shown significantly lower critical shear stress values for cohesive sediment of $0.2N/m^2$. Theoretical calculations for non-cohesive sediment with a median grain size diameter of 0.18mm (Price and Kendrick, 1964) produce a critical shear stress of 0.35 N/m^2 according to equation 2.6, supporting a lower critical shear stress value in the estuary. The critical shear stress value attained by Peirce *et al.* (1970) may have been taken on consolidated mud or be subject to measurement errors, but critical shear stress does not appear to be representative of the entire estuary. Nevertheless it clearly demonstrates that a substantial range of variation can exist in measurement of sediment parameters in the estuary, and that a degree of caution must be attached to employing observed values as definitive measurements.

Sediment properties in the estuary differ widely from the Narrows to the inner estuary. High flow speeds (which can exceed 3m/s) occur through the Narrows so the bed is scoured down to rock and gravel. In contrast the inner estuary comprises extensive intertidal banks of mud and sand, and dries out almost entirely at low water due to the high tidal range and a steep bedslope upstream of Eastham. It was observed by the WPRB (1938) that mudbanks are generally located adjacent to the shoreline, whilst sandbanks line the low water channel. Furthermore, in the inner estuary very little mud was found at the bottom of the low water channels. This led to the suggestion by the WPRB (1938), that the distribution of mud and sand in the inner estuary is correlated with the strength of tidal streams; the velocity over the surface of mud banks being lower than over sand banks, as mud banks are covered only near the time of high water.

The nature of the bed of Liverpool Bay has been studied by the WPRB (1938), which found that the bed was predominantly sandy with outcrops of mud, although no definitions were given for the criteria applied to identify mud or sand. Wright *et al.* (1971) found that within Liverpool Bay the seabed surface consists of fine to medium sized sand, formed by tidal current reworking of Pleistocene glacial and fluvioglacial deposits, overlying a partly eroded surface of boulder clay. In addition local outcrops of gravel filling depressions have been found in the boulder clay surface (Sly, 1966). Sands in water depths greater than 10 m occur as intersitial material or thin surface veneers on gravel substrates, or as thicker deposits with bedforms in restricted zones of greater sand supply. Detailed mapping of sand size distribution by Sly (1966) gives mean sand size diameter as high as 0.42mm in the outer areas of Liverpool Bay. A number of samples taken during a survey of dredged pits in Liverpool Bay indicated a median sand size of 0.29mm, although in places this was mixed with gravel of up to 15mm diameter (HR Wallingford, 1990a). Particle size reduces inshore, with material on inshore banks of 0.10-0.20mm, although median grain size diameter in the intertidal zone is slightly larger at 0.25mm (HR Wallingford, 1970).

The seabed of Liverpool Bay exhibits relatively little deposits of fine sediment due to exposure to tidal currents and wave action, although some mud deposits occur in deep holes. The distribution of fines smaller than 90μm in the sediments in surveys undertaken between 1975-1980 reported by Norton *et al.* (1984) showed consistency, with muddy sediments persisting in an east-west elongated zone off the entrance to the Mersey where fine concentrations up to 80% were found. Cores from the central region of the Mersey Bar show the mud and sand in the sediments to be thoroughly intermixed, but layering of sand and dark cohesive mud was common in the peripheral areas containing 5-10% of fines. In the vicinity of the sewage sludge dumping ground (see Figure 3.3) and offshore, the underlying gravel basement was reported to be frequently exposed by Norton *et al.* (1984). Elsewhere coverage by sand and/or mud is extensive to a thickness of 10-20cm in the buried channels of the bar area (Rees, 1984).

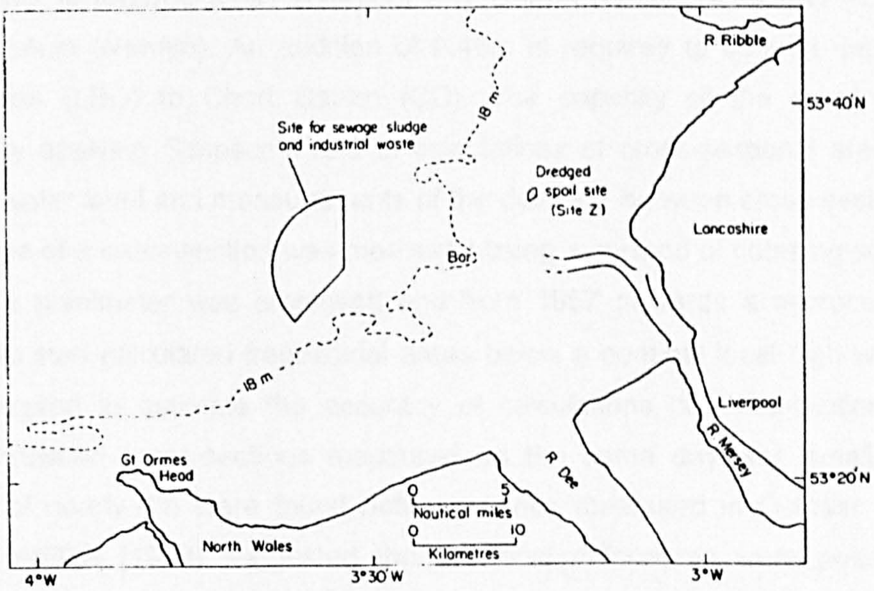


Figure 3.3 Liverpool Bay and the areas used for depositing sewage sludge/industrial waste and dredged spoils pre 1998, after Norton *et al.*, (1984)

3.4 Historical morphological change in the Mersey estuary

Morphological change in an estuary may consist of changes to a number of characteristic features. One of the most useful parameters to analyse regarding long-term trends is estuary capacity, indicating whether the estuary is acting as a sediment source or sink with net erosion or accretion respectively. In the case of the Mersey, various studies have analysed trends in estuary capacity and concluded a general trend of accretion in the estuary over the last 100 years. However, morphological change in the estuary is complex, and there have been important changes in the behaviour of the estuary through the period studied. Furthermore, there has been significant anthropogenic intervention in the Mersey, and it is important to assess capacity changes with consideration of issues, such as dredging activity, that can affect capacity computations.

3.4.1 The nature of morphological change

Previous studies of morphological change have focused upon volume change in the estuary, and have been undertaken employing an approach outlined in WPRB (1938). The capacity was defined as the volume of water between the bed of the estuary and the highest level reached locally of a spring tide rising to 9.95m above Chart Datum (CD) at Liverpool. Chart Datum is taken as Chart Datum (1975), which is 4.93m below Ordnance Datum (Newlyn), except where specified. Prior to 1974, the reference level for measurements is referred to as Liverpool Bay Datum (LBD), 14.54 feet (4.47m) below Ordnance Datum (Newlyn). An addition of 0.46m is required to convert depths for pre-1974 datasets (LBD) to Chart Datum (CD). The capacity of the estuary was then calculated by applying Simpson's rule to calculations of cross-sectional area below the designated water level and measurements of the distance between cross-sections. Before 1896 the area of a cross-section was measured using a method of counting squares, from 1896-1967 a planimeter was employed and from 1967 onwards a microcomputer was introduced to sum calculated trapezoidal areas below a nominal local high water. WPRB (1938) attempted to estimate the accuracy of calculations of cross-section area. The difference between cross-sections measured on the same day was small (0.6%) but differences of nearly 4% were found between areas measured in October and then in November, WPRB (1938) suggested the seasonal differences were possibly due to dredging or the occurrence of a strong gale in a period of spring tides. A small difference of 0.2% in area calculations was also found to result from three different researchers using the planimeter. During later analysis (HR Wallingford, 1997d) anomalies were found in the application of Simpson's rule to calculate estuary capacity by MDHC. Recalculated values for the capacity of the estuary resulted in small changes to the values of the tidal capacity of the estuary, with tidal capacity on average being 0.5% higher than those calculated by MDHC.

The WPRB (1938) analysed trends in MDHC estuary capacity calculations, identifying a reduction in capacity between Rock Lighthouse and Runcorn of 42.8Mm^3 between 1906-1936. Cashin (1949) attributed most of this change to the import of sediment to the estuary, as between 1861 and 1949 constructional works accounted for an abstraction of only 11.5Mm^3 of estuary capacity. However, the quantity of sediment that entered the estuary system through the period was significantly greater as dredging, which commenced in 1895, had removed an estimated 176Mm^3 of sediment by 1949. Analysis of hydrographic charts by Cashin (1949) demonstrated that just over 30% of capacity changes in the estuary occurred below low water level on mean spring tides, while 70% occurred inter-tidally. Approximately 16% of capacity change was associated with mud banks at levels above 1.2m CD. The WPRB (1938) concluded that the reduction in estuary capacity between 1906 and 1931 was mainly due to the deposition of sand in the inner estuary.

Price and Kendrick (1963) noted that the trend of accretion in the estuary continued beyond 1936, with a reduction in estuary capacity between 1861 and 1960 of approximately 76.5Mm^3. Price and Kendrick (1963) estimated that between 1897 and 1955 over 305Mm^3 of material was estimated to have been removed by dredging. The estimated quantity of dredged material removed was significantly larger than the 176Mm^3 of sediment removed between 1895-1949 estimated by Cashin (1949). This could result from the inclusion of additional material removed from areas such as the Manchester Ship Canal in the values presented by Price and Kendrick (1963), and indicates the uncertainty that is attached to analysis of dredging records. Nevertheless the overall point that estuary volume decreased despite the removal of substantial quantities of sediment from the system via dredging is clear.

Analysis of changes in estuary water volume up to 1977 by Kendrick and Stevenson (1985) identified three distinct periods of change in estuary capacity. The first period lasted between 1861-1911 when the estuary exhibited wide fluctuations in volume with a possible trend of gradual decrease, although volume generally remained relatively high. Between 1911-1961 there was a consistent and fairly rapid reduction in volume. From 1961 to 1977 there was an apparent levelling and volumes remained relatively constant. Overall the calculations by Kendrick and Stevenson (1985) showed the volume of the estuary fell from 745Mm^3 in 1911 to 680Mm^3 in 1961, representing a decrease of 65Mm^3, a reduction in estuary capacity of approximately 9%. The highest rate of accretion occurred through the period 1936-1956 with an average decline of 2Mm^3 per year.

Superimposed upon the trend of accretion within the estuary, however, there were significant fluctuations, such as an increase in estuary volume between 1953-4, which Price and Kendrick (1963) attributed to a period of intensive dredging activity within the estuary. Although analysis of estuary volume calculations demonstrate an apparent levelling of estuary capacity between 1960-1977, indicating the estuary experiences neither net accretion nor erosion, the overall behaviour of the estuary is obscured by dredging activity. A basic analysis of charts of Liverpool Bay from 1833, 1912, 1936 and

1955 undertaken by Price and Kendrick (1963) comparing average soundings for a grid covering Liverpool Bay, identified a trend of accretion in Liverpool Bay coincident with accretion in the estuary. The most rapid rates of accretion in Liverpool Bay were calculated for the period 1912-1936, indicating a probable movement from offshore into the Liverpool Bay and Mersey estuary system as the estuary also demonstrated a trend of accretion through this period. Pye and Neal (1994) suggest that material transferred from offshore was partly responsible for accretion in Liverpool Bay, along with material dredged from the Mersey approaches and material derived from the erosion of Formby Point.

O'Connor (1987) estimated the relative contributions of sand and mud fractions respectively to capacity loss by extrapolating from residual tidal sediment flux observations. The analysis suggested that the sand fraction accounted for approximately 90% of estuary capacity loss. A trend of increase in sand content defined as the fraction greater than 63μm diameter has also been observed in analysis of the upper 25Mm of sediment cores in Liverpool Bay taken annually between 1973-1989 by HR Wallingford (1989). Although the mud content found in the Bay was similar in distribution each year, absolute values were found to decrease to a minimum mean of 6.4% in 1989, largely due to a reduction in mud at mud-rich sites. A decrease in mud content in Liverpool Bay is also supported by Norton *et al.* (1984) who noted a decrease in the amount of fines between 1978 and 1980, although variations were observed with the amount of fines increasing from 1975-1978.

3.4.2 Causes of morphological change

Identifying the causes of morphological change in the Mersey is a complex task. The estuary may have experienced natural fluctuations in physical processes but limited information exists from which to examine the timescale or extent of such changes as little reliable monitoring of the estuary was undertaken in the pre-industrial era prior to 1850. Superimposed upon natural underlying changes to estuary processes and sediment regime there have been a number of anthropogenic impacts through the last one hundred years. Although monitoring has improved with increased use of the estuary for commercial purposes, determining the effects of different activities is a complex task due to the impact of dynamic feedback effects upon estuary functioning, and the considerable uncertainty that exists over the timescale of impacts residing in the estuary system.

The most likely source of sediment causing a reduction in capacity in the Mersey is Liverpool Bay, and several studies have identified Liverpool Bay and the Irish Sea as the most probable source of material (Price and Kendrick, 1963; O'Connor, 1987). Littoral and fluvial sources in the Mersey are unlikely to have provided sufficient sediment for the scale of accretion observed. In order for the pattern of capacity changes identified to occur, a mechanism must have enabled increased transportation of sediment into the estuary or increased retention of sediment transported into the estuary during the period of accretion between approximately 1911-1960. For significant transportation of sediment from Liverpool Bay into the estuary there must have been either a change in supply of sediment to the estuary or a change in the pattern of sediment transport patterns.

Dredging

Dredging may contribute to changes in estuary morphology both directly by removing sediment from the system, and indirectly by altering patterns of hydrodynamic flow and sediment transport in response to geometrical changes. Dredging and deposition of sediment can have a significant influence upon the nature of sediment in both the estuary and Liverpool Bay and has been undertaken in the approach channels in Liverpool Bay and within the estuary since 1890. The quantities of material dredged from the estuary and Liverpool Bay derived from reports on the Navigation of the River Mersey (HMSO) are illustrated in Figure 3.4. Dredging records are unreliable and may be inaccurate as they were recorded in hopper tons, an estimation of dredged quantities based upon changes in displacement of a vessel, and may not accurately represent the quantity of material removed. Furthermore, the water content varies considerably between different dredged materials; water content may be as high as 75% in sediment from silty areas but is less than this from sandy areas, and varies considerable according to the dredging technique used. However, the records are useful as a general guide to dredging activity in the estuary.

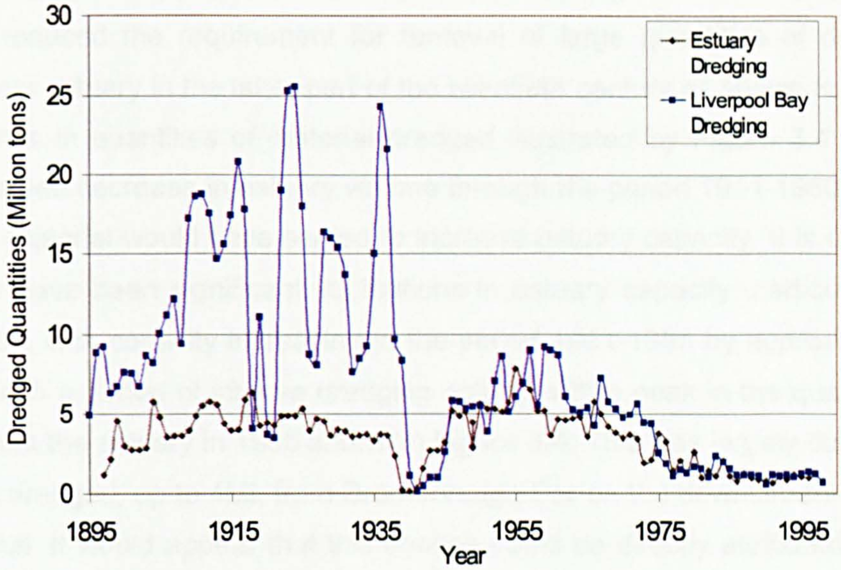


Figure 3.4 Quantities of material dredged from the Mersey estuary and Liverpool Bay (data source: reports on the Navigation of the River Mersey, HMSO)

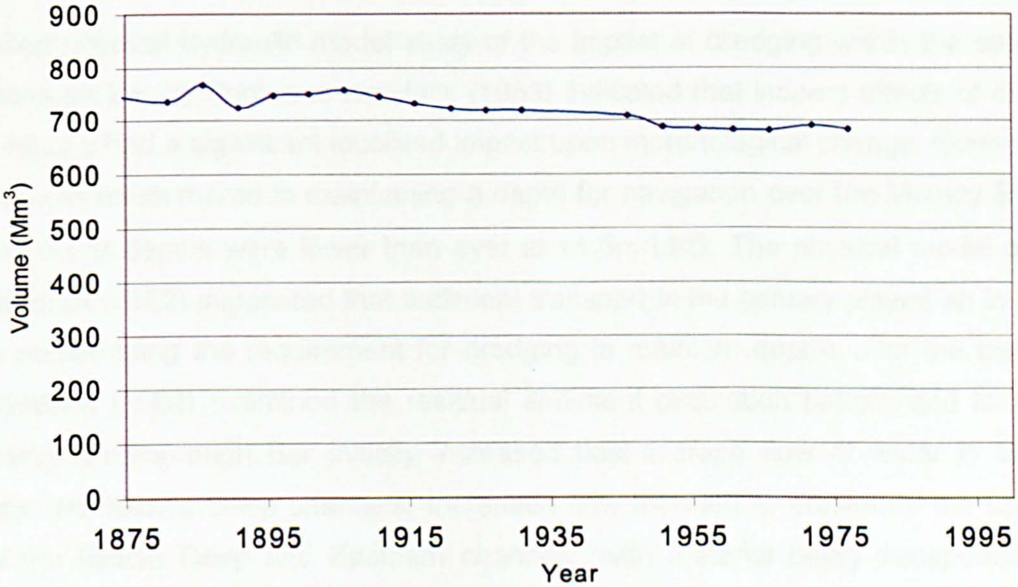


Figure 3.5 Change in total estuary volume from the Narrows landwards (data source: MDHC calculations based on Mersey surveys 1871-1977)

<u>Dredging activity within the estuary</u>

Dredging within the estuary began in 1890. In 1893 only 48,400 tons of material were removed by dredging, but by 1955 it is evident from Figure 3.4 that significant quantities of material were dredged. The closure of many of the older docks and seaward migration of newer docks, combined with the reductions in vessel traffic through the Manchester Ship Canal significantly reduced the requirement for removal of large quantities of dredged material from the inner estuary in the latter part of the twentieth century as shown in Figure 3.4. In general, trends in quantities of material dredged illustrated by Figure 3.4 do not directly explain observed decrease in estuary volume through the period 1911-1960 as the removal of dredged material would have served to increase estuary capacity. It is evident, however, that there have been significant fluctuations in estuary capacity, particularly in the period 1950-1960, with capacity increasing in the period 1951-1953 by approximately $10Mm^3$, coinciding with a period of intense dredging activity with a peak in the quantity of material removed from the estuary in 1955 shown in Figure 3.4. This was largely due to an increase in material dredged, up to 4Mt, from Bromborough Bar on the downstream end of the Eastham Channel. It would appear that this change could be directly attributed to the effects of dredging as a rough approximation of 2.7 hopper tons equalling $0.79m^3$ (WPRB, 1938) indicates that removal of 4Mt of dredged material could account for a volume decline of up to $1.2Mm^3$ per annum at the increased rate of dredging.

A detailed physical hydraulic model study of the impact of dredging within the estuary at Bromborough Bar by Price and Kendrick (1963) indicated that indirect effects of dredging in the estuary had a significant localised impact upon morphological change. Considerable difficulty was encountered in maintaining a depth for navigation over the Mersey Bar, and by 1962 water depths were lower than ever at −1.5m LBD. The physical model of Price and Kendrick (1963) suggested that sediment transport in the estuary played an important role in perpetuating the requirement for dredging to maintain depths over the bar. Price and Kendrick (1963) examined the residual sediment circulation pattern and found that deepening Bromborough Bar initially increased tidal-average flow of water in both the Eastham and Middle Deep channels. Increased flow then led to erosion of the upstream end of the Middle Deep and Eastham channels, with material being transported down Eastham channel to the bar area where sediment was deposited in large quantities as ebb flow decelerated into deep water downstream of the Mersey Bar. From 1953 onwards field surveys showed a widening and deepening of the head of the Middle Deep and erosion of large amounts of sediment from sands at its head. The increase in estuary capacity was caused not by an increase in capacity at the dredged site, but by an increase in capacity elsewhere in the estuary following the movement of sediment to replenish material removed from Bromborough Bar.

Dredging activity in the sea channels

Dredging of the sand bar at the seaward end of Gresswell in Liverpool Bay was first undertaken in the nineteenth century using a harrowing technique, a crude form of dispersal dredging (Mountfield, 1965). Towards the end of the nineteenth century, however, the development of Liverpool as an international port led to substantial changes in dredging practice. A major obstacle to navigation preventing use of the port at all stages of the tide was the outer bar depth of the Gresswell of approximately 4m below LBD. Thus in 1890 two 500ton self-propelled hopper barges were fitted with centrifugal suction pumps and employed to dredge the bar. Following the satisfactory removal of sand forming the bar, three vessels of 3000ton capacity equipped as sand pump dredgers were introduced between 1893 and 1903 to increase depth over the bar to 6.4m below LBD (Cashin, 1949).

Following dredging at the bar, currents in the channel increased, changing the channel from being straight to tortuous, and altering its position. The Queens and Crosby Channels became distorted by the eastward development of Askew Spit and the simultaneous encroachment upon Gresswell of Taylor's Spit. In addition to dredging at the bar, the changing pattern of siltation had by 1896, made it necessary to start dredging in the channels. Considerable tonnage had been dredged in the sea channels between 1890 and 1926, the proportions from the various sites according to Leighton (1950), being:

- From the Queen's Channel 40%
- From the Mersey Bar 23%
- From the Crosby Channel 37%

The successive surveys of the bar and sea channels from 1912 demonstrated that the extent of improvement in channel depth did not correspond with increased dredging activity. Extensive dredging operations were implemented and completed in 1937, but subsequent dredging activity was reduced and between 1946-56 the amount of dredging was about 6 million tons/year compared with an average of 14.5 million tons/year between 1905-15. Since 1967 a depth of greater than 8m has been maintained over the bar and in the channels relative to LBD.

The approximate composition of dredged material according to location for three sites is given by Shaw (1975):

- Gresswell West 90% Sand 10% Silt
- Gresswell East 60% Sand 40% Silt

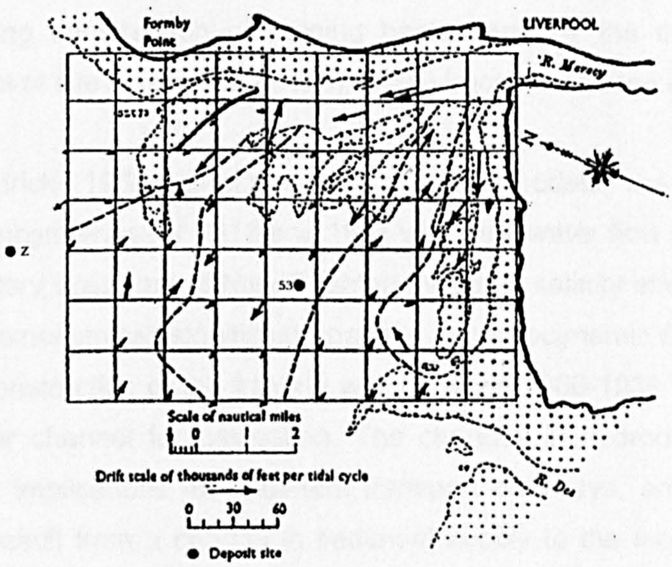
- Crosby Channel 20% Sand 80% Silt

However, it is not recorded how these quantities are derived. Shaw (1975) notes that in general dredged material from near the dock entrances in the river have a high silt concentration, and may be deposited in Liverpool Bay.

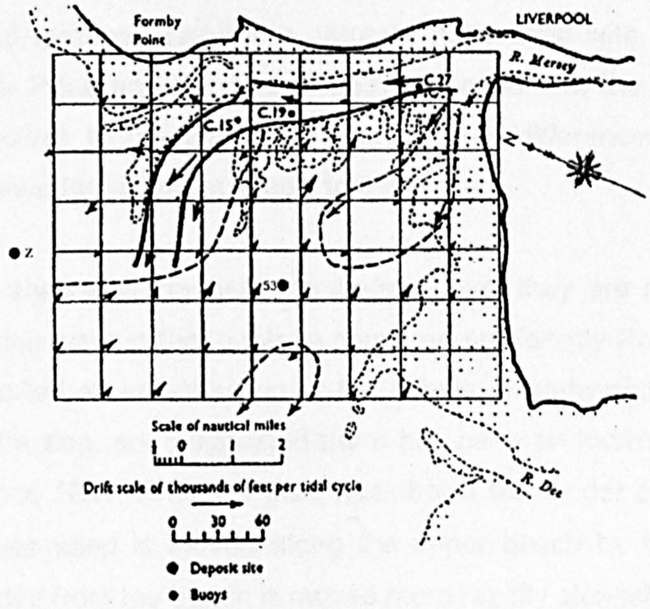
Construction of training walls

Following dredging, the main shipping channel in Liverpool Bay experienced an increased rate of flow. As the ebb channel from Crosby Channel swung seawards around the Askew's Spit into Queen's Channel it impinged with increased force upon Taylor's Bank (Allison, 1949). It thus quickened the rate of erosion at this point, while Askew Spit advanced into the channel. To stabilise the position of Queen's Channel and Crosby Channel, dredging alone was not sufficient. Between 1909-1910 a 3.6km length of training wall was constructed along Taylor's bank. However, the channel on the concave side although constrained by the revetment deepened, and eroded material was deposited on Askew Spit causing further narrowing. In 1912 plans were made for further revetments, and work on the West Crosby Training Bank was begun in 1923. Further extensions and modifications to the banks were begun in 1929, and by 1933 the new training banks had been completed. Commencing in 1945 the training walls were extended in a seawards direction. Seaward extensions of the training banks were completed by 1960, and topping up operations on the banks completed in 1962.

Price and Kendrick (1963) suggested that a major cause of increased accretion in the Mersey estuary had been the training of the sea approach channels. A physical model demonstrated changes in the complex long-term circulation patterns in Liverpool Bay (see Figure 3.6).



NET MOVEMENT PER TIDE OF WATER NEAR THE BED IN 1911, LIVERPOOL BAY MODEL



NET MOVEMENT PER TIDE OF WATER NEAR THE BED IN 1957, LIVERPOOL BAY MODEL

Figure 3.6 Flow patterns changes in Liverpool Bay simulated by Price and Kendrick (1963) in a physical model study

Following training wall construction ebb flow was increased in the navigation channel (maximum ebb velocities were increased on average by 18% over flood velocities (McDowell and O'Connor, 1977). Consequently ebb flow reduced in the channels outside the trained channels allowing strengthened flood tides a longer time to move sediment inshore. The supply of sediment was also increased, due to scour in the navigation channel, following construction of training banks, and by the continued placement of dredged material at site A (see Figure 3.6), which became an area of flood dominance.

Price and Kendrick (1963) employed two physical models, the first of Liverpool Bay configured to bathymetries for 1911 and 1957 with freshwater flow only, and the second of the Mersey estuary upstream of New Brighton including salinity effects. The Liverpool Bay model results demonstrated significant changes in hydrodynamic flow regime in Liverpool Bay following construction of the training wall between 1906-1936 to stabilise the position of the low water channel for navigation. The changes in hydrodynamic flow conditions have significant implications for sediment transport pathways, and suggest that estuary accretion may result from a change in sediment supply to the mouth. Field observations and a physical modelling study reported in Price and Kendrick (1963) demonstrated a residual current created by a small vertical salinity difference of between 1 to 2 parts per thousand in the Narrows causes a net landward drift of bed water. This is particularly important to sand transport since it is naturally associated with the movement of water close to the bed. Price and Kendrick (1963) proposed that the landward drift of saline water in layers close to the bed due to longitudinal differences in salinity formed the principal mechanism for sediment supply to the estuary.

As waves enter shallow water near the Sefton coast they are refracted by the seabed topography causing wave orthogonals to converge on Formby Point (Sly, 1966). Pye and Neal (1994) reported an investigation of the effects of bathymetric changes in Liverpool Bay on wave refraction, and suggested there has been an increase in wave focusing on Formby Point since 1847. Previous work has shown that under conditions of fair weather and oblique waves sand is moved along the upper beach by littoral drift, while during storms sand eroded from the beach is moved more rapidly alongshore by strong longshore currents (Gresswell, 1953; Parker, 1975). As a result it is possible that a subsidiary effect of changing the bathymetry of Liverpool Bay was the increased supply of sediment along the Formby coast to the mouth of the estuary for transportation into the estuary, enhancing accretion within the estuary.

Other engineering activity

Several major civil engineering works have been undertaken in the estuary and Liverpool Bay area that may have contributed to changes in estuary morphology. Within the estuary anthropogenic activity included:

- Construction of piers for the Runcorn Railway Bridge, completed in 1865;
- Construction of the Manchester Ship Canal with its associated reclamation of river and tidal water, completed in 1894;
- Diversion of the River Weaver, completed in 1896;
- Tipping of slag to form an embankment on the north-east side of the estuary between Runcorn and Hale Head, completed in 1896;
- Construction of piers for the Runcorn transporter bridge, completed in 1902.

The loss in capacity directly due to the construction of shore works between 1871 and 1906 was approximately 1.5% of the estuary capacity in 1871. Between 1906 and 1936 the reclamation and works in the estuary accounted for approximately 18.7% of the total loss observed reduction in the capacity of the estuary. The largest change in volume due to artificial works was caused by the construction of the Manchester Ship Canal commencing in 1887 and opened in 1894. For part of its length between Eastham and Runcorn the seaward bank of the canal was built on the foreshore of the estuary. The effect of the building of the canal was complex. Part of the estuary which was previously sounded, and the volume included in computations from surveys was enclosed, reducing the observed value of the capacity of the estuary in subsequent surveys. The Manchester Ship Canal between Eastham and Latchford is, however, tidal; water flows into the canal at Eastham on any tide rising to a height greater than 8m above LBD. The loss of tidal water on the larger tides was therefore smaller than indicated by changes in the computed capacity of the estuary. In addition the building of the canal caused other alterations in the estuary, principally the prevention of direct access of estuary water to the River Weaver. The freshwater discharged by the River Weaver was diverted to be admitted to the estuary through sluices reducing the scour caused by tidal water entering the River.

Kendrick and Stevenson (1985) suggested that these works, and particularly the tipping of inerodible slag to form an embankment on the northern side of the estuary, could have affected the estuary by influencing the behaviour of the low water channel. The channel was found to occupy a relatively stable position between 1916-1961, but exhibited greater variation in position in the periods 1867-1916 (for the whole estuary) and 1961-1977 (seawards of Hale Head). These periods broadly coincide with pattern of volume changes in the estuary. On the basis of this evidence it was suggested that the suppression of meandering, as a result of engineering works during the period 1916-1961, led to a reduction of the erosional capabilities of the low water channel, allowing greater intertidal deposition to occur. In contrast during the periods when the channel exhibited migratory behaviour progressive accumulation was prevented by the erosional capability of the low water channel to remove sediment.

Sewage disposal

Large quantities of crude sewage were discharged directly into the estuary through the course of the twentieth century, and the MDHC were interested in the effects of sewage upon the estuary. The quantities of sewage discharged into the estuary were insufficient to account directly for the scale of accretion experienced in the estuary. According to Cashin (1949) the average annual reduction of measured capacity over the ten years 1936-1946 was 1.9Mm^3 (0.19 Mm^3 annually) and the total quantity of inorganic suspended matter including road washings discharged into the estuary annually was 0.02Mm^3. However, it was hypothesised that the discharge of effluent and sewage caused a deposition of mud and a hardening of the banks in the upper estuary which were less easily eroded. An enquiry into the effect of discharging crude sewage into the estuary conducted by the WPRB (1938) concluded that there was no appreciable effect upon deposits in the estuary. Thus the decrease in capacity of the estuary was assumed not to have been affected to any considerable extent by the disposal of sewage within the estuary.

In addition to sewage disposal within the estuary, sewage material was also increasingly deposited in Liverpool Bay. In 1971 just over half a million tons of wet sewage sludge (equivalent to about 40000 tonnes of dry solids) were tipped annually by Manchester and Salford Corporations into Liverpool Bay in the vicinity of the North West Light Float (O'Sullivan, 1975). Dumping of sewage sludge stopped on 31 December 1998 under European agreement (Clift, 1998).

Natural changes in physical processes

In addition to anthropogenic activity, the long-term regime of the Mersey may have been influenced by natural change in physical processes. The principal processes affecting the estuary comprise tidal currents and wave activity. Both of these may have altered over the duration of the last century as a result of changes in natural forcing. However, assessing the nature of changes in these processes and their probable impacts is a complex task. The processes have not been accurately measured over a long timescale and the effects of natural changes in boundary forcing cannot be readily distinguished from the resultant effects of anthropogenic activity. Nevertheless, some points may be made concerning the nature of naturally induced changes in physical processes and its relation with morphological change in the estuary.

Regarding changes in tidal forcing through the last century, the only long-term record that exists of tidal conditions in the estuary is a tidal gauge record from within the estuary. Analysis of tidal records is complex due to the significant variation that occurs in tidal forcing on a range of scales up to an 18.9 year periodicity. Price and Kendrick (1964) refer to a study of tidal propagation by the Liverpool and Tidal Institute where no significant change to tidal propagation was detected between 1906-1956. The details and reliability of this study were, however, not available for scrutiny. More detailed analysis of changes in tidal characteristics was not available and it is possible that even without significant changes in tidal propagation, important changes in tidal currents may have occurred as a result of changes in density currents induced by changes in freshwater flow. Overall, however, there is no comprehensive evidence that natural changes in tidal forcing have exerted an influence sufficient to cause the scale of morphological change experienced in the estuary.

No long-term wave data exists for the Mersey estuary, instead recourse has to be made to long-term wind records as a proxy source of information on changes in wave climate. Analysis of wind records from Bidston reported by Pye and Neal (1994) indicated higher frequencies of winter gales in the late nineteenth century, between 1920 and 1940, during the 1950's and 1980's, with the periods 1905-1920 and 1940-1950 representing periods of low gale frequency. Pye and Neal (1994) suggested that strong winds were more frequent in the period 1914-1930 based on analysis of records from Southport. Davies *et al.* (1988) found evidence of a clear peak in windspeeds at Southport between 1900 and 1930. Although not conclusive, Pye and Neal (1994) suggest that the period immediately after the turn of the century appeared to be windier than the long-term average, and could have contributed to the coincidental onset of erosion at Formby Point around 1906. Hedges *et al.* (1991) analysed data for the period 1964-1970, and identified 1967 and 1970 as years with a greater incidence of storms than average, with a high number of severe storms in 1965.

3.5 Chapter summary

It is evident that the Mersey estuary is a complex system, which is influenced by a number of physical process variables interacting over a range of spatial and temporal scales. Understanding of the interaction of these processes over a timescale of the order of one hundred years is not well developed. Researching morphological behaviour over historic timescales is exacerbated by difficulties in measuring and analysing physical process data for long timescales, which has not been widely undertaken for the Mersey estuary. A particular shortcoming for analysis of the nature and causes of long-term morphological change is the shortage of data on the detailed distribution of sediment and its variation over time. However, the Mersey estuary is one of the best documented estuaries in the UK; the data resource is representative of data which is available for studying morphological change in other estuaries, and is more comprehensive than exists for many estuary systems. Although the data resource may not be complete, the purpose of this study is to examine how best use may be made of the existing data resource.

One of the most significant contributions to developing understanding of the long-term behaviour of the Mersey estuary has been made by Price and Kendrick (1963), employing field measurements and physical models. Physical models have made an important contribution to scientific experimentation in simulating and enabling examination of physical process behaviour in estuaries. Professor Osborne Reynolds (1887) constructed what is generally acknowledged as the first scientifically designed model of an estuary in 1885, which coincidentally represented the Mersey estuary between the Liverpool Narrows and Runcorn, at a horizontal scale of 1:31800 and a vertical scale of 1:960 (Price and Thorn, 1994). Increasingly detailed physical model representations of the estuary have been undertaken through the course of the last century. Difficulties have, however, been encountered with representation of natural estuarine features in physical models, particularly with mobile-bed models. Simulation of sediment transport in a physical model is a problematical subject, the cohesive characteristics of estuarine muds cannot be correctly scaled and non-cohesive sediment modelling has been most successful when confined to the examination of gross sedimentary features (Price and Thorn, 1994). Particular difficulties have been encountered in large-scale models where the necessarily limited simulation of estuary sediment properties by a model bed material is an integral component of model performance. Computational models are better suited to examination of the problems of representing estuarine sediments in large-scale models where the model bed topography is accurately represented without scaling distortions. Physical models in contrast are better suited to examinations of the effects of flow obstruction by physical structures, or where fine detail and secondary flow effects form and integral component of the study.

The construction of training walls to stabilise the location of the low water channel in Liverpool Bay was shown by Price and Kendrick (1963) to have exerted a considerable influence upon the long-term behaviour of the estuary, predominantly through secondary effects of altering tidal circulation patterns in Liverpool Bay. However, the long-term morphological behaviour of the estuary results from the interaction of a range of physical processes, and perturbations induced by anthropogenic activity over a range of temporal and spatial scales. To develop a more complete understanding of the long-term evolution of the Mersey estuary several important research issues may be identified. The study by Price and Kendrick (1963), examined residual tidal currents; a more detailed examination of the interaction of physical processes would provide greater understanding of the factors controlling sediment transport. The physical model of Liverpool Bay employed by Price and Kendrick (1963) for example did not include the salinity distribution, and reproduced seaward residual flow near the bottom of the Queens channel where current measurements demonstrated flow near the bed in the channel was landward (Bowden, 1975). Furthermore, wave effects were recognised by Halliwell and O'Connor (1975) as an important physical process in the Liverpool Bay area, particularly during neap tides when tidal effects are small. Bathymetric surveys conducted following the research undertaken by Price and Kendrick (1963), provide an opportunity to examine estuary behaviour over an extended period and analyse the processes causing the estuary to attain or deviate from a conceptual quasi-equilibrium state.

CHAPTER 4 INVESTIGATION OF CHANGES IN PHYSICAL MORPHOLOGY

4.1 Introduction

Relative changes in estuary geometrical parameters over an historical timescale provide important information on estuary behaviour. At a basic level changes in estuary volume indicate net trends of erosion, accretion, or stability over time. Geometrical characteristics can also indicate interaction between estuary morphology and physical processes as the shape of an estuary exerts an influence upon the movement of water through the system. However, analysis of historic bathymetric data requires account to be taken of the accuracy of data and the comparability of geometric parameter calculations between historic periods, as calculations may be influenced by errors introduced at various stages of the data handling process. The aim of this chapter is to examine the principal features of bathymetric change in the Mersey estuary. Of particular importance are errors in bathymetric data collection and processing, and determining whether they have a significant effect upon quantifying volumetric change and net sediment transport trends in the estuary. The importance of establishing accurate geometric parameters is emphasised by subsequent analysis of the implications of estuary form changes for tidal flow characteristics and calculation of a sediment budget.

The first stage of study examined changes in the total water volume of the estuary employing a Digital Ground Model to interpolate irregularly spaced bathymetric data onto a regularly spaced grid. Initial calculations of volume change used a constant geodetic level and examined the effects of different interpolation techniques and resolution. The accuracy of calculations was improved by accounting for differences between echo sounded measurements and lead line measurements taken prior to 1946 and also accounting for variations in water level along the estuary using the results from 1D models to describe historic tidal levels. The second stage of study examined historical changes in other geometrical parameters including subtidal and intertidal volume, cross-section form, surface area characteristics and integrated geometrical parameters identified by Dronkers (1998) and Friedrichs and Aubrey (1988) as indicative of estuary flow characteristics. The final stage of study comprised synthesising changes in the Liverpool Bay and Mersey estuary system to establish an estimated sediment budget based upon calculated volume changes and analysis of dredging records.

4.2 Data sources and accuracy

The data analysed for the Mersey estuary comprised bathymetric surveys, recorded by MDHC for the Acting Conservator of the River Mersey, of 172 cross-sections located as shown in Figure 4.1, resurveyed at predetermined locations and replicated for each survey for the years 1871, 1906, 1936, 1956, 1977 and 1997. The datasets were rare in terms of historical bathymetric coverage of estuaries as they included a substantial area of the intertidal zone, up to 10 m above CD, affording significant benefits for analysis of geometrical change. The longitudinal resolution of data coverage between cross-sections along the estuary was relatively coarse, ranging from 150/200m between cross-sections in the Narrows to approximately 600m between cross-sections in the basin area of the estuary. The data coverage of Liverpool Bay for 1904 and 1933 comprised charts compiled by MDHC. For 1977 data was obtained from Admiralty Chart 1951 (16^{th} September 1983 edition) containing data from surveys conducted by MDHC in 1975, 1977 and 1982 and data from MDHC charts based on surveys conducted between 1970-1981. The years for which Liverpool Bay data was available corresponded reasonably well with charts of the Mersey estuary for 1906,1936 and 1977 and also covered a period of significant morphological change in the estuary identified by Price and Kendrick (1963). The spatial coverage of data in Liverpool Bay is shown in Figure 4.2 for 1933, which is representative of coverage for other years.

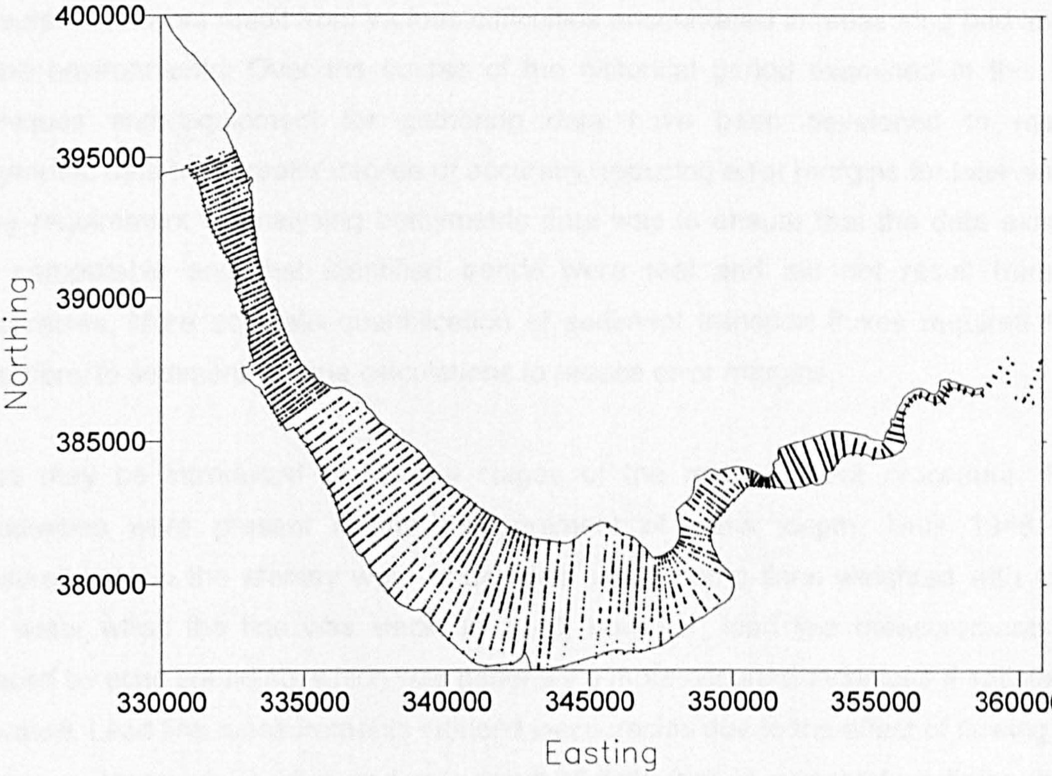


Figure 4.1 Bathymetric data measurement points in the Mersey estuary

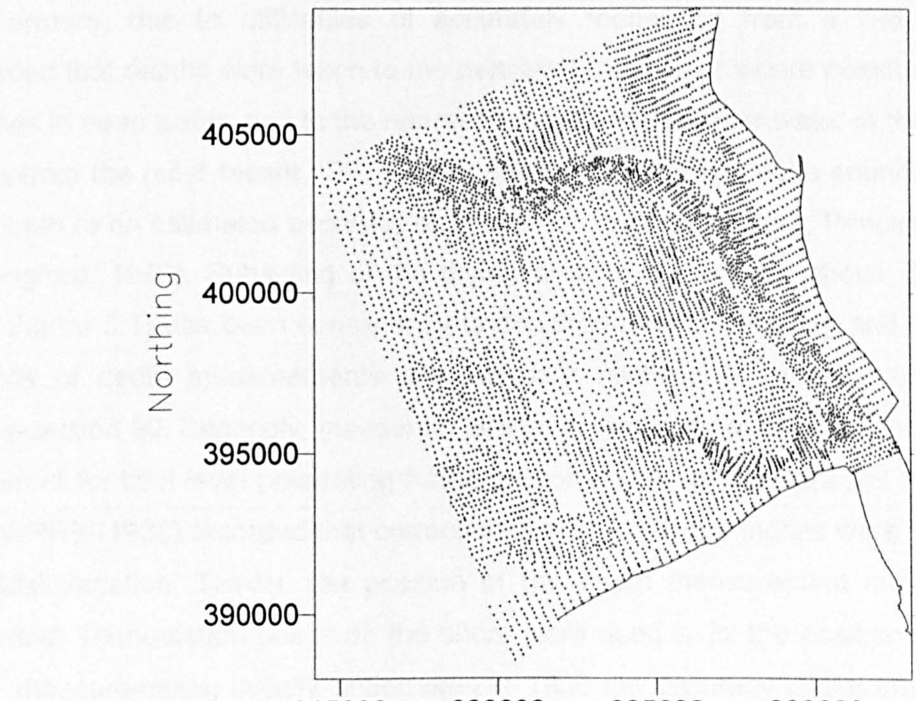


Figure 4.2 Bathymetric data measurement points in Liverpool Bay

Measurement errors result from various difficulties encountered in measuring bed levels in marine environments. Over the course of the historical period examined in this study, techniques and equipment for gathering data have been developed to measure bathymetric data to a greater degree of accuracy, reducing error margins for later surveys. A key requirement of analysing bathymetric data was to ensure that the data examined was comparable and that identified trends were real and did not result from data inaccuracies. More accurate quantification of sediment transport fluxes required further corrections to sediment volume calculations to reduce error margins.

Errors may be introduced at several stages of the measurement procedure. Firstly, inaccuracies were present in the measurement of water depth. Until 1946 depth measurements in the Mersey were undertaken using hemp lines weighted with lead at high water when the tide was slack. In 1946, however, lead line measurements were replaced by echo sounding, which was generally a more accurate technique if satisfactorily calibrated. Lead line measurements induced inaccuracies due to the effect of flowing water causing a catenary in the line and as a result of difficulties in accurately defining the bed level in soft bottomed areas; both of these effects resulted in overestimation of depths. Furthermore, due to difficulties of accurately measuring from a line, WPRB (1938) recorded that depths were taken to the nearest 12 inches or where possible to the nearest 6inches in deep water, and to the nearest 3 inches in shallower water in the upper estuary. In contrast the most recent 1997 survey employed a 210khz echo sounder that recorded the depth to an estimated accuracy of 5cm (pers. comm. S.Hearn, Principal Surveyor, HR Wallingford, 1999). Surveying of the drying area of the estuary above Cross-section 90 (see Figure 5.1) has been consistently undertaken through levelling and changes in error bounds of depth measurements are therefore confined to cross-sections seaward of Cross-section 90. Secondly, measuring bed level required adjustment to measured depths to correct for tidal level presenting further opportunities for inaccuracies to be introduced. The WPRB (1938) recorded that corrections to the nearest 3 inches were made to account for tidal variation. Thirdly, the position of the depth measurement must be accurately recorded. Triangulation points on the shore were used to fix the position of soundings for early measurements, initially undertaken in 1860 the accuracy of the triangulation points was checked in 1930 and found to be in agreement. The latest survey undertaken in 1997 employed a Satellite Positioning System to fix the position of depth measurements.

Where the difference between two surveys was considered the maximum possible error in calculations of volumetric change was doubled. The extreme of error may occur if one set of measurements was biased in one direction while the second set was biased in the other direction. One way this could occur was through changes in methods used to measure depths or changes used to convert depths measured from the survey vessel to CD elevations, particularly the method used to identify tidal level in the upper part of the estuary.

4.3 Data preparation and 3D surface mapping

To enable manipulation and quantification of the data, bathymetric data were obtained in digital XYZ format comprising Easting, Northing and depth variables for the years 1871, 1906, 1936, 1956, 1977 and 1997. These time intervals covered a period of significant morphological change in the estuary when it may be expected to illustrate differences in form and process characteristics. Adjustments were required to correct a change in Liverpool Bay Datum in 1974 from 14.54 feet (4.47m) below Ordnance Datum (Newlyn) to Chart Datum, 4.93m below Ordnance Datum (Newlyn) requiring an addition of 0.46m to depths for pre-1974 datasets.

Once suitable data was held in XYZ format, it was analysed by interpolating data into a 3D surface map using SURFER software (Golden Software, 1997). SURFER software was used for the study as it was considered to give a good visual display of results, and employs reliable interpolation and differencing methods. The boundary of the interpolated area was set as the National Grid co-ordinates below:

Easting: min.=330875 max.=360798

Northing: min.=376972 max.=395282

Following interpolation each bathymetry was blanked using an appropriate estuary outline taken as the estuary shoreline sea wall interface, which corresponded broadly with the HAT contour. The mask file varied slightly between years due to land reclamation and sea wall construction but ensured accurate volumetric calculations for intertidal and subtidal areas.

Errors in accurately positioning the depth measurement were contributed in digitising, particularly in calibrating the digitised chart. The 1997 and 1977 bathymetries were derived directly from the survey recordings, but data for the years 1871, 1906, 1936, and 1956 surveys was derived from bathymetric charts, creating error. However, these errors were unlikely to have a significant effect upon volume calculations.

4.4 Changes in estuary bathymetry

Changes in the form of the estuary have varied through the estuary system, and areas of the estuary referred to are shown in Figure 4.3.

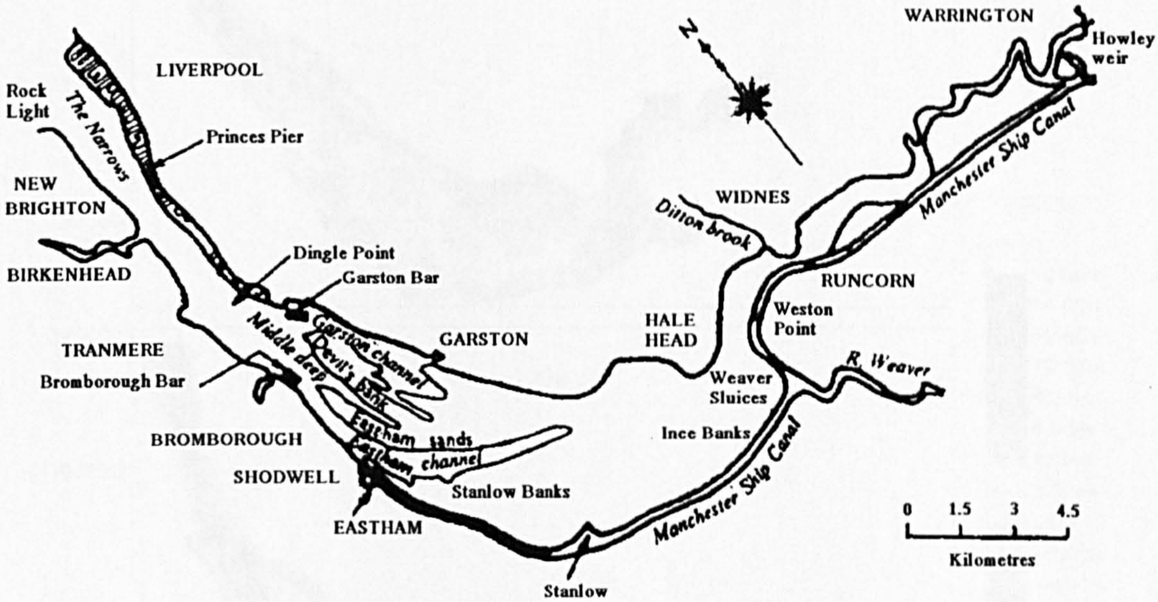


Figure 4.3 Plan of locations in the Mersey estuary

The Narrows has limited potential to adjust to changes in physical process regime as it is formed from hard inerodible material; in contrast the inner estuary is formed from more readily erodible material and has a much greater potential for change in bathymetric configuration. To examine in greater detail the principal trends that occurred in estuary form, bathymetric configurations as presented in Figure 4.4 and Figure 4.5 were examined, with bed levels represented as colour-shaded areas. The predominant change that was evident is the movement of the low water channel within the estuary. Contour lines for 2m CD were included to distinguish between changes to subtidal and intertidal areas. The 2m CD contour broadly corresponded with mean low water level at Princes Pier although it was noted that this approach provided a general view only.

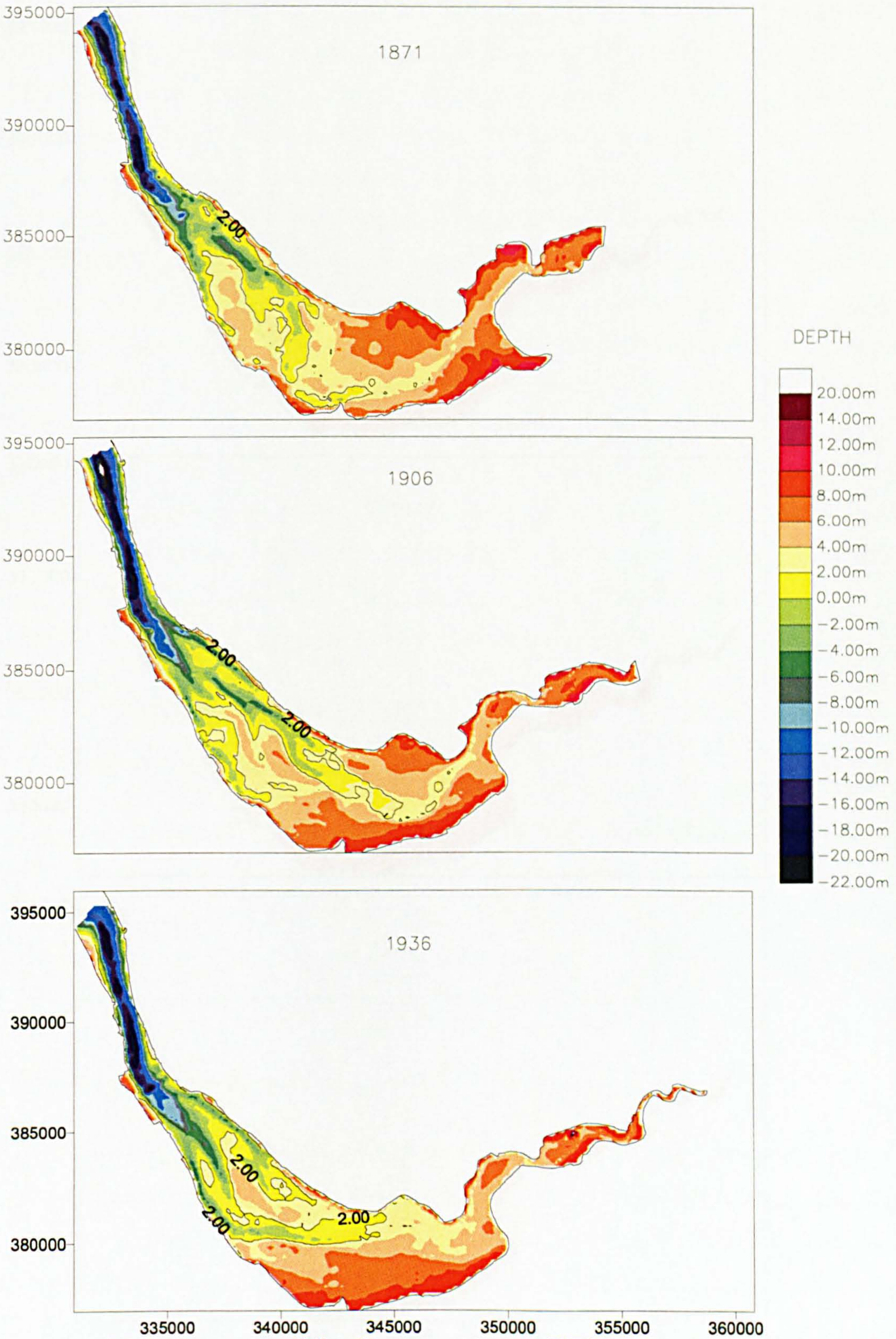


Figure 4.4 Bathymetry of the Mersey estuary 1871-1936

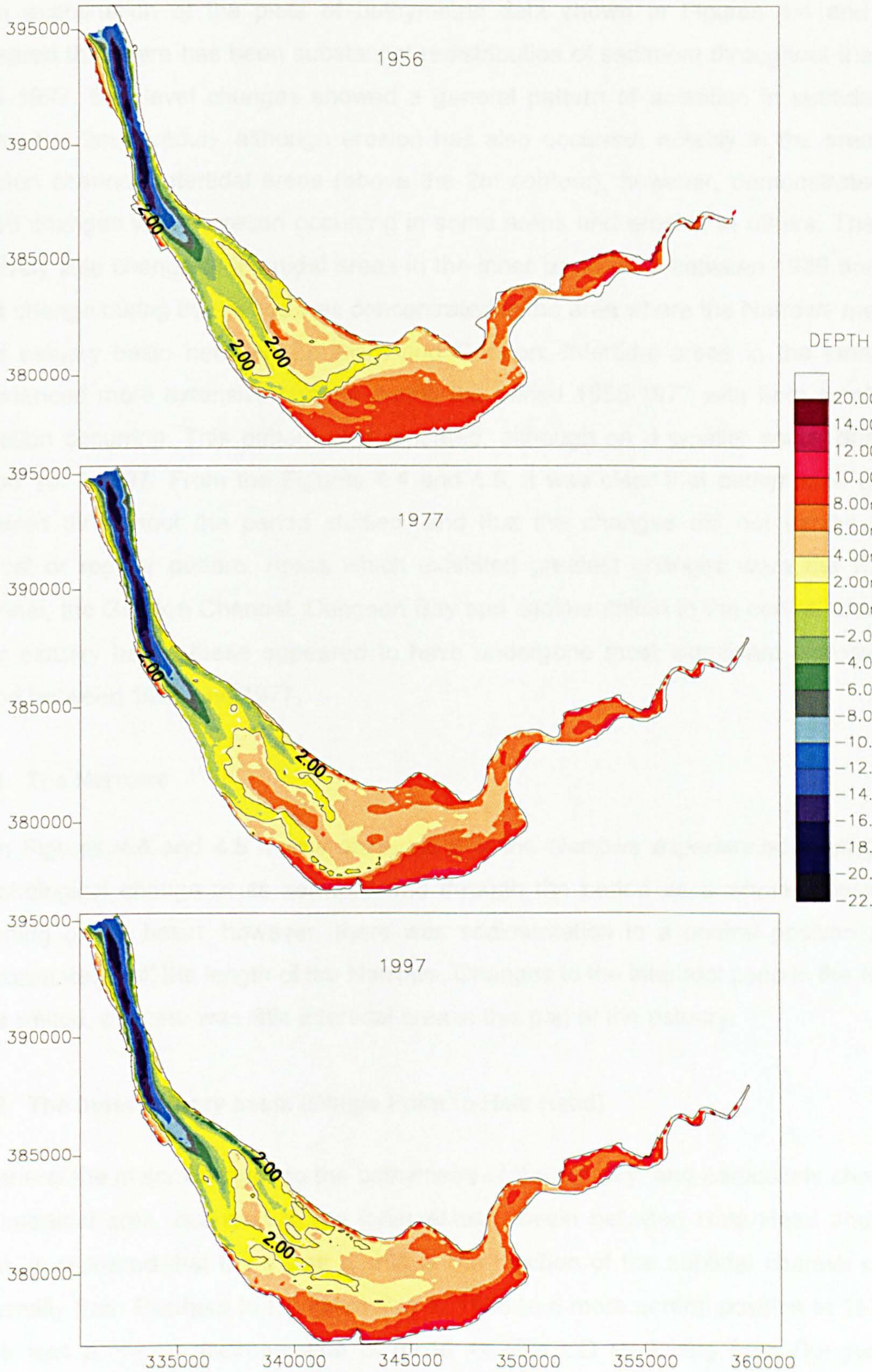


Figure 4.5 Bathymetry of the Mersey estuary 1956-1997

From examination of the plots of bathymetric data shown in Figures 4.4 and 4.5, it appeared that there has been substantial redistribution of sediment throughout the period 1871-1997. Bed level changes showed a general pattern of accretion in subtidal areas (below the 2m contour), although erosion has also occurred, notably in the area of the Garston channel. Intertidal areas (above the 2m contour), however, demonstrated more varied changes with accretion occurring in some areas and erosion in others. There was relatively little change to intertidal areas in the inner basin area between 1936 and 1956. Most change during this period was concentrated in the area where the Narrows meets the inner estuary basin between Eastham and Garston. Intertidal areas in the inner basin experienced more extensive change during the period 1956-1977 with both erosion and accretion occurring. This pattern was repeated, although on a smaller scale, during the period 1977-1997. From the Figures 4.4 and 4.5, it was clear that bathymetric changes occurred throughout the period studied, and that the changes did not exhibit a clear cyclical or regular pattern. Areas which exhibited greatest changes were the Eastham Channel, the Garston Channel, Dungeon Bay and sedimentation in the central area of the inner estuary basin; these appeared to have undergone most significant change in the period between 1956 and 1977.

4.4.1 The Narrows

From Figures 4.4 and 4.5 it was observed that the Narrows experienced relatively little morphological change at its seaward end through the period as a whole. Towards the widening of the basin, however, there was sedimentation in a central position running approximately half the length of the Narrows. Changes to the intertidal zone in the Narrows were limited, as there was little intertidal area in this part of the estuary.

4.4.2 The inner estuary basin (Dingle Point to Hale Head)

In general the major changes to the bathymetry of the estuary, and particularly changes to the intertidal area, occurred in the inner estuary basin between Hale Head and Dingle Point. It appeared that there was a shift in the position of the subtidal channel crossing diagonally from Eastham to Dungeon Bay in 1936 to a more central position in 1997. The result was a line of sedimentation of up to +4.75m CD stretching from Dungeon Bay, across diagonally to Eastham, and along the southern bank from Eastham seawards. In addition there was erosion of the estuary bed in relatively central positions in the basin, and on the opposite (northern) bank from the sedimentation running from Eastham seawards.

4.4.3 Ince and Stanlow Banks

The Ince and Stanlow Banks are within an SSSI (Site of Special Scientific Interest) located on the southern bank of the estuary. Previous studies (Kendrick and Stevenson, 1985) investigated the encroachment of the low water channel upon these areas. The channel was found to transgress the banks regularly between 1860 and 1920. Between 1920 and 1960, however, the course of the channel remained away from these areas. Following 1960 the channel again began to encroach on the banks, although less regularly than prior to 1920. It was proposed that as the channel transgressed these areas, it eroded the banks, and conversely whilst it occupied a position away from them accretion could occur. This pattern appeared to be reflected in the SURFER bathymetric plots, (see Figures 4.4 and 4.5) which demonstrated that the banks significantly increased in area between 1936-1956, extending further into the estuary at their western end, with only slight erosion to the East edge of the Ince Bank. In contrast, following 1956 the middle of the inner estuary basin experienced substantial erosion, which encroached particularly on the Stanlow Bank and the eastern end of the Ince Banks. This was followed by a substantial recession of the western end of the bank in the period up to 1977, and a subsequent advance of the eastern end and recession of the western end up to 1997. Overall through the period 1936-1997 there was an eastward shift in the location the Ince Banks.

4.4.4 Dungeon Bay

Bathymetric plots indicated a different pattern of change for Dungeon Bay in contrast with the Ince and Stanlow Banks (see Figures 4.4 and 4.5). Between 1936 and 1956 there was relatively little change, although some pockets of substantial deposition occurred adjacent to the shoreline. During the period 1956-1977 substantial deposition occurred in Dungeon Bay. This pattern reversed again during the period 1977-1997 when Dungeon Bay experienced substantial erosion.

4.4.5 Hale Head to Fiddlers Ferry

Although data was available to Warrington Bridge, the tidal limit of the estuary, this study concentrated on changes up to Fiddlers Ferry, approximately 7km downstream of the tidal limit. The intertidal area above that point is small and morphological change is therefore limited. From Figures 4.4 and 4.5 it was evident that there was comparatively little change above Hale Head, although there were small pockets of substantial deposition along the northern bank of the estuary.

4.4.6 Detailed cross-section plots

Figure 4.6, showing surveyed cross-sections in three different locations along the estuary, provided a more detailed illustration of changes in estuary bathymetry and emphasised the patterns identified in bathymetric plots. Changes in the form of Cross-section 27 representing the Narrows were limited, principally due to the immobile nature of the bed in the Narrows. Cross-section 47 around Dingle demonstrated greater changes in cross-section form as it was in the area where the estuary widened from the Narrows, causing current speeds to decrease and deposition of sediment to occur, so the area was sensitive to changes in physical process regime. Cross-section 72 from the basin area of the estuary near Stanlow showed considerable bathymetric change resulting from the channel shifting considerably over the period 1871-1997, which resulted in significant changes to the intertidal deposits on the neighbouring banks.

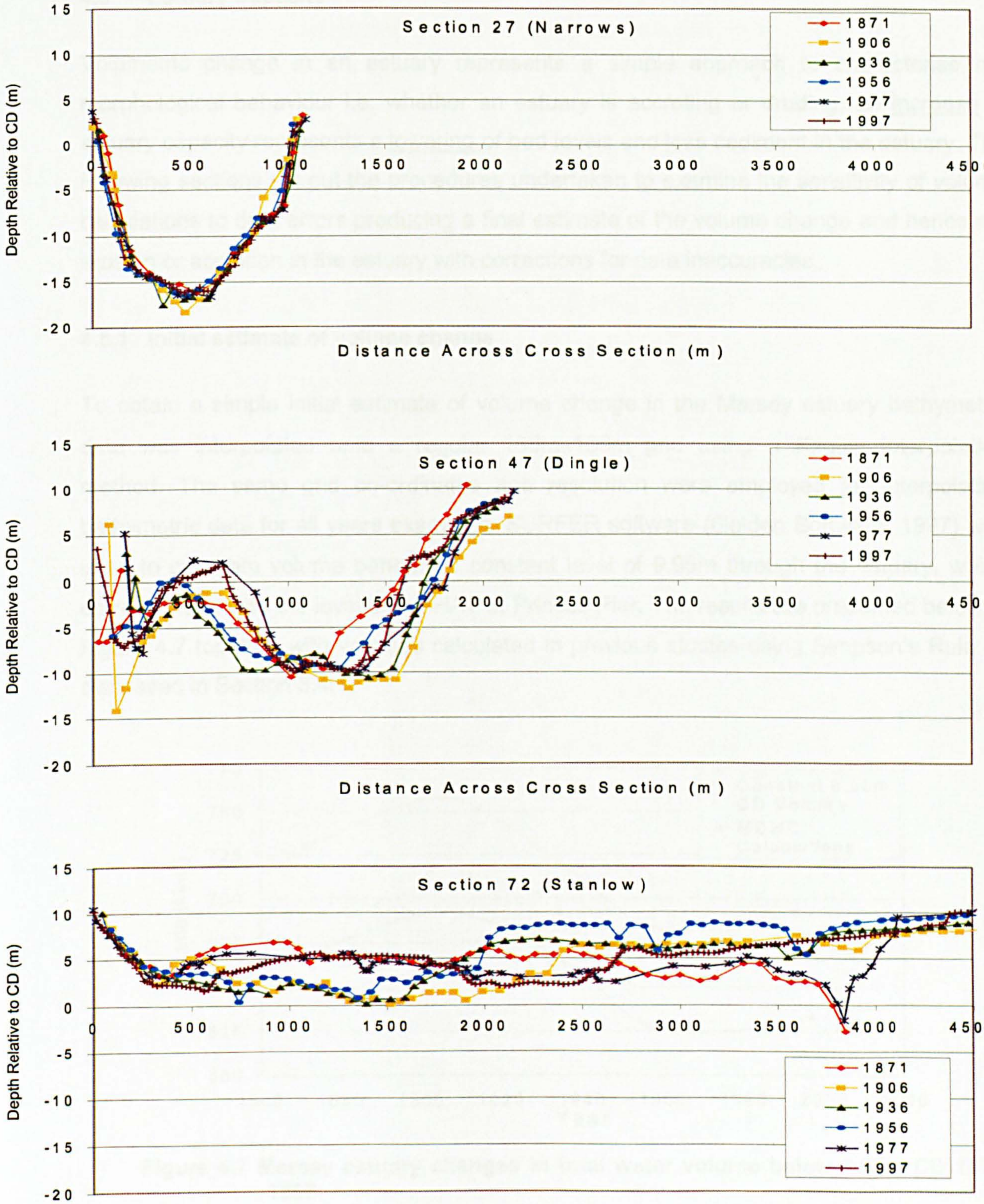


Figure 4.6 Plots of bathymetric change at different cross-sections Estuary capacity

4.5 Estuary Capacity

Volumetric change in an estuary represents a simple approach to characterise net morphological behaviour i.e. whether an estuary is accreting or eroding, an increase in estuary capacity represents a lowering of bed levels and less sediment in the estuary. The following sections set out the procedures undertaken to examine the sensitivity of volume calculations to data errors producing a final estimate of the volume change and hence net erosion or accretion in the estuary with corrections for data inaccuracies.

4.5.1 Initial estimate of volume change

To obtain a simple initial estimate of volume change in the Mersey estuary bathymetric data was interpolated onto a regular 150m×150m grid using a Kriging interpolation method. The same grid co-ordinates and resolution were employed for interpolating bathymetric data for all years examined. SURFER software (Golden Software, 1997) was used to calculate volume beneath a constant level of 9.95m through the estuary, which corresponded with the level of the HAT at Princes Pier. The results are presented below in Figure 4.7 together with volumes calculated in previous studies using Simpson's Rule as discussed in Section 3.4.1.

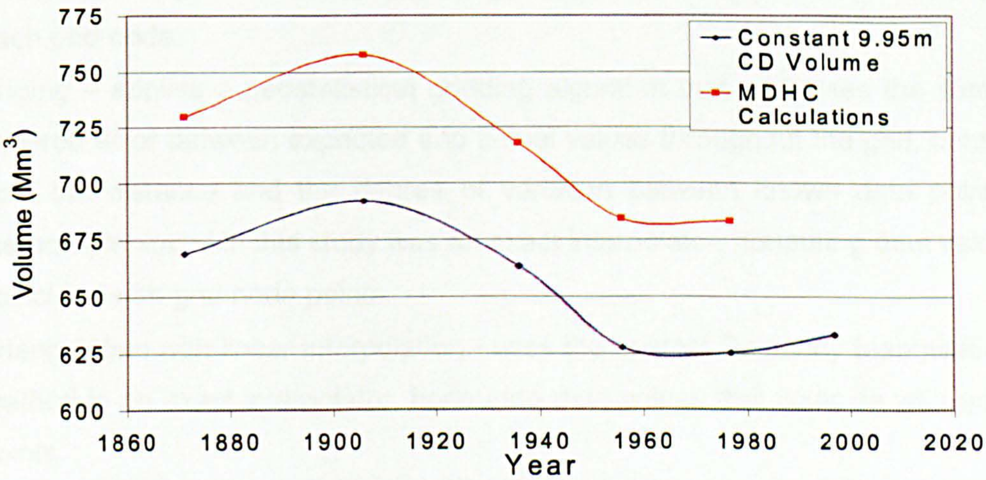


Figure 4.7 Mersey estuary changes in total water volume below 9.95m CD 1871-1997

The volumes calculated using a constant level of 9.95m CD were significantly lower than previous computations, which employed a varying tidal, level because shallow water effects of the estuary cause tidal level to increase landwards. However, the absolute magnitude of volume change was similar for both sets of computations indicating that changes in volume at a level above 9.95m in the landward reaches of the estuary contributed a limited amount to overall change. As a result of underestimating estuary volume the percentage change in volume was greater for calculations using a constant level.

Sensitivity to interpolation

Error may arise in volumetric calculations by interpolation and averaging processes. Although likely to have an equal affect on volume calculations assuming the initial bathymetric data was of similar resolution, the effects of applying different interpolation algorithms and resolutions were examined. The following interpolation techniques, representing a range of available mathematical approaches to interpolating data, were employed to calculate estuary volume beneath a constant level of 9.95m CD with the results shown in Table 4.1:

- Minimum curvature - repeatedly applies an equation over a grid to smooth the values. Grid node values are recalculated until successive changes in values are less than a specified maximum residual value. Minimum curvature is not an exact interpolator so data values coinciding with grid node points are not honoured.
- Near Neighbour - the simplest gridding technique, which does not apply any interpolation algorithm but simply assigns the value of the nearest datum point to each grid node.
- Kriging – applies a geostatistical gridding algorithm that minimises the sum of the squared error between expected and actual values throughout the grid, considering both the distance and the degree of variation between known data points. The method employed in this study was an exact interpolator, honouring data values that coincided with grid node points.
- Triangulation with linear interpolation - uses the optimal Delauney triangulation. The method is an exact interpolator, honouring data values that coincide with grid node points.

Gridding technique	Volume (Mm^3)	
	150m grid	**25m grid**
Near Neighbour	631	665
Minimum Curvature	633	629
Triangulation with linear interpolation	628	627
Kriging	633	633

Table 4.1 Total estuary water volumes derived with different interpolation techniques

The volume calculations presented in Table 4.1 demonstrated that grid resolution had little effect on estuary volume calculations using the more complex Triangulation with linear interpolation and Kriging interpolation techniques. The significant deviation of volume calculated by Nearest Neighbour technique for the 25m grid from other computed volumes suggested that the method did not provide a reliable means of calculating estuary volume for this study. The volume calculations using a 150m grid size were of approximately the same order of magnitude with regard to overall change observed through the last century, the maximum variation being 0.79% which was considerably less than the magnitude of volume change calculated between bathymetric datasets. The similarity between calculated values derived using Kriging interpolation, indicated that it was a robust and reliable method of computing volume for the purposes of this study.

<u>**Sensitivity to data resolution**</u>

Bathymetric data studied was recorded at different resolutions of depth measurements along the survey lines, which could affect parameter calculations. The resolution of measurements was examined by comparing the distance between depth measurements along Cross-section 77, representing the longest cross-section in the estuary, for different years, as shown in Table 4.2.

Year	Distance Between Depth Measurements (m)
1871	67.6
1906	87.6
1936	63.1
1956	59.9
1977	112.6
1997	6.3

Table 4.2 Variations in distance between depth measurements along Cross-section 77 for surveys of the Mersey estuary

The effect of different survey resolutions on volume calculations was examined using the 1997 survey as it had the highest resolution data coverage. The number of depth measurements was reduced to produce four different datasets covering the range of resolutions of other survey data. The bathymetric data was then interpolated onto a 150m×150m grid using the same boundary co-ordinates as in Section 4.3 and employing the same 1997 estuary outline for blanking. The results of volume calculations from the gridded data are shown below in Table 4.3.

Data resolution	Total volume (Mm^3)
Complete data (6.3m between data points)	633
Every 5th point (29.5m between data points)	632
Every 10th point (58.7m between data points)	634
Every 20th point (110.85m between data points)	631

Table 4.3 Volume computations for 1997 bathymetry with differing resolution of spatial data

The resulting volume calculations demonstrated that the resolution had little effect on estuary volume calculations in the context of overall change observed through the last century. The values were of approximately the same order, the maximum variation being 0.47%, and there was no systematic variation in calculated volume so there was no clear means of adjusting volume calculations for the effects of variations in resolution.

4.5.2 Sensitivity of volume calculations to bathymetric measurement errors

In 1946 a survey was conducted using both lead line and echo sounded measurements, providing data to compare the two techniques. MDHC calculations of cross-section area using a planimeter were examined for the 1946 echo-sounded and lead-line surveys as depth measurements were not available for direct comparison. Only Cross-sections 0-90 were considered, as land surveying techniques were employed exclusively for cross-sections landward of Cross-section 90. The mean depth for each cross-section was derived by dividing the cross-section area calculated by MDHC from the lead line and echo-sounded surveys for 1946 by average width of the cross-section for 1936 and 1956 bathymetries at a level corresponding to high water for a HAT derived for each cross-section from a 1D model of the estuary described in Section 5.4.1 and interpolating linearly between depth measurements.

The average absolute difference between the lead line survey and the echo sounded survey was calculated as -8.69cm and the average percentage difference was calculated as 0.090%. Lead line measurements were found to overestimate depth as expected, possibly due to catenary effects of flowing water on the line and difficulties of defining the exact bottom position in muddy areas. To examine whether the correction factors were representative a histogram was produced showing percentage difference between cross-section mean depths measured using lead line and echo sounding (see Figure 4.8). Figure 4.8 approximated a normal (Gaussian) probability distribution centred around an average percentage value of 0.090% indicating that it was representative of the difference between the lead line and echo sounded measurements. Systematic variation of errors in depth measurement with depth was examined further by plotting percentage errors against cross-section averaged depth (see Figure 4.9) but this did not show a clear correlation between depth and measurement error. The calculated percentage difference for each cross-section was applied as a correction factor to surveys prior to 1946 for Cross-sections 0-90, and interpolated as per Section 4.3 onto a 150m×150m grid permitting calculation of volumes calculated and correction for lead line measurement errors.

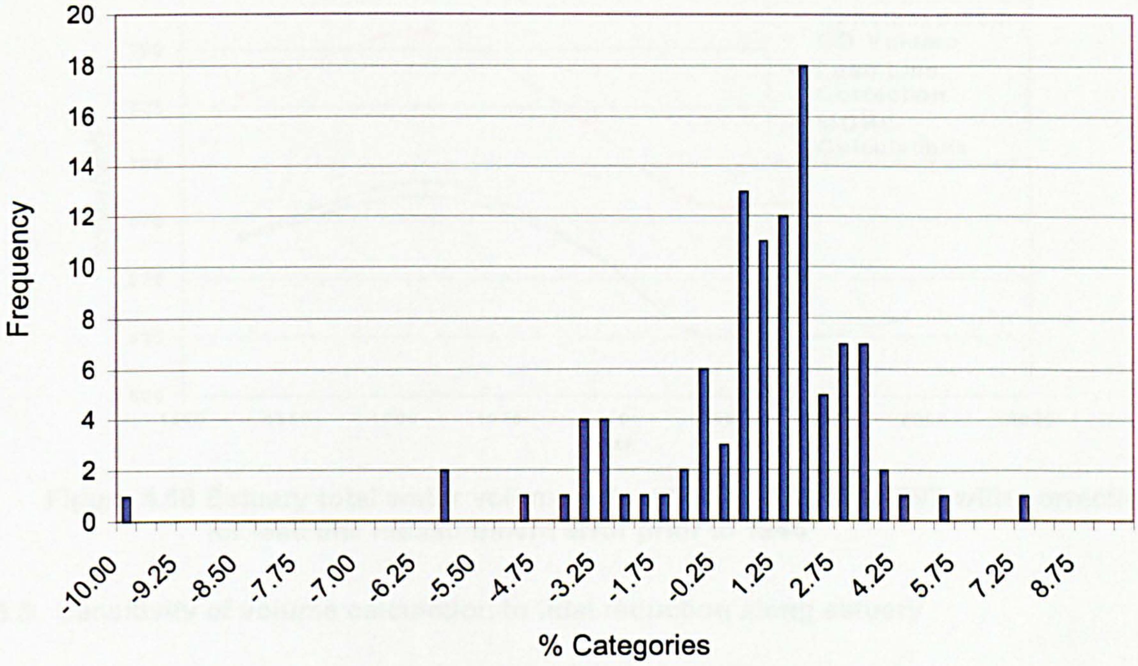


Figure 4.8 Histogram of percentage mean difference between cross-section mean depth measured using lead line and echo-sounder

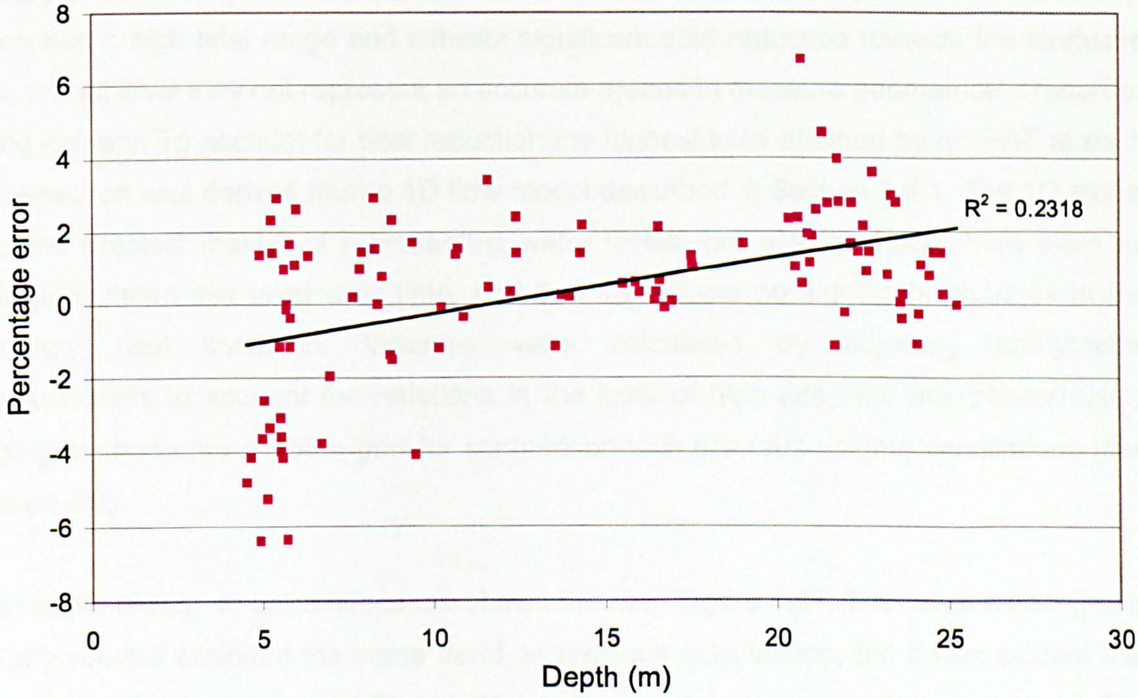


Figure 4.9 Plot of percentage mean error against cross-section averaged depth

The results of the volume calculations are shown below in Figure 4.10. It was evident that the effect of lead line measurement errors had relatively little effect in comparison with volume calculations presented in Section 4.5.1.

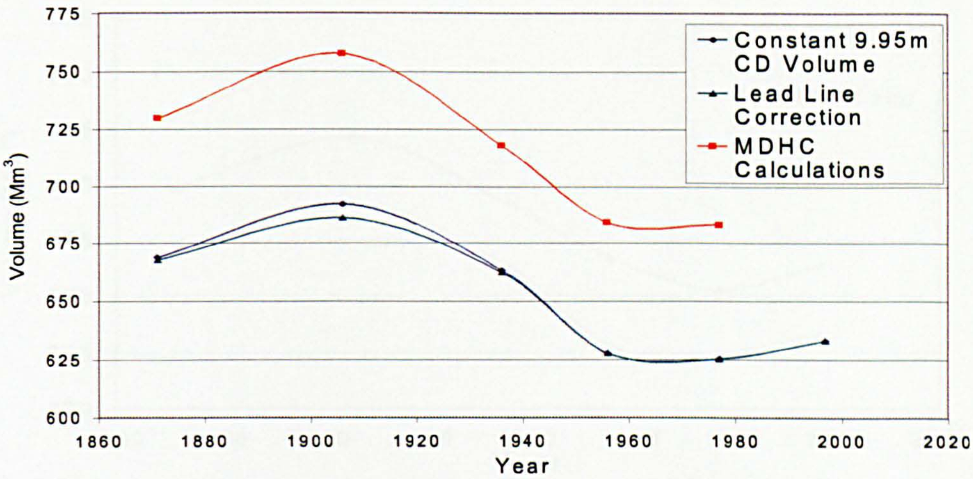


Figure 4.10 Estuary total water volume below 9.95m CD 1871-1997 with correction for lead line measurement error prior to 1946

4.5.3 Sensitivity of volume calculation to tidal reduction along estuary

Previous studies have calculated parameters at constant geodetic levels taken to represent significant levels such as high/low water for spring or neap tides through an estuary or tidal inlet (Schroeder *et al.*, 1995). However, in an estuary such as the Mersey, which has a high tidal range and exhibits significant tidal reduction towards the landward end, a fixed level may not represent an accurate means to measure geometrical properties of the estuary. To account for tidal reduction the highest level attained by an HAT at each cross-section was derived from a 1D flow model described in Section 5.4.1. The 1D model was the simplest means of representing water levels, but assumed that there were no change in mean sea level over time, and that there were no significant changes in the boundary tidal condition. Volumes were calculated by adjusting bathymetric measurements to account for variations in the level of high tide, and interpolated using Kriging method onto a 150m grid for comparison with previous volume calculations (see Section 4.3).

The results of volume calculations are shown below in Figure 4.11. The relative changes in estuary volume exhibited the same trend as previous calculations, but it was evident that the calculated volume was significantly higher than applying a constant geodetic level. The calculated values fall in between MDHC calculations using Simpson's rule and the smaller volumes calculated using a constant geodetic level. As a percentage, the net change in estuary volume between 1906-1977, the period of greatest volume change, was 9.6%, an increase compared with 8.8% derived from applying a constant geodetic level.

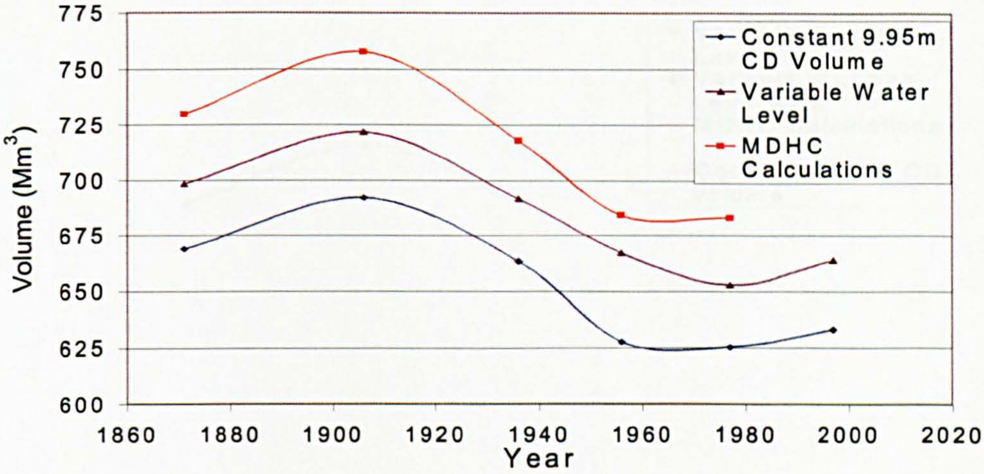


Figure 4.11 Estuary total water volume below a HAT with varying height along the estuary

4.5.4 Effect on volume calculation of sea level rise

Changes in sea level over time can affect volume computations and the WPRB (1938) examined water level records from Princes Pier to determine whether any alteration occurred in the height of a standard tide in different parts of the estuary. Although no correlation was found between observed variations in water level from year to year, a more recent study of tidal level records by Woodworth (1999) identified an average sea level rise of approximately 1mm/year for the duration of the last century. To account for the effects of sea level rise upon volume calculations the same method was employed as for a HAT of varying level through the estuary in Section 4.5.3, but with a decrease in the mean height of the tidal boundary condition employed in the 1D modelling by 1mm for each year prior to 1977, and increased by 1mm for each year after 1977. Volumes were calculated by adjusting bathymetric measurements to account for variations in the level of high tide, and interpolating using Kriging method onto a 150m grid for comparison with previous volume calculations (see Section 4.3).

The results in Figure 4.12 demonstrated that changes in sea level rise had not had a significant effect upon net volume changes. As a result of a lower sea level, volume computations prior to 1977 were reduced. The percentage volume change in estuary volume between 1906-1977 also reduced to 8.8% compared with 9.6% derived using a HAT with varying water level through the estuary.

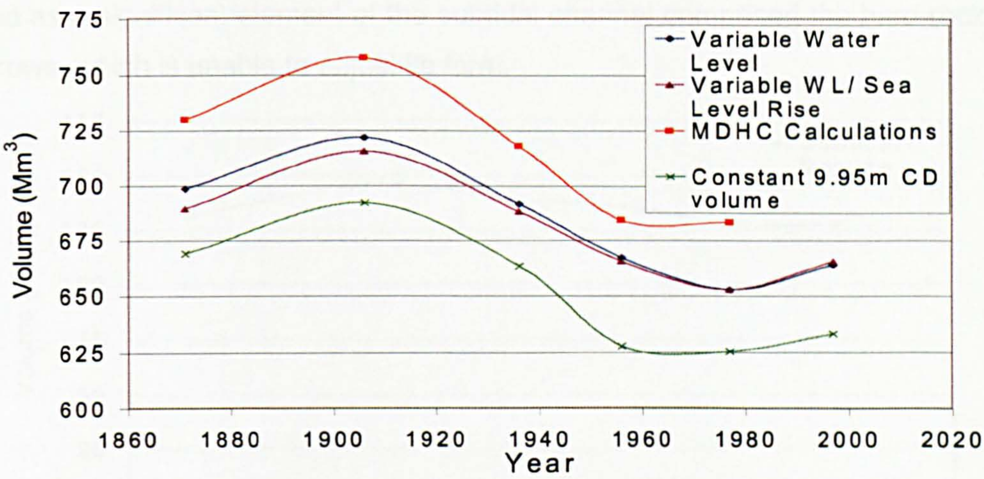


Figure 4.12 The effects of annual sea level rise on estuary total water volume below a HAT with varying height along the estuary

4.6 Estuary subtidal and intertidal volume

Based upon the best estimate of estuary volume derived by accounting for the effects of varying water levels along the estuary and correcting for errors in lead line measurement, the relative changes in subtidal and intertidal volume in the estuary were calculated. Subtidal volumes were calculated employing the method specified in Section 4.5.3 to derive the low water levels of an HAT at each cross-section through the estuary. Volumes were calculated by adjusting bathymetric measurements to account for variations in the level of low tide, and interpolated using Kriging method onto a 150m grid for comparison with previous volume calculations (see Section 4.3). Intertidal volume was then calculated by subtracting the subtidal volume from the total estuary water volume. Defining the extent of intertidal and subtidal areas was arbitrary, but the approach adopted in this study was considered satisfactory to examine the broad changes in each area of the estuary.

The relative trends in subtidal volume (see Figure 4.13) and intertidal volume (see Figure 4.14), indicated that more substantial changes occurred in the intertidal area of the estuary. As a percentage of total volume change between 1906-1977, the changes in intertidal volume accounted for 73.8% whilst the changes in subtidal volume accounted for 26.4%. Based on this evidence, the intertidal area responded more readily to morphological change, with greater accretion occurring over intertidal banks where the current speeds are lower. Due to the high tidal range of the estuary, the intertidal component of the estuary is large and comprised an extensive area over which accretion has occurred. Morphological change in the subtidal area of the estuary in contrast was restricted as a significant element of the subtidal channel comprised the hard-rock area of the Narrows, which is unable to adjust its form.

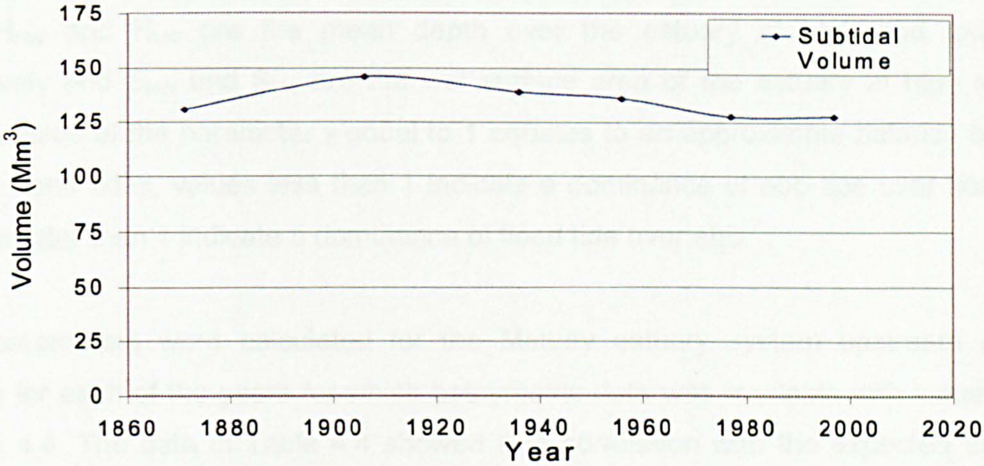


Figure 4.13 Changes in the subtidal volume of the estuary

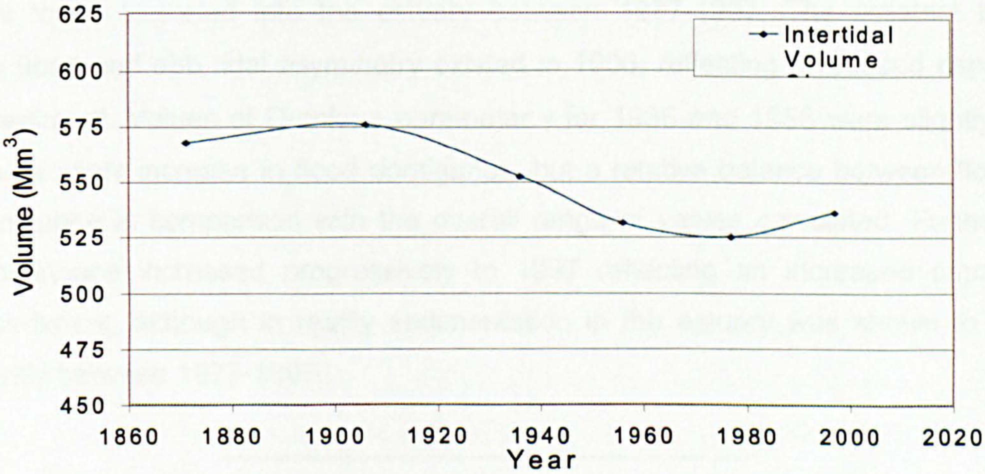


Figure 4.14 Changes in the intertidal volume of the estuary

4.7 Integrated geometrical parameters

Studies have attempted to relate the geometric properties of estuary systems with theoretical tidal asymmetry. Dronkers (1998) refers to several studies (Fitzgerald *et al.*, 1976; Friedrichs and Aubrey, 1988; Van Dongeren and de Vriend, 1994) demonstrating that widening cross-sectional area shortens flood duration with respect to ebb duration, and deepening causes the opposite to occur. Based upon parameterisation of one-dimensional tidal equations, Dronkers (1998) proposed the following analytical approach to relate inlet geometry to flow characteristics:

$$\gamma = \frac{H^2{}_{HW} S_{LW}}{H^2{}_{LW} S_{HW}} \qquad \text{Eq. 4.1}$$

where H_{HW} and H_{LW} are the mean depth over the estuary at high and low water respectively and S_{HW} and S_{LW} are the wet surface area of the estuary at high and low water. A value of the parameter γ equal to 1 equates to an approximate balance between ebb and flood tides, values less than 1 indicate a dominance of ebb tide over flood, and values greater than 1 indicate a dominance of flood tide over ebb.

The γ parameters were calculated for the Mersey estuary system upstream of New Brighton for each of the years for which bathymetric data was available with values given in Table 4.4. The data in Table 4.4 showed little correlation with the expected trends in hydrodynamic regime, that would have been required to account for increased import of sediment into the estuary between 1936-1956, and a relative reduction in potential for sediment to be imported into the estuary between 1977-1997. The greatest balance between flood and ebb tidal asymmetry existed in 1906, reflecting a reduced capacity to import sediment. Values of Dronkers parameter γ for 1936 and 1956 were slightly larger indicating a slight increase in flood dominance, but a relative balance between flood and ebb dominance in comparison with the overall range of values calculated. Furthermore, flood dominance increased progressively to 1997 reflecting an increased capacity to import sediment, although in reality sedimentation in the estuary was shown to reduce significantly between 1977-1997.

YEAR	γ
1871	1.13
1906	1.00
1936	1.27
1956	1.36
1977	1.60
1997	2.09

Table 4.4 Changes in Dronkers γ parameter

Friedrichs and Aubrey (1988) devised a similar approach to Dronkers based upon examination of the effect of geometrical parameters upon tidal distortion using a 1D flow model with linearised friction. The work concentrated upon the effects of the non-dimensional ratio a/h (offshore M2 amplitude/average channel depth at mean sea level) and V_s/V_c (intertidal storage in flats and marshes/volume of channels at mean sea level). Channels are defined as areas of the estuary submerged at mean low water and intertidal areas defined as areas between mean low water level and mean high water level. The findings demonstrated that the geometry of an estuary contributed more to the extent of asymmetry than the offshore tidal boundary condition, and that the parameter a/h was very strongly associated with flood/ebb dominance. Values of a/h less than 0.2 were associated with ebb dominance, and values greater than 0.3 were associated with flood dominance, based on model results and observations of a large number of inlets on the eastern coast of the USA. The parameter V_s/V_c influenced flood/ebb dominance to a lesser extent, largely determining ebb or flood dominance in systems with moderate values of a/h (0.2-0.3). High values of the parameter V_s/V_c are associated with ebb dominance, and low values are associated with flood dominance.

It was evident that the values calculated for changes in the parameters a/h and V_s/V_c in the Mersey estuary presented in Table 4.5 reflected broad trends in Dronkers γ parameter. Values for the parameter a/h indicated that the estuary was flood dominant throughout the period examined, but calculated values increased progressively from 1906 to 1997 indicating an increase in flood dominance. Calculated values for the parameter V_s/V_c also indicated a progressive increased in flood dominance between 1906-1977. The work of Friedrichs and Aubrey and Dronkers does in fact form equivalent conclusions as noted by HR Wallingford (1996) because Dronkers γ parameter is equivalent to:

$$\gamma = \left(\frac{h+a}{h-a}\right)^2 \frac{S_{LW}}{S_{HW}} = \left(1 + 2\frac{a}{h}\right)\left(\frac{V_c}{V_c + V_s}\right) + O\left(\frac{a^2}{h^2}\right) \qquad \text{Eq.4.2}$$

which is equivalent to saying that increases in the parameters a/h and V_s/V_c produce increases in flood and ebb dominance respectively. These approaches, however, represent a significant simplification of the morphological behaviour of estuarine environments, and do not take full account of the complexity of physical process interaction that occurs in estuarine environments. Dronkers (1998) method, for example, is derived from a one-dimensional tidal equation, and hence does not account for stratification effects. The similarity between the two approaches implies that Friedrichs and Aubrey's (1995) approach, which was based upon a 1D hydrodynamic model is also not suitable for stratified situations. To derive a more comprehensive analysis of the causes of morphological change, a more detailed examination of the complexity of physical process interaction is required.

YEAR	a/h	Vs/Vc
1871	0.68	0.39
1906	0.61	0.38
1936	0.66	0.29
1956	0.68	0.26
1977	0.72	0.22
1997	0.77	0.19

Table 4.5 Geometric parameters a/h and Vs/Vc after Friedrichs and Aubrey (1988)

4.8 Sediment budget

To assemble a picture of the net patterns of change in the Mersey estuary and hence establish net trends of sediment transport, the derivation of a sediment budget is a useful tool. By comparing net rate of volume change for different time periods with data on dredging activity it is possible to examine whether volume change is simply a reflection of dredging practice or a more fundamental change in the morphological behaviour of the system.

A sediment budget devised for the Mersey estuary and Liverpool Bay system is shown in Table 4.6 below. The data employed were taken from different historical sources as shown. Net volume change as derived from data presented in Section 4.5.3 based on digitised bathymetric charts was more reliable than data summarising other changes in the system. Dredging records for example must be treated with a degree of caution as historical records may have significant error margins and there is a degree of uncertainty involved in comparing data from different sources. Nevertheless, the accuracy of the calculations presented is sufficient to identify the main historical trends.

Period	Total Water Volume Change in the Mersey estuary (Mm^3)[(1)]	Volume Change due to Reclamation (Mm^3)[(2)]	Material Dredged from Mersey estuary (Mm^3)[(3)]	Disposal Of Dredged Material Within Mersey (Mm^3)[(4)]	Net Annual Sediment Flux (Mm^3)[(5)]
1871-1906	+23.3	**-6.8**	***After 1890*** **9.3**	**n/a**	**-0.59**
1906-1936	**-30.2**	**-4.5**	**39.8**	**n/a**	**+2.18**
1936-1956	**-24.4**	**-6.4**	**19.9**	**n/a**	**+1.75**
1956-1977	**-14.5**	**-2.3**	**29.3**	**0.2**	**+1.97**
1977-1997	**+11.2**	**0.0**	**8.8**	**1.5**	**-0.20**

(1), (2) Totals derived from digitising bathymetric data.

(3), (4) From Water Pollution research (1938) and Mersey Conservator Annual Reports to Secretary of State (1939-79), using a rough approximation of $0.79m^3$ = 1 cubic yard ≡ 2.7 hopper tons (Water Pollution research, 1938). Where no data is available for quantity of dredged material deposited in the estuary it is assumed to be 0.

(5) The sum of columns 2 and 3, minus columns 1 and 4, divided by the number of years in the period covered.

Table 4.6 Sediment budget comprising historical volume changes, dredging and disposal in the Mersey estuary

The key features of the sediment budget indicated a higher net sediment transport rate between 1906-1977, demonstrating a net import of sediment into the system. A sediment budget was of particular value in attempting to establish the stability or otherwise of an estuary system, indicating net flux of sediment. Between 1977-1997 there was a relatively small net sediment flux out of the estuary indicating that the estuary established an equilibrium state in terms of net flux of sediment through the estuary mouth, although volume change still occurred as a result of dredging activity. The interpretation of these trends led to the conclusion that although dredging within the estuary was ongoing, it was largely overridden by the effects of a greater net flux of sediment into the estuary through the period 1906-1977. Intensive dredging activity within the estuary over short periods, however, proved sufficient to reverse the net trend of accretion, such as high levels of dredging in Eastham Channel between 1953-4 (Price and Kendrick, 1963), which caused estuary volume to increase. As the net flux of sediment into the estuary has declined, however, dredging within the estuary has exerted a greater influence upon morphological change in the estuary and now appears to be the dominant influence upon net morphological change. Thus an ordering of impacts may be defined; dredging within the estuary was a largely second order effect whilst estuary behaviour was dominated by sediment import through the estuary mouth, but dredging within the estuary became a dominant impact as the flux of sediment into the estuary reduced. Although estuary volume increased between 1977-1997 as a result of sediment removal via dredging, this only represented the net estuary trend with localised patterns of erosion and accretion within the estuary maintaining the requirement for dredging.

Considerable quantities were dredged from the estuary through the course of the last century to maintain navigation channels, dock entrances and the entrance to the Ship Canal. Dredging was undertaken by various agencies and estimates of the quantity removed can only be approximate since in most cases the volume is calculated from the difference between the draught of the dredger or hopper before and after loading. The greater part of the material removed by dredging was taken from the bed of the estuary below the level of low water of a mean spring tide and the change in volume therefore did not directly affect the volume of water passing into and out of the estuary. The volume lost by the construction of shore works lay almost entirely below the high water mark of a mean spring tide and the volume lost therefore directly affects the scouring capacity. It is probable that over the period of accretion the capacity was affected more by the shore works than by dredging. Where the bed of the estuary below low water mark was lowered by dredging it seems probable that the effect was temporary and that material from Liverpool Bay filled the holes formed by dredging. This trend may have altered following 1977 when sediment no longer accreted in the estuary.

4.9 Bathymetric changes in Liverpool Bay

Considerable bathymetric changes occurred in Liverpool Bay through the late nineteenth and early twentieth century. At the end of the nineteenth century a rapid expansion of Askew Spit occurred on the inside of Crosby channel as the channel cut into Taylor's Bank following the introduction of dredging in the sea channels in 1890. At the same time Taylor's Bank Taylor's Bank advanced into the approach channel from the north. As a direct result of this a decision was taken to construct a training wall to stabilise the position of the Queen's and Crosby channels. Following the construction of the training walls a major redistribution sediment occurred in Liverpool Bay, with the changes between 1904-1977 illustrated in Figure 4.15.

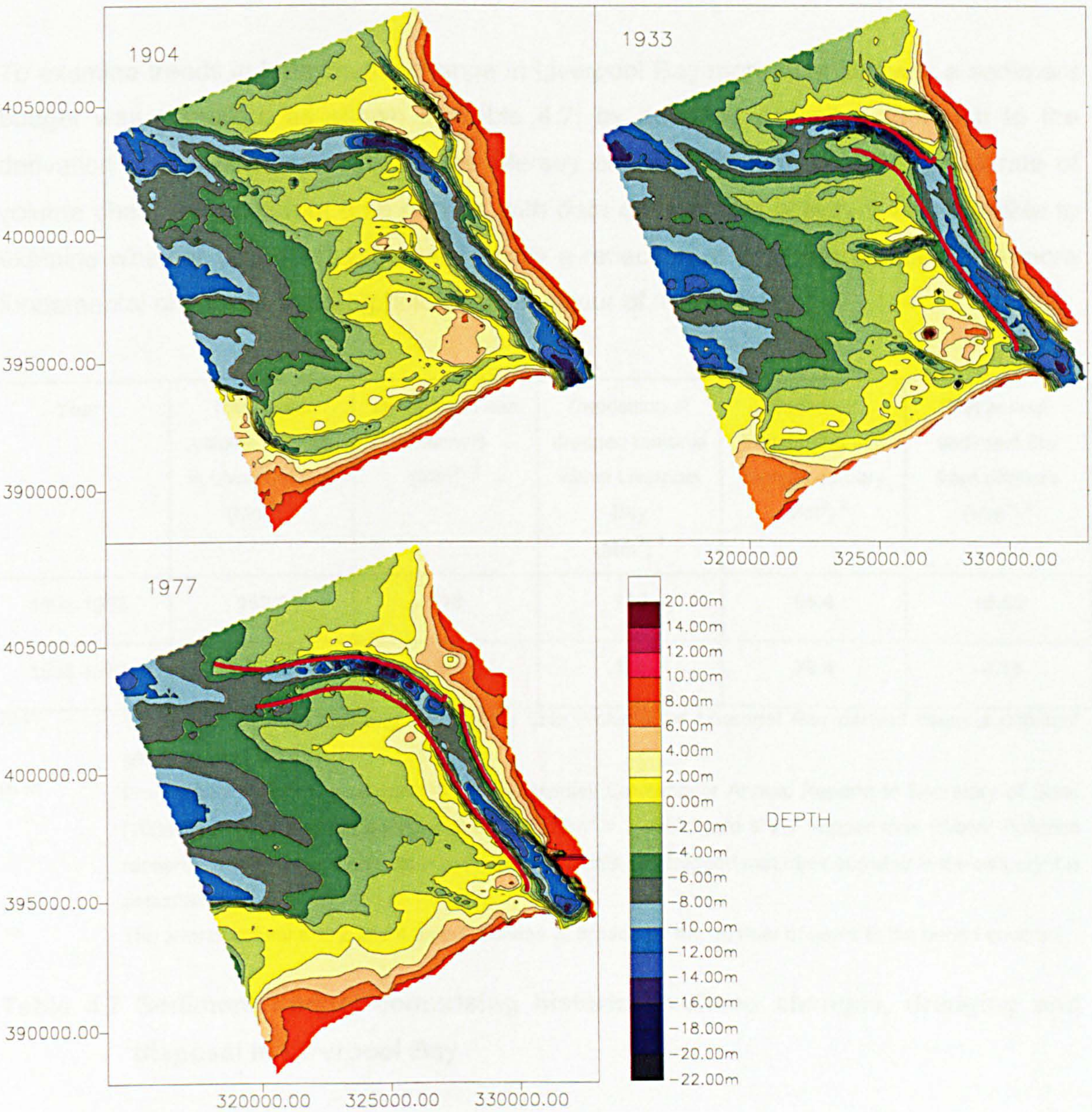


Figure 4.15 Bathymetry of Liverpool Bay 1904-1977

Figure 4.15 shows that after 1904 sediment accreted in the Rock and Formby channels, and in the channel through Great Burbo Bank and Little Burbo. By 1957 these channels had largely disappeared (Price and Kendrick, 1963). An increase in the height of Great Burbo Bank occurred in the vicinity of the training walls, and was such that the training wall was overtopped at both the northern and southern end of the bank (McDowell and O'Connor, 1977). Despite the accretion of sediment in low water channels other than the main navigation channel, however, it was evident that erosion occurred over a significant seaward area of Great Burbo Bank. The deep water area at the boundary of plots shown in Figure 4.15 penetrated further landwards in 1933, and the Great Burbo Bank clearly receded landwards between 1936-1977.

To examine trends in bathymetric change in Liverpool Bay more quantitatively a sediment budget was compiled, as shown in Table 4.7, by adopting a similar approach to the derivation of a sediment budget for the Mersey estuary. Through comparing net rate of volume change for different time periods with data on dredging activity it was possible to examine whether volume change was simply a reflection of dredging practice or a more fundamental change in the morphological behaviour of the system.

Year	Total water volume change in Liverpool Bay (Mm^3) [1]	Dredging in sea channels (Mm^3) [2]	Deposition of dredged material within Liverpool Bay (Mm^3) [3]	Sediment transported into Mersey estuary (Mm^3) [4]	Net annual sediment flux from offshore (Mm^3) [5]
1904-1933	**163.1**	**110**	**140**	**65.4**	**+6.62**
1933-1977	**-203.8**	**90**	**131**	**76.4**	**-4.11**

(1), (4) Totals derived from digitising bathymetric data, volume for Liverpool Bay derived using a constant geodetic level of 9m

(2), (3) From Water Pollution research (1938) and Mersey Conservator Annual Reports to Secretary of State (1939-79), using a rough approximation of $0.79m^3$ = 1 cubic yard ≡ 2.7 hopper tons (Water Pollution research, 1938). Where no data is available for quantity of dredged material deposited in the estuary it is assumed to be 0.

(5) The sum of columns 1, 2 and 4, minus column 3, divided by the number of years in the period covered.

Table 4.7 Sediment budget comprising historical volume changes, dredging and disposal in Liverpool Bay

Care had to be taken with analysis of these calculations, as an assessment of the overall changes in the bay was not straightforward. Firstly, the accuracy of surveys may have varied, and secondly, the situation was complicated by large-scale dredging and dumping in the area studied. There was some uncertainty as to whether the dredged material placed offshore was placed inside or outside the Liverpool Bay system. Based upon the evidence of a physical model by Price and Kendrick (1963), it was assumed that material placed at site 53, (see Figure 3.6). However, it is possible that some of the material placed at disposal site Z, behind Taylor's Bank, (see Figure 3.6) may have contributed to the system.

Between 1904-1933 a trend of net accretion of sediment in the Liverpool Bay signified a considerable influx of sediment into the Liverpool Bay area from offshore. Through the period 1933-1977 there was a reversal in the trend of sediment flux between Liverpool Bay and offshore. A significant decline in the volume of Liverpool Bay between 1933-1977 indicated large-scale movement of material seawards. It was likely, however, that a net seaward movement of sediment only occurred following 1955, as Price and Kendrick (1963) found that 10.5Mm^3 of sediment accreted in Liverpool Bay through the period 1936-1955. Hence, through the period of most significant accretion in the estuary between 1904-1955 there was a net movement of sediment into Liverpool Bay from offshore, which could have supplied a source of sediment for the observed accretion that occurred in the estuary.

The scale of dredging in Liverpool Bay was clearly significant with respect to morphological change. Between 1904-1933 the volume of material dredged from the sea channels was of a similar order of magnitude to the volume of accretion that occurred in Liverpool Bay. The volume of material removed by dredging was, however, largely balanced by the quantity of dredged material deposited in the Liverpool Bay area. Hence from the sediment budget it appeared that dredging activity had little net effect on morphological change in Liverpool Bay during the period 1904-1933. Through the period 1933-1977 the influence of dredging activity on overall morphological change in the Liverpool Bay was also limited, as the difference between the quantities of material dredged and deposited in Liverpool Bay was significantly less than calculated change in volume.

Dredging activity could, however, have exerted an influence upon morphological change in the Mersey estuary if dredged material was re-deposited in Liverpool Bay in an area where conditions were conducive for transport into the estuary. Dredged material would therefore have formed a source of sediment contributing to accretion in the Mersey estuary. Indeed the study of Price and Kendrick (1963) did suggest that this was the case, and that sediment deposited at site 53, was in an area subject to landwards transport of sediment in 1957. Whilst the examination of bulk volume change and dredging records could be used to provide a broad indication of the morphological behaviour and Mersey estuary and Liverpool Bay system, it was, therefore, clear that they could not provide a detailed elucidation of the causes of morphological change.

4.10 Chapter summary

The principal purpose of this chapter was to accurately quantify the nature of morphological change in the Mersey estuary through the period 1871-1997. Bathymetric data have proved of significant value, and a detailed investigation of volume change in the estuary has been undertaken to establish the sensitivity of calculation to measurement and analysis techniques. Overall the volume calculations for the Mersey estuary demonstrated a uniform trend of an approximately 10% decline in estuary volume between 1906-1977, although the precise calculations exhibited slight variation. Differences in interpolation techniques and resolution and correcting for errors in depth measurement resulting from using a lead line prior to 1946 resulted in a small percentage change to volume calculations. Larger variations in volume calculations resulted from adjusting calculations to represent variation in tidal levels along the estuary due to the significant variation in tidal propagation as the tide travels up the estuary. The most accurate volume computations presented in Section 4.5.3 were smaller than the volumes calculated by MDHC using Simpson's method, since employing a 3D surface map accounted for longitudinal variations in width and depth of the estuary. However, the magnitude of volume change calculated in Section 4.5.3 was comparable with the MDHC values.

The nature of morphological change was indicated with greater clarity through derivation of a sediment budget. Employing the most accurate computation of volume change presented in Section 4.5.3, it was evident from Table 4.6 that an influx of sediment consistently greater than 1.75Mm^3/annum occurred in the estuary between 1906-1977. Anthropogenic activity such as dredging and reclamation cannot account directly for this importation of sediment, so it is has probably been transported into the estuary by physical processes. Although the volume of the estuary increased between 1977-1997, the sediment budget indicated that this was predominantly accounted for by the removal of material from within the estuary by dredging. This suggests that the estuary may have attained a state of quasi-equilibrium between 1977-1997, with a relatively insignificant net flux of sediment occurring, indicating that the estuary has recovered from the effects of earlier perturbation.

Changes in the volume of the estuary between 1906-1977 are largely accounted for by changes in the intertidal area of the estuary, with relatively little change in subtidal volume compared to the overall magnitude of volume change. The nature of detailed geometrical changes in the estuary can reflect changes in tidal propagation through the estuary as a result of feedback between form and process. Examination of trends in integrated geometrical characteristics of the estuary in Table 4.4, demonstrated that there were significant changes in the system geometry of the estuary, with implications for the hydrodynamic and sediment regimes in the estuary. Of critical importance to potential morphological evolution is the balance between the rate of changes in width and depth of subtidal and intertidal areas: a relatively greater decrease in the depth of the estuary indicates that hydrodynamics should shift toward flood dominance, and a relatively greater decrease in the width of the estuary indicates that hydrodynamics should shift toward ebb dominance. The relation of these changes according to parameters proposed by Dronkers (1998) and Friedrichs and Aubrey (1988) indicated that tidal propagation became increasingly flood dominant between 1906-1977, which is not indicative of a reduction in the quantity of sediment imported into the estuary. From analysis of changes in the form of the estuary based upon examination of bathymetric survey data, it is not possible to distinguish between the cause and effect of morphological change. To examine the causes of morphological evolution, and the principal forcing factors determining the gross behaviour of the estuary a more thorough examination of historical changes in physical process behaviour is required, as undertaken in Chapters 5 and 6.

CHAPTER 5 EVOLUTION OF ESTUARINE HYDRODYNAMICS

5.1 Introduction

The availability of historical hydrographic surveys enables comparison of historical hydrodynamic regimes by applying numerical hydrodynamic models to estuary bathymetric configurations. Due to a scarcity of observed historical data on physical processes for direct analysis, this provides the most suitable means for examining changes in flow conditions. A range of modelling tools may be employed to represent estuary hydrodynamics employing different assumptions and degrees of representation of the physical processes occurring in an estuary. If applied properly, modern numerical models can provide robust tidal hydrodynamic predictions. However, a balance is required between cost, particularly in terms of computational time, and degree of simplification of the estuary system. Multi-dimensional models may not be cost effective in treating simple channel flow but conversely oversimplified models may be unable to simulate fine details in multi-dimensional time dependent processes (Cheng *et al.*, 1991).

This section of study examined the value of results that may be obtained using different model representations of the estuary and Liverpool Bay with respect to understanding the causes of changes in the physical morphology of the Mersey estuary. Model simulations were undertaken for three periods:

- Bathymetric data covering the estuary for 1906 with data from 1904 for Liverpool Bay.
- Bathymetric data covering the estuary for 1936 with data from 1933 for Liverpool Bay.
- Bathymetric data covering the estuary for 1977 with a combination of survey data recorded in the late 1970's and early 1980's covering Liverpool Bay.

These three periods were chosen because significant change occurred between each time interval and suitable surveys for Liverpool Bay and the estuary were available to document these changes. The simulations isolated the interaction between system geometry and physical process, particular attention was paid to changes in flow parameters within the estuary, and to changes in flow interaction between the estuary and broader seaward environment. The modelling tools were analysed for their ability to represent relative changes in hydrodynamic conditions resulting from changes in historic bathymetries.

5.2 Description of modelling tools

Different approaches to the representation of an estuary for the purposes of modelling hydrodynamic flows were discussed in detail in Section 2.7.1. For the purposes of this research, a hierarchical approach was adopted beginning with a simple 1D representation of the estuary system moving to a more detailed 2DH representation, and then an increasingly detailed 3D representation of the hydrodynamic flow field. The spatial scale of the modelled area comprised the estuary and offshore area. Four models were employed and the hydrodynamic performance of each evaluated within a context of its utility for examining relative trends in hydrodynamics for historical bathymetric configurations. The four models were:

- A 1D model of the Mersey alone with an observed tide of approximately mean spring range as a boundary condition.
- A 2D model of the Mersey alone, provided by HR Wallingford, with an observed tide of approximately mean spring range as a boundary condition.
- A 2D model of the Mersey estuary and Liverpool Bay extending approximately 55km offshore with a harmonic derived tide for the day of the observed tide obtained from a larger scale model of the Irish Sea.
- A 3D model of the Mersey estuary and Liverpool Bay extending approximately 55km offshore with a harmonic derived tide for the day of the observed tide obtained from a larger scale model of the Irish Sea.

5.2.1 1D modelling

The simplest approach to representing hydrodynamic flow in an estuary involves specifying a sequence of parallel cross-sections separated by varying distances (Cunge and Rahuel, 1994). Cross-section averaged flow characteristics were calculated by solving equations derived from the St Venant equations for shallow water waves in open channel flow using ISIS software (Halcrow/HR Wallingford, 1999). In order to achieve reasonable simulations using a one-dimensional approach an estuary needs to fulfil certain criteria; the ratio of tidal prism to freshwater needs to be high to prevent stratification or salt wedges developing, and tidal amplitude must be sufficient to induce vertical mixing. Both of these criteria are met in the Mersey estuary implying that the estuary meets the assumptions required for a 1D model, which are that, at a single point in time, the estuary is a vertically and horizontally homogenous environment. However, studies have shown that stratification effects do exist in the estuary, particularly in the Narrows area (Price and

Kendrick, 1963) and also extending into Liverpool Bay (Czitrom, 1986) and that these effects can have a significant effect upon sediment transport (Price and Kendrick, 1963). 1D models have been employed in other studies to predict velocity trends using system geometry and elevation data (Aubrey and Friedrichs, 1988).

5.2.2 2D modelling

The most commonly applied form of flow model is a 2D model that vertically averages flow through depth but allows for lateral variation in flow. To model estuary hydrodynamics in this study, shallow water equations were solved using a finite element method employing the TELEMAC system developed by Laboratoires Nautiques et Hydrauliques (LNH), Paris (Hervouet and Van Haren, 1994). TELEMAC 2D computes hydrodynamics as horizontal depth-averaged velocities and water depth, by solving the Navier Stokes equations in two dimensions. Many physical phenomena can be taken into account including friction, turbulence, wind velocity and variations of atmospheric pressure. The TELEMAC system uses a completely unstructured grid providing the user with maximum control of the model resolution. A fine grid can be used in an area of interest and larger elements used to keep any imposing boundary conditions distant from the area of study. It is also important to balance the demands of a detailed bathymetry represented by a fine mesh with computational efficiency that is better served with a coarser mesh.

5.2.3 3D modelling

To model estuary hydrodynamics in 3D, shallow water equations were solved using TELEMAC-3D, a finite element method developed by LNH. A general description of TELEMAC-3D is given by Hervouet *et al.* (1994). The TELEMAC-3D code solves the three-dimensional Navier Stokes equations with a free surface boundary condition and the advection diffusion equations of temperature, salinity and any other required variables. Physical phenomena that affect flow may be represented including the influence of temperature and salinity on density, wind stress on the free surface, heat exchange with the atmosphere and the Coriolis force. The model domain discretization comprises quadrangular prisms with vertical sides, so the planform of the mesh is the same as for TELEMAC-2D. To mesh the 3D domain, the 2D domain is meshed and then replicated through the vertical avoiding the need for a 3D mesh generator. For every point M(x,y) of the 2D mesh several points are defined N(x,y,z) for which:

$$z = Z_f(x,y) + \vartheta(S(x,y,t) - Z_f(x,y)) \quad \text{with } 0. \leq \vartheta \geq 1. \qquad \text{Eq. 5.1}$$

The number and magnitude of the values of ϑ are selected by the user with the only compulsory requirements that $\vartheta = 0$ (the bottom) and $\vartheta = 1$ (the free surface). TELEMAC-3D is able to deal with the effects of a vertical density resulting from temperature and/or salinity fluctuations. Difficult problems such as the simulation of a salt wedge, or the turbidity maximum in an estuary can be tackled.

5.3 Validation calibration and verification of model tools

Model validation refers to testing of models against data, and, if required, subsequent amendments to the model to improve simulations. Verification is often used interchangeably with validation. However, the precise meaning of validation may vary in different contexts, and is frequently not specified, or specified with only a loose definition (Southgate and Brampton 2001). In academic research validation refers to testing the accuracy of model predictions against detailed data sets or closed analytical solutions. In engineering applications validation refers to the usefulness of model simulations in real or simulated engineering design problems. Validation also refers to the intended scope of the model, and may be defined on two different scales:

- Global Validation. The objective for most models is to derive generic tools for application to a range of physical settings. A thorough validation exercise would therefore require that the full range of intended applications of the model had been explored, and that within these limits the user can be confident of the results obtained.
- Local Validation. The application of a model to a particular investigation requires a validation that is considerably reduced from that required for the full range for which the model is designed. Validation for this specific use of the model therefore needs to focus only on the parameter ranges that pertain to that use.

The tools employed in this study are commercially available and have been applied to a wide range of applications in academic research and commercial consultancy projects including studies of estuaries and may, therefore, be considered to have been globally validated for the purposes of this study. The objective of this study was, therefore, to achieve local validation of the model for application to the specified area of Liverpool Bay and the Mersey estuary.

In order to achieve localised validation of the model, it had to be calibrated, involving repetitive simulation of past, observed events for a given water course, while the empirical and otherwise defined coefficients are modified until an acceptable reproduction is achieved. A model's potential for reproducing and predicting real flow events, and the potential quality of its calibration depends on the amount and quality of topographical, topological and hydraulic data available. If topography is represented with 100% accuracy only the empirical coefficients in the conveyance equation should require tuning. However, such an ideal situation rarely exists and model calibration may require adjustments of the representation of geometric elements or modification of the boundary conditions.

The first alternative for calibrating a model is to modify the empirical coefficients for roughness, and, in 3D models, turbulence. The lack of reproduction of observations may alternatively be due to discretization in time or space, which may be improved by adjusting the model time step. Inadequate representation of geometry and topology may also explain inadequate model performance, and through altering model resolution of estuary geometry improvements may be achieved. Finally the lack of coincidence may be a result of the inadequacy of the basic hypothesis. In the case of 1D modelling for example it is possible that the cross-sectional form of an estuary is too complex to be represented one-dimensionally. During calibration it is thus possible to obtain a similar degree of coincidence in different ways. If the methods used correspond to physical reality the predictive capability of the model increases, if not, the utility of the model is compromised.

In applying models to historical scenarios there is often no historic data against which to compare the model and thus no means of determining that the model is faithfully reproducing the physical processes. This is particularly relevant to the boundary conditions that may have changed over time or changes in sediment characteristics within the model domain, which may have altered friction characteristics. Field data are often quite noisy, incorporating some natural variability, so subjective judgements are required in adjusting model parameters to achieve satisfactory calibration. The model of the 1977 bathymetry was calibrated to spring tidal level measurements recorded simultaneously at several points along the estuary by West (1980). This model was then validated by running the model for a neap tide and comparing tidal levels with neap tidal level measurements recorded simultaneously at several points along the estuary by West (1980). Parameter values providing satisfactory calibration to the observed data were then applied to models for other bathymetries. Detailed calibration and validation data for 1D, 2D and 3D models is presented in Appendix 1.

Tidal currents vary naturally both temporally and spatially, and given these variations model results cannot be expected to match particular data sets exactly, but must reproduce the essential features of the observations. Attention should be given to the source of observations employed for calibration. For example, allowance should be made for the height of current meters in the vertical profile. The source of data employed must also be carefully considered. Tidal Diamond data on Admiralty Charts was employed in this study where no suitable alternative was available, and may be derived from a wide range of sources. Some Tidal Diamond measurements may have been made from recording current meters, but the most common method employed by the Admiralty is the logship. This consists of a staff weighted at one end such that it floats vertically. Movements of the logship are tracked and speeds calculated. Speeds derived in this way are averages over the upper portion of the water column. Measurements are usually made on mean spring tides, and neap tide values are obtained by scaling. The basis of the Admiralty method is to provide the navigator with information on the currents that will influence a ship, not to provide data for numerical models, and they must therefore be employed with an element of caution.

5.4 Application of hydrodynamic models

Four hydrodynamic models were set up according to the criteria set out in Section 5.2. The first stage of modelling comprised a 1D representation of flow, this was the simplest approach, and can be applied to channels that can be represented as a sequence of cross-sections. The approach was unsuited to modelling irregular shapes or unconstrained areas. A 2D model of the estuary was set up to compare model reproductions of flows for 1D and 2D simulations. The effect of moving the boundary condition offshore was examined by extending the model domain for the 2D model to include Liverpool Bay, employing bathymetric measurements of Liverpool Bay and Admiralty data for seaward areas. Finally, a 3D model of Liverpool Bay and the Mersey estuary was set up to examine the influence of gravitational circulation upon tidal flow, which was not represented in 1D or 2D modelling approaches.

The 1D model was run for 9 repeating tidal cycles to provide a run-in period prior to the analysed tide. 2D and 3D models were run for two spring tides using a repeated cycle starting from high water, due to the more extensive computational requirements. The main source of uncertainty in the numerical modelling was in defining calibration parameters, model resolution and boundary conditions. Boundary conditions can be specified in three different respects:

- **Seawards boundary**. As an ideal most models require (or tacitly assume) uniform hydrodynamic and sediment conditions along a specified seaward boundary. This may also imply uniform depths or deep water along that boundary. However, there are rarely any data to support these assumptions and the sensitivity of model results was examined by moving the boundary offshore.
- **Landwards boundary**. Specifying landwards boundary conditions is usually much simpler than along the seawards boundary. In the cases examined in this study fluvial flow and sediment input was an order of magnitude less than tidal flow and fluvial sediment input and was considered to have a negligible effect for the purposes of the analyses undertaken.
- **Lateral boundaries**. Specifying lateral boundaries can present problems where bathymetric data coverage of intertidal areas is poor. In these cases assumptions are required concerning the positions of the high water boundary. In the case of this study this did not present significant difficulties as the area under investigation is largely comprised of engineered boundaries, which have not altered significantly over time.

The stages of the study were repeated for each modelling approach and consisted of:

- Gathering available data
- Constructing a model for the 1977 bathymetry
- Running the model, calibrating against tidal elevation and/or current data for a spring tide for 1977
- Validation of the model against neap tide data for 1977
- Building a replicated model for 1906 and 1936 bathymetries
- Running the model for 1906 and 1936 using identical calibration parameters and boundary conditions

It was particularly important to establish boundary conditions that were independent of physical process behaviour within the area of prime interest. However, while the area under investigation may be clearly identified, in many situations it is difficult to discern the extent of the area over which physical processes are interacting to control morphology. A significantly larger model domain area frequently had to be included to allow boundary conditions to be accurately represented.

5.4.1 1D model of Mersey estuary

The 1D model of the Mersey estuary consisted of 160 elements of varying length (see Figure 5.1) comprising the measured survey data, which was recorded in cross-section form.

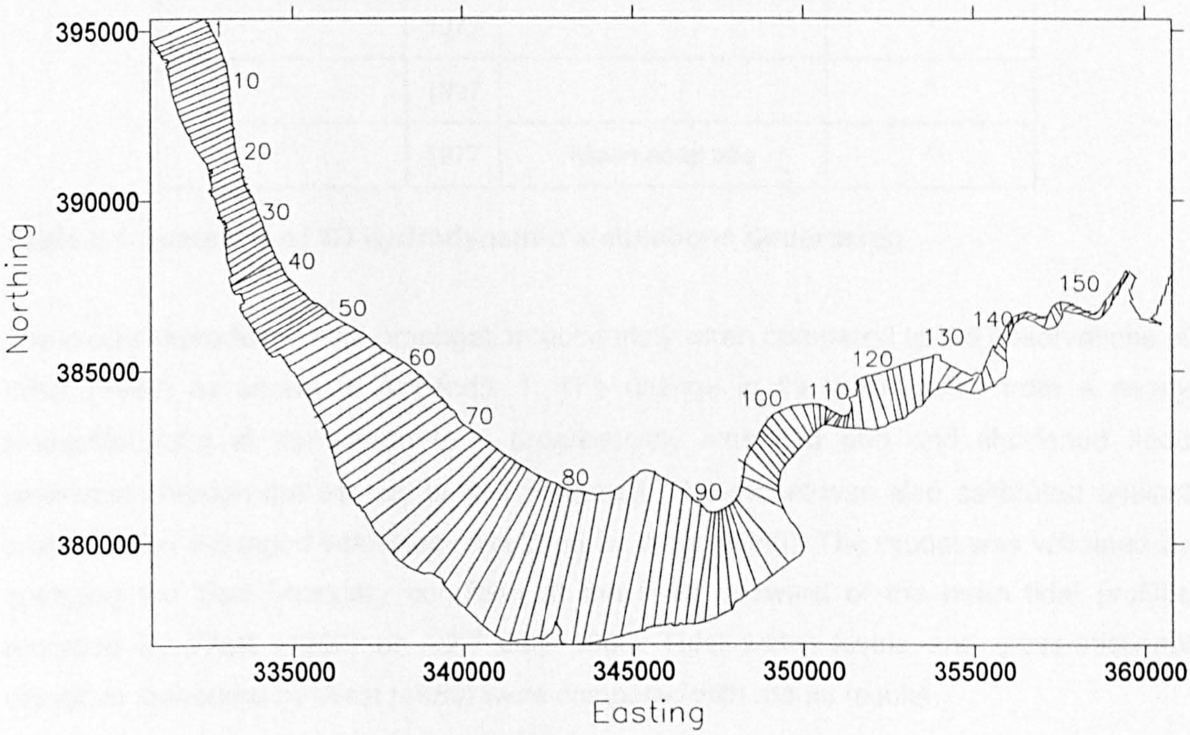


Figure 5.1 Cross-section locations for the 1D model of the Mersey estuary

The model extended from the mouth of the Narrows to the tidal limit. The model approach assumes that water level is constant across the estuary for the specified cross-sections, and predicts a mean water level along the cross-section. The boundary condition was specified as the most seaward of the tidal profiles observed by West (1980). During calibration of the models employed in this study, model parameters were adjusted to give the best fit to field observations of tidal levels recorded by West (1980) recorded for a tide on 29th July 1980 of approximately mean spring range (8.5m). Calibration of the tidal level was achieved for the 1977 bathymetric configuration using a bed roughness length of 0.025 for Cross-sections 1-88 and 0.015 for Cross-sections 89-161. These values corresponded with an estuary that becomes smoother upstream. The range of simulations undertaken using a 1D model of the Mersey estuary are summarised below in Table 5.1.

Domain area	Year	Tidal condition	Training wall
Mersey estuary	1871	Mean spring tide	N/A
"	1906	"	"
"	1936	"	"
"	1956	"	"
"	1977	"	"
"	1997	"	"
"	1977	Mean neap tide	"

Table 5.1 Summary of 1D hydrodynamic simulations undertaken

The model reproduced tidal propagation accurately when compared to the observations of West (1980) as shown in Appendix 1. The change in the tidal profile from a nearly sinusoidal form at the mouth to a progressively extended ebb and shortened flood landwards through the estuary is well produced. The model was also calibrated against cross-section averaged velocities calculated by West (1980). The model was validated by changing the tidal boundary condition at the most seaward of the neap tidal profiles recorded by West (1980) on 22nd July 1980. Tidal water levels and cross-sectional velocities measured by West (1980) were compared with model results.

5.4.2 2D model of Mersey estuary

The 2D model of the Mersey estuary provided by HR Wallingford, represented wetting and drying of intertidal areas in greater detail than the 1D approach and also variations in water level across the estuary. The estuary bathymetry was interpolated onto a finite element grid (see Figure 5.2), and therefore did not represent the same actual bathymetry as the 1D model.

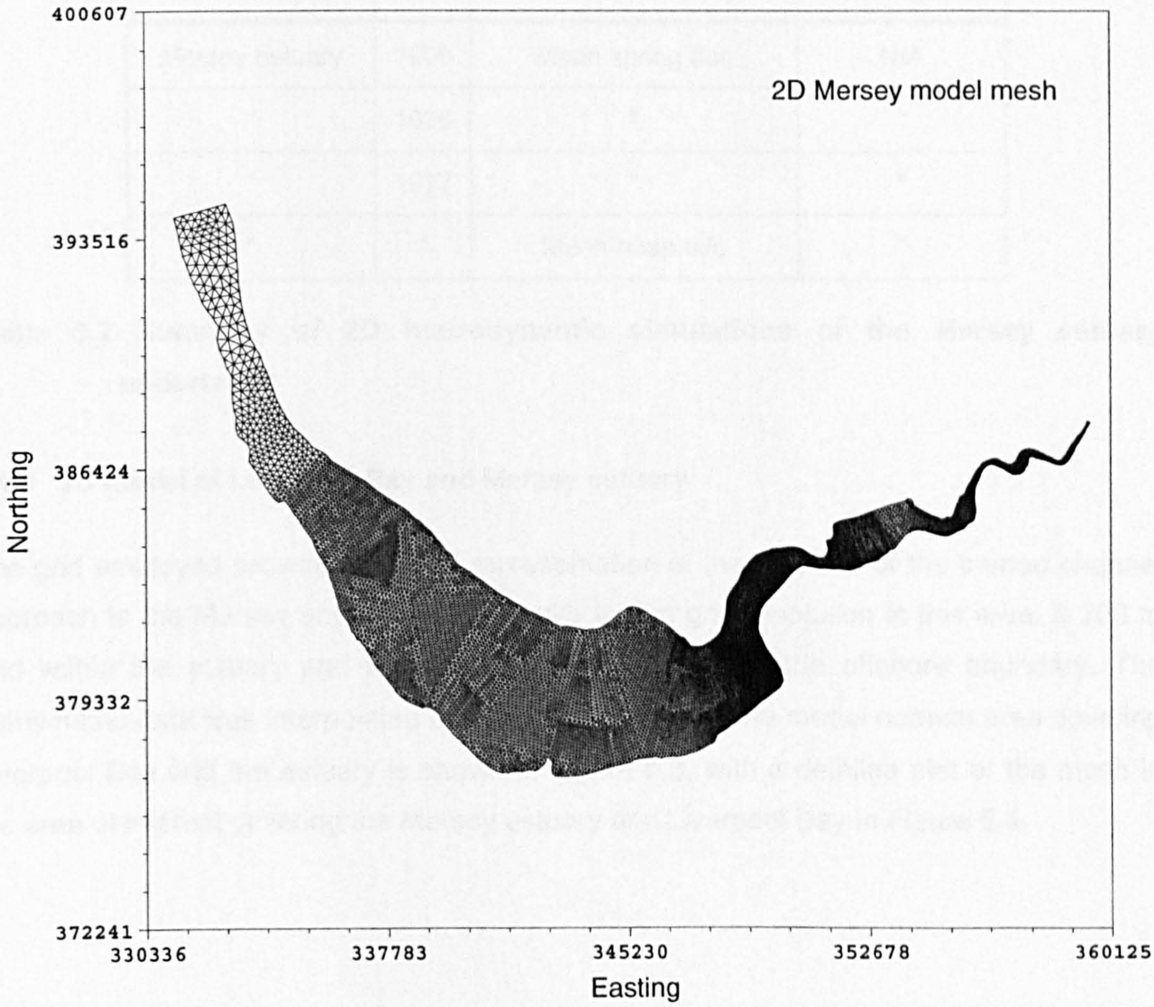


Figure 5.2 Mesh for the 2D model of the Mersey estuary only

The model employed the same tidal boundary condition as the 1D model and calibration was achieved using a bed roughness length of 0.005. The 1977 configuration was calibrated against tidal level data recorded by West (1980), and depth–averaged velocity measurements recorded through a mean spring tidal cycle recorded in the Narrows and inner estuary areas. The model was validated for the 1977 configuration against neap tidal profiles recorded by West (1980) and neap tidal velocity data. The range of simulations results available for the 2D model of the Mersey estuary are summarised below in Table 5.2.

Domain area	Year	Tidal condition	Training wall
Mersey estuary	1906	Mean spring tide	N/A
"	1936	"	"
"	1977	"	"
"	"	Mean neap tide	"

Table 5.2 Summary of 2D hydrodynamic simulations of the Mersey estuary undertaken

5.4.3 2D model of Liverpool Bay and Mersey estuary

The grid employed provided detailed representation of the features of the trained channel approach to the Mersey and the Narrows with a 75m grid resolution in this area, a 200 m grid within the estuary and a grid extending to 1.5km at the offshore boundary. The bathymetric data was interpolated onto the model mesh. The model domain area covering Liverpool Bay and the estuary is shown in Figure 5.3, with a detailed plot of the mesh in the area of interest covering the Mersey estuary and Liverpool Bay in Figure 5.4.

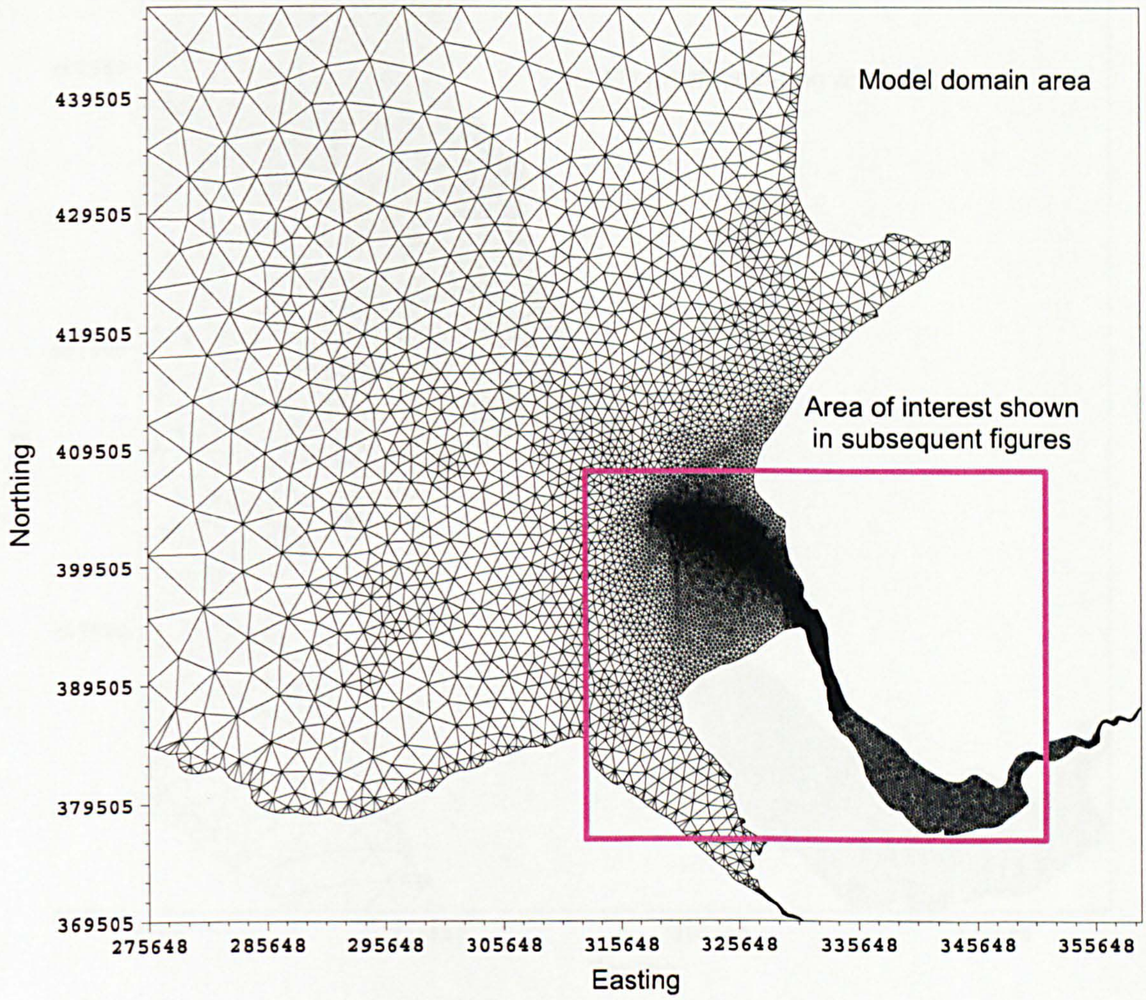


Figure 5.3 Model domain area for 2D and 3D models of Mersey estuary and Liverpool Bay

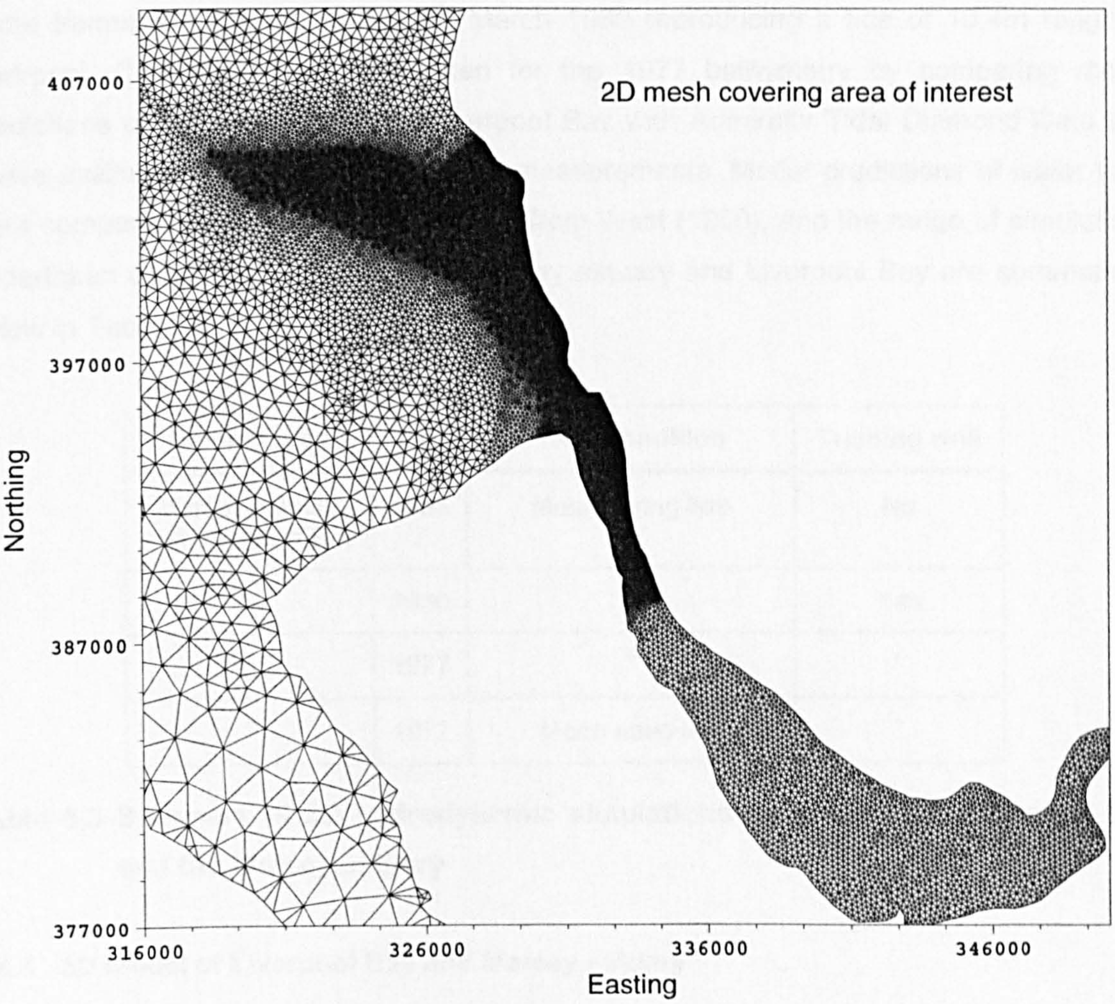


Figure 5.4 Detailed mesh structure in area of interest for 2D model of Mersey estuary and Liverpool Bay

The boundary conditions were obtained by running a 2D numerical model of the Irish Sea with open boundaries at the Northern and Southern ends. The boundary conditions for the Irish Sea model were derived from harmonic constant data for Belfast, Dublin and Holyhead (see Appendix 2) to derive a spring tide for the day of the observed tide, 29th July 1980. The Irish Sea Model was calibrated against observed elevation and velocity data and showed good agreement in the area of Liverpool Bay. The same boundary condition was employed for the 1906 and 1936 bathymetry models as it reproduced a tidal range of 8.6m at Liverpool approximately equivalent to a mean spring tidal range for Liverpool of 8.5m given by the Hydrographer of the Navy (1977). To provide boundary conditions for a mean neap tide, the Irish Sea model was run with the same harmonic constituents for 22nd July 1980 reproducing a tide of 4.4m range, approximately equivalent to a mean neap tidal range for Liverpool of 4.5m given by the Hydrographer of the Navy

(1977). To provide boundary conditions for a HAT, the Irish Sea model was run with the same harmonic constituents for 18th March 1980 reproducing a tide of 10.4m range at Liverpool. Calibration was undertaken for the 1977 bathymetry by comparing model predictions of current velocities in Liverpool Bay with Admiralty Tidal Diamond Data and where available depth averaged velocity measurements. Model predictions of water level were compared with measurements taken from West (1980), and the range of simulations undertaken using a 2D model of the Mersey estuary and Liverpool Bay are summarised below in Table 5.3.

Domain area	Year	Tidal condition	Training wall
Mersey estuary and Liverpool Bay	1906	Mean spring tide	No
"	1936	"	Yes
"	1977	"	"
"	1977	Mean neap tide	"

Table 5.3 Summary of 2D hydrodynamic simulations undertaken of Liverpool Bay and the Mersey estuary

5.4.4 3D model of Liverpool Bay and Mersey estuary

Both 2D and 3D modelling approaches employed an unstructured mesh, and employed the same model domain, but a lower resolution grid was employed for the 3D model (see Figure 5.5) for the purposes of computational efficiency. The 3D model incorporated 5 layers to resolve the vertical variation in flow, comprising the surface, just above the bed and three further layers spaced equally through the water column. As the model employed a sigma system, coverage of the intertidal areas comprised all five layers. The same seaward boundary conditions were applied to both the 2D and 3D models. Identical calibration parameters were applied to the flow model representing each bathymetric configuration so differences in calculated flow conditions result from system geometry alone. The model employed a finite element mesh extending to a boundary approximately 40km offshore. Flow conditions were represented 3 dimensionally, resolving full horizontal and depth variation of flow.

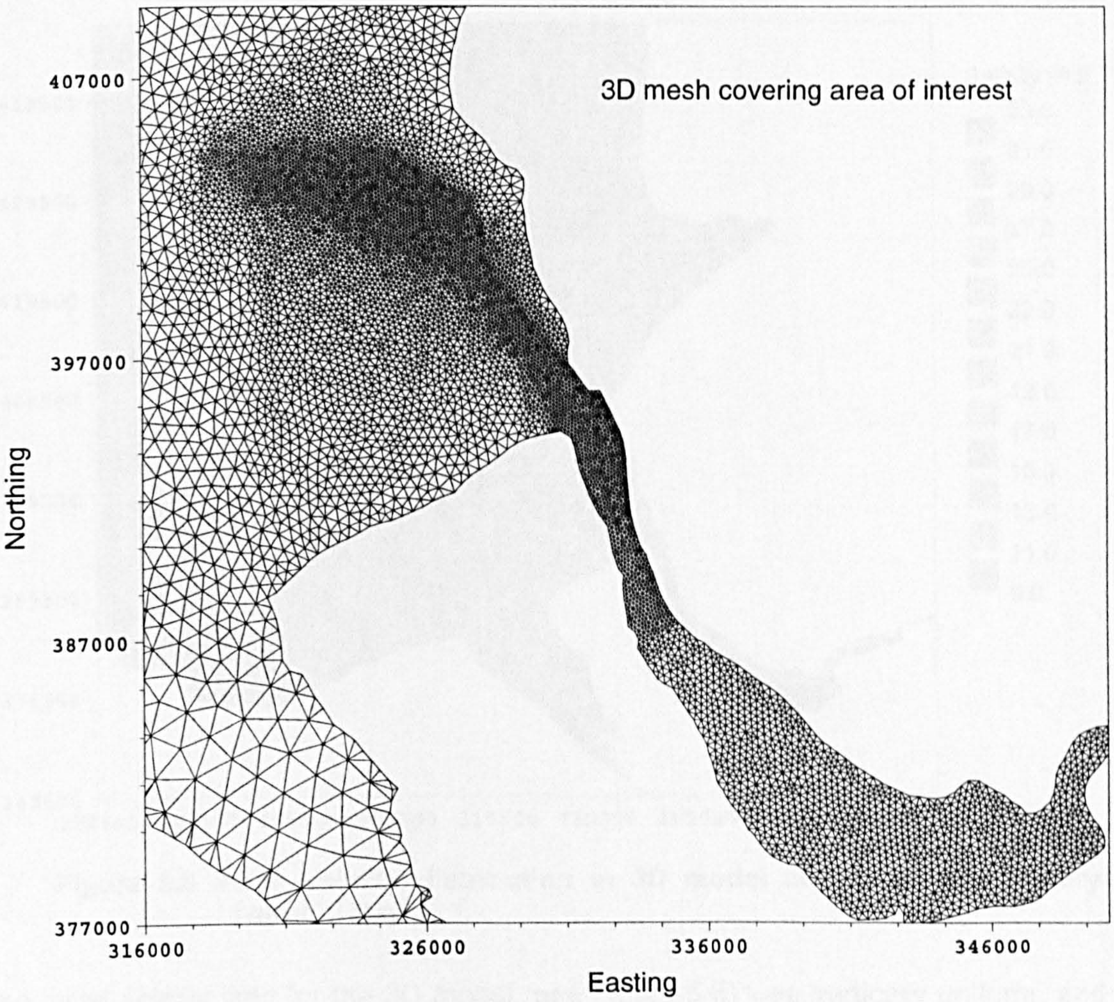


Figure 5.5 Detailed mesh structure in area of interest for 3D model of Mersey estuary and Liverpool Bay

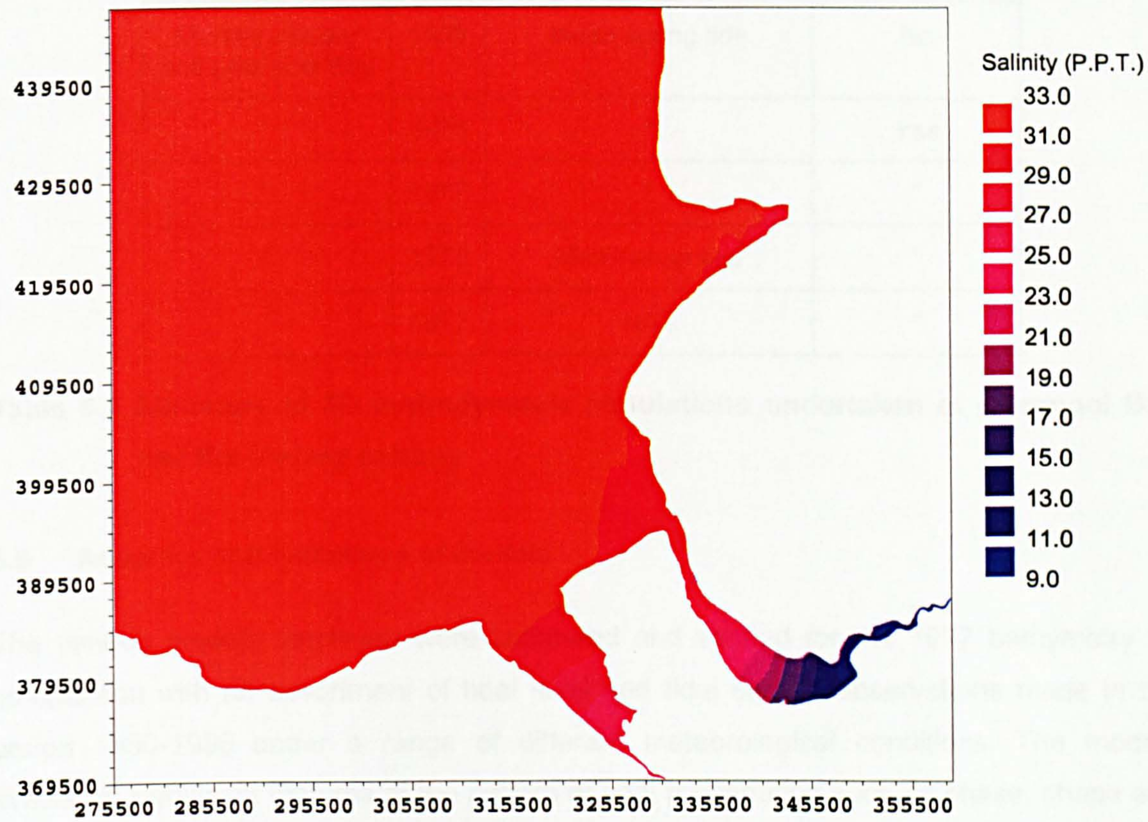


Figure 5.6 Initial salinity distribution in 3D model of the Mersey estuary and Liverpool Bay

The initial salinity field for the 3D model (see Figure 5.6) was vertically uniform, and was prescribed according to data derived from several sources (Heaps and Jones, 1977; Winters, 1984; Ramster, 1975; WPRB, 1938). No freshwater flow was prescribed for the models; the 3D model was dependent upon the provision of freshwater given in the initial conditions to drive density induced circulation patterns. The model was run for a period sufficiently short that there was no significant decay in stratification in the system although salinity was slightly redistributed during the simulation. The surface momentum flux (wind stress) was prescribed as zero for all model simulations. The range of simulations undertaken using a 3D model of the Mersey estuary and Liverpool Bay are summarised below in Table 5.4.

Domain area	Year	Tidal condition	Training wall
Mersey estuary and Liverpool Bay	1906	Mean spring tide	No
"	1936	"	Yes
"	1977	"	"
"	1977	Mean neap tide	"
"	1977	HAT	"

Table 5.4 Summary of 3D hydrodynamic simulations undertaken of Liverpool Bay and the Mersey estuary

5.5 Accuracy and limitations of models

The various models employed were calibrated and verified for the 1977 bathymetry by comparison with an assortment of tidal level and tidal current observations made in the period 1980-1990 under a range of different meteorological conditions. The models simulated significant features of the pattern of tidal propagation such as phase, shape and amplitude of the vertical tide and phase shape and amplitude of tidal currents, with direction of tidal currents represented in 2D and 3D models. The 2D and 3D model results did, however, exhibit limitations with regard to representation of the ebb tide, and the peak of the flood tide.

The models represented certain features of tidal propagation to differing degrees of accuracy. The 1D (cross-sectionally averaged model) provided accurate simulation of tidal elevation amplitudes and cross-sectionally averaged currents for most of the estuary and performed better in relation to observed data than the 2D and 3D models in the upper estuary. However, the 1D model demonstrated significant deviations from observed data at Stanlow, which may be attributed to the curvature of the estuary at this point, a feature that could not be represented in the 1D model as it assumes a straight channel of parallel cross-sections. The 2D (vertically averaged models) afforded significant advantages over the 1D by resolving pronounced lateral variations in flow. It was apparent, however, that the 2D models were least accurate in the upper estuary, a probable consequence of the inability of the model mesh to resolve important details of the bathymetry. The 3D model employed the same algorithms as the 2D model to calculate water level and thus exhibited similar limitations in representing tidal elevation in the upper estuary.

The 1D model exhibited similar difficulties in reproducing cross-sectionally averaged velocities as it did in simulating tidal elevations, which may also be attributed to its inability to represent the curvature of the estuary. The 2D model of the Mersey only broadly reproduced observed patterns of velocity although observations were only available in the Narrows and Basin area of the estuary where it has been noted that the model was more accurate. The 2D and 3D models including Liverpool Bay broadly reproduced observed current amplitudes. Some discrepancy was visible in model reproduction of flow data for Admiralty Diamonds (see Appendix 5), particularly for Diamond J where the modelled current amplitude was too small. The important factor was that the broad trends of the Admiralty data were reproduced. In comparison with observed data in the trained channel and Narrows the model performed satisfactorily, and it was possible that observed data employed for calibration was influenced by meteorological and other factors as discussed in Section 2.4.

Despite the shortcomings of the model results, they were adjudged representative for the purposes of this study due to their consistency with other sources of information. To improve the performance of the 2D and 3D models the main option remaining was to apply subtle adjustments to the model mesh to ensure that it represented important features of the bathymetry. Such an approach was not suitable for this study, as it did not enable the model mesh to be applied to different bathymetries to examine changes in tidal propagation resulting from changes in the form of the estuary.

5.6 Analysis of hydrodynamic flow computations

Hydrodynamic flow computations may be analysed both quantitatively and qualitatively. In this section two principal characteristics of flow patterns were examined. The initial feature of hydrodynamics analysed comprised examination of tidal distortion in the Narrows area of the estuary. The Narrows represented an important area because it links the estuary with the seaward environment, and hence acts as a conduit for sediment into and out of the system. The purpose of the analysis was to identify a contiguous area influencing tidal propagation through the Narrows, which has significant implications for the specification of tidal boundary conditions. Comparing trends in the model representations of tidal distortion enabled the nature of historical changes in tidal propagation, and the ability of modelling approaches to represent them to be discerned. Extending the analysis to examine tidal distortion within the inner estuary then enabled identification of the relative effects on tidal distortion of tidal boundary conditions and changes in bathymetric configuration within the estuary.

The second element of analysis comprised analysis of hydrodynamic changes relevant to issues of sediment transport. The evolution of hydrodynamic flow patterns had implications for sediment transport patterns. As tidal asymmetry is considered to exert a significant influence upon sediment transport patterns the correlation between modelled tidal asymmetry and sediment transport patterns was investigated. Due to the non-linear relationship between sediment transport rate and flow velocity, which is often expressed in a form which is proportional to $(\text{velocity})^3$, the magnitude of peak current velocities has significant importance for sediment transport rate. However, sediment transport is also determined by characteristics such as the duration of flood and ebb tides. To examine more fully the changes in hydrodynamics with regard to sediment transport processes, qualitative changes in current velocity profiles through a tidal cycle for locations within the Narrows were assessed.

5.6.1 Sea surface elevation M2/M4 harmonics

It has been established that distortion of a tide propagating into a shallow water area can be represented by the non-linear growth of compound constituents and harmonics of the principal tidal components (e.g., Dronkers, 1964; Speer and Aubrey, 1985). The dominant astronomical constituent for most of the world's coastline including the UK is M2, the semi-diurnal lunar tide, and thus the most significant overtide is M4, the first harmonic of M2.

The distorted sea-surface height A can be modelled by a superposition of M2 and M4:

$$A = a_{M_2} \cos(\omega t - \vartheta_{M_2}) + a_{M_4} \cos(2\omega t - \vartheta_{M_4}) \qquad \text{Eq. 5.2}$$

where t is time, ω is tidal frequency, a is amplitude of tidal height and ϑ is phase of tidal height. The sea surface phase of M4 relative to M2 is defined as

$$2M_2 - M_4 = 2\vartheta_{M2} - \vartheta_{M4} \qquad \text{Eq. 5.3}$$

The M4 to M2 sea-surface amplitude ratio represents a direct measure of non-linear distortion, defined as:

$$M_4 / M_2 = a_{M4} / a_{M2} \qquad \text{Eq. 5.4}$$

An undistorted tide has M4/M2 amplitude ratios of zero (Friedrichs and Aubrey, 1988). The larger the M4/M2 ratio, the more distorted the tide and more strongly flood or ebb dominant the system becomes. Assuming that a linear relationship exists between M4 and M2 tidal constituents, a flood dominant system has a sea-surface phase of 0°-180° (see Figure 5.7). If M4 is locked in a sea-surface phase of 180°-360°, the relationship is reversed, resulting in an ebb-dominant system.

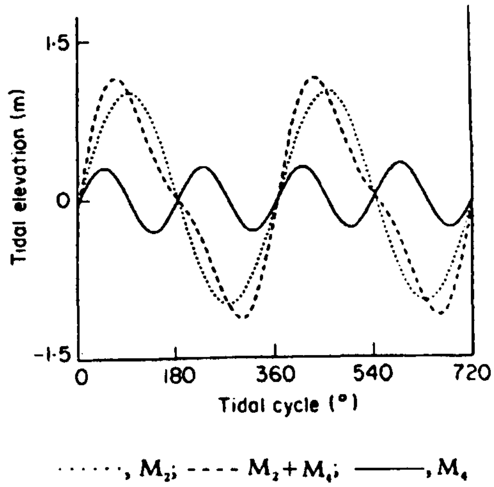


Figure 5.7 Model of a flood dominant distorted tide: M4/M2 sea-surface amplitude ratio=0.3, 2M2-M4 relative surface phase=90° (after Friedrichs and Aubrey, 1988).

The relationships between M2 and M4 sea-surface phase and amplitude are summarised in Figure 5.8.

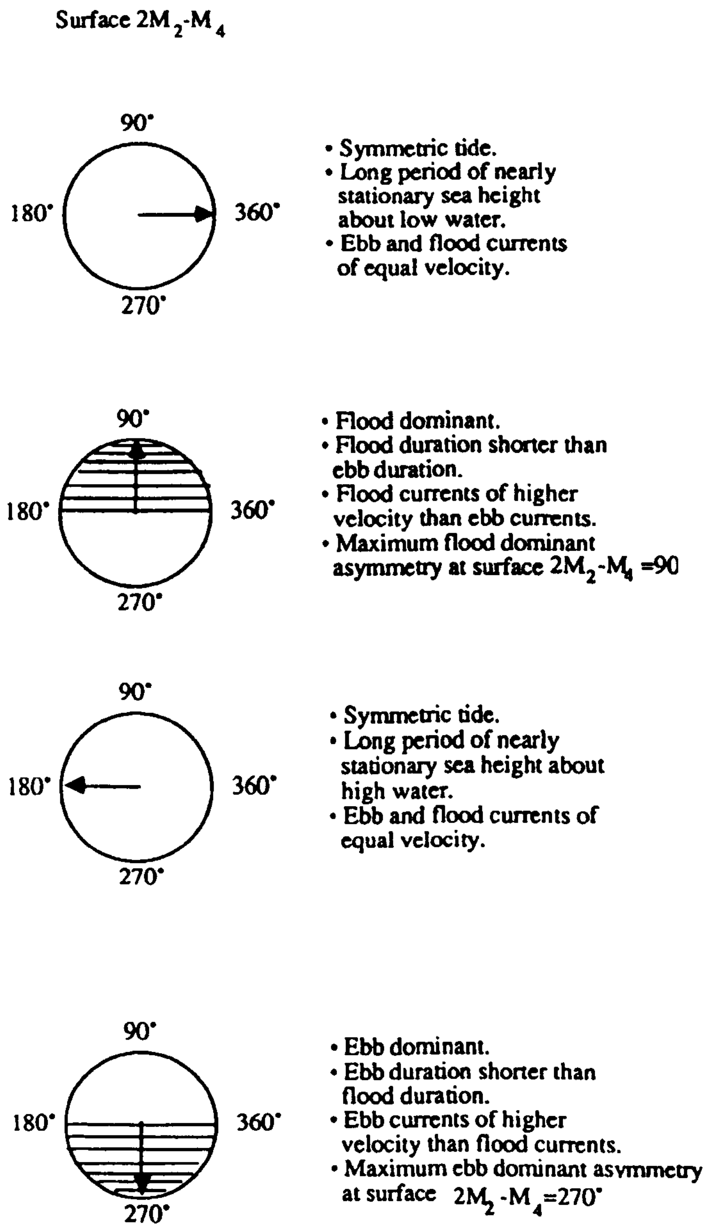


Figure 5.8 Linear relationships between relative phase and tidal distortion for M4/M2>0 (after Friedrichs and Aubrey, 1988)

The Narrows

It is evident from the shape of the observed spring tidal curve recorded on the 29th July 1980 and from the Admiralty Tide Tales, that the flood tide is shorter (approximately 5.5 hours) than the duration of the ebb tide (approximately 7 hours), indicating that the tide in the Narrows is flood dominant tide as the same volume of water flowed into the estuary in a shorter period. An initial comparison of tidal data was undertaken between harmonic constant data obtained from the Hydrographer of the Navy (1977), data derived by Amin

(1982) from analysis of a 9-year tidal record (1963-71), and analysis of West's (1980) measurement of a single tide of mean spring tidal range at Princes Pier in the Narrows using equation 5.2. The results (see Table 5.5) of amplitude analysis demonstrated that tidal distortion exists within the Narrows and falls within the range of values 0.003-0.133 derived from analysis of tidal data for 26 US East Coast tidal inlets by Friedrichs and Aubrey (1988). The calculated sea surface phases of approximately 71-80° indicated a flood dominant distortion, compatible with a shorter duration flood tide than ebb tide.

A more detailed analysis of Table 5.5 demonstrated that the single tide of West (1980) exhibited characteristics similar to the long-term record analysed by Amin (1982). The tide was therefore very suitable for analysing long-term morphological change. Greater differences were demonstrated between harmonic data derived from the Hydrographer of the Navy (1977) and analyses of Amin's (1982), and West's (1980) data. This may have resulted from the fact that the Admiralty data was based upon analysis of tidal records from a position further seaward where the tide was less distorted.

	Sea Surface Amplitude M2/M4	**Relative Sea Surface Phase**
Analysis of Hydrographer of the Navy (1977) data	0.071	71.0
Analysis of Amin's (1982) data	0.078	80.0
Analysis of West (1980) spring tidal cycle for Princes Pier	0.079	78.0

Table 5.5 Results of analysis of sea surface distortion in the Narrows based on observational data

Analysis of 1D simulations of the estuary hydrodynamics in the Narrows (Table 5.6) demonstrated that the tide exhibited similar characteristics to the tide applied at the boundary. The distortion of the tidal curve through the Narrows was minimal. Furthermore, there was little variation through time in the distortion of the tide. Analysis of elevation data demonstrated relatively constant values.

Year	Sea Surface Amplitude M2/4	Relative Sea Surface Phase
1906	0.083	71
1936	0.081	74
1977	0.083	72

Table 5.6 Results of analysis of sea surface distortion in the Narrows based on 1D model

Analysis of the depth-integrated flow results from 2D simulation of hydrodynamics in the Mersey estuary (see Table 5.7) illustrated similar characteristics in the Narrows to the 1D model for sea-surface amplitude and phase. The results correlated well with the boundary condition tide, and exhibited little variation with changes in bathymetric configuration over time. Specification of the tidal boundary condition therefore appeared to be the most important factor influencing tidal propagation through the Narrows.

Year	Sea Surface Amplitude M2/M4	Relative Sea Surface Phase
1906	0.081	72
1936	0.084	73
1977	0.082	74

Table 5.7 Results of analysis of sea surface distortion in the Narrows based on 2D Mersey model

Analysis of the depth integrated flow results from 2D simulation of hydrodynamics in the Mersey estuary and Liverpool Bay (see Table 5.8) exhibited significantly greater sea-surface distortion than evident for simulations of the estuary only. The model including Liverpool Bay was driven by an offshore tidal boundary condition, which propagated across Liverpool Bay before entering the estuary. The tidal distortion indicated that the shallow water effects of changes in the bathymetry of Liverpool Bay have had a significant influence upon tidal conditions in the Narrows. The tidal propagation indicated by the relative sea-surface phase was flood dominant throughout, but the nature of changes in relative sea-surface amplitude characteristics suggested tidal distortion increased between 1906-1936, and subsequently decreased to a smaller extent between 1936-1977. The sea-surface characteristics in the Narrows for 1977 differed from Amin's (1982) analysis of a long-term tidal record between 1963-1971, indicating that the tidal profile was more accurately simulated in the models of the estuary alone. However, the representation of tidal distortion effects of bathymetric changes in Liverpool Bay meant that the models with an offshore boundary condition were more representative of historic changes in flow properties within the Narrows.

Year	Sea Surface Amplitude M2/M4	Relative Sea Surface Phase
1906	0.055	63
1936	0.077	73
1977	0.065	61

Table 5.8 Results of analysis of sea surface distortion in the Narrows based on 2D Liverpool Bay and Mersey estuary model

<u>The inner estuary</u>

As the tide progresses up the estuary it becomes increasingly flood dominant, as evident in Figure 3.2 * MERGEFORMAT . Analysis of tidal elevation through tidal cycles observed by West (1980) at locations progressively landwards through the estuary demonstrated a relationship between M2/M4 sea-surface phase and amplitude consistent with increased flood dominance (see Table 5.9). It was evident that the shallow water effects of the estuary bathymetry exert a significant control upon tidal propagation within the estuary. From the perspective of analysing historical changes in tidal propagation within the estuary, it was important to establish whether bathymetric change in the estuary predominated over the effects of changes in the tidal boundary condition, which have been shown to influence tidal propagation within the Narrows.

Year	Sea Surface Amplitude M2/M4	Relative Sea Surface Phase
Eastham	0.078	81
Hale	0.514	25
Stanlow	0.305	43

Table 5.9 Results of analysis of sea surface distortion in the inner estuary based on West's (1980) observational data

Relative changes in tidal propagation within an area of the estuary that is more adaptable than the Narrows, and hence affected to a greater extent by bathymetric change within the estuary, were examined. The results of tidal elevation computations were analysed for a comparable location approximately 20km into the estuary for the 1D and 2D models of the estuary, and the 2D model of the estuary and Liverpool Bay. Difficulties were encountered in achieving accurate computations for comparison for locations landwards of this point due to changes in the position of the low water channel. The results analysed from the 2D models were located in areas of sufficient water depth for all bathymetries that calculations were not distorted by the effects of drying out at low water.

Results from analysis of the 1D cross-sectionally averaged simulation of hydrodynamics in the Mersey estuary (see Table 5.10) did not show large differences from the boundary condition tide (see Table 5.5). However, it was evident that greater changes in tidal distortion over time were exhibited than in analysis of 1D simulation of tidal propagation in the Narrows, (see Table 5.6). Greater deviation from the boundary condition tide indicated that tidal propagation may be distorted to a greater degree by the shallow water effects of bathymetry within the estuary. The results demonstrated that tidal propagation has remained flood dominant for each bathymetric configuration, but that flood dominance became weaker between 1906-1936, and then strengthened between 1936-1977. It was evident, however, that the changes in tidal propagation for a particular bathymetric configuration relating to a specific year under different modelling representations were relatively small in comparison with changes in tidal propagation between bathymetric configurations for different years. This was demonstrated in the analysis of the Narrows, derived from a 2D model of the Mersey estuary and Liverpool Bay, where changes in tidal propagation were attributed to changes in the tidal boundary condition at the mouth of the estuary due to changes in the bathymetry of Liverpool Bay.

Year	Sea Surface Amplitude M2/M4	Relative Sea Surface Phase
1906	0.078	81
1936	0.073	80
1977	0.088	74

Table 5.10 Results of analysis of sea surface distortion in the Mersey estuary basin based on 1D Mersey estuary model

Results from analysis of the depth-integrated flow results, from 2D simulation of hydrodynamics in the Mersey estuary (see Table 5.11), did not correlate as accurately with the boundary condition tide as the results for the Narrows, (see Table 5.7). Greater deviation from the boundary condition tide indicated that tidal propagation was distorted to a greater degree by the shallow water effects of bathymetry within the estuary. The results demonstrated that tidal propagation has remained flood dominant for each bathymetric configuration, but that flood dominance strengthened between 1906-1977 in contrast with the results derived from 1D simulation.

Year	Sea Surface Amplitude M2/M4	Relative Sea Surface Phase
1906	0.081	37
1936	0.091	41
1977	0.122	37

Table 5.11 Results of analysis of sea surface distortion in the Mersey estuary basin based on 2D Mersey estuary model

Analysis of the depth integrated flow results from 2D simulation of hydrodynamics in the Mersey estuary and Liverpool Bay (see Table 5.12) indicated that the estuary was flood dominant throughout the period examined, and exhibited greater fluctuations in tidal asymmetry in the estuary basin than were evident in analysis of the results for locations in the Narrows derived from the same model. The greater magnitude of fluctuations over time reflected the larger changes of bathymetry within the estuary compared to the Narrows, indicating that the bathymetry of the estuary has influenced tidal propagation. However, the results exhibited a different trend in sea-surface distortion than was evident for 1D and 2D simulations of the estuary only, with a trend of decrease in flood dominance between 1906-1977. The results demonstrated that although tidal asymmetry within the estuary was affected by the bathymetry of the estuary, the net trends in tidal propagation over time were more substantially dependent upon changes in the tidal boundary condition. Although the results suggest that the 2D Mersey only model is closer to the measured data for the basin area, the 2D Liverpool Bay and Mersey model represents changes over time to the tidal propagation through the Narrows which is of key importance to changes in sediment import and export to the estuary.

Year	Sea Surface Amplitude M2/M4	Relative Sea Surface Phase
1906	0.113	24
1936	0.105	50
1977	0.067	39

Table 5.12 Results of analysis of sea surface distortion in the Mersey estuary basin based on 2D Liverpool Bay and Mersey estuary model

5.6.2 Hydrodynamic flow patterns at intervals through a tidal cycle

Changes in hydrodynamic flow patterns can provide a useful indication of potential causes of morphological change in the Mersey estuary. Examining relative changes in flow through a tidal cycle can illustrate the underlying changes in behaviour of the system with greater clarity. In particular, it provided a means of examining changes in flow patterns following training wall construction, and changes in the interaction between Liverpool Bay and the Mersey estuary. The results were produced as vector plots (see Figures 5.7-5.9) of instantaneous flow resulting from hydrodynamic simulation. Plots were produced at 2.5 hour intervals throughout the tide, commencing and finishing at high water. Results for 2D depth averaged simulations only were examined. Flow at the bed was likely to follow a similar trend in direction although the strength of the current may differ affecting residual transport.

The principal changes apparent from Figures 5.7-5.9 were evident in the plots of 5 hours after high water when the tide was ebbing and flowing out from the estuary. It was apparent that there were changes in the flow of the ebb tide across Liverpool Bay, and that the westward flow of water through Great Burbo Bank was significantly reduced following training wall construction. This was a result of the training wall acting to constrain flow within the trained channel when the water level in Liverpool Bay dropped beneath the height of the training wall. The training wall does not protrude above the water level at high water on a spring tide and therefore had little effect upon the ebb tidal flow around high water but affected flow at lower tidal levels. On a flood tide the pattern of flow across Liverpool Bay appeared to alter little, although it may be expected to adjust in close proximity to the training wall, which was difficult to discern from the plots produced. Thus the net effect of training wall construction was to reduce the ebb flow of water over Great Burbo Bank relative to flood tidal flow, leading to the effect of increasing flood dominance of flow in this area identified by Price and Kendrick (1963).

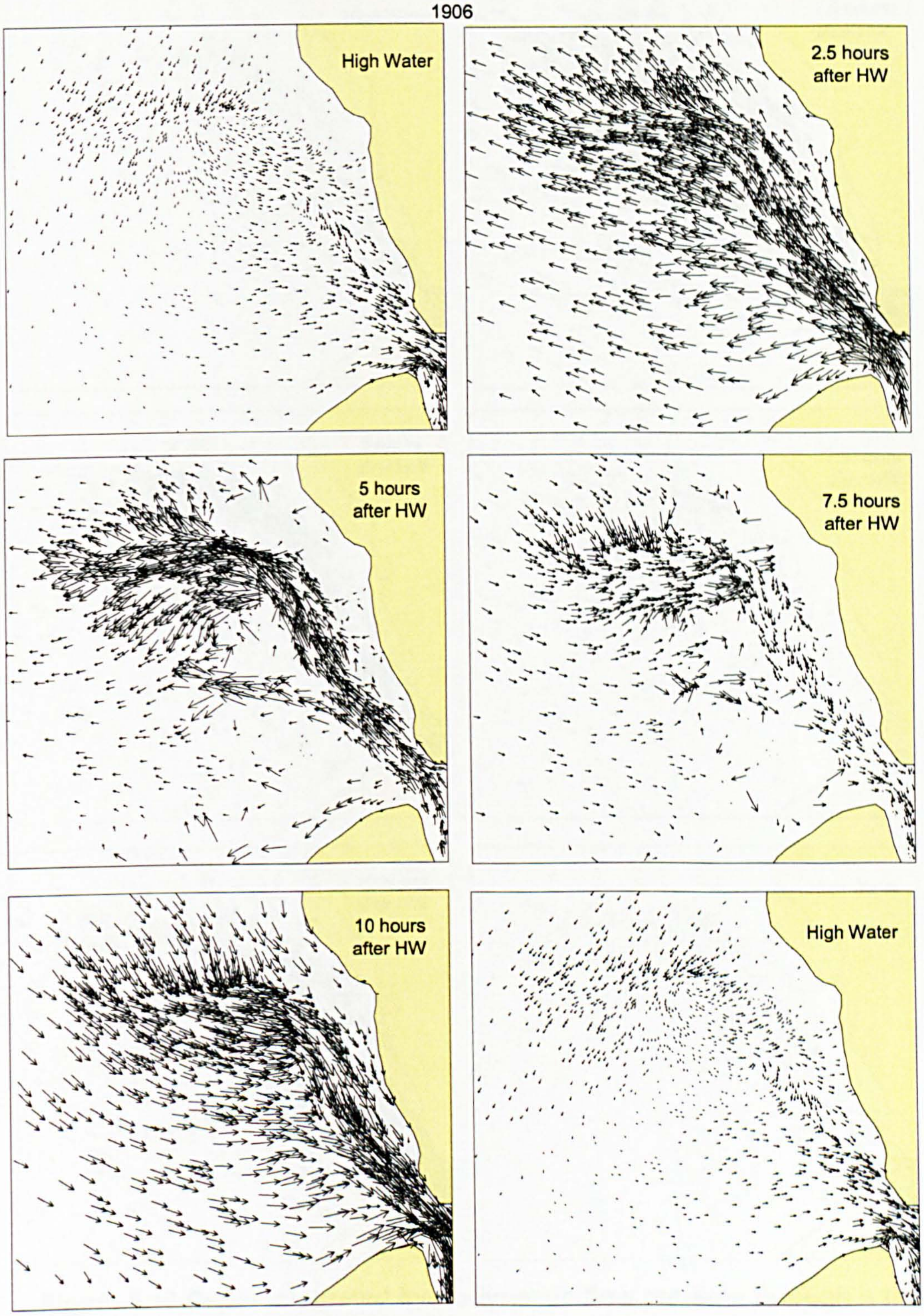


Figure 5.9 Depth integrated hydrodynamic flow patterns through a tidal cycle for the 1906 bathymetric configuration

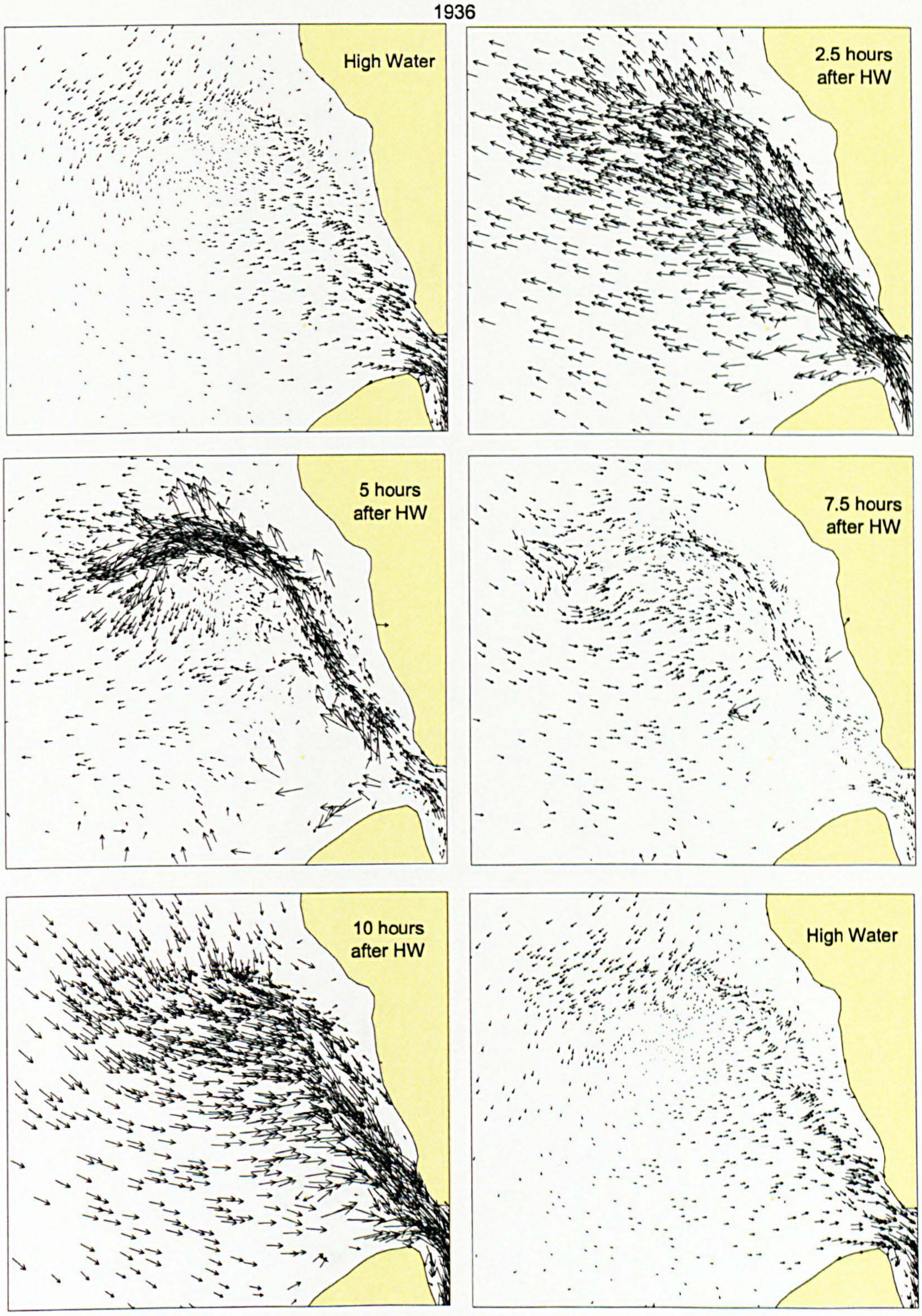


Figure 5.10 Depth integrated hydrodynamic flow patterns through a tidal cycle for the 1936 bathymetric configuration

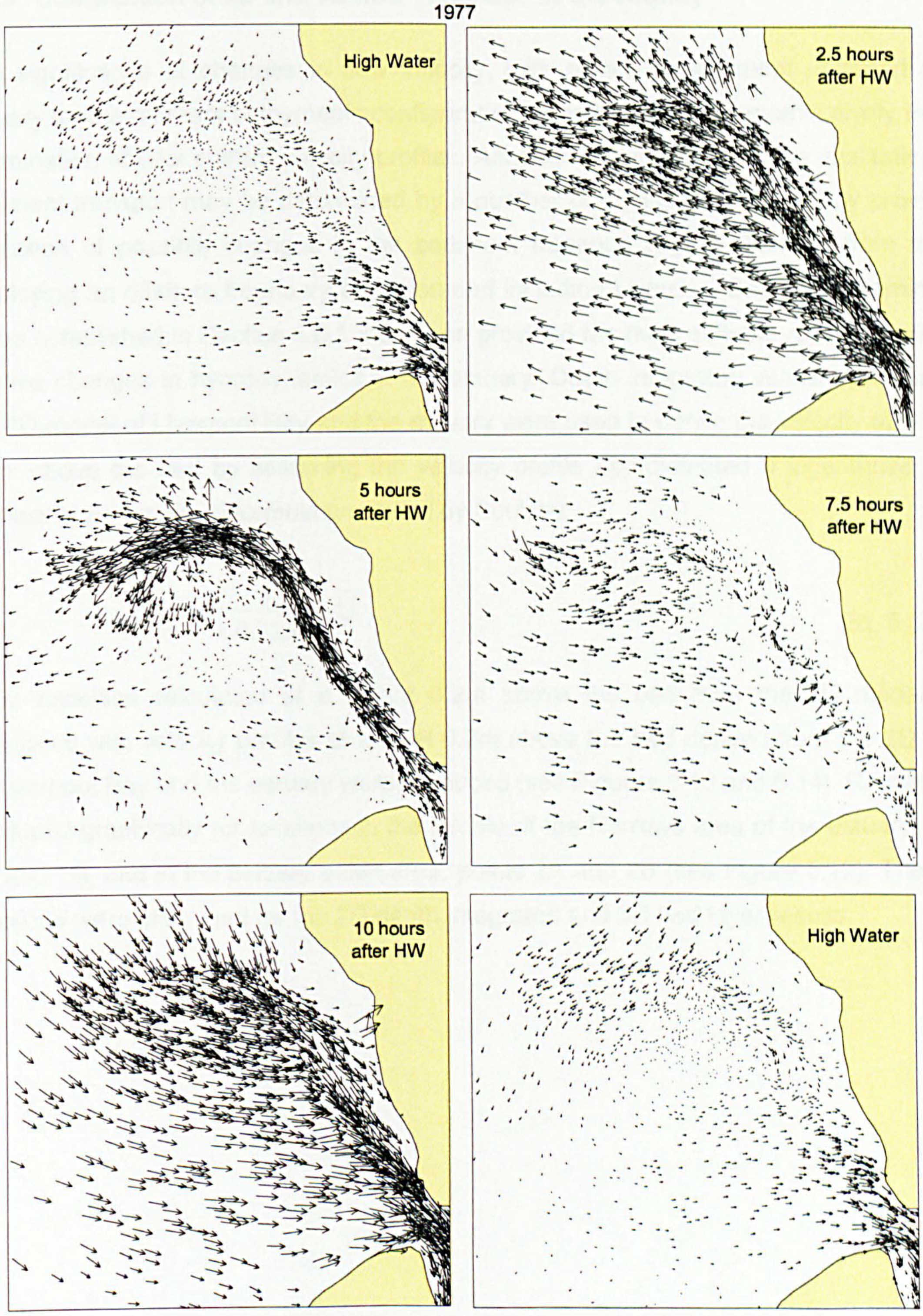


Figure 5.11 Depth integrated hydrodynamic flow patterns through a tidal cycle for the 1977 bathymetric configuration

5.6.3 Comparison of 2D and 3D flow velocities in the estuary

The significance of changes in flow velocity, with regard to sediment transport in the estuary for the different bathymetric configurations, can be assessed quantitatively through examination of tidal current velocity profiles. Although velocity profiles are qualitative, and sediment transport may be determined by a number of additional factors, they provide an indication of possible changes in the sediment transport regime. Results from models employing an offshore boundary condition and including Liverpool Bay were examined as it was established in Section 5.6.1 that these provided the most suitable representations of relative changes in hydrodynamics in the estuary. Depth integrated velocity profiles from the 2D model of Liverpool Bay and the estuary were used to derive the velocity at a height 0.2m above the bed by assuming the velocity profile approximated a logarithmic profile and using the empirical formula proposed by Soulsby:

$$U(z) = \left(\frac{z}{0.32h}\right)^{\frac{1}{7}} \overline{U} \qquad \text{Eq. 5.5}$$

Flow velocities calculated at a height 0.2m above the bed from the 2D model were compared with velocity profiles at a level 0.2m above the bed derived from the 3D model of Liverpool Bay and the estuary were produced (see Figures 5.13 and 5.14). Results were produced graphically for locations in the middle of the Narrows area of the estuary, points 1A and 1B, and in the estuary basin area, points 2A and 2B (see Figure 5.12). The same locations were examined for the 2D depth integrated and 3D bed layer results.

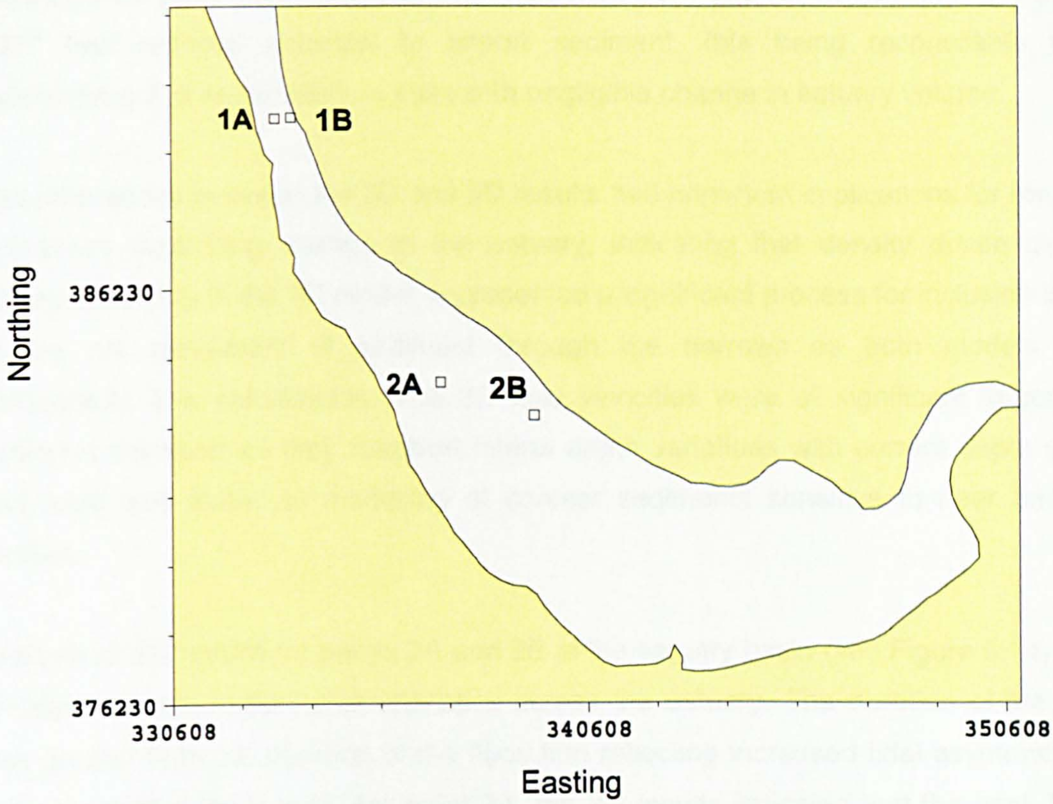


Figure 5.12 Locations of velocities analysed

Significant differences in flow characteristics can occur across the estuary due to flood and ebb channels. However comparison with other nearby locations demonstrated limited variation across the cross-section for the Narrows. Significantly the results presented for the Narrows were representative of the relative change in flow characteristics, a general feature of the hydrodynamics, not just a localised feature. Analysis of 2D results for points 1A and 1B in the Narrows (see Figure 5.13), showed an increase in tidal current speeds on both the ebb and flood tides between 1906-1977. Peak ebb velocity was stronger than peak flood velocity for both positions for all years, although the peak flood velocity was significantly lower in 1906, and peak flood was only slightly lower than peak ebb velocity for 1977. Analysis of 3D near bed layer results at points 1A and 1B (see Figure 5.13), demonstrated that flow velocities differed from changes in 2D depth averaged flow velocities, although the duration of flood and ebb tides was approximately equal for all model simulations. Tidal current speeds decreased on both ebb and flood tides between 1906-1977, and flood velocity was larger than ebb velocity for all years, demonstrating potential for the estuary to import sediment via hydrodynamic flow conditions. The two velocities became more equal in 1977, exhibiting a greater balance between ebb and flood velocity than other years studied. The indication from this result was that the estuary in 1977 had reduced potential to import sediment, this being reconcilable with the establishment of an equilibrium state with negligible change in estuary volume.

The differences between the 2D and 3D results had important implications for the physical processes controlling change in the estuary, indicating that density driven circulation, represented only in the 3D model, represented a significant process for inclusion in studies of the net movement of sediment through the narrows as both models produce comparable flow calculations. The 3D flow velocities were of significant importance to sediment transport as they resolved lateral depth variations with current depth structure, and were well suited to modelling of coarser sediments sensitive to near bed current profiles.

Analysis of 2D results for points 2A and 2B in the estuary basin (see Figure 5.14), showed greater variation in flow characteristics across the estuary. The duration of the ebb tide was greater than the duration of the flood tide reflecting increased tidal asymmetry as the tide propagates landwards. For point 2A, the 2D results indicated that the peak flood tide current velocity was stronger than the peak ebb tide current velocity for all years, with the greatest difference occurring in 1936. For point 2B the 2D results indicated a more complex pattern of change, with peak flood tide current velocity being stronger than the peak ebb tide current velocity for 1906 and 1936, but peak ebb tide current velocity being stronger than the peak flood tide current velocity for 1977. Analysis of 3D bed layer results at points 2A and 2B (see Figure 5.14), demonstrated that flow velocities differed from changes in 2D depth averaged flow velocities, although the duration of the ebb tide was consistently greater than the duration of the flood tide. The 3D results indicated a more consistent trend of a higher peak flood tide current velocity than peak ebb tide current velocity, a reversal in particular of the trends indicated for point 2B from the 2D results.

The complexity of tidal flow characteristics within the estuary basin was greater than in the Narrows. The basin area was more dynamic than the Narrows, and tidal flow characteristics were affected by shifts in the position of ebb and flood dominant subtidal channels. Changes in the flow properties within the Narrows were smaller and more consistent, as a result of the inerodible nature of the channel. Overall the results from examination of tidal current velocity profiles supported a general trend of flood dominance in tidal flow at the bed of the estuary, indicating a potential to import sediment into the estuary. There was some evidence to support a reduction in flood dominant tidal flow at the bed of the estuary in the Narrows and basin area of the estuary, coinciding with a reduction in the quantity of sediment imported into the estuary in 1977. However, the evidence was tentative, and examination of tidal current velocity profiles was qualitative; long-term residual sediment transport patterns required more precise analysis of sediment transport processes for reliable interpretation of the effects of changes in current velocities.

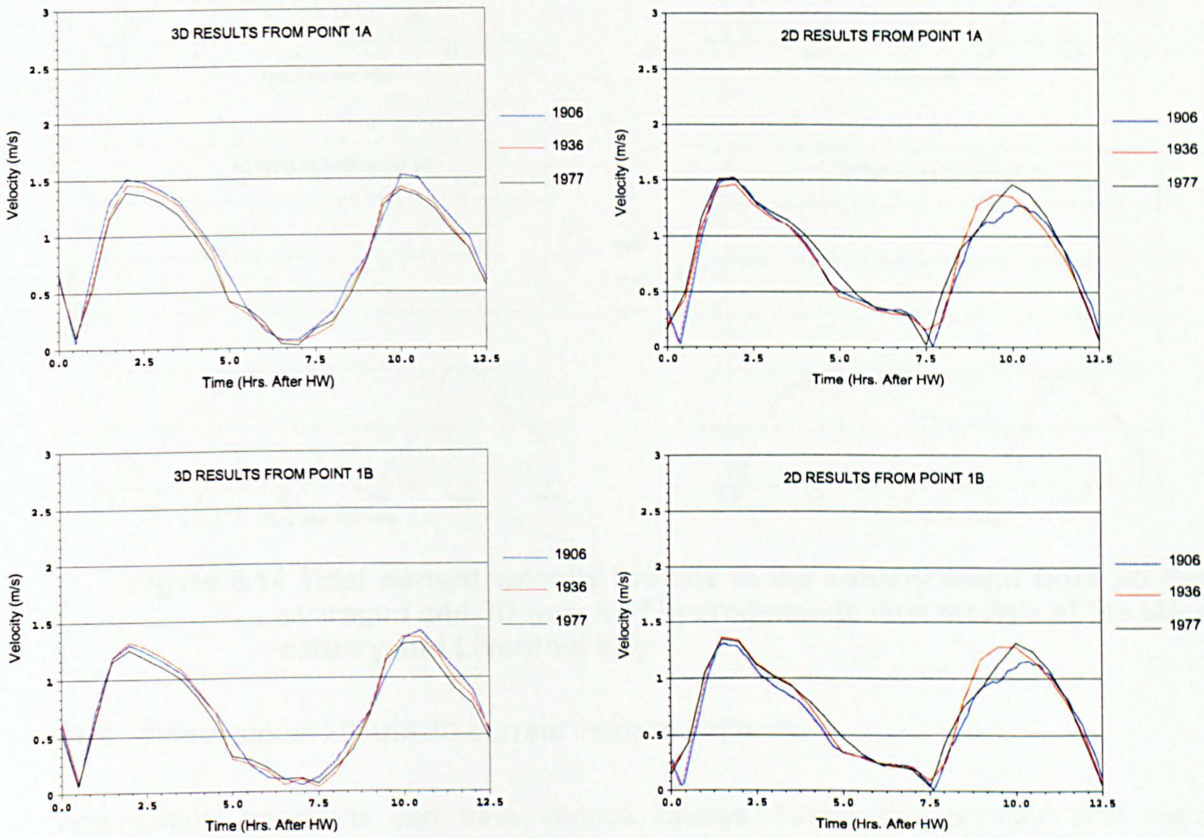


Figure 5.13 Tidal current velocity profiles in the Narrows from 2D depth averaged and 3D near bed hydrodynamic flow models of the Mersey estuary and Liverpool Bay

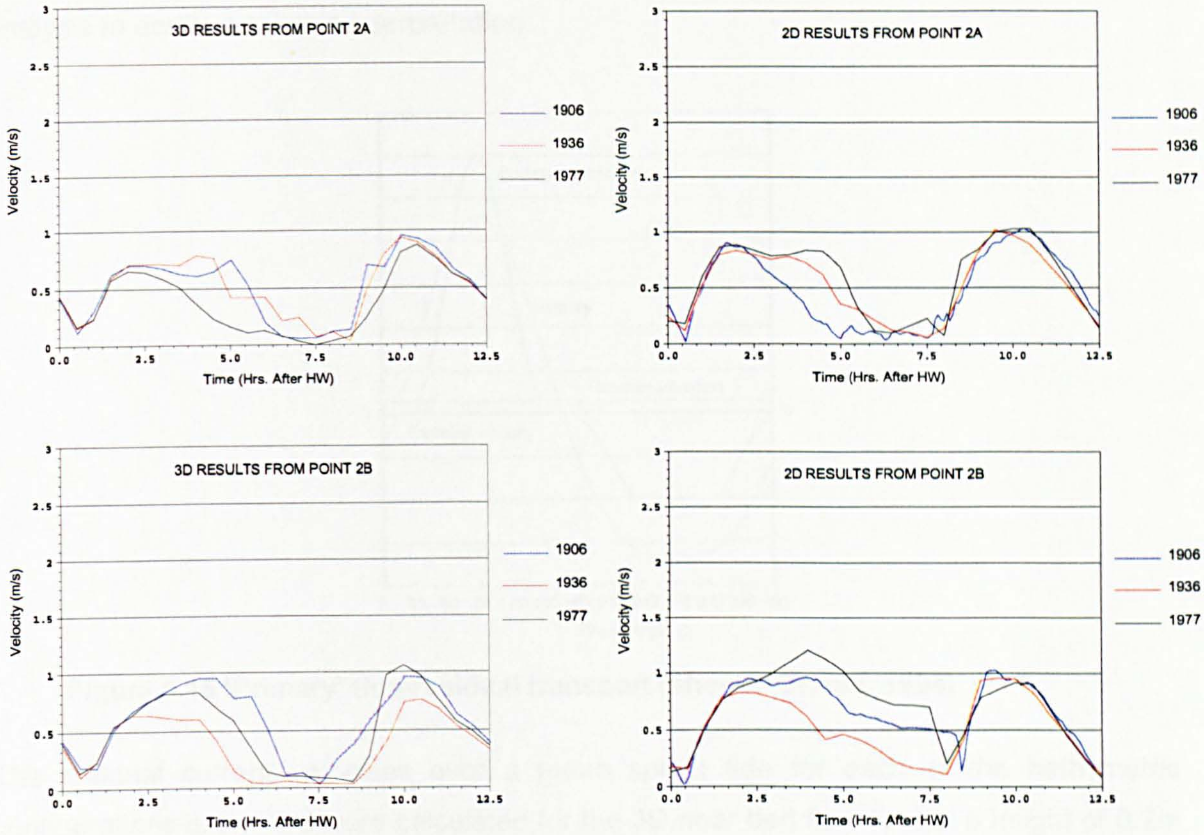


Figure 5.14 Tidal current velocity profiles in the estuary basin from 2D depth averaged and 3D near bed hydrodynamic flow models of the Mersey estuary and Liverpool Bay

5.6.4 Tide-residual 2D and 3D current velocity patterns

Tide-residual transports can have various causes. Firstly, the 'primary' tidal current, defined as the current described by the shallow-water equations, can induce tide-residual transport of sediment as a result of the asymmetry of tidal flow. These effects are evident in 2D depth integrated hydrodynamic modelling flow field results through examination of residual velocity patterns. 'Secondary' tidal flow effects may be caused by accelerations such as Coriolis forces, or by depth-varying external forces such as gravitational circulation. Coriolis forces were represented in both 2D and 3D simulations. Gravitational circulation, however, which causes the near bed velocity to deviate from the 'primary' flow velocity, were represented in the 3D simulation but not included in the 2D depth integrated simulation of flow patterns. It is important to note, however, that there is no direct relationship between residual current velocity and residual transport of sediment due to the effects of threshold for sediment movement (see Figure 5.15). Thus analysis of hydrodynamic flow patterns relevant to sediment transport patterns provides only an initial estimation of changes in patterns of sediment transport which require more complete analysis to derive a reliable interpretation.

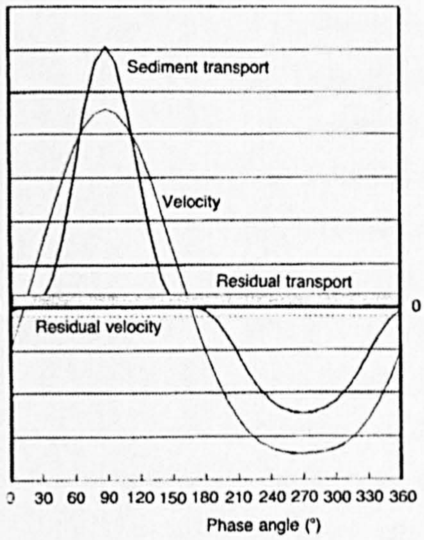


Figure 5.15 'Primary' tide-residual transport (after de Vriend, 1994)

The residual current velocities over a mean spring tide for each of the bathymetric configurations examined were calculated for the 3D near bed flow field at a height of 0.2m above the bed, and for the 2D depth integrated flow field. The results were produced as vector plots of Liverpool Bay and the Mersey estuary; the plots based on 2D results are presented in Figures 5.16-5.18, and the plots based on 3D near bed flow field are presented in Figures 5.19-5.21. The results show that the strongest residual current velocities were in the low water channel, and that the 2D residual current velocities were stronger than those derived from the 3D near bed flow field as a result of slower current velocities near the bed due to the effects of friction.

The results demonstrated some similarities in features derived from calculations based upon 2D depth integrated flow field and 3D near bed flow field, such as a seaward residual flow in the low water channel in Liverpool Bay. Furthermore, the 1906 bathymetric configuration demonstrated a westward residual flow from the mouth of the estuary through a channel in the middle of Great Burbo and Little Burbo Banks in Liverpool Bay for both 2D depth integrated flow field and 3D near bed flow field results, correlating with the ebb tidal flow across Liverpool Bay evident in the plot 5 hours after high water illustrated in Figure 5.9. The 1936 bathymetric configuration, however, illustrated a reversal in this feature for both 2D and 3D results with a dominant eastwards residual current velocity across Great Burbo Bank. By 1977 both sets of results demonstrated weaker residual current velocities across Liverpool Bay.

Despite the elements of similarity between calculations derived from 2D depth integrated flow field and 3D near bed flow field results, some important differences were evident between 2D and 3D results. Most notably it was evident that plots based on 2D depth integrated flow results showed that all bathymetric configurations indicated a net seaward residual current velocity within the Narrows of the Mersey estuary, whilst all sets of results based upon 3D near bed flow field results indicated a strong net landward residual current velocity on the east side of the estuary mouth and a weaker seaward residual current velocity on the westward side. Further differences were also evident in residual current velocities at the western limit of Liverpool Bay shown in Figures 5.16-5.21, where it was clear that 2D results illustrated a general westward residual current velocity, whilst 3D results indicated a general southward residual current velocity, although current velocities in this area were considerably smaller than in the low water channel.

Although it was noted earlier that residual current velocity can differ from residual transport of sediment, the elements of residual current velocities discussed, and particularly those in the Narrows where current velocities are high, are likely to exert a significant influence upon net sediment transport. In Liverpool Bay sediment transport processes are more complicated due to the effects of waves, but the principal effects of waves are to increase the quantity of sediment in suspension, which is then transported in the direction of the prevailing tidal current. Residual tidal current velocities can therefore provide a useful indication of changes in sediment regime even in Liverpool Bay.

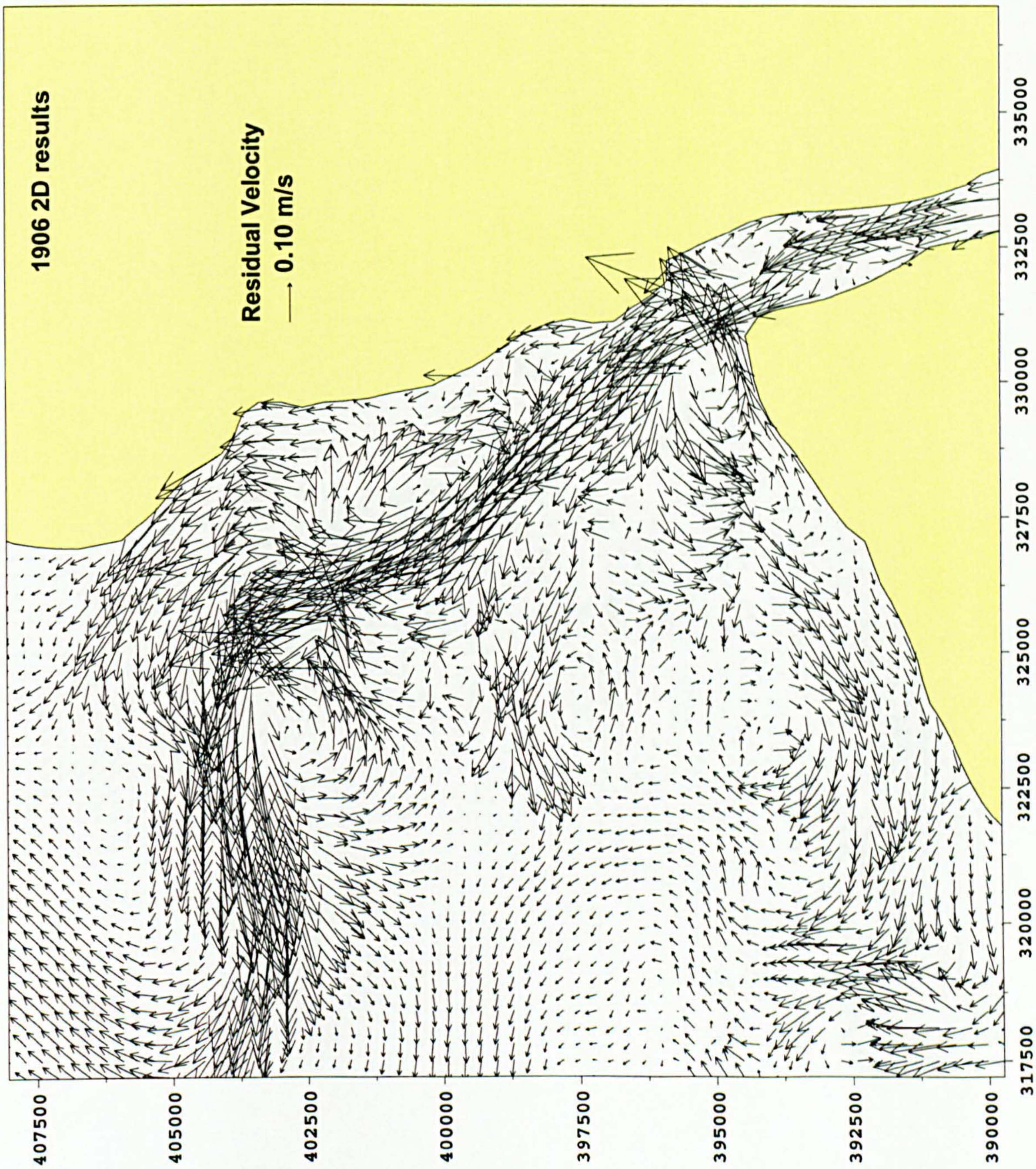


Figure 5.16 2D depth integrated mean spring tide residual current velocity patterns for 1906 bathymetric configuration

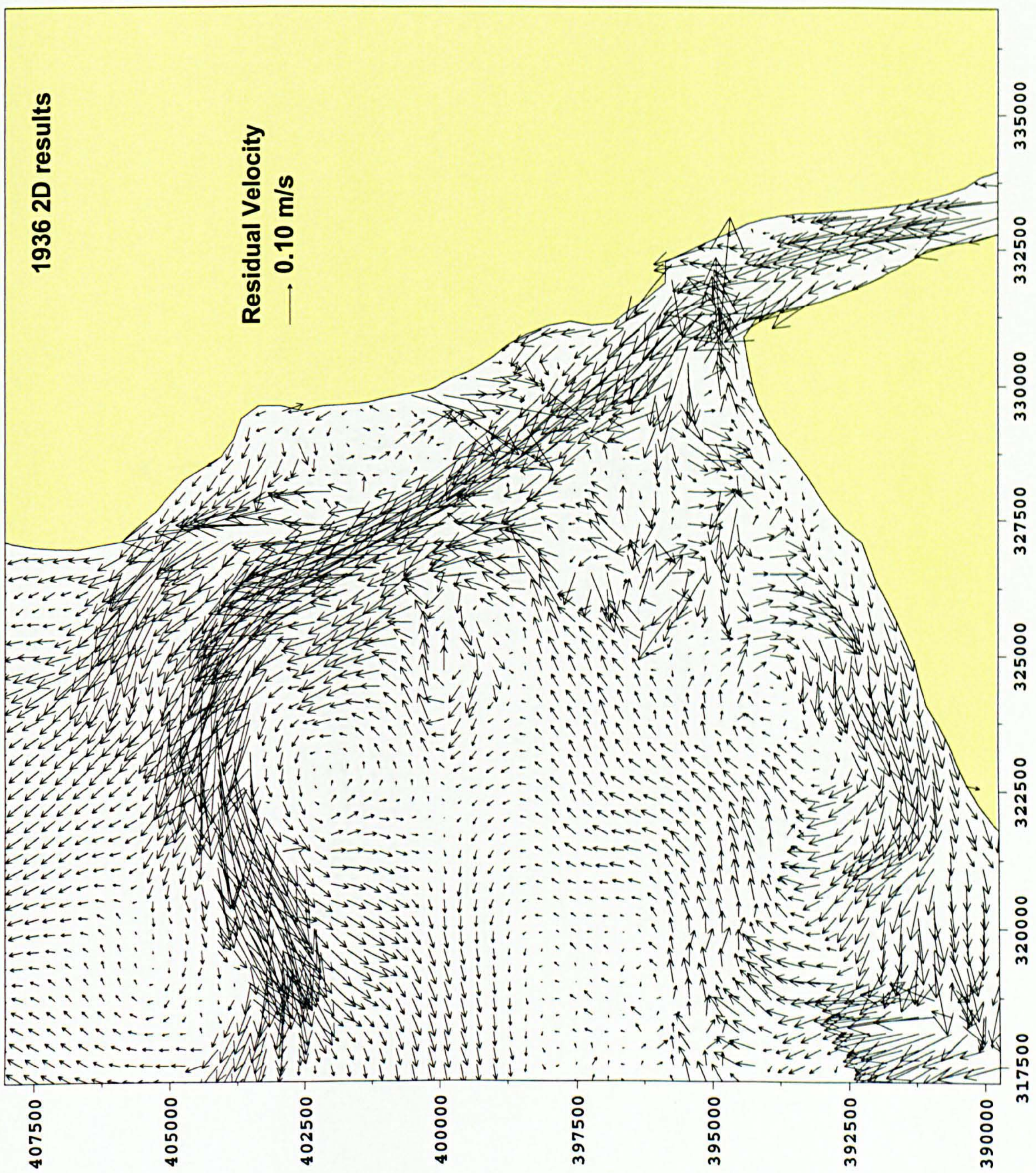


Figure 5.17 2D depth integrated mean spring tide residual current velocity patterns for 1936 bathymetric configuration

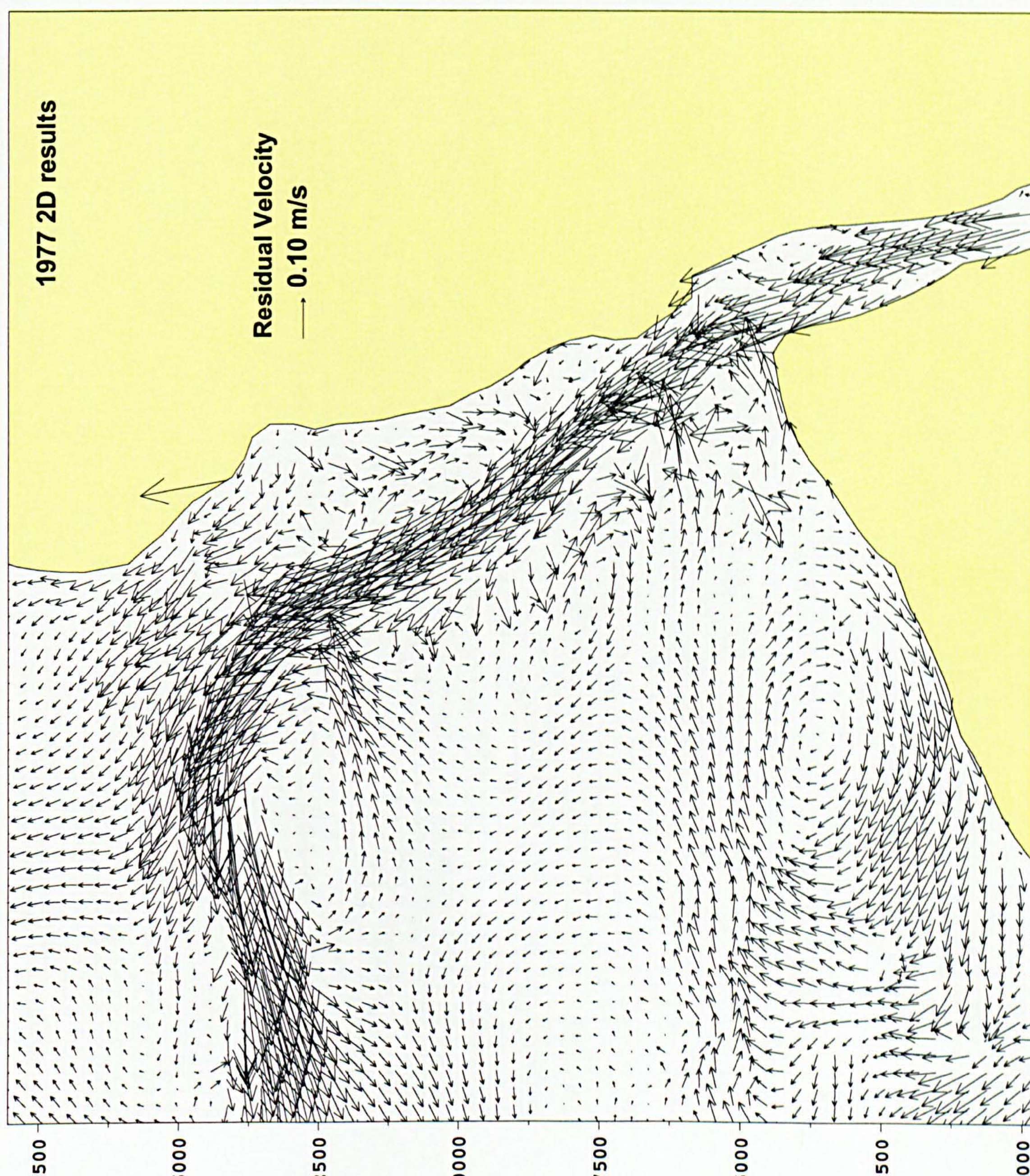


Figure 5.18 2D depth integrated mean spring tide residual current velocity patterns for 1977 bathymetric configuration

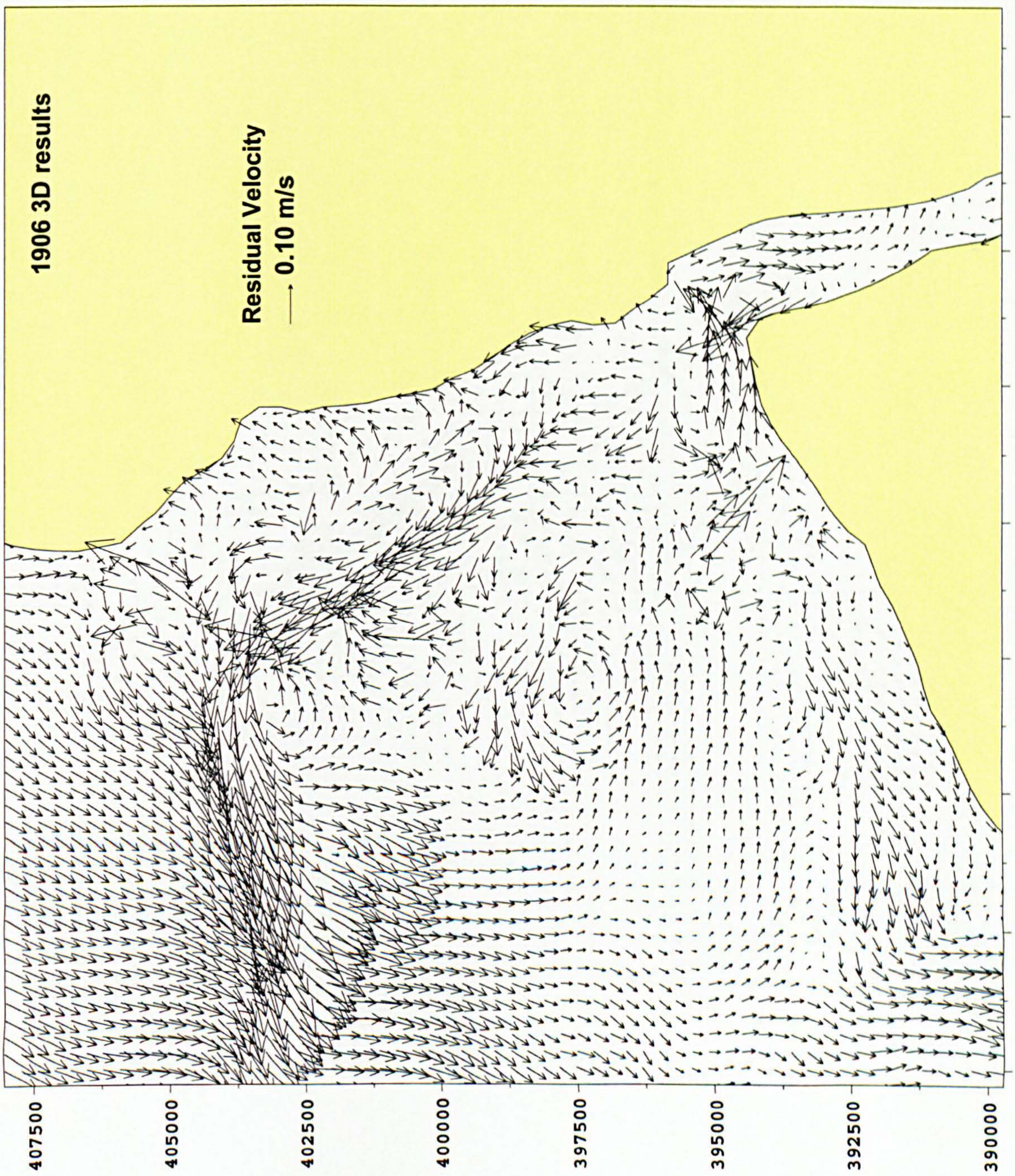


Figure 5.19 3D near bed mean spring tide residual current velocity patterns for 1906 bathymetric configuration

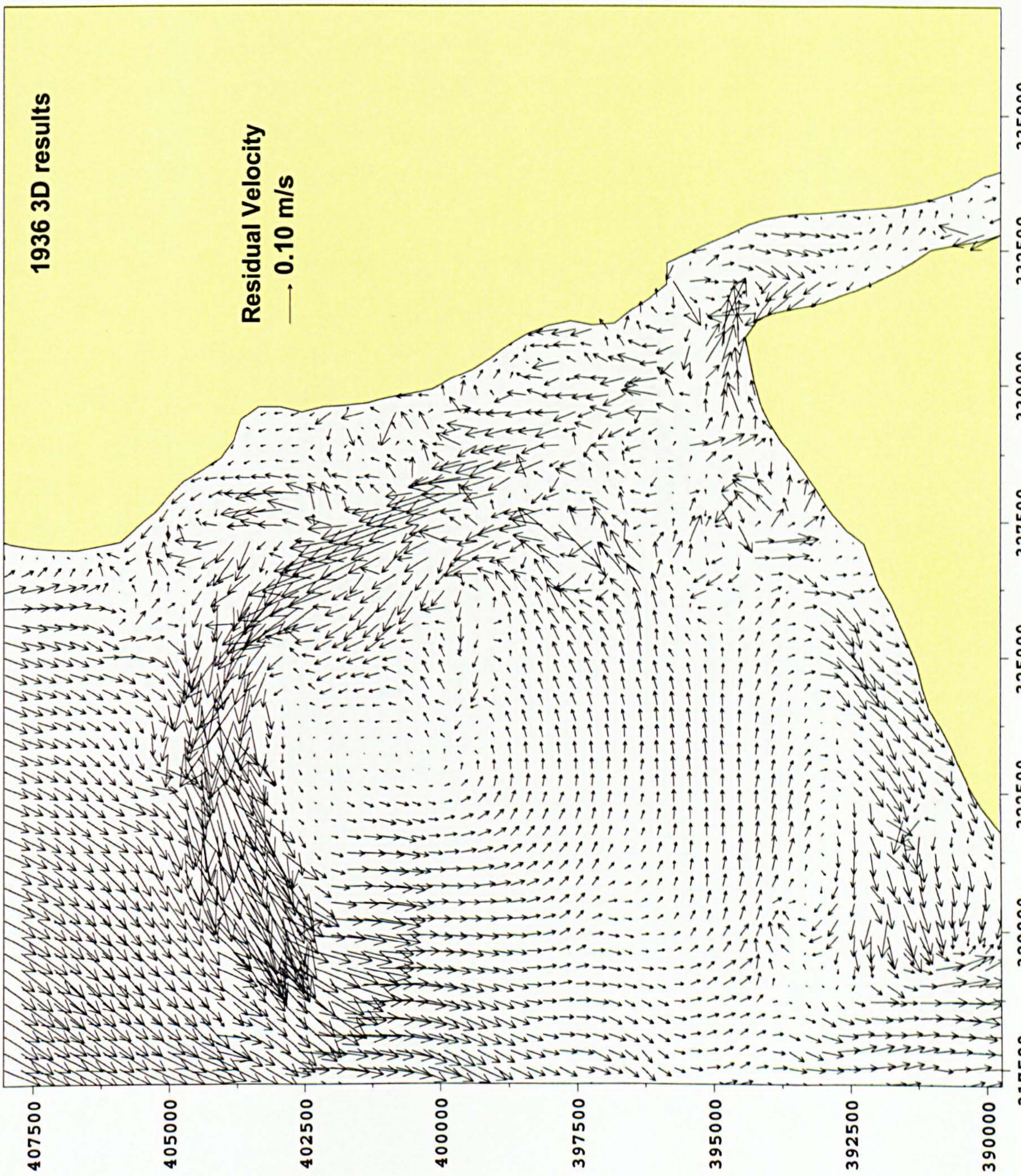


Figure 5.20 3D near bed mean spring tide residual current velocity patterns for 1936 bathymetric configuration

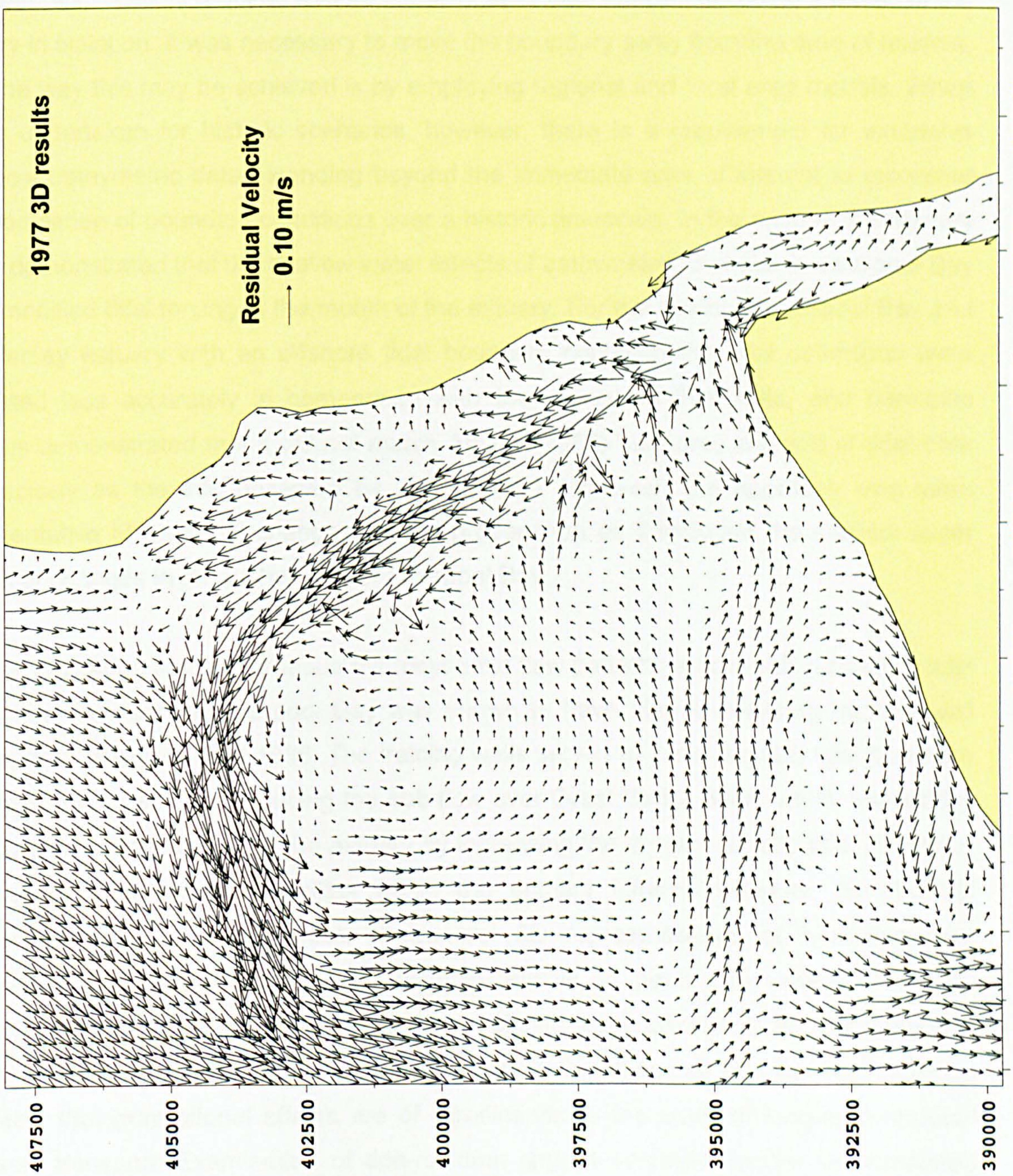


Figure 5.21 3D near bed mean spring tide residual current velocity patterns for 1977 bathymetric configuration

5.7 Chapter summary

It has been demonstrated that the formulation of a consistent set of boundary conditions for the purposes of examining historical changes in tidal flow properties is not a straightforward task, it requires a more complex approach than simply using a model of the estuary in isolation. It was necessary to move the boundary away from the area of interest, and one way this may be achieved is by employing regional and local area models. When this is undertaken for historic scenarios, however, there is a requirement for extensive historical bathymetric data extending beyond the immediate area of interest to represent the modulation of boundary conditions over a historic timescale. In the case of the Mersey it was demonstrated that the shallow water effects of bathymetric changes in Liverpool Bay have modified tidal forcing at the mouth of the estuary. For the model of Liverpool Bay and the Mersey estuary with an offshore tidal boundary condition the tidal conditions were simulated less accurately in comparison with the measured tidal data, and harmonic analysis demonstrated that it did not match Amin's (1982) harmonic analysis of tidal data as precisely as the tide observed by West (1980). However, the approach was more representative of historical changes in tidal propagation as it included the shallow water effects of changes in the bathymetry of Liverpool Bay.

From examination of instantaneous hydrodynamic flow patterns at intervals through a tidal cycle, tidal flow across Liverpool Bay was shown to have altered following training wall construction between 1906-1936. The training walls served to constrain ebb tidal flow from the mouth of the estuary, reducing the ebb flow over Great Burbo Bank, which altered the tidal condition at the mouth of the estuary by increasing the duration of ebb tide. However, changes in tidal current velocities within the estuary differed between 2D and 3D representations of hydrodynamics. In general 3D representations of hydrodynamics demonstrated a stronger peak flood velocity relative to peak ebb velocity, than 2D representations of hydrodynamics. This has significant implications for non-cohesive sediment transport processes, which are predominantly influenced by near bed currents, indicating that gravitational effects are of significance to the study of long-term residual sediment transport. Examination of tide-residual current velocities further demonstrated the importance of gravitational circulation by indicating a net landward pattern of flow for 3D model results, in comparison with a net seaward pattern of flow for 2D model results.

Qualitative analysis of tidal current velocity profiles indicated a possible reduction in flood dominance within the estuary coincident, with a reduction in large-scale accretion in the estuary in 1977. However, analysis of tide-residual current velocities based upon 3D representation of flow characteristics indicated that the net current velocity was landwards for all three bathymetric configurations modelled. In order to draw conclusions relating to long-term residual sediment transport in Liverpool Bay and the Mersey estuary, a more comprehensive analysis of the relation between historical changes in hydrodynamic flow regimes and sediment transport is required, this described in Chapter 6.

CHAPTER 6 EVOLUTION OF SEDIMENT TRANSPORT PATTERNS

6.1 Introduction

Analysing sediment transport processes is an inexact science due to the difficulties of parameterising sediment properties, exacerbated in this study by a lack of data on historical changes in sediment characteristics. Sediment transport is determined by the interaction of a range of different processes, which vary in terms of magnitude and chronology of occurrence. The selection and application of tools for analysing sediment transport issues is strongly related to the type and scale of the problem studied. A simplified approach to investigation comprises examining several conditions, representative of the range of physical processes experienced in the specified estuarine environment, to elucidate the relative interaction of physical processes and their effect upon the sediment transport regime. Computational calculations may be parameterised to obtain an overall view of trends in the estuary where accurate quantification is unrealistic. In studies of sediment transport a useful and necessary distinction must be made between cohesive and non-cohesive sediment transport processes, treating each separately to examine the potential influence of each on sedimentation in the estuary. Distinctions also need to be drawn between transport of non-cohesive sediment under the influence of currents alone and under the influence of currents and waves in order to examine the relative importance of different processes to transport of sediment in the estuary.

This chapter examines possible mechanisms causing accretion in the estuary in a structured, coherent manner. The results from 2D and 3D numerical hydrodynamic simulations described in Chapter 5 were employed diagnostically. The first stage of study examined changes in non-cohesive sediment transport patterns by applying sediment transport equations to hydrodynamic flow modelling results. Comparisons were drawn between sediment transport patterns resulting from 2D and 3D model simulations. Analysis was extended by examining sediment transport under the combined influence of waves and currents by combining results from wave models with 3D hydrodynamic flow results to examine the effects of wave stirring upon sediment transport patterns. Cohesive sediment transport was considered separately and was divided into two processes for analysis, advection and bed exchange. Advection was examined by tracking particles assigned with cohesive sediment characteristics under 3D hydrodynamic flow results, to examine relative changes in the movement of particles in and out of the estuary system. Deposition and erosion was examined by applying simple cohesive erosion and deposition equations to computations of hydrodynamic flow fields to examine relative changes in bed exchange relations.

6.2 Description of the approach to sediment transport investigation

The modelling of hydrodynamic processes is generally better able to be validated than the modelling of sediment transport and morphological changes. However, there are inevitable errors in predicting current or wave conditions, even in the most accurate models, and these can create significant errors in subsequent calculations of sediment transport. Errors in representing the hydrodynamics of the Mersey estuary and Liverpool Bay were examined in the previous chapter. On this basis the 2D and 3D hydrodynamic simulations with a model domain comprising the estuary and Liverpool Bay were employed for examining sediment transport patterns, as they were found to provide the most reliable representation of historical changes in hydrodynamics. Sediment transport was examined using the computed hydrodynamic results on the model grid. This allowed examination of the sediment transport over the whole area under investigation under a range of tidal and wave conditions.

For analysis of sediment transport though, it is not only important to understand the hydrodynamics, but also to accurately represent the physics of the sediment transport mechanism. Inaccuracies in the representation of the hydrodynamics will lead to uncertainties in identification of the most important sediment transport mechanisms, but inadequate representation of the physical properties of the sediment itself may lead to greater uncertainties. In the absence of detailed information on the sediment properties at a particular site it is possible to make useful predictions of sediment transport by applying some sensible assumptions on the nature and properties of the sediment and to use this as a basis for a series of sensitivity tests. Application of appropriate assumptions, however, needs to be undertaken with care.

Sediment transport modelling can be undertaken at varying levels of complexity. The analysis undertaken in this study comprised a relatively simple approach of applying an instantaneous relationship between transport rate and a number of hydrodynamic and sediment parameters to provide basic short-term descriptions. This approach reduces the complexity of the morphological behaviour of the system by eliminating the need to consider feedback between estuary form and process. The model employs historical data to examine a sequence of snapshots of changes in estuary behaviour. The interaction of a range of variables such as tidal and wave conditions can then be explored by calculating the effect of each upon net sediment transport patterns for different bathymetric configurations. Whilst many different formulae have been devised to predict sediment transport in marine conditions, most have been calibrated using laboratory data and all make assumptions about the predicted processes. As no agreement has yet been reached concerning the most appropriate formulation of sediment transport, empirical formulae have been compiled for specific sediments in a given range of conditions. No case is made for the universal applicability of sediment transport relations employed in this study; the selection of formulae is based upon their previous use in many practical applications, and the ease of deriving the required parameters.

6.3 Specification of conditions investigated

The most important sediment transport processes for the coastal area under investigation as a whole are stirring by wave and tidal bed shear stresses and transport by tidal currents. Most models consider one of these types of hydrodynamic forcing conditions i.e. waves or currents, although a few can include both. In general, tidal conditions dominate long-term changes in morphology in estuaries and deeper water areas (deeper than 10m) along the open coast. Waves are the most important process in the shaping of beaches, the inter-tidal zone and shallow water areas (less than 5m depth). The domain investigated in this study included both areas that were likely to be dominated by wave processes and those that were likely to be dominated by tidal processes. Some models may be applied for just one or two wave or tidal conditions. The increasing power of computers, however, means it is often possible to consider a wide range of hydrodynamic events and the resultant changes in morphology. Nevertheless, there is little benefit in simulating a multitude of conditions at the expense of the clarity of analysis, where a few well-chosen simulations can inform more succinctly on the interaction of processes responsible for morphological evolution.

6.3.1 Sediment characteristics

One of the most important considerations for addressing changes in sediment transport regime is the sediment characteristics in the area under investigation. The median grain size, in particular is of significance as it may be used to provide a general distinction between sediment type. Sand is conventionally defined as having grain diameters in the range 63μm -200μm, and mud is defined as material smaller than 63μm. In many natural situations, however, mixed sediments may occur, and the effect of cohesion is important in determining the sediment properties if more than 10% of sediment is finer than 63μm (Soulsby, 1997). Such mixtures are more resistant to erosion than either a pure sand or a pure mud. Evidence from particle size analyses of Liverpool Bay demonstrated that sediment is principally comprised of particles greater than 63μm, representing non-cohesive sediment (Sly, 1966). This thesis predominantly investigated non-cohesive sediment transport, although cohesive sediment was also examined using a simple approach to analysis to assess whether any historical pattern coincident with morphological change could be identified.

Greater emphasis was placed in analysis upon investigation of non-cohesive sediment transport, as there was evidence that sandy sediment was predominantly responsible for accretion in the estuary. Anecdotal evidence (Kendrick, pers. comm.) from dredging observations suggested that it was principally sand that accreted in the estuary. A study by HR Wallingford (1988) reported fractions of sediment greater than 63μm as high as 99% in the Narrows, and Peirce *et al.* (1970) reported a sand fraction of 50% at Bromborough in the inner estuary, indicating non-cohesive sediment transport was an important component of Mersey estuary morphology. Furthermore, the sediment seaward of Liverpool Bay was found to have a very low mud content, with only 5-10% fines, in a study of the effects of sludge disposal in Liverpool Bay (Norton *et al.*, 1984).

Research reported by Halliwell and O'Connor (1975) indicated that sand deposits in the Mersey estuary were mostly derived from the Irish Sea, and that there was a movement of sediment into Liverpool Bay from seaward sources coincident with accretion in the estuary. Further investigation by O'Connor (1987) by extrapolating from observed residual tidal fluxes of sediment to derive annual sediment fluxes. Through derivation of sediment budgets for sandy and silt/clay material respectively, O'Connor (1987) estimated that sandy material accounted for 91% of the decrease in estuary volume, with silt/clay material contributing 6%, and land-derived sediments contributing about 3%. The influx of sand into the estuary was estimated to be 1.9Mm^3/year, which accounted for substantial morphological change in the estuary. The source of sand that accreted in the estuary was unlikely to be dredged material deposited in Liverpool Bay, as analysis of hydrographic surveys indicated that little sandy sediment (an estimated 11%), returned to the estuary from deposit grounds in Liverpool Bay. This inferred that non-cohesive sediment was derived from sources in Liverpool Bay and the Irish Sea.

Non-cohesive sediment

Available evidence (Price and Kendrick, 1964) suggested a typical grain size in the estuary of 0.18mm, which represented a fine sand expected to behave as non-cohesive material. Assuming that in-situ sediment was mostly composed of grains less than 0.2mm diameter, the predominant mode of transport was suspended load (Soulsby, 1997). Observational studies reported by Halliwell and O'Connor (1975) supported the fact that sand entered the estuary mainly as suspended load. The influence of wave activity upon sediment transport in Liverpool Bay was also noted; measurements indicated little movement of sediment in suspension during calm periods. It was therefore of benefit to examine the transport of sediment as bed load and suspended load under the influence of tidal and wave forcing.

Cohesive sediment

The processes of erosion and deposition of cohesive sediment is dependent upon a combination of different factors, including the size, settling velocity and strength of the sediment. The processes of cohesive sediment transport are more complex and may be parameterised to a greater degree than representation of non-cohesive sediment transport processes, particularly due to the nature of cohesive sediment particles, which can behave as single particles, or as flocs that are bound together. In order to reduce the complexity of simulation, a uniform sediment may be assumed, which can be approximated using representative values for sediment parameters. For engineering applications it is often necessary to model cohesive sediment transport in complex situations, and the errors due to using a uniform sediment may be quite small compared to errors introduced as a result of other assumptions.

For the purposes of this study a simplified approach to representing cohesive sediment transport was adopted. In order to elucidate trends in sediment behaviour relative to changes in bed shear stresses under different bathymetric configurations of the estuary, a uniform sediment with representative values of median settling velocity, critical stress for deposition, critical stress for erosion and erosion constant was assumed, and employed for all simulations. A median settling velocity value of 0.00003ms^{-1}, and a critical stress for deposition of 0.08 Nm^{-2} were employed, based upon values presented by Ockenden

(1993). A critical stress for erosion of 0.2 Nm^{-2} and an erosion constant value of $0.0005kgN^{-1}s^{-1}$ were obtained from a study of mud properties of the Mersey estuary by HR Wallingford (1989). These values of cohesive sediment properties were employed in schematised studies of both historical changes in the erosional and depositional regime of the Mersey estuary, and changes in the advection of cohesive sediment through the estuary system. However, there was a degree of uncertainty attached to the cohesive sediment parameters, as significant developments have occurred in means of measuring cohesive sediment parameters since the values presented were measured. To account for this uncertainty, sensitivity analyses were undertaken by selecting alternative values for these parameters, and examining their effect upon the resulting calculations.

6.3.2 Tidal conditions

In the Mersey estuary the tide is likely to have played an important role in long-term morphological evolution. The representation of tidal effects in examinations of sediment transport patterns is an issue of considerable importance. A thorough investigation of sediment transport issues could comprise investigation of the net transport of sediment over a spring-neap cycle. However, such an approach is complex and creates difficulties in; selecting a representative cycle for examining long-term sediment transport behaviour; and sequencing the tidal forcing for input to a cohesive sediment transport model. In addition, representing a spring-neap cycle is computationally expensive and therefore unsuitable for representation in a high resolution 3D hydrodynamic flow model. Tidal input filtering can be used to simulate net sediment transport over a long period by using one or more representative tidal cycles (de Vriend *et al.*, 1993). If a single cycle is used, that which yields the same long-term sediment transport as the actual tide is taken as being representative. However, the choice of a single representative tide over the whole domain was not appropriate for this study because the complex topography of Liverpool Bay and the Mersey estuary affects the shape of the tidal curve and the current patterns change with tidal range. Furthermore, data on sediment transport rates was insufficient to calibrate and validate the derivation of a representative tide approach.

In this study the principal tidal conditions investigated comprised a mean spring tide. Within the yearly cycle significant modulation existed in tidal conditions, such as variation between spring and neap cycles. However, in areas that have significant variations between spring and neap tidal range, spring tides can dominate sediment transport patterns. In the case of the Dutch coast for example, it was found that the transport of sediment during spring tides was so much greater than under neap and mean tidal conditions that the large-scale morphology was predominantly influenced by spring tides alone (de Vriend *et al.*, 1994). In the case of the Mersey there is a substantial difference between mean spring tidal range and mean neap tidal range of approximately 3.9m. Thus tidal currents are significantly stronger under spring tidal conditions and have a more significant effect upon sediment transport. Simulating mean spring tides is a more extensive approach than a representative tide approach, facilitating the incorporation of wave effects, as correlations between wave activity under conditions of storms combined with high tidal currents can be examined. To assess the relative importance of spring tidal conditions to sediment transport, simulations employing a mean neap tidal boundary condition, and a highest astronomical tidal condition were also undertaken for the 1977 bathymetric configuration. These scenarios thus covered al range of tidal conditions experienced in the Mersey estuary (see Figure 6.1), and provided a suitable basis for examining the controls on net sediment transport patterns.

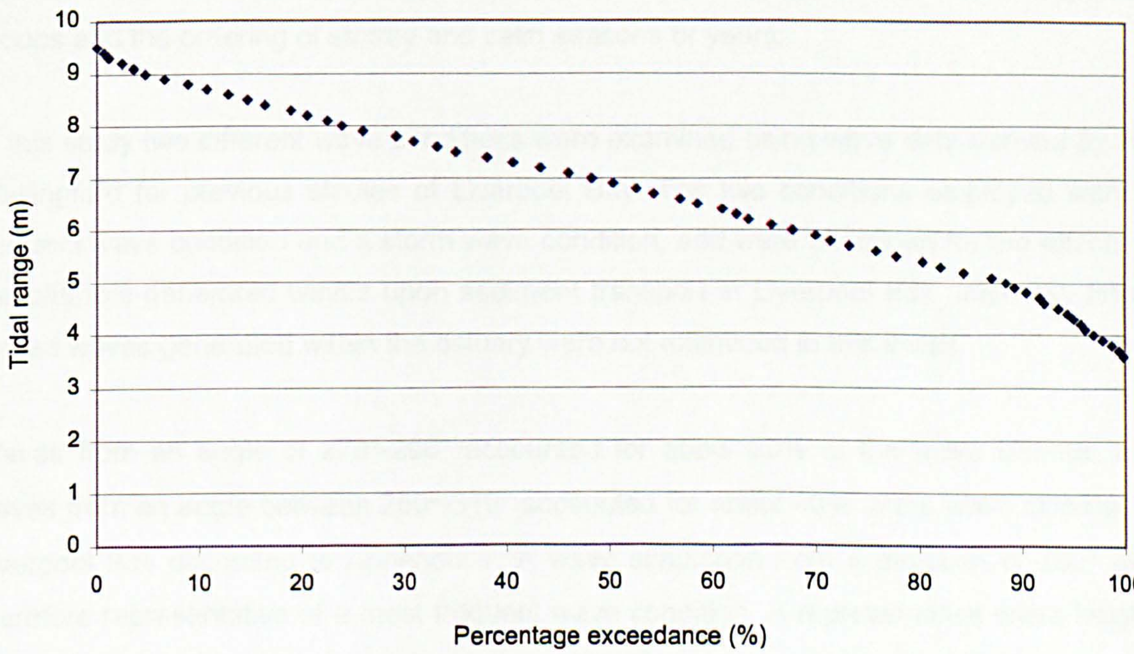


Figure 6.1 Graph of tidal predicted range at Princes Pier against percentage exceedance for 1977 (source: Hydrographer of the Navy [1977])

6.3.3 Wave conditions

Waves can have a significant impact upon sediment transport calculations, and the effect of combined wave and tidal forcing upon non-cohesive sediment transport have been examined. Bed-shear stress beneath combined waves and currents is enhanced compared to simply adding both together, due to the non-linear interaction between wave and current boundary layers. The addition of wave stirring effects also allows substantial sediment transport to occur at current speeds below the threshold of sediment motion in their absence. Wave chronology, i.e. differences in the sequencing of input data, can have a significant effect upon model outcome. Actual sequences of wave conditions are not known, but the probability distribution can be determined relatively accurately (Southgate, 1995). Usually this is based upon wave data recorded over time-scales greater than a few days. The non-linear response of morphology to wave input increases the importance of chronology to simulation. A linear response would be independent of the sequencing of wave conditions and would depend only on the overall statistics of the complete wave sequence. Wave chronology effects can be studied by re-ordering the wave data in a time sequence and rerunning a simulation for each reordered sequence to examine the effects upon sediment transport patterns. Chronology effects can potentially occur on all time-scales from wave sequences lasting a few days up to decades. The morphological effects can be sensitive to the ordering of storms, the occurrence of storms individually or in groups and the ordering of stormy and calm seasons or years.

In this study two different wave conditions were examined using wave data derived by HR Wallingford for previous studies of Liverpool Bay. The two conditions employed were a frequent wave condition and a storm wave condition, and were examined for the effects of the offshore-generated waves upon sediment transport in Liverpool Bay. Internally fetch-limited waves generated within the estuary were not examined in this thesis.

Waves from an angle of 270°-290° accounted for about 20% of the wave climate, and waves from an angle between 250°-310° accounted for about 40% of the wave climate for Liverpool Bay according to Appendix 7. A wave simulation from a direction of 280° was therefore representative of a most frequent wave condition. A representative wave height, $H\phi$, for waves from directions between 270°-290° was calculated according to the weighting algorithm derived by Chesher and Miles (1992):

$$H_{\phi} = \left[\frac{\sum\left(fH^{2.4}\right)}{\sum f}\right]^{\frac{1}{2.4}} \qquad \text{Eq. 6.1}$$

In which H is the wave height and f is the frequency of occurrence. The value 2.4 represents the exponent of the wave height in the sand transport formula.

A storm condition was simulated with a wave from an angle of 290°, representing the direction from which the largest representative wave conditions were experienced and also coincided with the direction of the greatest fetch length across the Irish Sea. The wave height was calculated for a probability of occurrence of twice per year according to Appendix 7, Column 3.

6.4 Analysis of changes in non-cohesive sediment transport

Results presented for the sediment transport scenarios examined, comprise analyses of sediment transport under; 2D tidal conditions, 3D tidal conditions and 3D tidal and wave conditions. Results of non-cohesive sediment transport calculations as both bed and suspended load are presented as colour plots in the same format for all scenarios examined, to show the magnitude of sediment transport fluxes. The plots were overlaid with vector plots to indicate the direction of sediment transport and reflect the strength of transport, although vectors were capped at a maximum of $1m^3/m$ to enable general patterns of sediment transport to be discerned. To analyse the significance of the non-cohesive sediment transport results for morphological change, tide residual fluxes were calculated through transects at locations of interest, shown on plots of residual sediment transport patterns.

6.4.1 Changes in potential non–cohesive sediment transport patterns under tidal conditions

Sediment transport patterns may exhibit characteristics distinct from hydrodynamic flow characteristics due to the nature of sediment behaviour and particularly the influence of a sediment transport threshold. However, limited data was available to calibrate models of sediment transport in Liverpool Bay. The most efficient form of examining sediment transport pathways between the estuary and wider environment was therefore to simplify or schematise the system. In the context of the current study, a schematisation of the system was achieved by assuming an inexhaustible supply of uniform sediment throughout the system. The only limiting factor on sediment transport was the force exerted by hydrodynamic flow. Although the outputs from the modelling were more qualitative, uncertainties in the results due to parameterisation and calibration were reduced, and relative changes in patterns of sediment transport for the different historical configurations could be examined.

A single value of median grain diameter d50 = 0.18mm (180μm) was assumed for the whole of the model domain area. The median grain sediment diameter was combined with the appropriate hydrodynamic flow model results as input parameters for sediment transport formulae specified in Section 6.4. The sediment transport formulae applied had the advantage that they were computationally fast, included a threshold current term and coped with varying bed slopes. However, Soulsby (1997) noted that the formulae should be used with caution in areas where the bed is not rippled. Furthermore, the sediment transport values derived were approximate as sediment transport calculations have significant error bounds. Soulsby (1997) suggested, for example, that in complicated marine environments, the best methods of calculating non-cohesive sediment transport rates may not be able to achieve much better than an accuracy of a factor of 5 in 70% of cases.

Potential non-cohesive bed load transport based upon 2D depth integrated flow simulation results

Bed load transport (q_b) of non-cohesive sediment was calculated for depth integrated flows from the 2D model using van Rijn's (1984) parameterisation of full sediment transport formulae to determine a depth-averaged sediment concentration employed in bed exchange relations:

$$q_b = 0.005\overline{U}h\left\{\frac{\overline{U}-\overline{U}_{cr}}{\left[(s-1)gd_{50}\right]^{1/2}}\right\}^{2.4}\left(\frac{d_{50}}{h}\right)^{1.2} \qquad \text{Eq. 6.2}$$

where, $$\overline{U}_{cr} = 0.19(d_{50})^{0.1}\log_{10}\left(\frac{4h}{d_{90}}\right) \qquad \text{for } 100 \le d_{50} \le 500\mu\text{m} \qquad \text{Eq. 6.3}$$

where $\bar{U}$ is depth averaged velocity, $\bar{U}_{cr}$ is threshold depth-averaged current speed, h is water depth, s is the ratio of densities of grain and water (2.65), g is gravitational acceleration (9.81m/s^2), d_{50} is median grain diameter and d_{90} is 90 percentile grain size diameter. Equation 6.2 was applied to 2D depth integrated flow field results of Liverpool Bay and the Mersey estuary (see Section 5.4.3), which employed a mean spring tide boundary condition. The scenarios for which sediment transport was calculated are summarised in Table 6.1.

Domain area	Year	Mode of sediment transport	Tidal condition	Wave conditions	Training wall
Mersey estuary and Liverpool Bay	1906	Non-cohesive bed load	Mean spring tide	None	No
"	1936	"	"	"	Yes
"	1977	"	"	"	"

Table 6.1 Summary of potential non-cohesive bed load transport simulations undertaken based upon 2D depth integrated flow results

From the potential bed load residual sediment transport results (see Figures 6.2-6.4) it was clear that the net movement of sediment for all bathymetric configurations was greatest in the Narrows and in the low water channel approach to the estuary mouth of the estuary in Liverpool Bay. The fluxes reflected the residual current velocity patterns shown in Figures 5.16-5.18 with areas of greatest sediment movement occurring in areas of greatest residual current velocity. The net movement of sediment through the Narrows was seawards for each of the bathymetric configurations examined. The bathymetric configuration for 1906 showed a stronger transport of sediment towards the estuary on the east side of the Narrows at the estuary mouth, reflected in a landwards net flux of sediment across Transect A in Table 6.2. Further landwards in the Narrows, however, it was evident that the residual transport was clearly seawards across the width of the channel. At the mouth of the low water channel in Liverpool Bay the residual transport was seawards, preventing sediment from entering, and indicating that the most probable pathway for sediment to enter the estuary was across Liverpool Bay.

Year and tidal condition simulated	Net sediment flux across transect (m^3)				
	A	B	C	D	E
1906 Mean spring tide	-115	48	-577	276	-212
1936 Mean spring tide	671	1287	98	-206	440
1977 Mean spring tide	165	-3063	-2366	-1199	-578

Table 6.2 Net tide-residual sediment fluxes across transects in Figures 6.2-6.4

The residual sediment transport patterns were, however, not exactly the same as the residual current velocity patterns as a result of a threshold current velocity for sediment transport. Moreover, it was evident that the effects of changes in bathymetry upon sediment transport regime were more apparent in plots of calculated bed load sediment transport than from plots of residual current velocity (see Figures 5.16-5.18). Sediment transport along the Formby coast, across Taylor's Bank to the north of the low water channel in Liverpool Bay and across Liverpool Bay was limited. Nevertheless, a more extensive spatial area of sediment transport across Liverpool Bay was evident for the 1906 bathymetric configuration, with a progressive decline to 1936 and 1977. Changes in residual sediment transport across Liverpool Bay were related to changes in bathymetry, and particularly to the accretion of sediment over Burbo Bank evident in Figure 4.15.

By integrating across the transects in Figures 6.2-6.4, it was evident from Table 6.2 that a pathway for the transport of sediment across Liverpool Bay towards the estuary mouth could only be identified for the 1936 bathymetric configuration. Net residual sediment transport fluxes towards the estuary mouth, i.e. positive fluxes, across Transects A-C only occurred for the 1936 bathymetric configuration. These results showed that sediment transport calculations derived from 2D depth integrated flow field results, could account for changes in transport of non-cohesive bed load material to the mouth of the estuary as a result of changes in flow across Liverpool Bay, resulting from bathymetric change. This may have contributed to changes in estuary morphological behaviour. However, the 2D flow results could not account for the movement of material into the estuary via the Narrows as they did not include stratification effects. Furthermore, the extent to which bathymetric changes in Liverpool Bay could be attributed to the construction of training walls was uncertain.

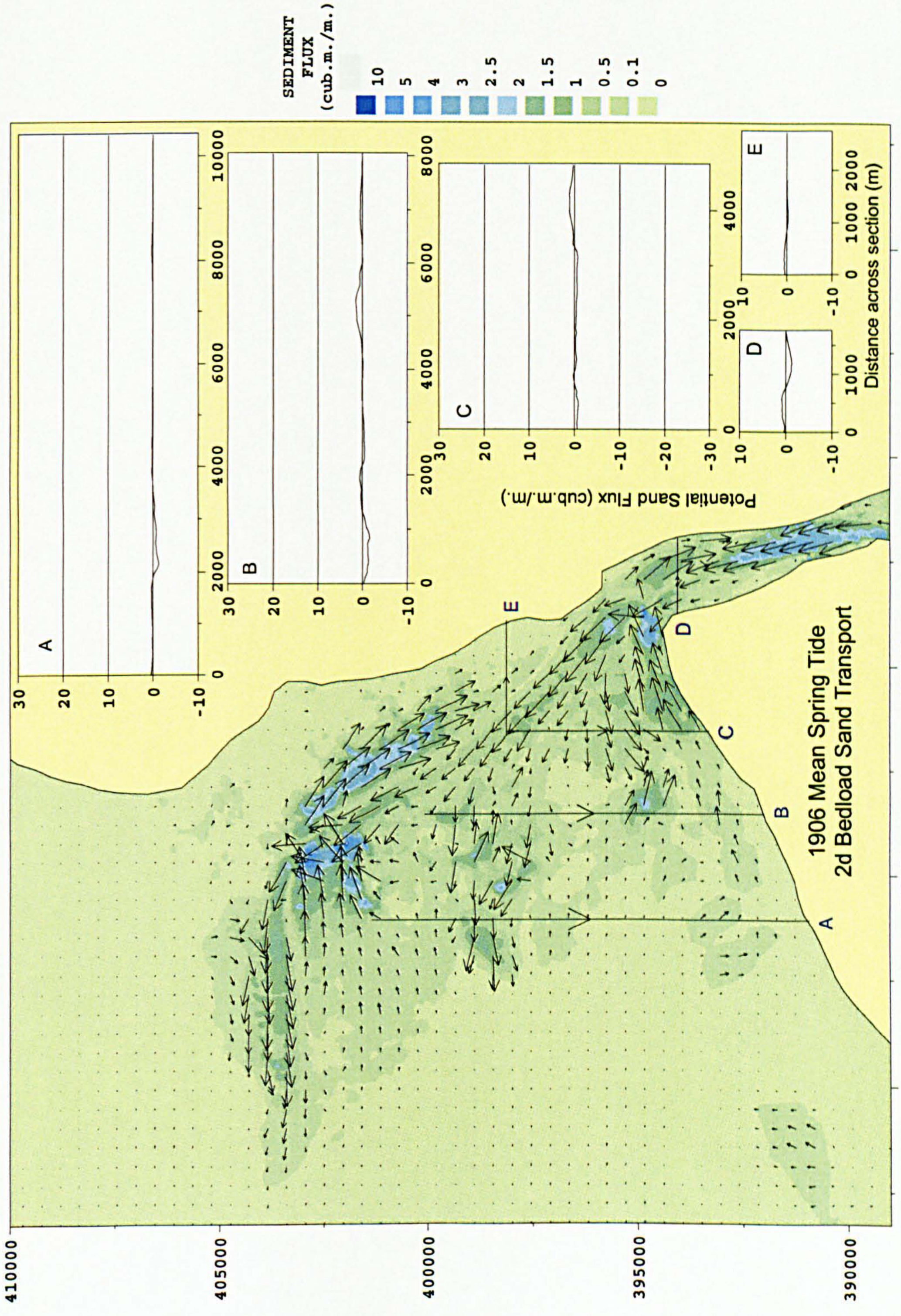


Figure 6.2 Potential non-cohesive bed load residual transport through a mean spring tide based upon 2D depth integrated flow simulation results for 1906

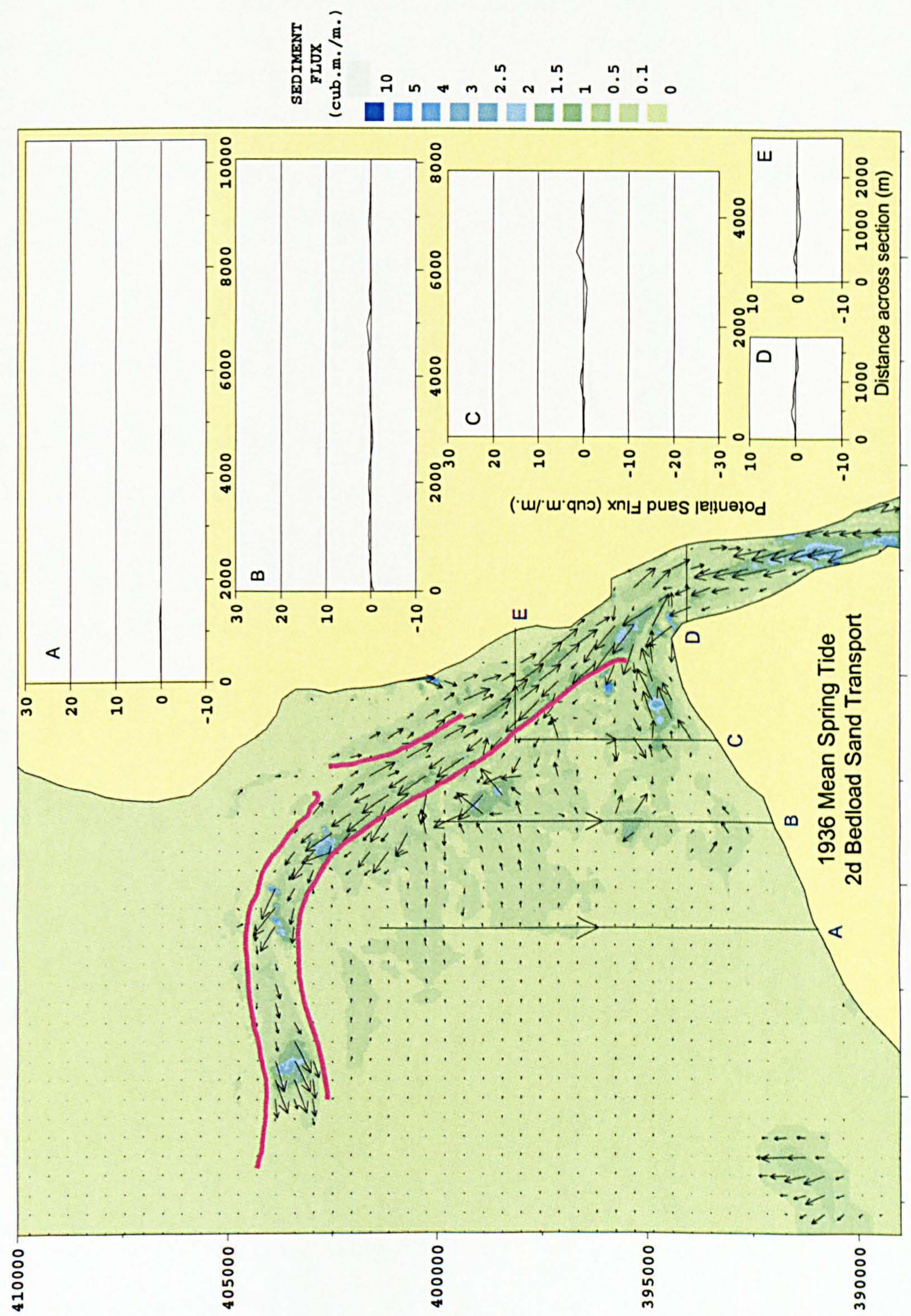


Figure 6.3 Potential non-cohesive bed load residual transport through a mean spring tide based upon 2D depth integrated flow simulation results for 1936

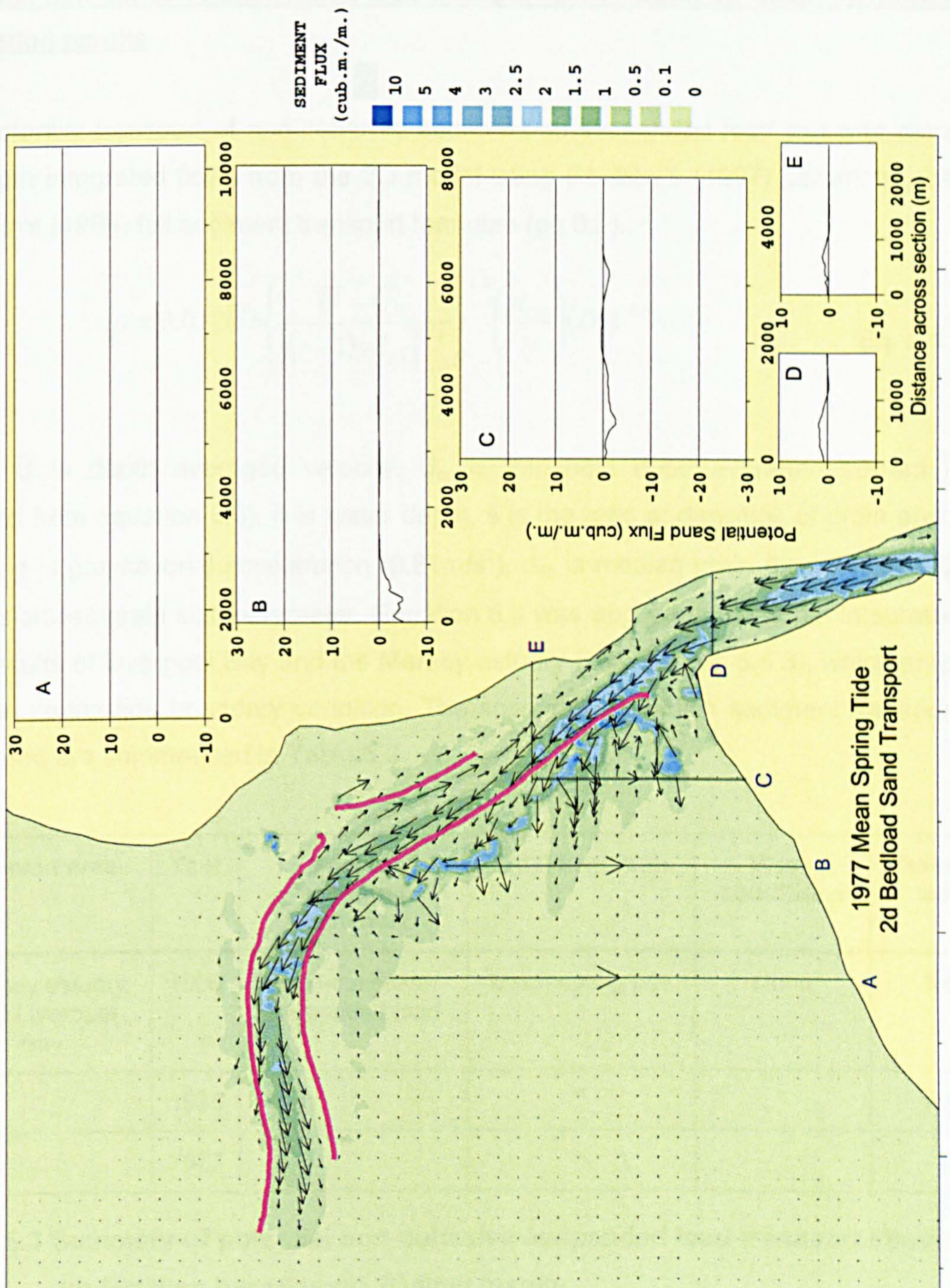


Figure 6.4 Potential non-cohesive bed load residual transport through a mean spring tide based upon 2D depth integrated flow simulation results for 1977

Potential non-cohesive suspended load transport based upon 2D depth integrated flow simulation results

The potential transport of non-cohesive sediment as suspended load (q_s) was calculated for depth integrated flows from the 2D model using Soulsby's (1997) parameterisation of van Rijn's (1984) full sediment transport formulae (eq.6.5).

$$q_s = 0.012\overline{U}h\left\{\frac{\overline{U}-\overline{U}_{cr}}{\left[(s-1)gd_{50}\right]^{1/2}}\right\}^{2.4}\left(\frac{d_{50}}{h}\right)(D_*)^{-0.6} \qquad \text{Eq. 6.4}$$

where $\bar{U}$ is depth averaged velocity, $\bar{U}_{cr}$ is threshold depth-averaged current speed (derived from equation 6.3), h is water depth, s is the ratio of densities of grain and water (2.65), g is gravitational acceleration (9.81m/s^2), d_{50} is median grain diameter and D_* is a dimensionless grain size parameter. Equation 6.3 was applied to 2D depth integrated flow field results of Liverpool Bay and the Mersey estuary (see Section 5.4.3), which employed a mean spring tide boundary condition. The scenarios for which sediment transport was calculated are summarised in Table 6.3.

Domain area	Year	Mode of sediment transport	Tidal condition	Wave conditions	Training wall
Mersey estuary and Liverpool Bay	1906	Non-cohesive suspended load	Mean spring tide	None	No
"	1936	"	"	"	Yes
"	1977	"	"	"	"

Table 6.3 Summary of potential non-cohesive suspended load transport simulations undertaken based upon 2D flow results

It was evident that patterns of suspended sediment transport calculated from the 2D depth integrated flow field results exhibited several characteristics that were similar to bed load transport derived from 2D depth integrated flow results (see previous section). These similarities resulted from the use of the same flow field results and the same critical velocity in sediment transport equations 6.2 and 6.4. The net movement of sediment for all bathymetric configurations was greatest in the Narrows and in the low water channel approach to the mouth of the estuary in Liverpool Bay according to the potential suspended load residual sediment transport results (see Figures 6.5-6.7). The trends in sediment transport through the Narrows were similar to the trends in computed bed load transport, with a residual seaward movement of sediment for each of the bathymetric configurations examined. The bathymetric configuration for 1906 also showed a stronger transport of sediment towards the estuary on the east side of the Narrows at the mouth of the estuary, reflected in a landwards net flux of sediment across Transect D in Table 6.4, but residual transport was clearly seawards across the width of the channel further landwards in the Narrows. At the mouth of the low water channel in Liverpool Bay the residual transport was seawards, preventing sediment from entering, and indicating that the most probable pathway for suspended sediment to enter the estuary was also across Liverpool Bay.

Year and tidal condition simulated	Net sediment flux across transect (m^3)				
	A	B	C	D	E
1906 Mean spring tide	-720	932	-4891	3751	-2157
1936 Mean spring tide	6049	10202	337	-1989	4540
1977 Mean spring tide	1545	-19033	-17286	-11583	-6093

Table 6.4 Net tide-residual sediment fluxes across transects in Figures 6.5-6.7

In comparison with bed load transport calculated from 2D depth integrated flow, the quantities of sediment transported as suspended load were significantly greater. These results were in agreement with Soulsby (1997), stating that if in-situ sediment was mostly composed of grains less than 0.2mm diameter, the predominant mode of transport was suspended load. The application of Equations 6.2 and 6.4 resulted in higher computed transport of sediment as suspended load due to a higher empirical coefficient, and the non-linear relation of sediment transport to flow velocity resulted in larger net fluxes of suspended sediment in comparison with bed load. Furthermore, it was evident that the spatial extent of sediment transport as suspended load extended over a significantly larger area of Liverpool Bay than bed load transport, and that the residual suspended sediment transport patterns differed noticeably from residual current velocity patterns in Liverpool Bay. Transport of suspended sediment across Liverpool Bay was eastwards in contrast to residual current velocities, which demonstrated a westward residual current velocity for all bathymetric configurations. An eastward residual sediment flux through Liverpool Bay agreed with net sediment transport direction published in MAFF (1981). A more extensive spatial area of sediment transport across Liverpool Bay was evident for the 1906 bathymetric configuration, with a progressive decline to 1936 and 1977, which could be attributed to the effects of changes in bathymetry, and particularly the accretion of sediment over Burbo Bank evident in Figure 4.15.

Integrating across the transects in Figures 6.5-6.7, indicated in Table 6.4 that, similarly to bed load transport calculations, a pathway for the transport of suspended sediment across Liverpool Bay towards the estuary mouth could be identified for the 1936 bathymetric configuration. Net residual sediment transport fluxes towards the estuary mouth, i.e. positive fluxes across Transects A-C occurred only for the 1936 bathymetric configuration. Moreover, the net quantities of suspended sediment transport across Transects A-C were significantly larger than the net quantities of bed load sediment transport indicated in Table 6.2, which suggested that suspended load sediment transport represented a more important mechanism for examination when investigating morphological change in the Mersey estuary. Based on the results presented in Tables 6.2 and 6.4 suspended sediment accounted for net fluxes of sediment across transects studied between 3.5 to 20 times larger than bed load transport. The suspended sediment transport calculations presented, which employed 2D depth integrated flow field results demonstrated that changes in flow across Liverpool Bay resulting from bathymetric change could account for changes in transport of non-cohesive material to the mouth of the estuary. Furthermore, suspended sediment transport accounted for a greater proportion of sediment transport in Liverpool Bay and the Mersey estuary, and was likely to have contributed to changes in estuary morphological behaviour to a greater extent than bed load transport of sediment. However, as for bed load, 2D flow results employed as a basis for sediment transport computations could not account for the movement of material into the estuary via the Narrows, as they did not include stratification effects.

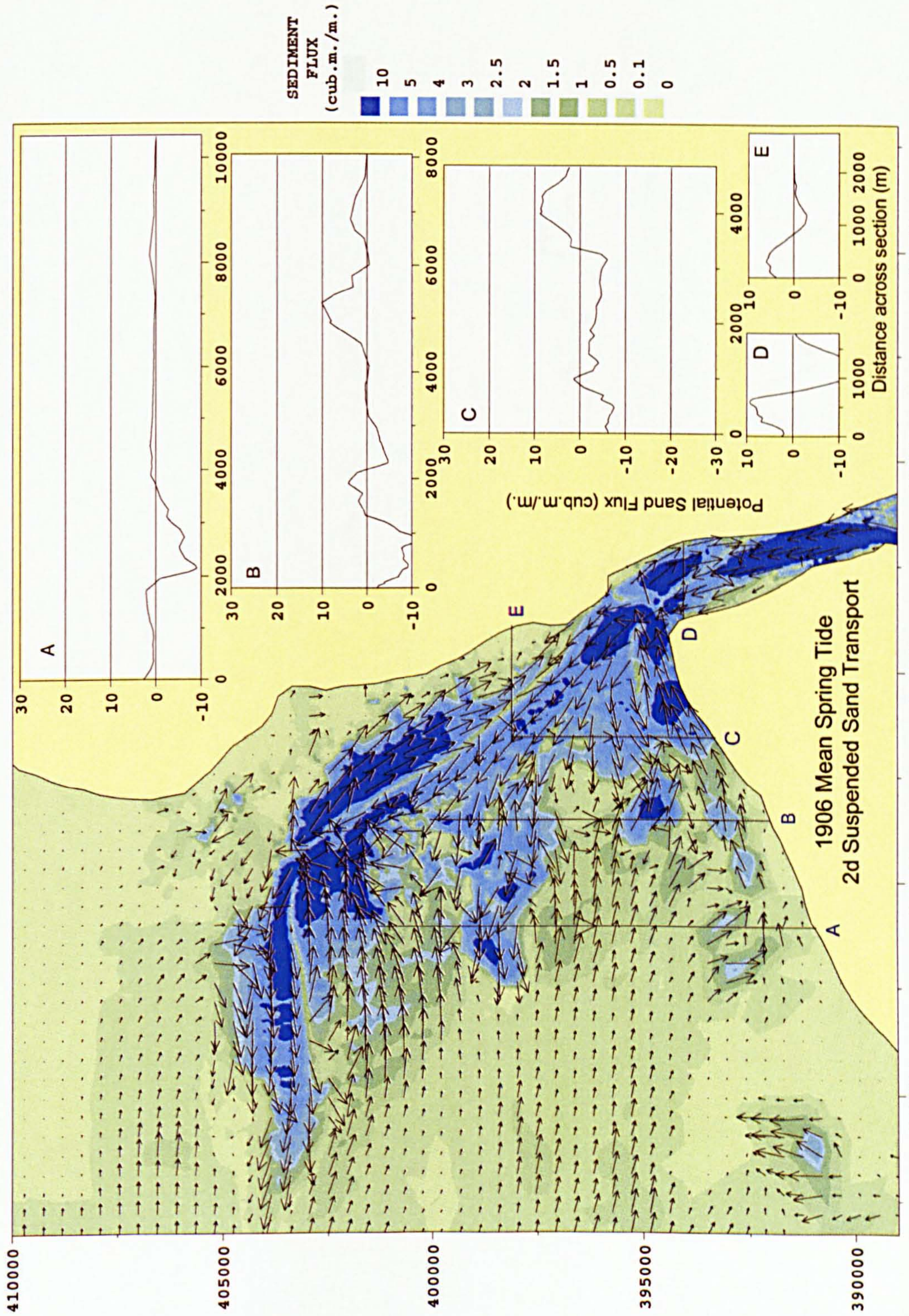


Figure 6.5 Potential non-cohesive suspended load residual transport through a mean spring tide based upon 2D depth integrated flow simulation results for 1906

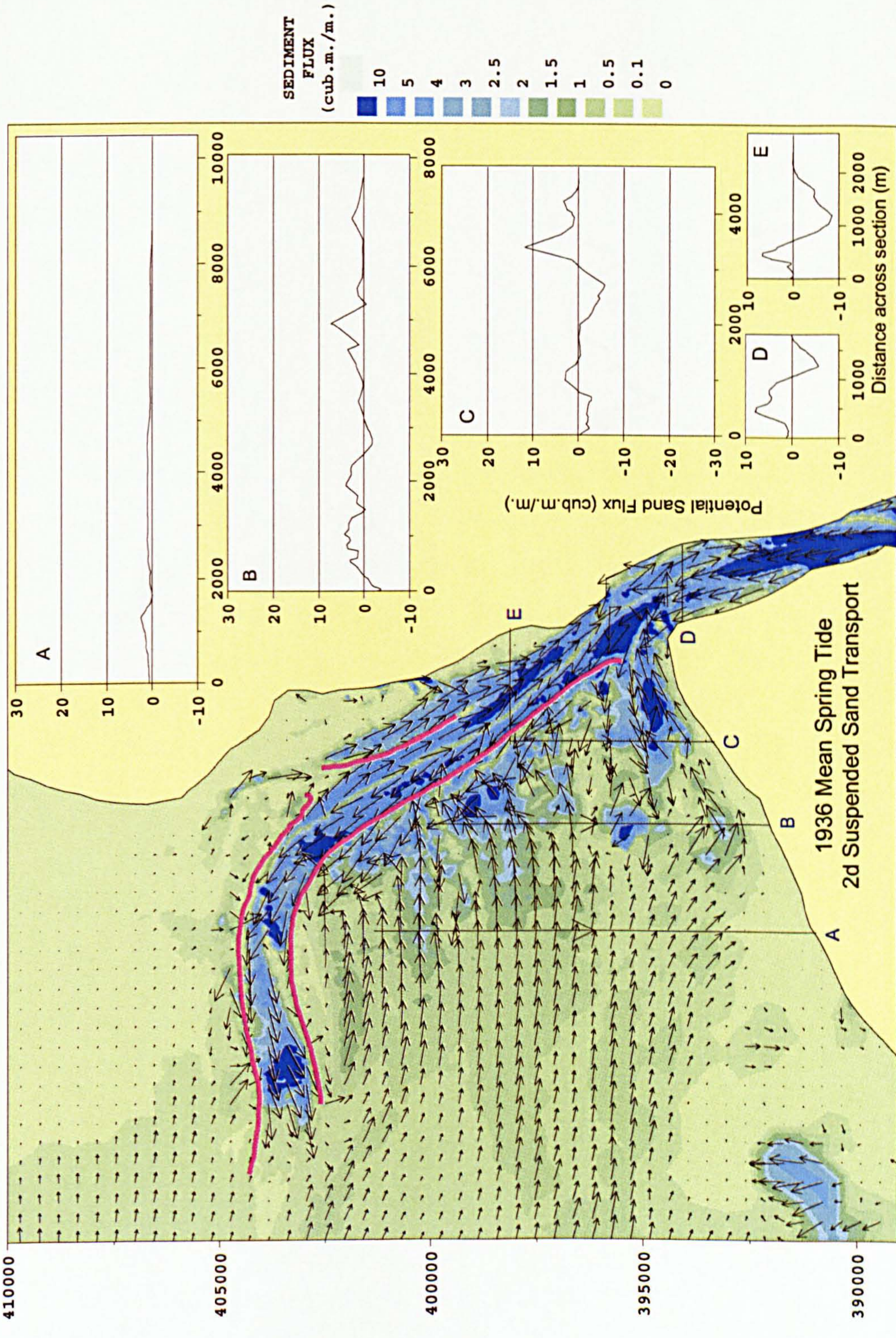


Figure 6.6 Potential non-cohesive suspended load residual transport through a mean spring tide based upon 2D depth integrated flow simulation results for 1936

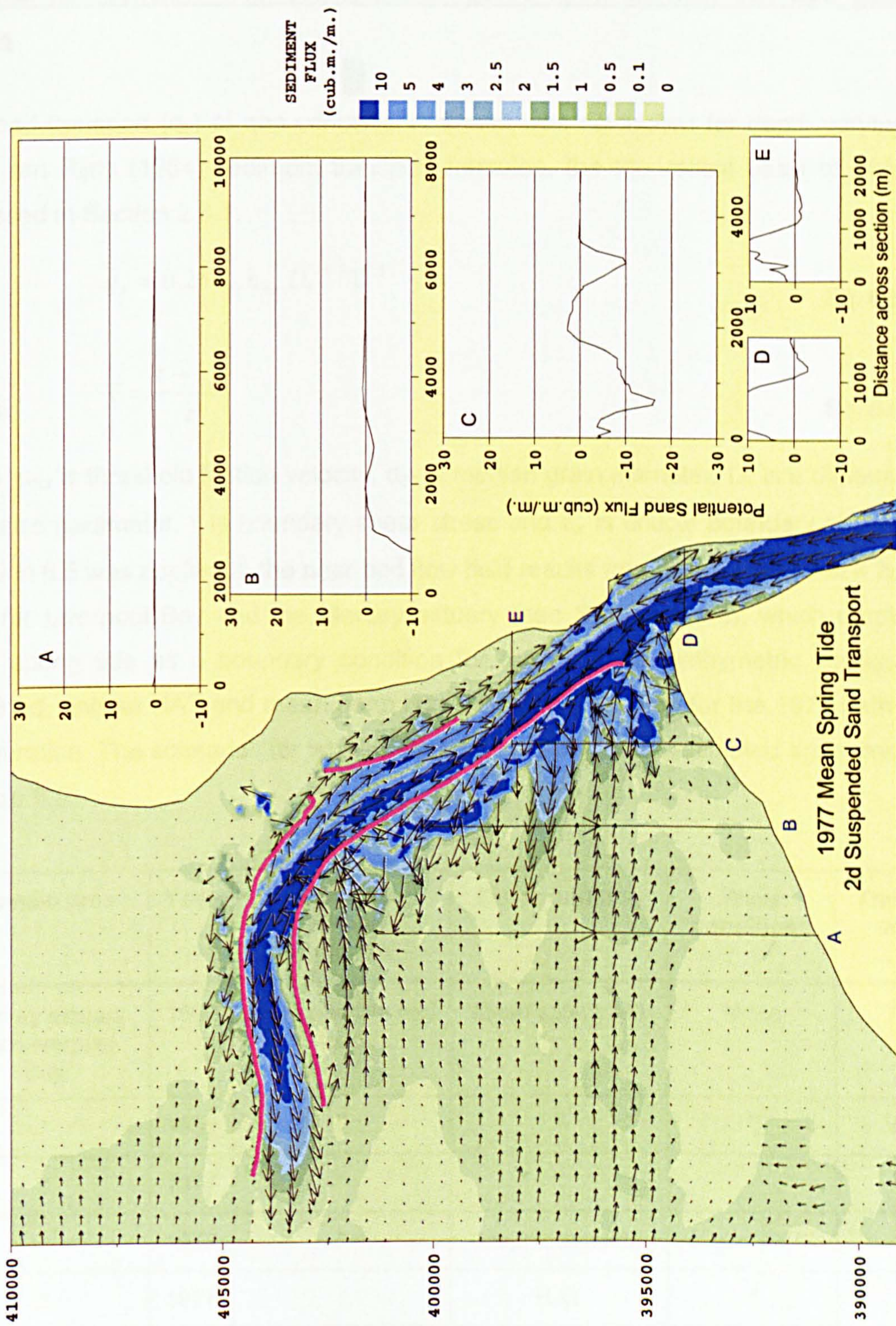


Figure 6.7 Potential non-cohesive suspended load residual transport through a mean spring tide based upon 2D depth integrated flow simulation results for 1977

Potential non-cohesive bed load transport based upon 3D near bed flow simulation results

Bed load transport (q_b) of non-cohesive sediment was calculated for depth varying flows using van Rijns (1984) sediment transport formulae, the theoretical basis of which was discussed in Section 2.3.1:

$$q_b = 0.25 d_{50} u_{*cr} D_*^{-0.3} \mathrm{T}^{1.5} \qquad \text{Eq. 6.5}$$

with,

$$\mathrm{T} = \frac{\tau - \tau_{cr}}{\tau} \qquad \text{Eq. 6.6}$$

where, u_{*cr} is threshold friction velocity, d_{50} is median grain diameter, D_* is a dimensionless grain size parameter, τ is boundary shear stress and τ_{cr} is critical boundary shear stress. Equation 6.5 was applied to the near bed flow field results from the 3D model at a height of 0.2m for Liverpool Bay and the Mersey estuary (see Section 5.4.4), which employed a mean spring tide as a boundary condition for the historical bathymetric configurations examined, and an HAT and mean neap tidal boundary condition for the 1977 bathymetric configuration. The scenarios for which sediment transport was calculated are summarised in Table 6.5.

Domain area	Year	Mode of sediment transport	Tidal condition	Wave conditions	Training wall
Mersey estuary and Liverpool Bay	1906	Non-cohesive bed load	Mean spring tide	None	No
"	1936	"	"	"	Yes
"	1977	"	"	"	"
"	1977	"	Mean neap tide	"	"
"	1977	"	HAT	"	"

Table 6.5 Summary of potential non-cohesive bed load transport simulations undertaken based upon 3D near bed flow results

The figures for the 3D results are presented in the same format as for the 2D results (see Figures 6.8-6.12 and Table 6.7). It was evident that the spatial extent of areas of sediment transport in Liverpool Bay correlated reasonably well with 2D bed load calculations, and several similarities between features in computed net bed load sediment transport derived from 2D and 3D near bed flow fields were apparent. Firstly, residual sediment transport was greatest in the Narrows and low water channel for all sets of results. Secondly, sediment transport was more extensive across Liverpool Bay for the 1906 bathymetric configuration, with a progressive decline to 1936 and 1977. Thirdly, there was little transport of sediment along the Formby coast, and the net transport of sediment at the mouth of the low water channel was seawards, which indicated that the most probable source of sediment to the estuary was across Liverpool Bay, although the patterns of sediment movement across Liverpool Bay were less clear from Figures 6.8-6.12.

Year and tidal condition simulated	Net sediment flux across transect (m^3)				
	A	B	C	D	E
1906 Mean spring tide	-236	-355	-248	435	-47
1936 Mean spring tide	342	-485	1135	228	183
1977 Mean spring tide	294	-1083	-2730	-25	-155
1977 HAT	146	-3756	-6866	217	-108
1977 Mean neap tide	1	-18	-35	-15	-7

Table 6.6 Net tide-residual sediment fluxes across transects in Figures 6.8-6.12

The 3D near bed results, however, also exhibited differences when compared with the 2D results. Firstly, the calculated residual sediment transport fluxes were generally stronger for computations employing the 2D depth integrated flow field, than for computations that employed the 3D near bed flow field. This was due to differences in the calculation of bed shear stress, which was more accurately derived from a 3D model which computed near bed flow. Secondly, there was a difference in the direction of net bed load sediment transport in the Narrows, which was predominantly landwards in the computations that employed the 3D near bed flow field, although the potential for importing sediment into the estuary declined progressively between 1906-1977 according to Table 6.7. The results evident in Figures 6.8-6.12 contrasted with the seaward direction of net residual that were evident in the computations employing the 2D depth integrated flow field. This difference reflected differences in the residual current velocities illustrated in Figures 5.16-5.21, and could be attributed to the effects of salinity induced gravitational circulation that were represented in the 3D flow model. There was also some evidence that the net movement of sediment through the trained channel was towards the estuary at the southern end in 1936; but further away from the estuary mouth, at the mouth of the trained channel where stratification effects were reduced the movement of sediment was in a seaward direction.

Furthermore, the movement of sediment across Liverpool Bay evident in Table 6.7 did not correlate with the interpretation of historic changes sediment transport regime derived from calculations employing the 2D depth integrated flow results. It was evident that there was no clear pathway of sediment across Liverpool Bay to the estuary mouth for any year, as Transect B demonstrated a net seaward sediment flux for all bathymetric configurations examined. However, a similar pattern of changes in sediment transport to that derived from calculations employing the 2D depth integrated flow results did exist for Transect C. For the bathymetric configurations of 1906 and 1977 there was a net westward movement of sediment across Transect C, which prevented sediment from reaching the estuary. For the 1936 bathymetric configuration, however, there was a reversal of this trend and the net transport of sediment across Transect C was towards the estuary mouth.

Under neap tidal forcing it was illustrated in Figure 6.12 that very little sediment transport occurred, and that which did occur was largely restricted to localised areas of the Narrows, indicating that neap tidal conditions played a significantly less important role in morphological change than spring tidal conditions. Under the forcing of a HAT it was evident from Figure 6.11 that there was enhanced movement of sediment in the low water channel and the Narrows area of the estuary. From Figure 6.11 the trends in sediment transport appeared similar to trends exhibited in Figure 6.10 for forcing under a mean spring tide, with a strengthening of sediment transport fluxes but there was no noticeable increase in the extent of sediment transport across Liverpool in comparison with 1906 and 1936, when more extensive sediment transport across Liverpool Bay was demonstrated.

The trends evident from Table 6.7 substantiated a strengthening of sediment fluxes under forcing by a HAT. They indicated that westward transport of sediment away from the estuary across Transects B and C increased, although landward movement of sediment across Transect A exhibited a small reduction. A notable feature of Table 6.7, however, was a reversal in the net residual transport across Transect D at the mouth of the estuary, where a substantial quantity of sediment was transported towards the estuary under forcing by a HAT. This was due to a significant strengthening of the landward residual sediment transport on the eastern side of the Narrows, a feature that was evident under mean spring tide forcing in 1977, but which was enhanced with respect to seaward residual sediment transport on the western side of the Narrows under forcing by a HAT. An increase in current velocities associated with a larger tidal range, may have reduced possible eddy effects in the mouth of the Narrows, and increased flood tide current velocity asymmetry with the concentration of the flood tide on the eastern side of the Narrows, resulting in an increase in net landward transport of bed load sediment across Transect D due to the non-linear relationship between current velocity and sediment transport. The forcing of a HAT was unlikely to have exerted a significant influence upon the morphological behaviour of the estuary for the 1977 bathymetric configuration, as the transport of sediment across Liverpool Bay was in a seaward direction. Nevertheless, the effects of tides with a range greater than a mean spring tide could have exerted a significant influence upon the transportation of sediment into the estuary during the period when significant accretion was observed.

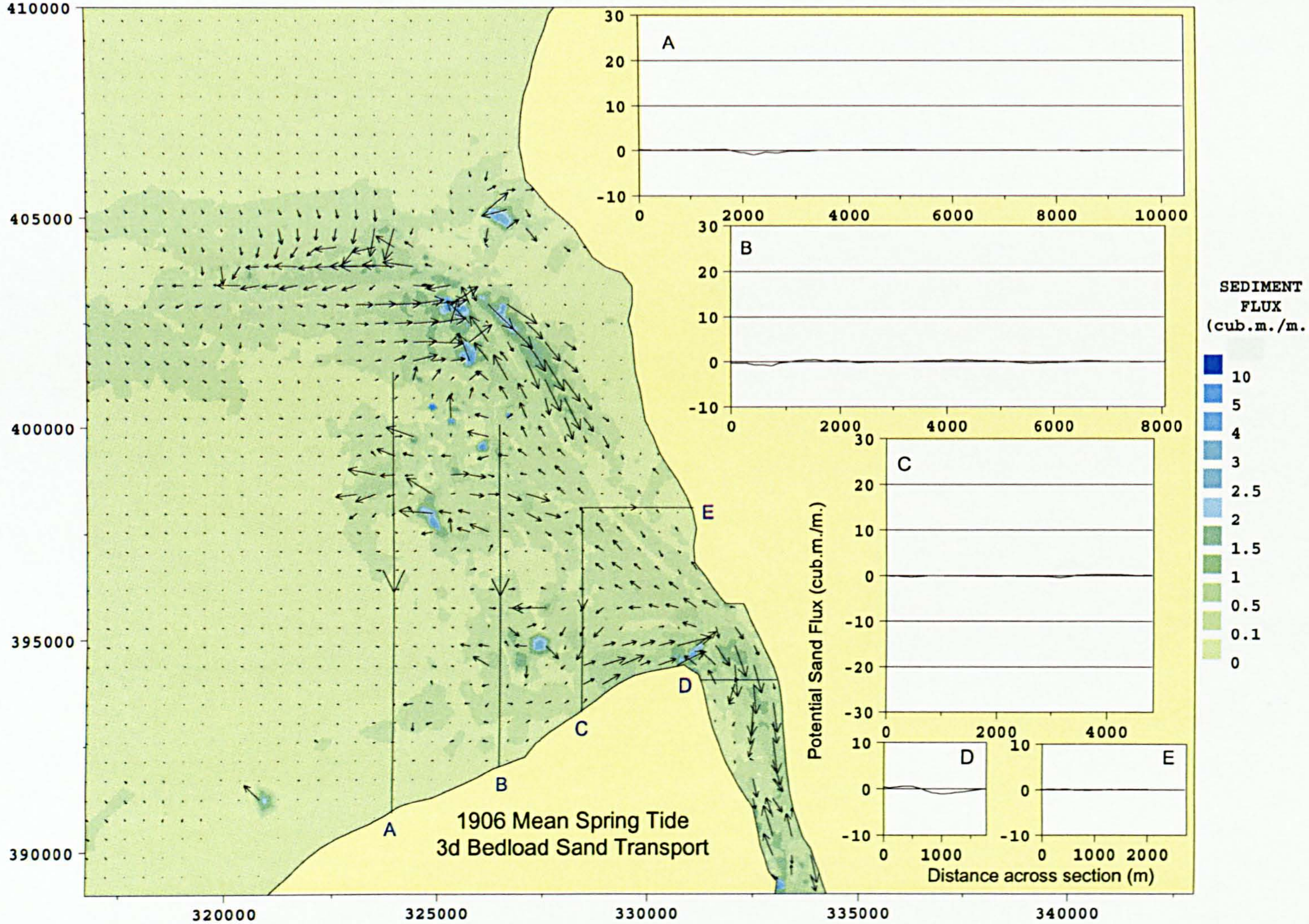


Figure 6.8 Potential non-cohesive bed load residual transport through a mean spring tide based upon 3D near bed flow simulation results for 1906

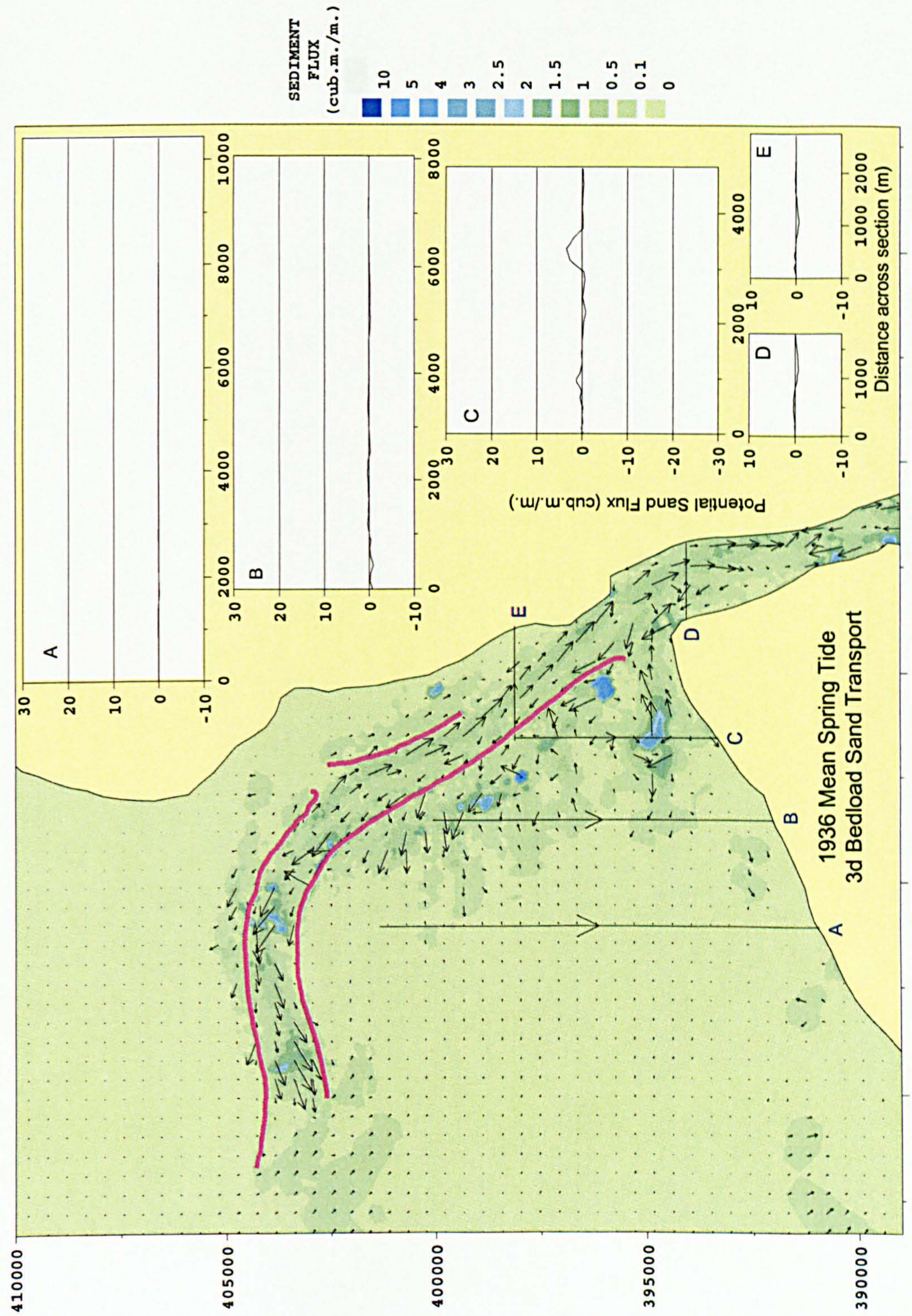


Figure 6.9 Potential non-cohesive bed load residual transport through a mean spring tide based upon 3D near bed flow simulation results for 1936

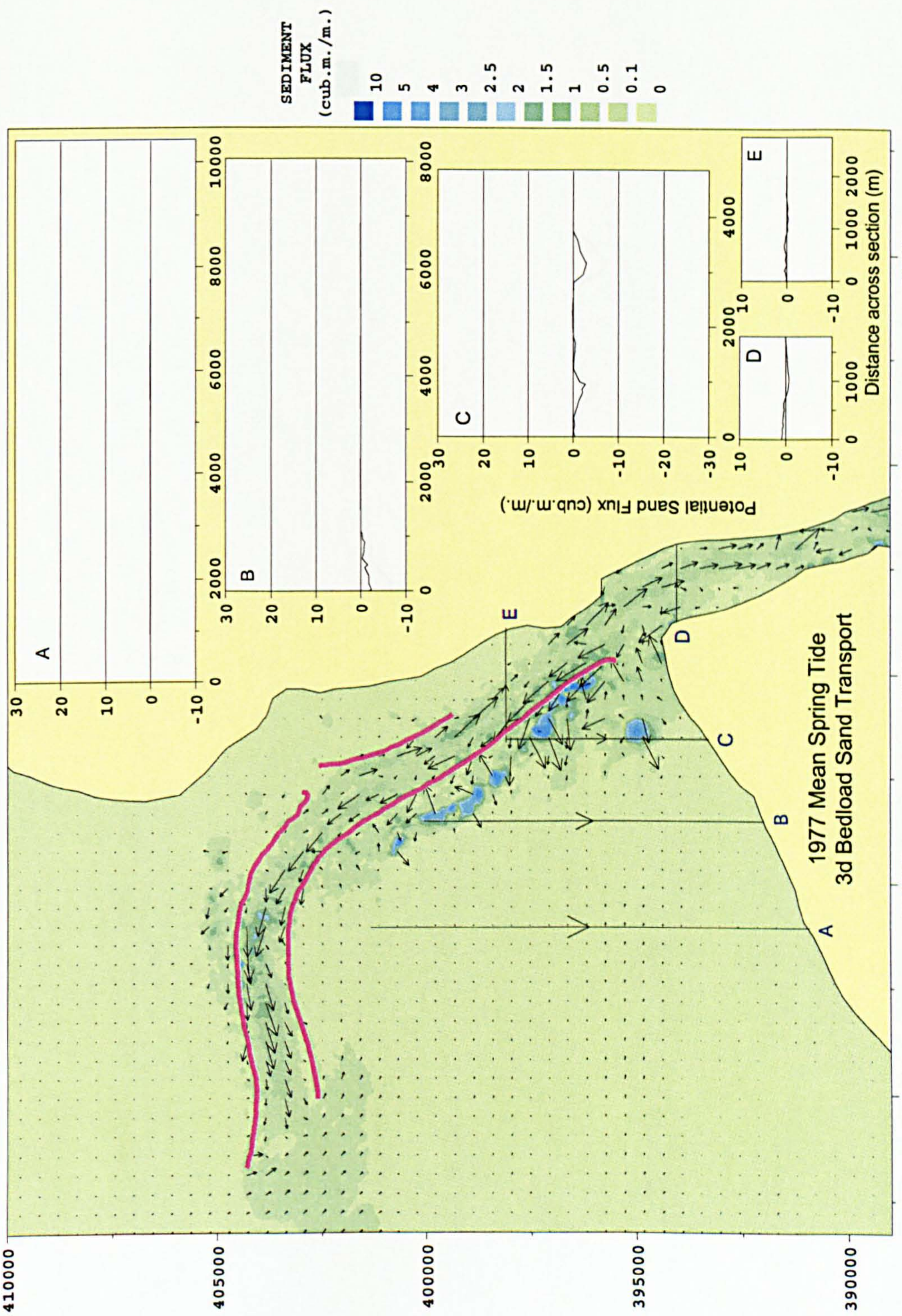


Figure 6.10 Potential non-cohesive bed load residual transport through a mean spring tide based upon 3D near bed flow simulation results for 1977

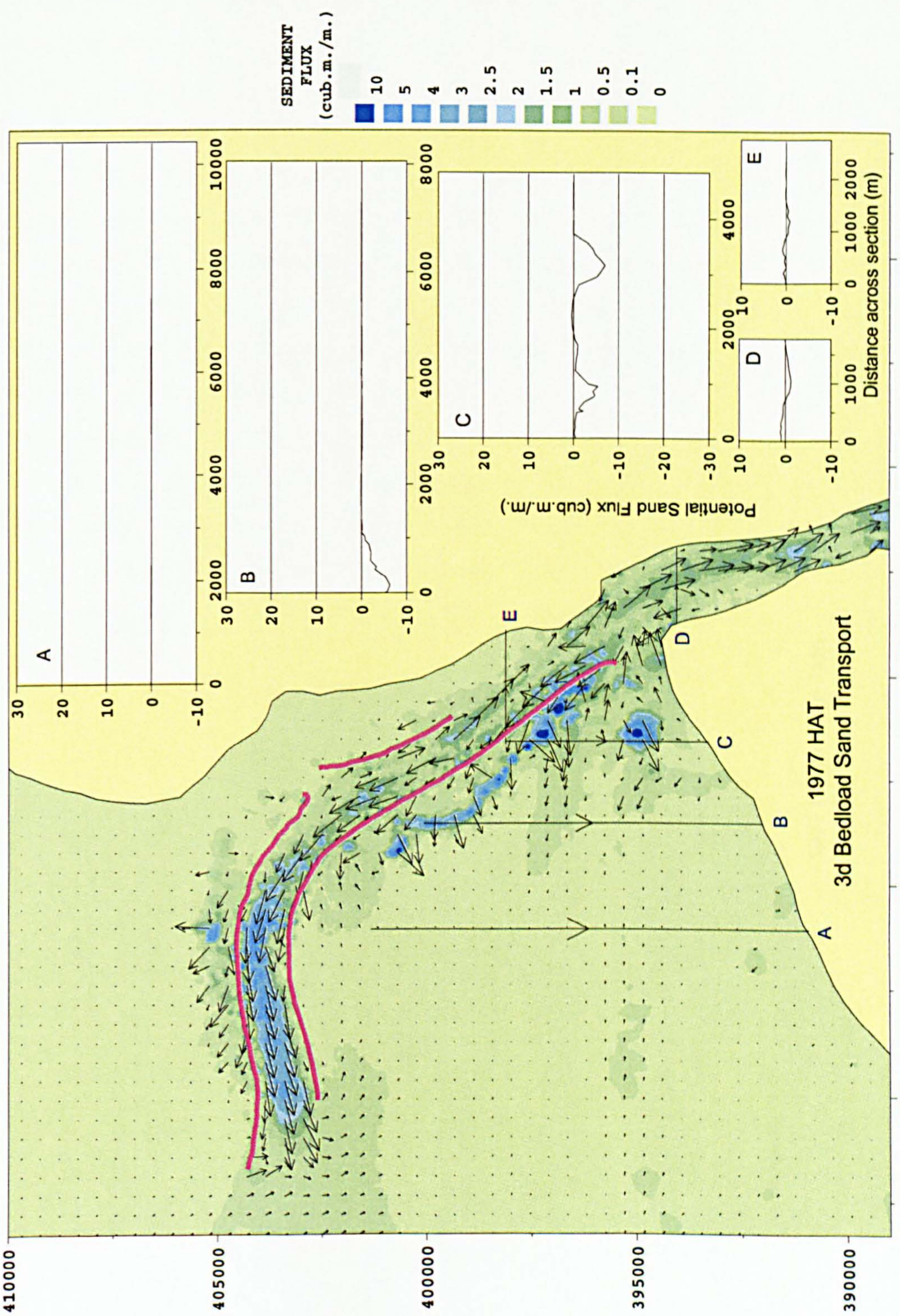


Figure 6.11 Potential non-cohesive bed load residual transport through a HAT based upon 3D near bed flow simulation results for 1977

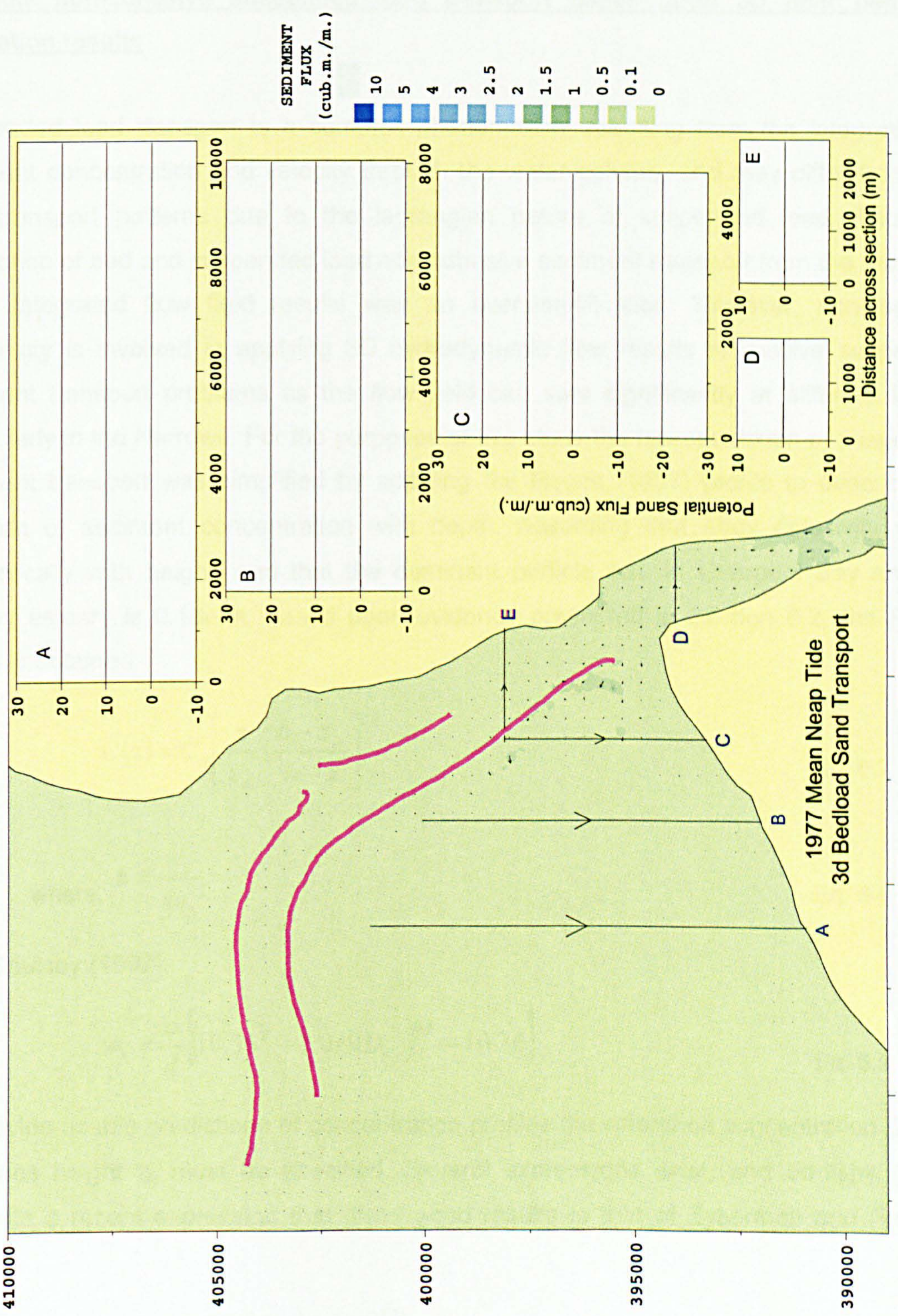


Figure 6.12 Potential non-cohesive bed load residual transport through a mean neap tide based upon 3D near bed flow simulation results for 1977

Potential non-cohesive suspended load transport based upon 3D near bed flow simulation results

Suspended load transport is a complex phenomenon, resulting from the integration of sediment concentration and velocity through the water column, and may differ from bed load transport patterns due to the lagrangian nature of suspended load. Thus the calculation of bed and suspended load non-cohesive sediment transport from the same 2D depth integrated flow field results was an oversimplification. However, considerable complexity is involved in applying 3D hydrodynamic flow results to resolve suspended sediment transport problems as the flow field can vary significantly at different levels, particularly in the Narrows. For the purposes of this study the representation of suspended sediment transport was simplified by applying the Rouse (1937) profile to describe the variation of sediment concentration with depth. Assuming that eddy diffusivity varies parabolically with height, and that the dominant particle size in Liverpool Bay and the Mersey estuary is 0.18mm, based upon evidence presented in Section 6.2, the Rouse profile is obtained:

$$C(z)=C_a\left[\frac{z}{z_a}\cdot\frac{h-z_a}{h-z}\right]^{-b} \qquad \text{Eq. 6.7}$$

where, $b=\dfrac{w_s}{\kappa u_*}$ Eq. 6.8

after Soulsby (1997),

$$w_s=\frac{\upsilon}{d}\left[\left(10.36^2+1.049D_*^3\right)^{0.5}-10.36\right] \qquad \text{Eq. 6.9}$$

To provide usable predictions of concentration profiles the reference concentration C_a and reference height z_a must be specified. Several expressions exist, and Soulsby (1997) suggests a recent expression that gives good results is that of Zyserman and Fredsøe (1994):

$$C_a=\frac{0.331(\vartheta_s-0.045)^{1.75}}{1+0.720(\vartheta_s-0.045)^{1.75}} \qquad \text{Eq. 6.10}$$

at height, $z_a=2d_{50}$

where, z is height above the sea bed, z_a is a reference height near the sea bed, C(z) is the concentration of sediment at height z, C_a is the sediment reference concentration at height z_a, H is water depth, and b is Rouse number. The results of the calculations of Rouse profiles shown in Figure 6.14 for 3 different positions in Liverpool Bay shown below in clearly indicated that the concentration of suspended sediment transport in the bottom 1m of the flow field accounted for more than 90% of suspended sediment transport. Hence, the assumption that suspended sediment occurred predominantly in the bottom 1m of flow was a valid means of simplifying suspended sediment transport using the results of a 3D flow model

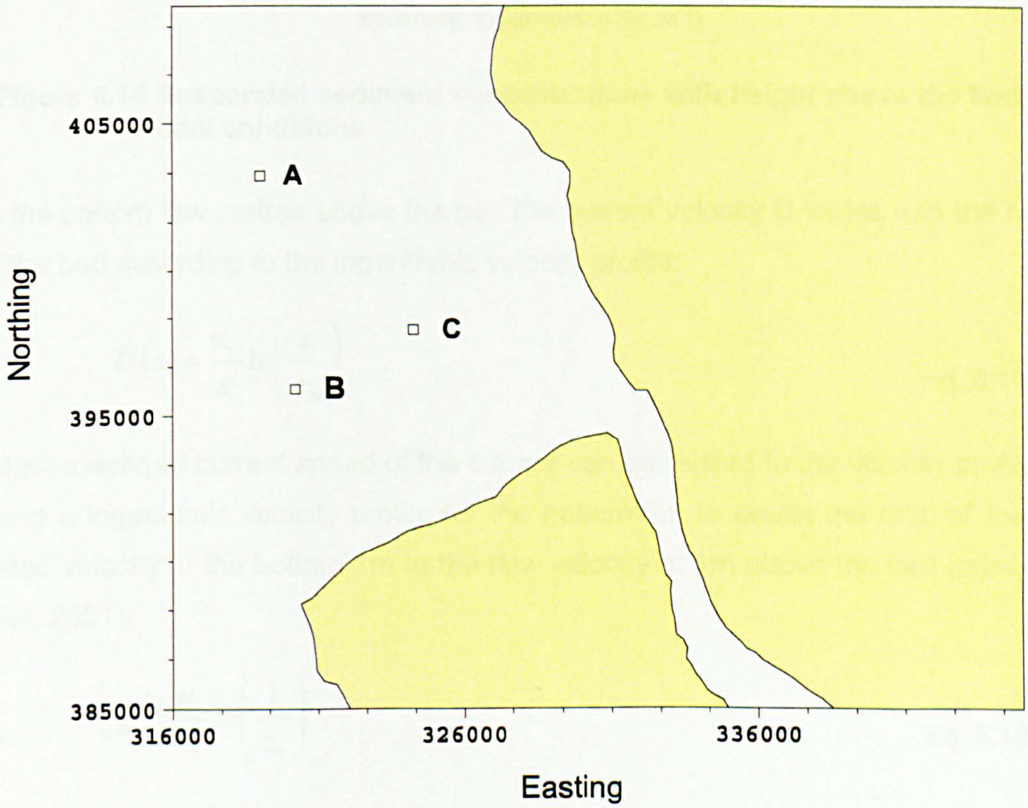


Figure 6.13 Locations of data employed in Rouse profile locations

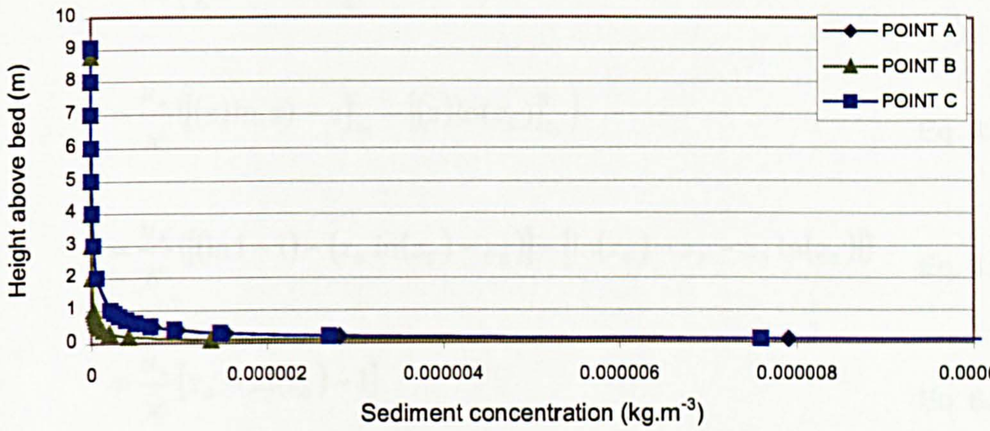


Figure 6.14 Suspended sediment concentrations with height above the bed under tidal conditions

Within the bottom few metres above the bed the current velocity U varies with the height z above the bed according to the logarithmic velocity profile:

$$U(z) = \frac{u_*}{\kappa}\ln\left(\frac{z}{z_0}\right) \qquad \text{Eq. 6.11}$$

The depth averaged current speed of the current can be related to the velocity profile U(z), assuming a logarithmic velocity profile for the bottom 1m to obtain the ratio of the depth integrated velocity in the bottom 1m to the flow velocity at 1m above the bed (pers.comm. Chesher, 2001):

Where, $$U_{(1m)} = \frac{u_*}{\kappa}\ln\left(\frac{1}{z_0}\right) \qquad \text{Eq. 6.12}$$

$$= \frac{u_*}{\kappa}\ln(0 - \ln z_0) \qquad \text{Eq. 6.13}$$

$$= -\frac{u_*}{\kappa}\ln z_0 \qquad \text{Eq. 6.14}$$

And, $$\overline{U}_{(1m)} = \frac{1}{h}\int_{z_0}^{1}\frac{u_*}{\kappa}\ln\left(\frac{z}{z_0}\right)dz \qquad \text{Eq. 6.15}$$

$$= \frac{u_*}{\kappa}\left(\int_{z_0}^{1} \ln(z)dz - \int_{z_0}^{1} \ln(z_0)dz \right) \qquad \text{Eq. 6.16}$$

$$= \frac{u_*}{\kappa}\left([(z)\ln(z) - z]_{z_0}^{1} - [(z)\ln(z_0)]_{z_0}^{1} \right) \qquad \text{Eq. 6.17}$$

$$= \frac{u_*}{\kappa}\left([(\ln 1 - 1) - (z_0 \ln(z_0) - z_0)] - [\ln(z_0) - z_0 - z_0 \ln(z_0)] \right) \qquad \text{Eq. 6.18}$$

$$= \frac{u_*}{\kappa}[z_0 - \ln(z_0) - 1] \qquad \text{Eq. 6.19}$$

Thus,

$$\frac{\overline{U}_{(1m)}}{U_{(1m)}} = \frac{\frac{u_*}{\kappa}[z_0 - \ln(z_0) - 1]}{-\frac{u_*}{\kappa}\ln(z_0)} \qquad \text{Eq. 6.20}$$

$$= -\left[\frac{z_0 - \ln(z_0) - 1}{\ln(z_0)} \right] \qquad \text{Eq. 6.21}$$

Equation 6.4 was applied to the 3D results by extracting current velocities at a height of 1m above the bed from the simulation results, and multiplying by equation 6.20 to derive a depth integrated velocity for the bottom 1m of flow. This approach assumed that the bottom 1m comprised a homogenous flow field with no significant variation in direction of residual transport. The scenarios for which sediment transport was calculated are summarised in Table 6.7.

Domain area	Year	Mode of sediment transport	Tidal condition	Wave conditions	Training wall
Mersey estuary and Liverpool Bay	1906	Non-cohesive suspended load	Mean spring tide	None	No
"	1936	"	"	"	Yes
"	1977	"	"	"	"
"	1977	"	Mean neap tide	"	"
"	1977	"	HAT	"	"

Table 6.7 Summary of potential non-cohesive suspended load transport simulations undertaken based upon 3D near bed flow results

Patterns of suspended sediment transport exhibited several characteristics that were similar to calculations of suspended load transport derived from 2D depth integrated flow. The principal feature that was evident from Figures 6.15-6.19 was that larger quantities of sediment were transported as suspended load transport than as bed load transport. Although the net sediment fluxes for all bathymetric configurations were greatest in the Narrows and the low water channel approach to the mouth of the Mersey estuary in Liverpool Bay, the transport of suspended sediment was more significant over a larger area of Liverpool Bay than bed load transport. However, temporal variations in fluxes of suspended sediment within Liverpool Bay were demonstrated, and were found to be most extensive across Liverpool Bay in 1906 with a progressive decline to 1936 and 1977. A further feature of suspended sediment transport derived from 2D results which correlated with 3D near bed results was that fluxes derived from 3D near bed flow results showed a westward flux of suspended sediment transport across Great Burbo Bank for the 1906 bathymetric configuration shown in Figure 6.15, which corresponded with changes in the ebb tidal current velocities across Liverpool Bay evident in the plot 5 hours after high water illustrated in Figure 5.9. The westwards residual sediment flux was diminished in plots of residual suspended sediment transport for 1936 and 1977.

It was apparent, however, that the residual suspended sediment transport rates derived from the 3D near bed flow results were significantly lower than those derived from the 2D depth integrated flow results. The reduced fluxes were the result of employing the assumption, in 3D calculations, that suspended sediment occupied only the bottom 1m of the water column rather than the full extent of the water column, together with more accurate calculation of bed shear stress from the 3D near bed flow results. The reduction in computed suspended transport was also evident in Table 6.8 which showed generally smaller residual suspended sediment transport fluxes across transects than was evident for calculations from 2D depth integrated flow results shown in Table 6.4.

Year and tidal condition simulated	Net sediment flux across transect (m^3)				
	A	B	C	D	E
1906 Mean spring tide	-1723	-3073	-1456	1066	112
1936 Mean spring tide	-521	-3433	2441	445	627
1977 Mean spring tide	113	5378	-9626	-399	-415
1977 HAT	56	-9018	-20680	-394	-238
1977 Mean neap tide	0	-20	-32	-68	4

Table 6.8 Net tide-residual sediment transport across transects in Figures 6.15-6.19

Several differences that were similar to those identified between 3D and 2D bed load calculations could be identified between suspended load sediment calculations derived from 3D near bed flow results and 2D depth integrated flow results. Most notable was the residual transport of sediment landwards through the Narrows, which was only evident in calculations employing 3D near bed flow results due to a salinity induced gravitational circulation causing a landwards residual flow at the bed. The residual flux of sediment into the estuary mouth across Transect D declined progressively between 1906-1977 according to Table 6.8, and in 1977 it was evident that the net flux of sediment across Transect D was in a seaward direction in contrast with the net flux for bathymetric configurations for 1906 and 1936. Although the changes in net sediment flux across Transect D may be taken to indicate a change in tidal propagation in the Narrows, the same landward direction of residual sediment transport along the eastern side of the Narrows evident for 1906 and1936 bathymetric configurations was a feature of Figures 6.17 and 6.18 for 1977 under mean spring tide and highest astronomic tide forcing respectively. Thus, changes in sediment flux through the mouth of the estuary were most probably the result of localised changes in circulation patterns at the estuary mouth.

A further feature of note that could be identified in bed and suspended load residual sediment transport calculations based upon 3D near bed current velocities, in contrast with computations derived from 2D depth integrated flow fields, was that no clear pathway could be identified for sediment to cross Liverpool Bay and reach the mouth of the estuary. It was evident from Table 6.8 that for the 1906 and 1936 bathymetric configurations there was a net seawards transport of sediment across Transects A and B in Liverpool Bay, and for the 1977 bathymetric configuration under mean spring tidal forcing a net landward transport of sediment occurred.

Figure 6.18 illustrated that under neap tidal forcing very little suspended sediment transport occurred, as was the case for computations of bed load transport. Suspended sediment transport that did occur was largely restricted to localised areas of the Narrows indicating that neap tidal conditions played a significantly less important role in morphological change than spring tidal conditions. This was due to the reduced current velocities under neap tidal conditions which were insufficient to overcome the threshold shear stress of the sediment for transport, and thus resulted in low rates of sediment transport as both bed load and suspended load. Under the forcing of a HAT it was evident from Figure 6.18 that the movement of sediment in the low water channel and the Narrows area of the estuary was enhanced. From Figure 6.18 the trends in sediment transport appeared similar to trends exhibited in Figure 6.17 for forcing under a mean spring tide. Sediment transport fluxes strengthened, but there was no noticeable increase in the extent of sediment transport across Liverpool Bay. More extensive sediment transport across Liverpool Bay was demonstrated under mean spring tidal forcing for 1906 and 1936 bathymetric configurations.

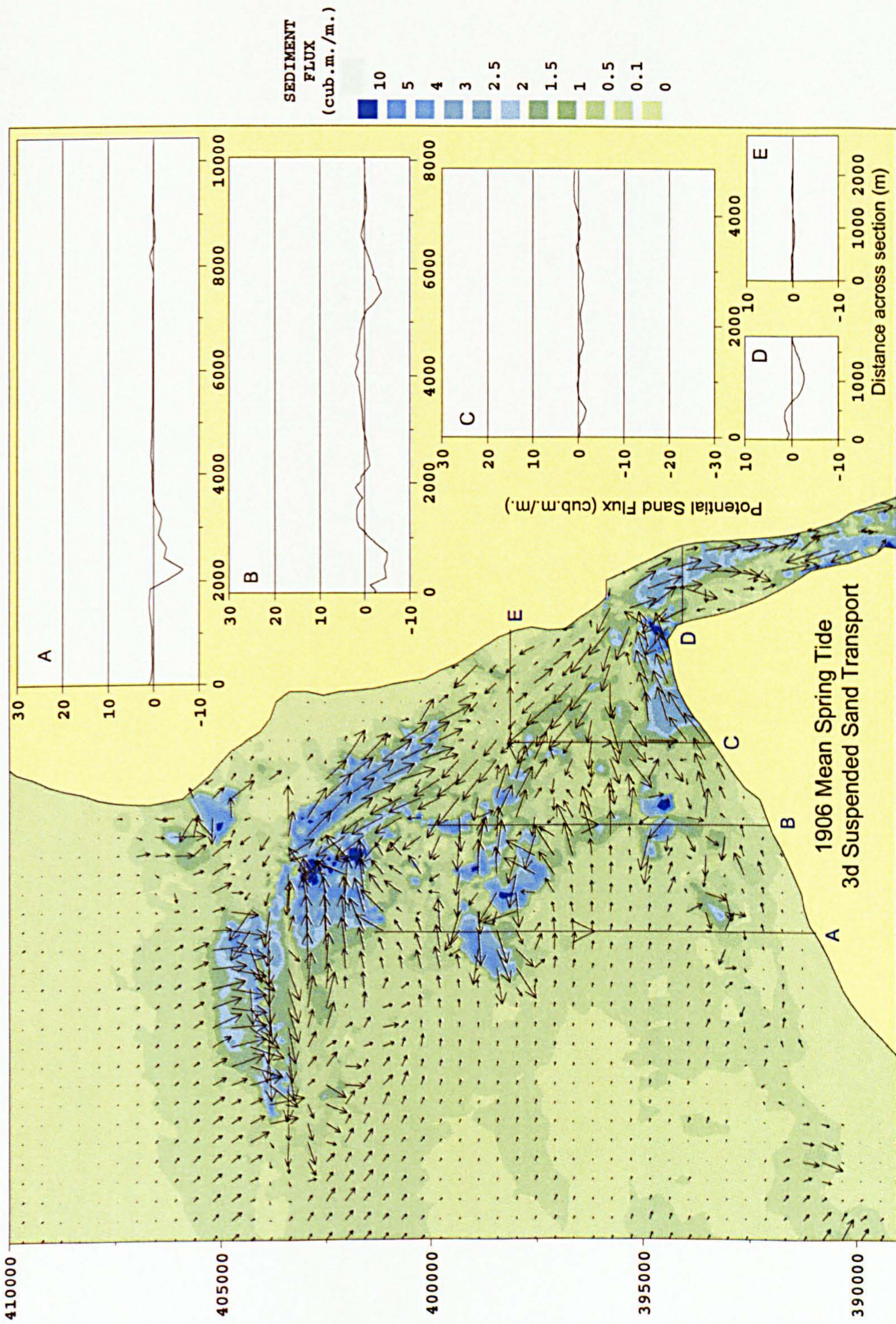


Figure 6.15 Potential non-cohesive suspended load residual transport through a mean spring tide based upon 3D near bed flow simulation results for 1906

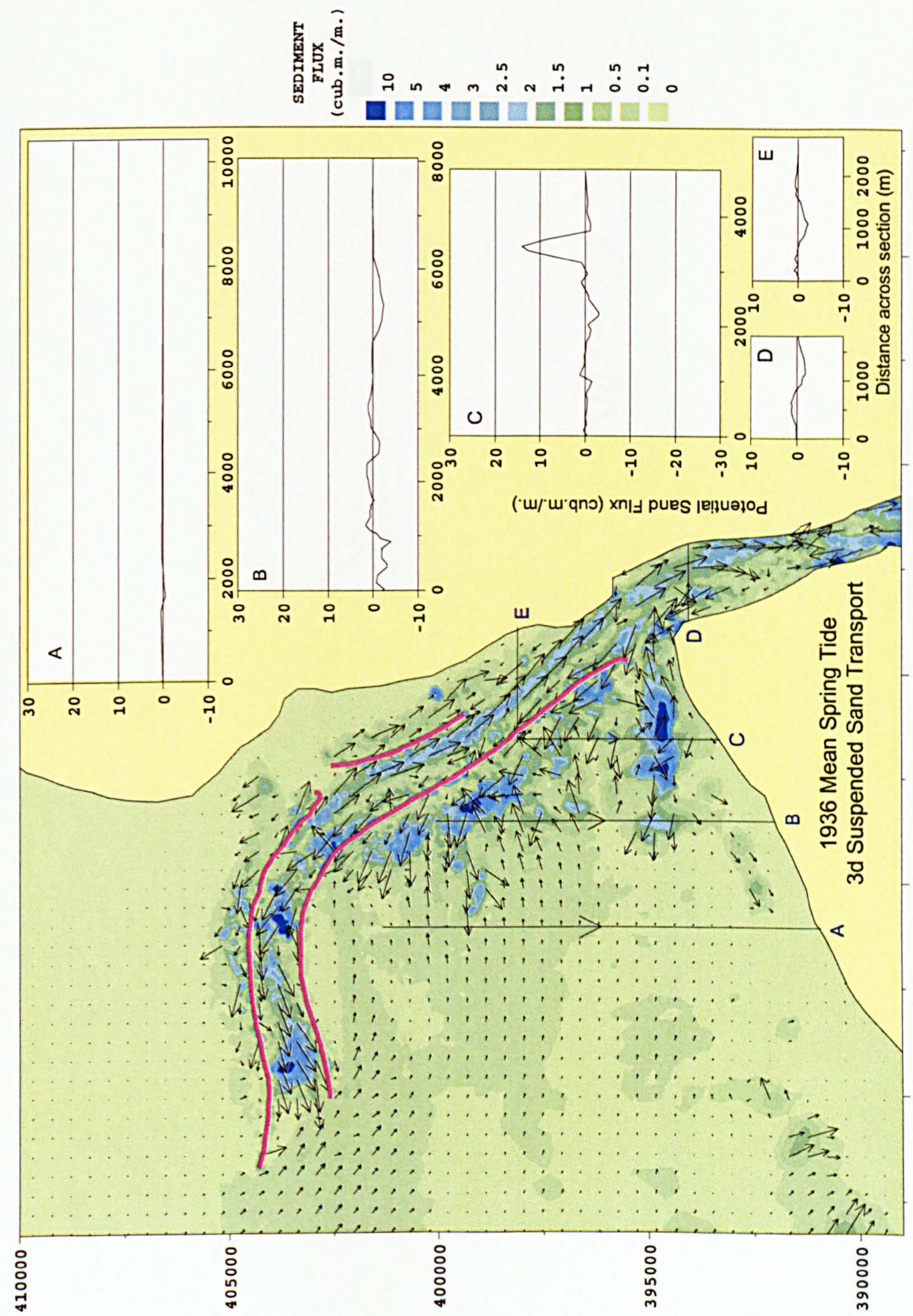


Figure 6.16 Potential non-cohesive suspended load residual transport through a mean spring tide based upon 3D near bed flow simulation results for 1936

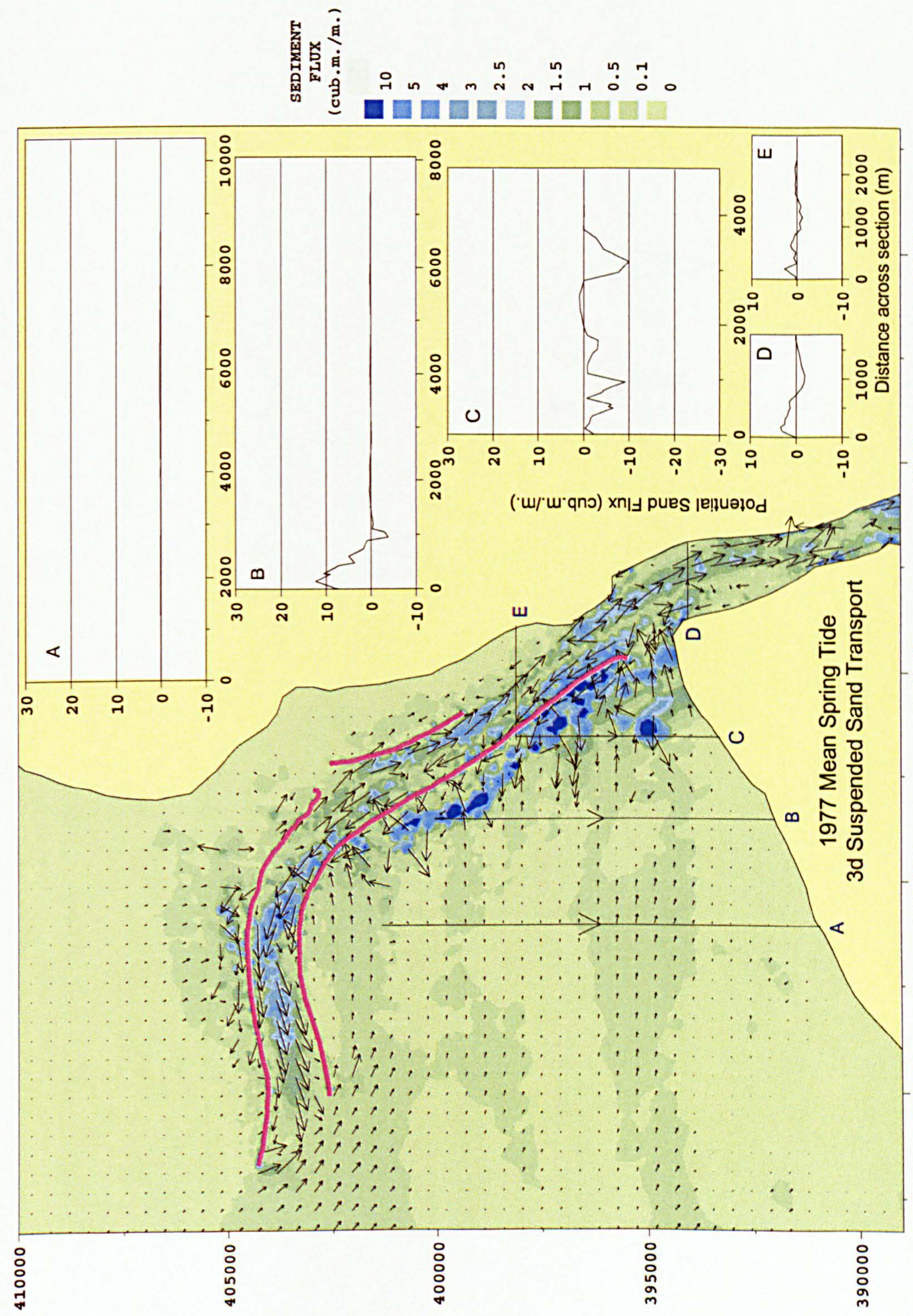


Figure 6.17 Potential non-cohesive suspended load residual transport through a mean spring tide based upon 3D near bed flow simulation results for 1977

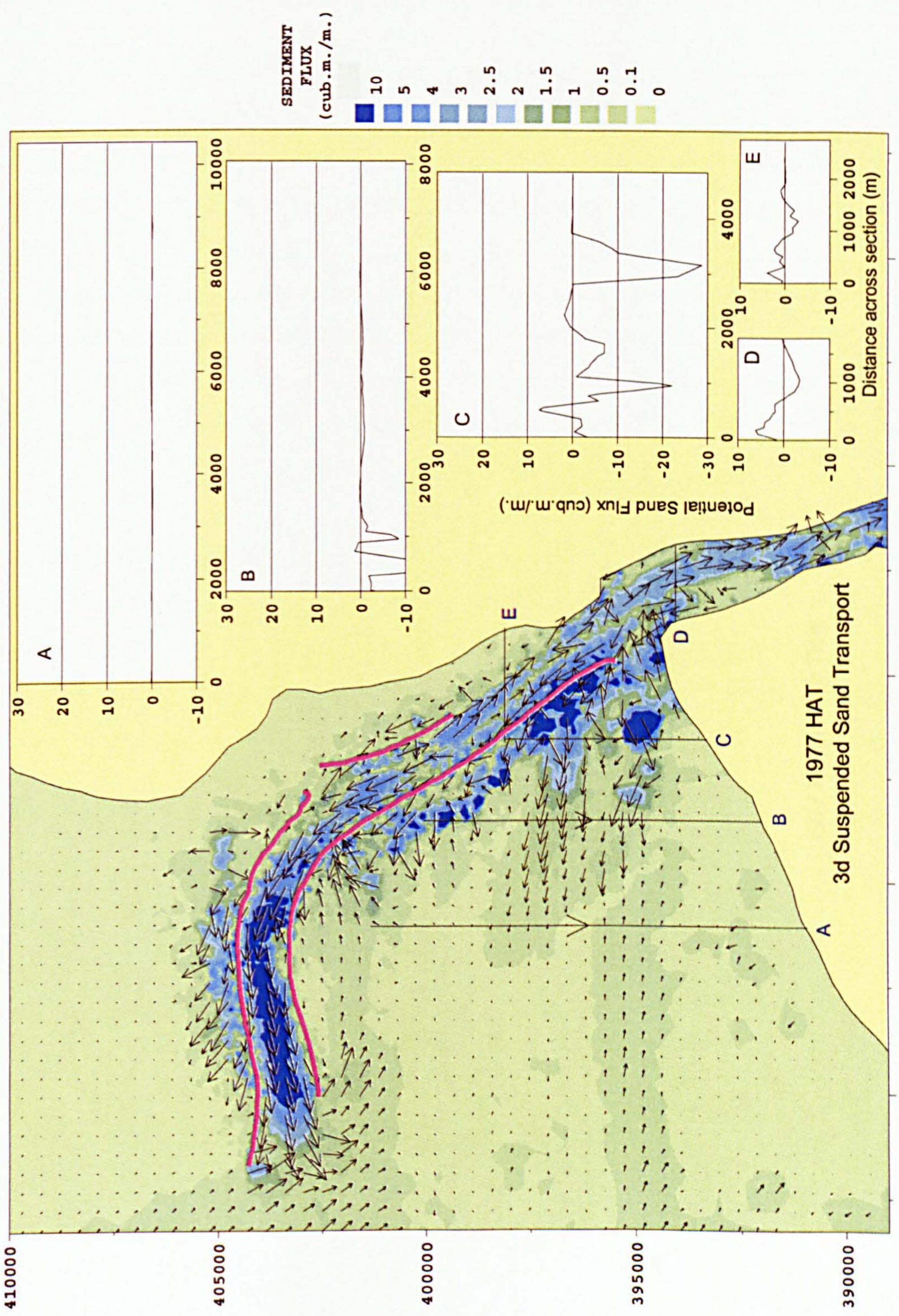


Figure 6.18 Potential non-cohesive suspended load residual transport through a HAT based upon 3D near bed flow simulation results for 1977

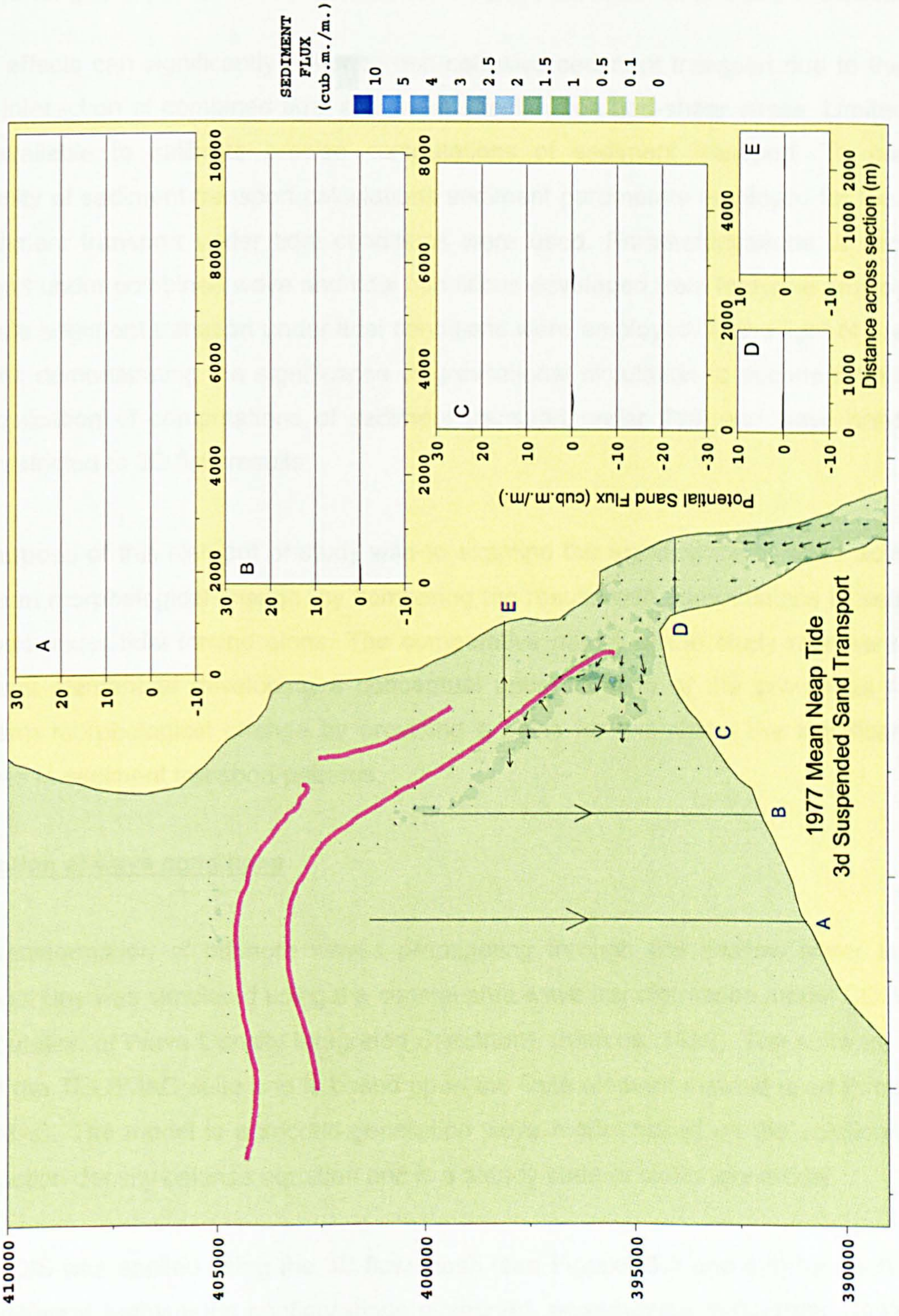


Figure 6.19 Potential non-cohesive suspended load residual transport through a mean neap tide based upon 3D near bed flow simulation results for 1977

6.4.2 Changes in potential sediment transport patterns under tidal and wave conditions

Wave effects can significantly enhance non-cohesive sediment transport due to the non-linear interaction of combined tidal and wave effects upon bed-shear stress. Limited data was available to calibrate precise computations of sediment transport. To maintain uniformity of sediment transport calculations sediment parameters employed for the study of sediment transport under tidal conditions were used. Parameterisations of sediment transport under combined wave and tidal conditions developed from formulae employed to calculate sediment transport under tidal conditions were employed. In the light of previous sections demonstrating the significance of gravitational circulation to sediment transport, the application of computations of sediment transport under tidal and wave conditions were restricted to 3D flow results.

The purpose of this element of study was to examine the significance of wave activity to long-term morphological change, by comparing the results with computations of sediment transport under tidal forcing alone. The comparative nature of the study represented an important element of developing a conceptual understanding of the processes forcing long-term morphological change by providing a basis for examining the significance of changes in sediment transport patterns.

Simulation of wave conditions

The transformation of offshore waves propagating through the shallow water area of Liverpool Bay was simulated using the coastal area wave transformation model COWADIS (Computation of Wave Density Integrated Spectrum), (Marcos, 1998). The software forms part of the TELEMAC suite and is based upon the finite element method used throughout TELEMAC. The model is a second-generation wave model based on the solution of the wave action density balance equation and is a steady state or stationary model.

COWADIS was applied using the 3D flow mesh (see Figures 5.3 and 5.5) for each of the three different bathymetric configurations examined, representing 1904/1906, 1933/1936 and 1977/1970-1980's. Two forcing conditions were specified at the offshore boundary comprising the conditions specified in Section 6.3.3 representing a frequent wave condition and a storm wave condition. Simulations were undertaken for four stages through a tidal cycle corresponding to high water, the mid-point of the ebb tide, low water and the mid-point of the flood tide. Flow conditions for each point in the tidal cycle were included in the simulation. The output from the model comprised the significant wave height, the wave frequency and the water depth for each node. From this data the wave orbital velocity was calculated from:

$$\hat{U}_{\delta} = \frac{\pi H}{T \sinh\left(\frac{2\pi h}{L}\right)} \qquad \text{Eq. 6.22}$$

Wave orbital velocity was calculated for each timestep in the flow results for inclusion in sediment transport calculations by linear interpolation according to water depth.

Radiation wave stress effects were not included in the model. These can be significant in areas of wave breaking, causing an additional force to be exerted on the sediment inducing transportation. Although these effects can be very significant locally, wave stirring under a reduced wave height which induces a wave orbital velocity was considered to contribute in greater measure to the transport of sediment over the areas as a whole. The generally high tidal flows in the area examined meant that combined wave and tidal forcing could be expected to transport large quantities of sediment, and this formed the principal element of investigation.

<u>**Potential non-cohesive bed load transport based upon 3D near bed flow simulation results and wave forcing**</u>

An instantaneous approach to computing bed load transport was employed using van Rijn's (1993) parameterisation of equation 6.4.

$$q_b = 0.25\alpha d_{50} D_*^{-0.3} \left[\frac{\tau'_{b,cw}}{\rho}\right]^{0.5} \left[\frac{\left(\tau'_{b,cw} - \tau_{b,cr}\right)}{\tau_{b,cr}}\right]^{1.5} \qquad \text{Eq. 6.23}$$

with, $\alpha = 1 - \left(\frac{H_s}{h}\right)^{0.5}$

where, α is a calibration factor, d_{50} is median grain diameter, D_* is a dimensionless grain size parameter, ρ is density of water (1027kg/m^3), τ is boundary shear stress due to currents and waves and τ_{cr} is critical boundary shear stress. Equation 6.5 was applied to the near bed flow field results from the 3D model at a height of 0.2m above the bed for Liverpool Bay and the Mersey estuary (see Section 5.4.4), which employed a mean spring tide as a boundary condition for the historical bathymetric configurations examined, and an

HAT and mean neap tidal boundary condition for the 1977 bathymetric configuration. The scenarios for which sediment transport was calculated are summarised in Table 6.5.

Domain area	Year	Mode of sediment transport	Tidal condition	Wave conditions	Training wall
Mersey estuary and Liverpool Bay	1906	Non-cohesive bed load	Mean spring tide	Frequent wave	No
"	1936	"	"	"	Yes
"	1977	"	"	"	"
"	1977	"	Mean neap tide	"	"
"	1977	"	HAT	"	"
Mersey estuary and Liverpool Bay	1906	Non-cohesive bed load	Mean spring tide	Storm wave	No
"	1936	"	"	"	Yes
"	1977	"	"	"	"
"	1977	"	Mean neap tide	"	"
"	1977	"	HAT	"	"

Table 6.9 Summary of potential non-cohesive bed load transport simulations undertaken based upon combined 3D near bed flow results and wave forcing

The results for computations of sediment transport under combined tidal and wave forcing conditions are presented in the same format as for previous results (see Figures 6.20-6.29 and Tables 6.10 and 6.11). It was evident from the results that bed load sediment transport under wave effects was significantly enhanced when compared with bed load sediment transport under tidal conditions alone. Both the spatial extent of residual sediment transport across Liverpool Bay and the strength of sediment transport fluxes was increased for all bathymetric configurations under combined wave and tidal forcing. In areas of Liverpool Bay exposed to waves propagating from offshore greater quantities of sediment were transported as bed load under combined tidal and wave forcing than as suspended load transport under tidal forcing alone. Furthermore, the transport of bed load sediment calculated from the 3D near bed flow field under tidal and wave conditions was greater than that calculated under tidal conditions alone from a 2D depth integrated flow field. In this study it was more important to examine processes that can affect sediment transport than accurately computing sediment transport rate from simulations to develop understanding of the morphological behaviour of the system.

It was evident from Figures 6.20-6.29 that sediment transport in Liverpool Bay over Burbo Bank was particularly enhanced under wave forcing, as this represented the shallow water area where waves propagating from offshore broke. This resulted in significant wave orbital velocities and hence, an increase in bed shear stress. It was also evident that the patterns of sediment transport exhibited under both wave forcing conditions represented similar patterns of sediment transport. Several features contrasted with forcing under tidal conditions alone, although the strength of sediment transport fluxes varied considerably according to the magnitude of wave forcing. Figures 6.20-6.29 also illustrated that the wave conditions examined induced significant transport of sediment from the North of Taylors Bank, and southwards of Formby Point. There was no clear indication of the movement of sediment along the Formby Coast, which suggested that sediment would have accreted over Taylors Bank following the construction of the training wall which prevented westwards movement of sediment through the low water channel. Figure 4.15 supported this observation by indicating that accretion did occur over Taylors Bank between 1906-1977. Littoral drift processes resulting from the refraction of waves from the coastline were not represented in the calculations of bed load sediment transport presented, and could have provided a mechanism for sediment to be transported along the Formby coast to the mouth of the estuary.

Under neap tidal conditions, even with storm wave forcing, the transport of sediment was significantly less than under mean spring tidal conditions with no wave activity. Sediment transport under neap tide conditions and wave forcing was largely restricted to localised areas of Liverpool Bay and the Narrows, except for an area of southwards sediment transport over Taylor's Bank. Under HAT and wave forcing it was evident that patterns of residual sediment transport across Transects A-C were enhanced in comparison with mean spring tide forcing combined with wave activity. The net direction of sediment transport across Transects A-C under HAT forcing, was the same as the 1977 bathymetric configuration with a mean spring tide under both frequent wave and storm wave conditions, but the residual fluxes were considerable larger under a HAT. The trends in residual transport of sediment across Transects D and E differed under highest astronomical and mean spring tidal conditions, but it was apparent that the characteristics were similar to residual transport under tidal forcing alone.

Year and tidal condition simulated	Net sediment flux across transect (m^3)				
	A	B	C	D	E
1906 Mean spring tide	1086	1223	51	435	-40
1936 Mean spring tide	979	773	1636	228	249
1977 Mean spring tide	1093	-26	-2008	-25	-56
1977 HAT	1478	-1675	-5885	217	-91
1977 Mean neap tide	140	287	106	-15	-3

Table 6.10 Net tide-residual sediment fluxes across transects in Figures 6.20-6.24

Year and tidal condition simulated	Net sediment flux across transect (m^3)				
	A	B	C	D	E
1906 Mean spring tide	4660	3229	411	435	-30
1936 Mean spring tide	2859	3632	2149	229	346
1977 Mean spring tide	3491	2498	-945	-24	76
1977 HAT	4144	994	-4588	217	-59
1977 Mean neap tide	847	1519	487	-14	21

Table 6.11 Net tide-residual sediment fluxes across transects in Figures 6.25-6.29

According to the fluxes of sediment transport presented in Tables 6.10 and 6.11, it was evident that, under wave forcing, significantly larger quantities of sediment were transported landwards across Transect A under combined tidal and wave forcing for all bathymetric configurations, with a reversal of seaward transport of sediment across Transect A in 1906. The residual fluxes of sediment transported landwards across

Transect A with a mean spring tide and frequent wave conditions and a mean spring tide combined with a storm wave condition were at least 2.5 times and 8 times the sediment transported under mean spring tidal forcing alone respectively. A similar trend was also evident for Transect B with a significant increase in landward sediment transport leading to a net landward flux of sediment in 1906 and 1936, and a significant reduction in seaward transport for 1977 with a frequent wave condition and mean spring tide, and a landwards residual flux of sediment for all bathymetric configurations with a storm wave condition and mean spring tide.

Tables 6.10 and 6.11 indicated that wave activity did not enhance bed load sediment over the whole of the area studied. Bed load residual transport fluxes across Transect D, at the mouth of the estuary, remained constant for all computations of sediment transport whether including wave activity or not. Even under storm wave conditions, the sediment fluxes were comparable with fluxes under tidal forcing alone, indicating that the mouth of the estuary was sheltered from waves propagating from offshore by the banks of sediment in Liverpool Bay where the waves break. Thus in the Narrows area of the estuary it was demonstrated that tidal conditions were the dominant influence upon bed load transport, and accentuated the importance of representing gravitational circulation resulting from salinity induced stratification, which was shown to strongly influence residual bed load transport.

From examination of residual sediment transport fluxes across Transect C presented in Tables 6.10 and 6.11 it was evident that wave activity affected net sediment transport. The effects of wave forcing were, however, more complex than for Transects A and B, as it was apparent that wave activity did not enhance landward transport of sediment for all bathymetric configurations. Although the effect of wave activity increased the landward residual transport of bed load sediment for the 1906 and 1936 bathymetric configurations, reversing a seaward residual transport of bed load transport for the 1936 bathymetric configurations under tidal forcing alone, it was evident that the impact of wave activity in the vicinity of Transect C was not as large as Transects A and B. Furthermore, the net seaward transport of bed load sediment across Transect C remained in a seaward direction, but of reduced magnitude, for the 1977 bathymetric configuration under wave forcing combined with both mean spring tide and HAT forcing. The results demonstrated that although wave effects influenced sediment transport in the vicinity of Transect C, they were not as dominant as in seaward areas of Liverpool Bay. The influence of wave effects in proximity to Transect C were reduced sufficiently that they could not cause a dominant landward flux of bed load sediment for all conditions.

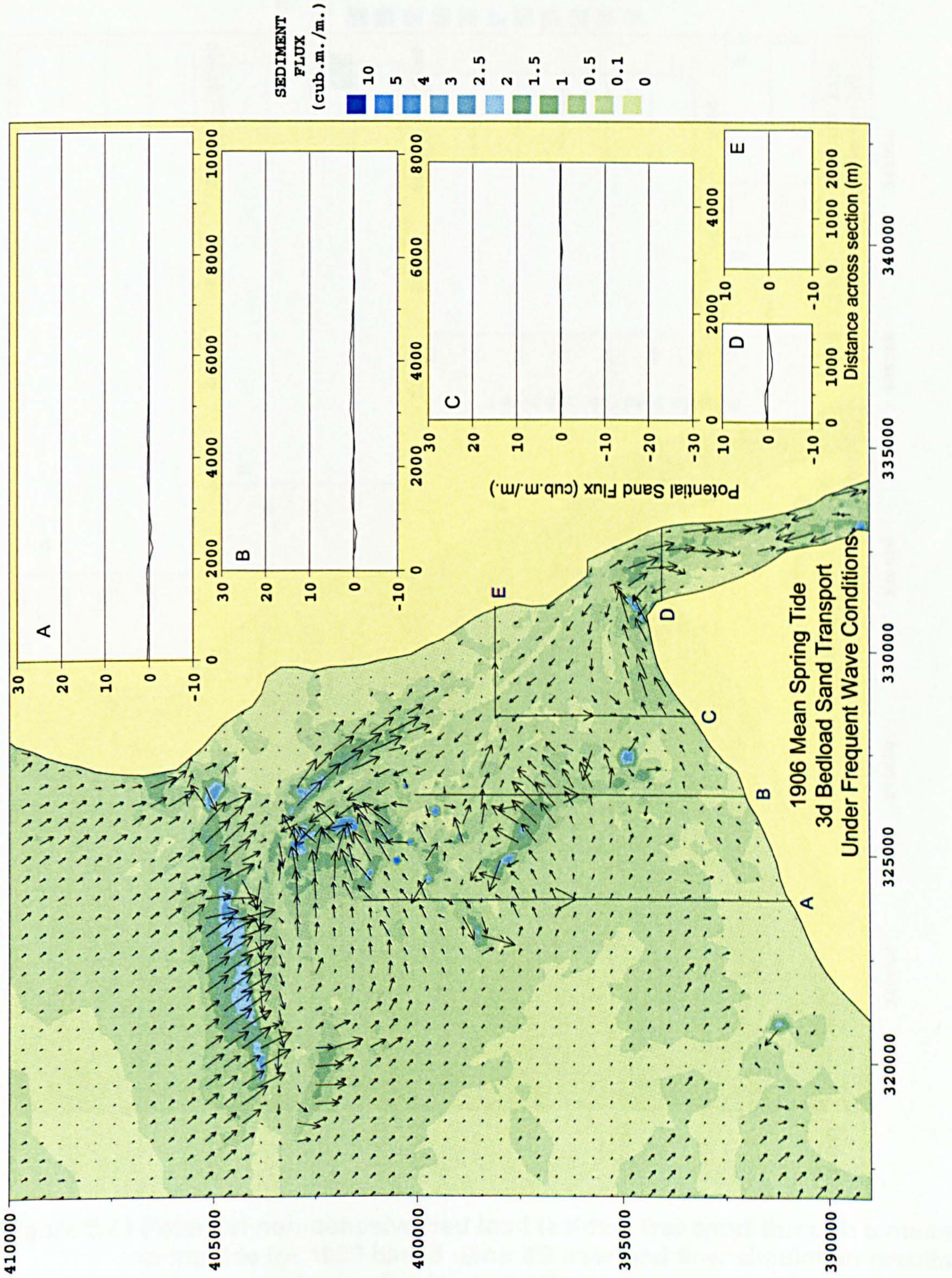


Figure 6.20 Potential non-cohesive bed load residual transport through a mean spring tide for 1906 based upon 3D near bed flow simulation results and a frequent wave forcing condition

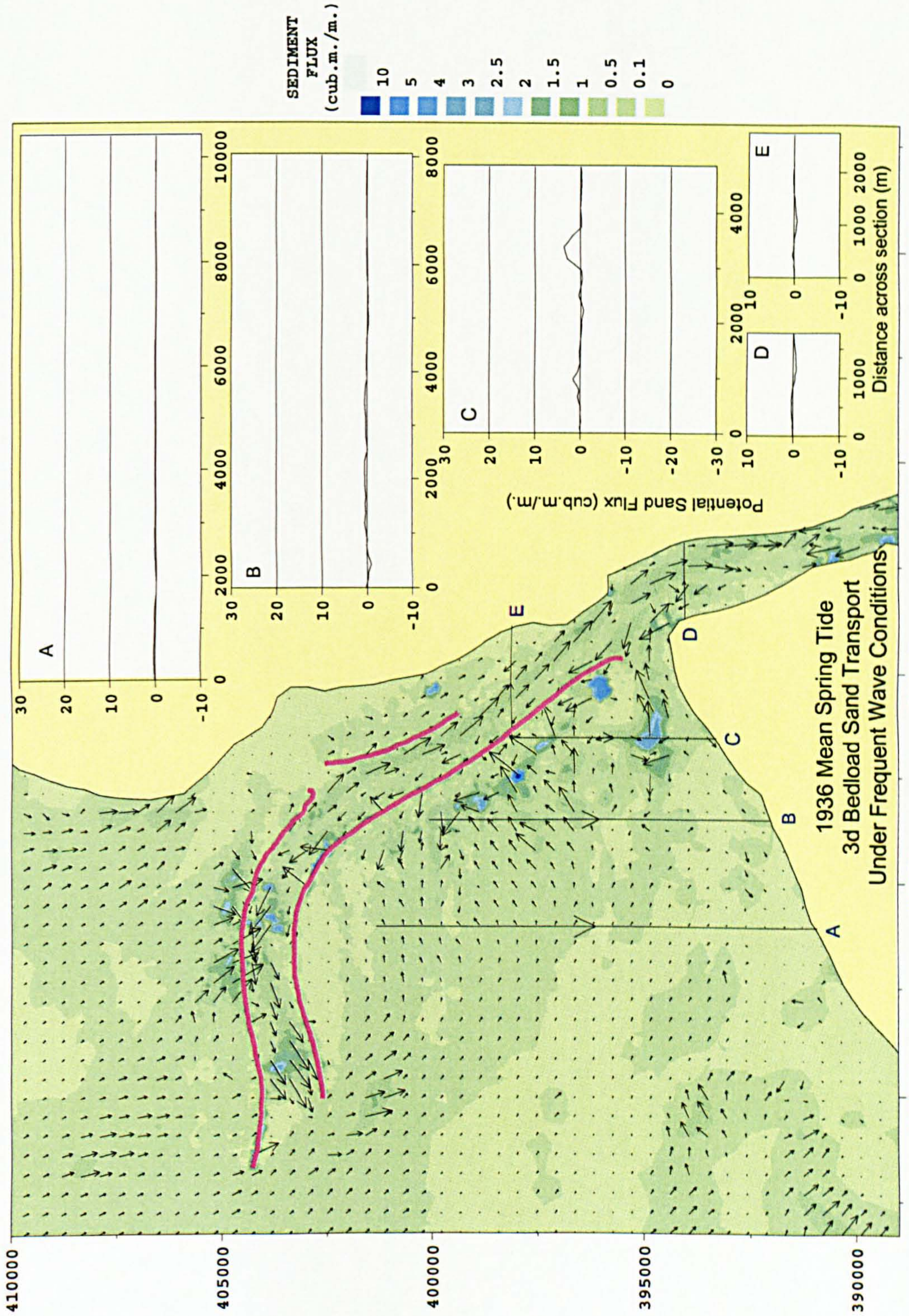


Figure 6.21 Potential non-cohesive bed load residual transport through a mean spring tide for 1936 based upon 3D near bed flow simulation results and a frequent wave forcing condition

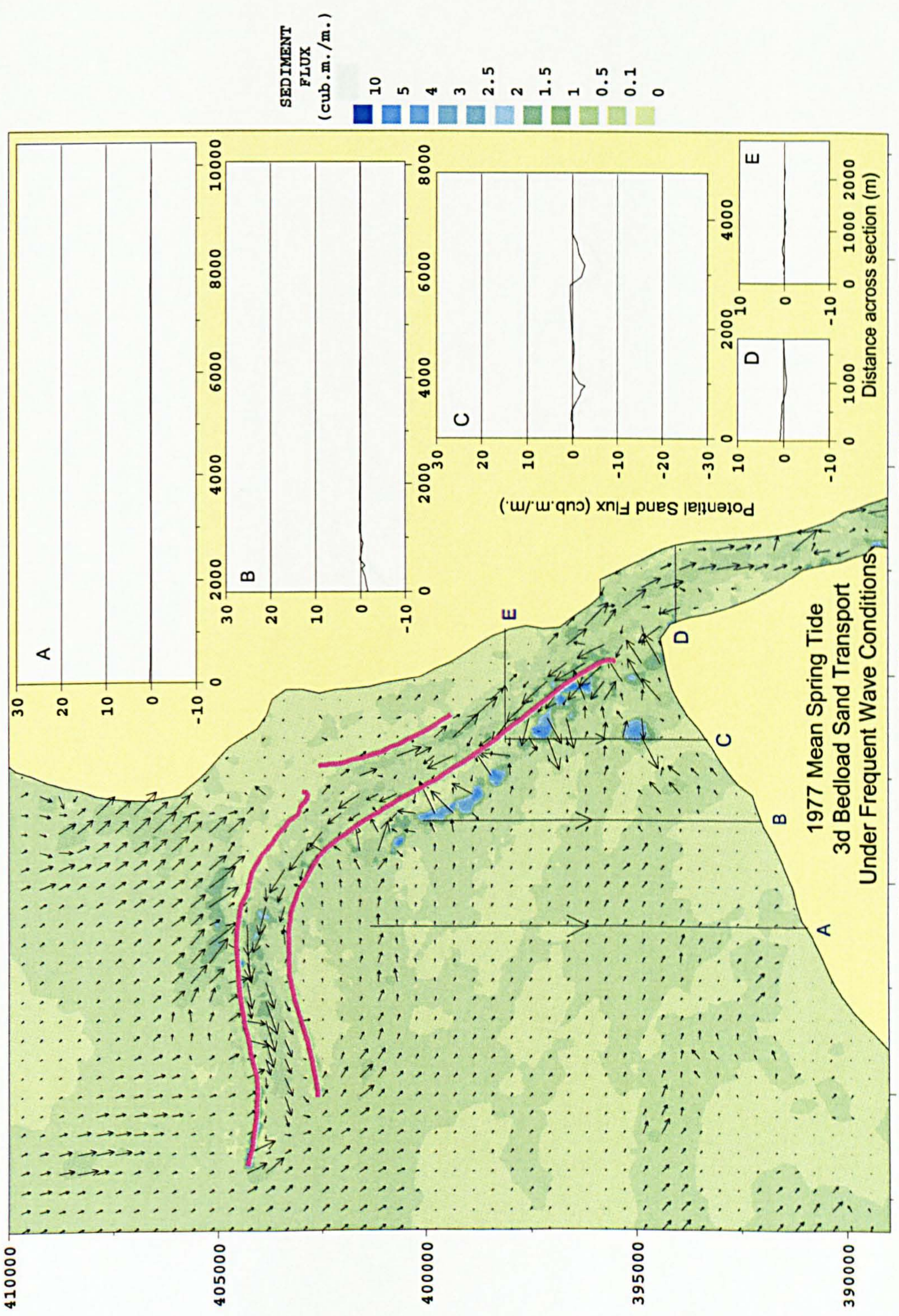


Figure 6.22 Potential non-cohesive bed load residual transport through a mean spring tide for 1977 based upon 3D near bed flow simulation results and a frequent wave forcing condition

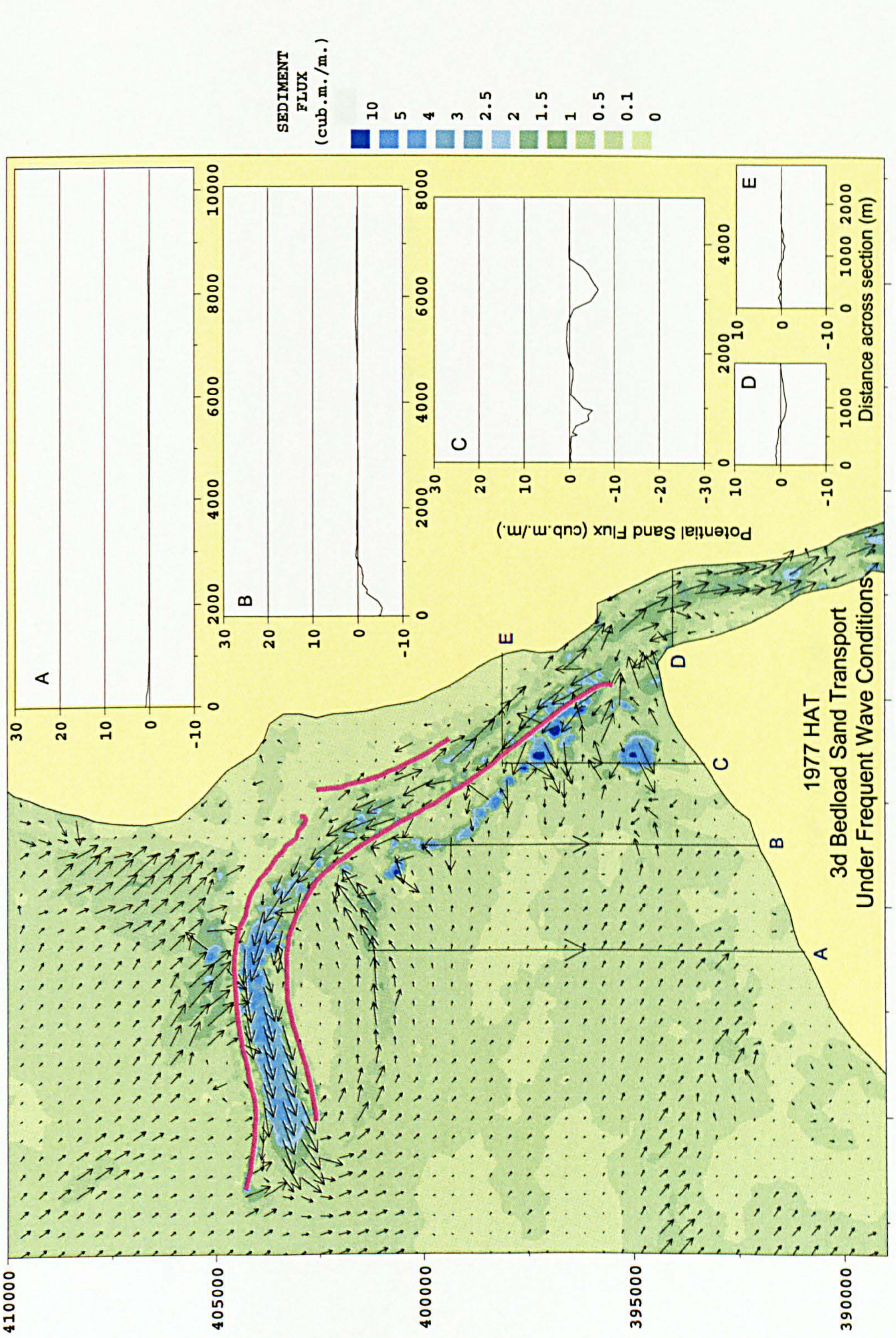


Figure 6.23 Potential non-cohesive bed load residual transport through a HAT for 1977 based upon 3D near bed flow simulation results and a frequent wave forcing condition

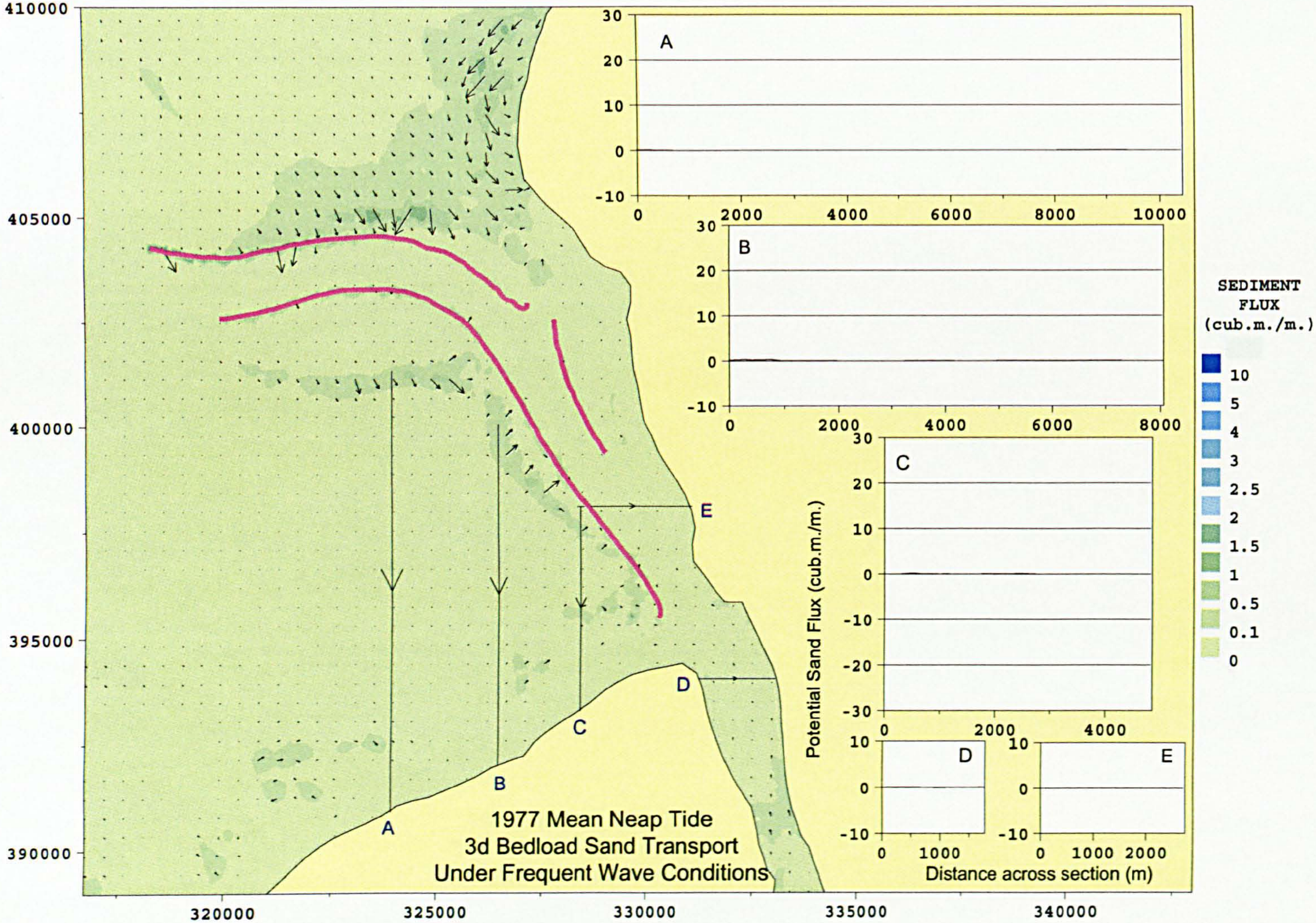


Figure 6.24 Potential non-cohesive bed load residual transport through a mean neap tide for 1977 based upon 3D near bed flow simulation results and a frequent wave forcing condition

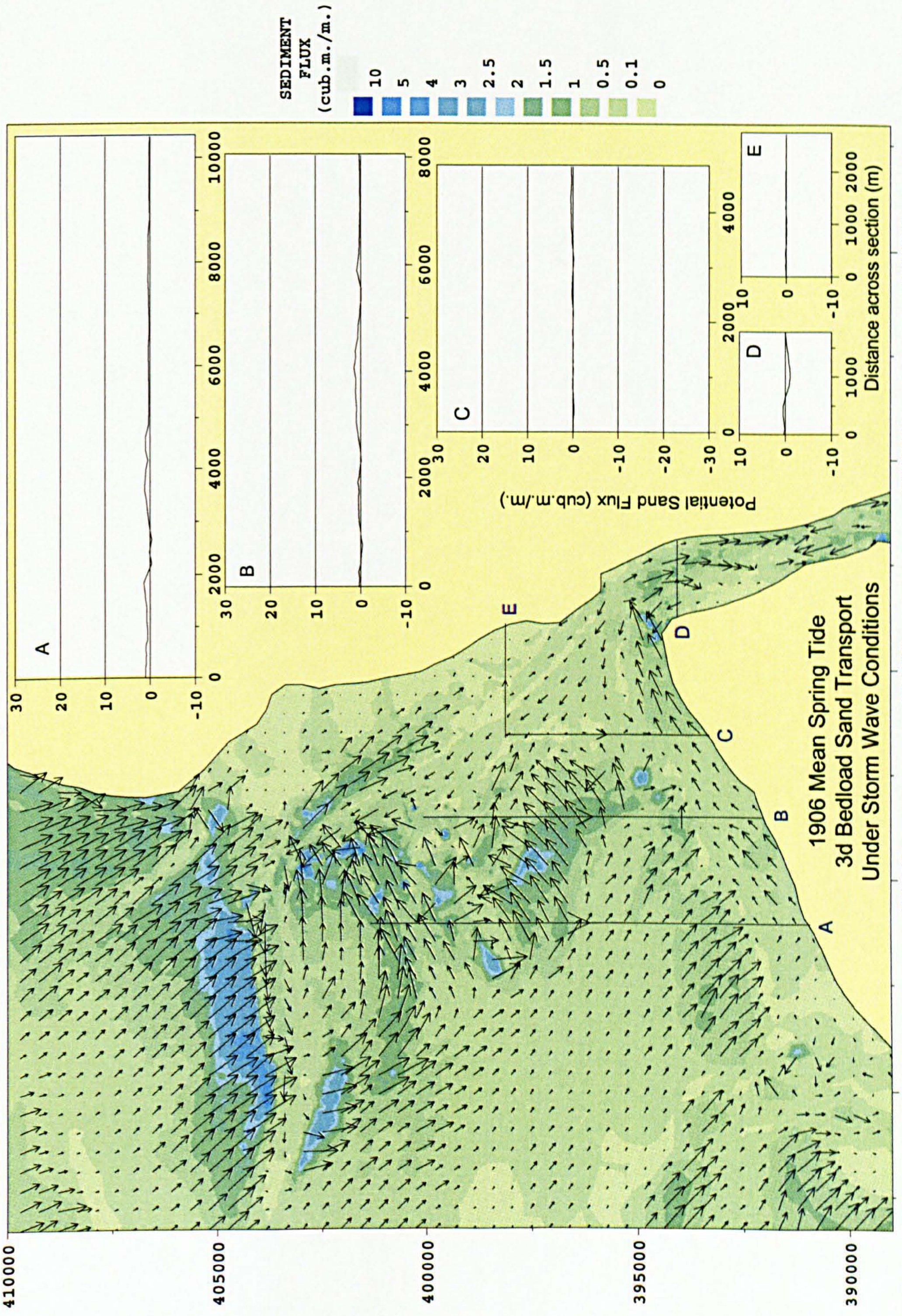


Figure 6.25 Potential non-cohesive bed load residual transport through a mean spring tide for 1906 based upon 3D near bed flow simulation results and a storm wave forcing condition

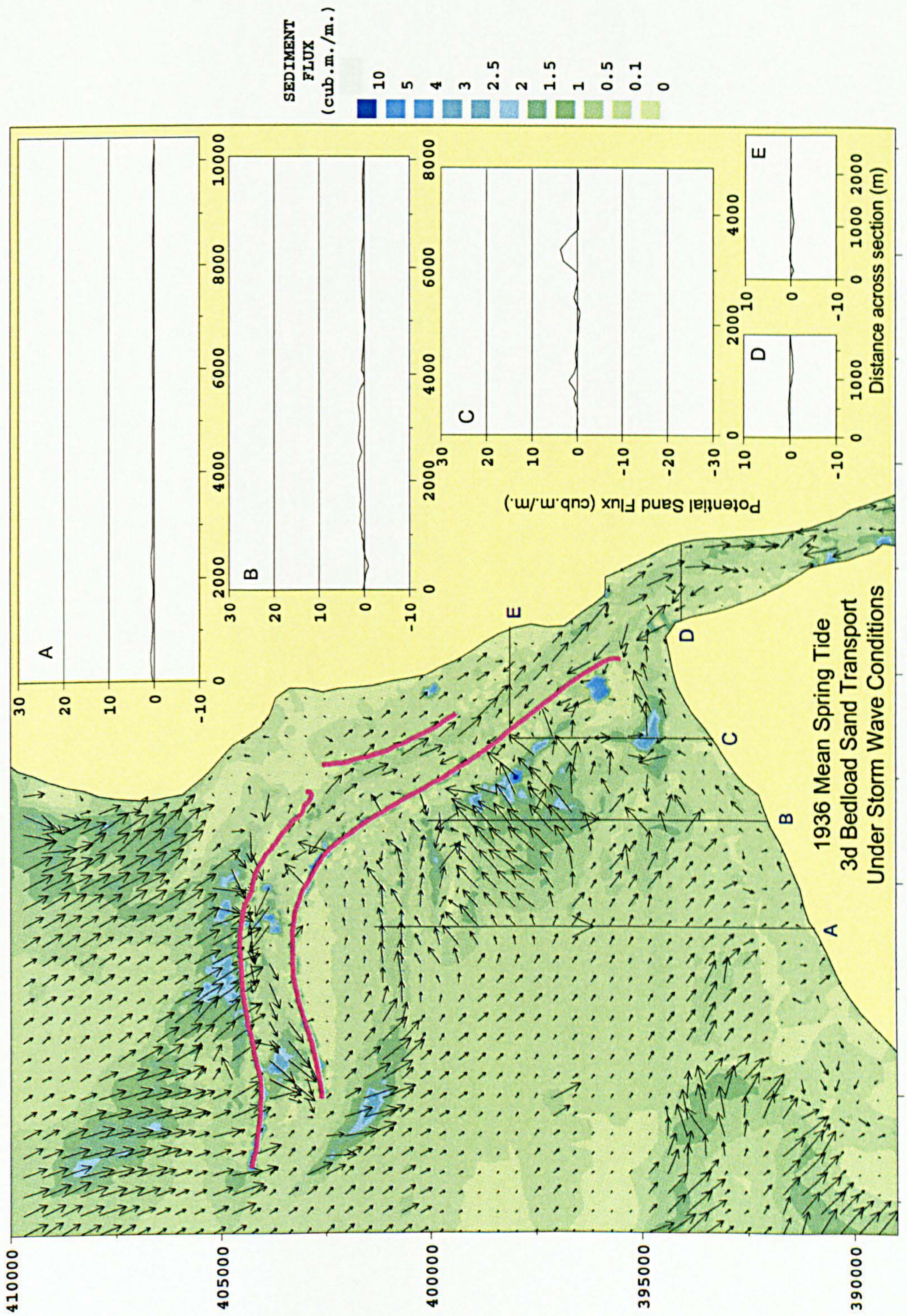


Figure 6.26 Potential non-cohesive bed load residual transport through a mean spring tide for 1936 based upon 3D near bed flow simulation results and a storm wave forcing condition

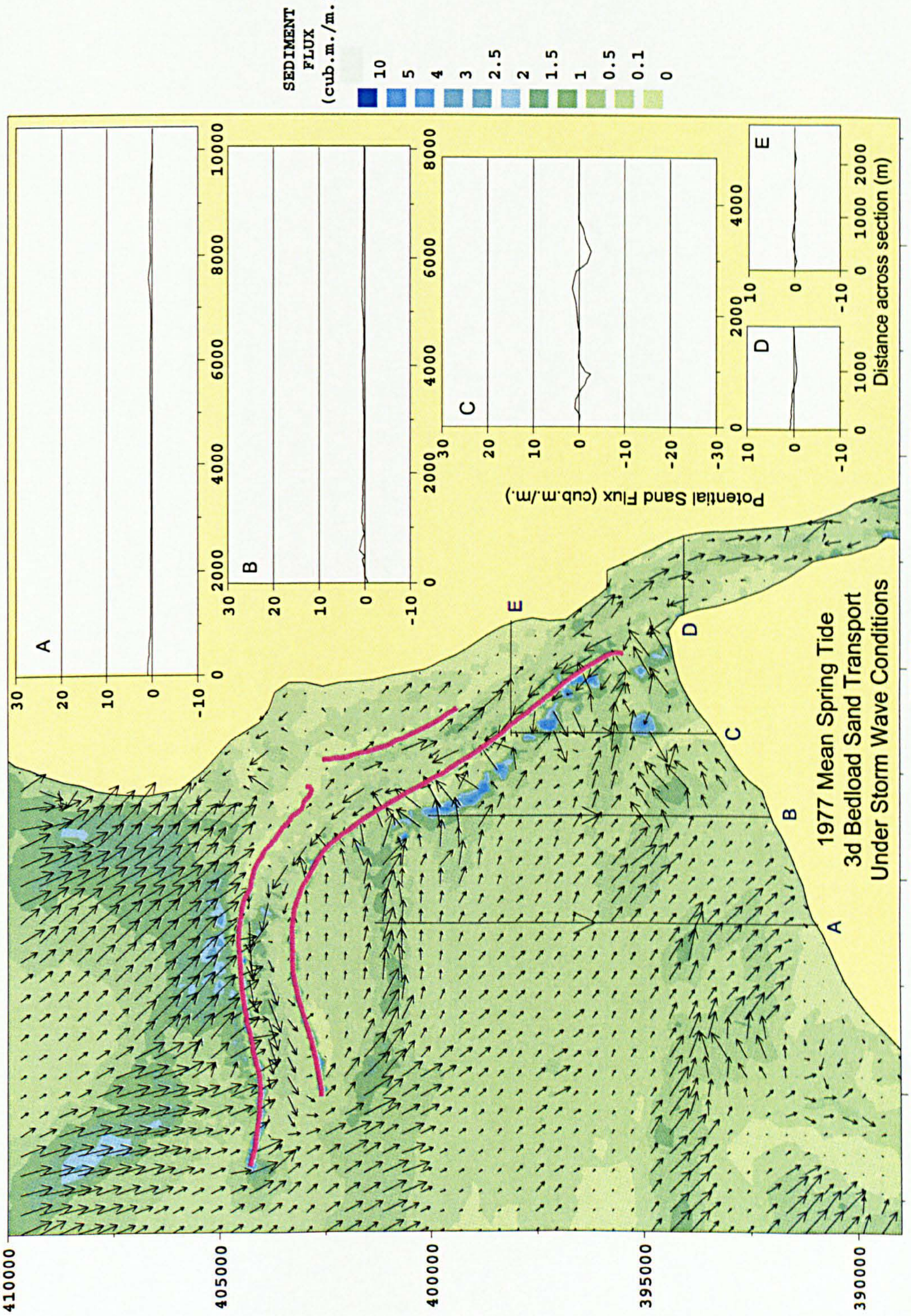


Figure 6.27 Potential non-cohesive bed load residual transport through a mean spring tide for 1977 based upon 3D near bed flow simulation results and a storm wave forcing condition

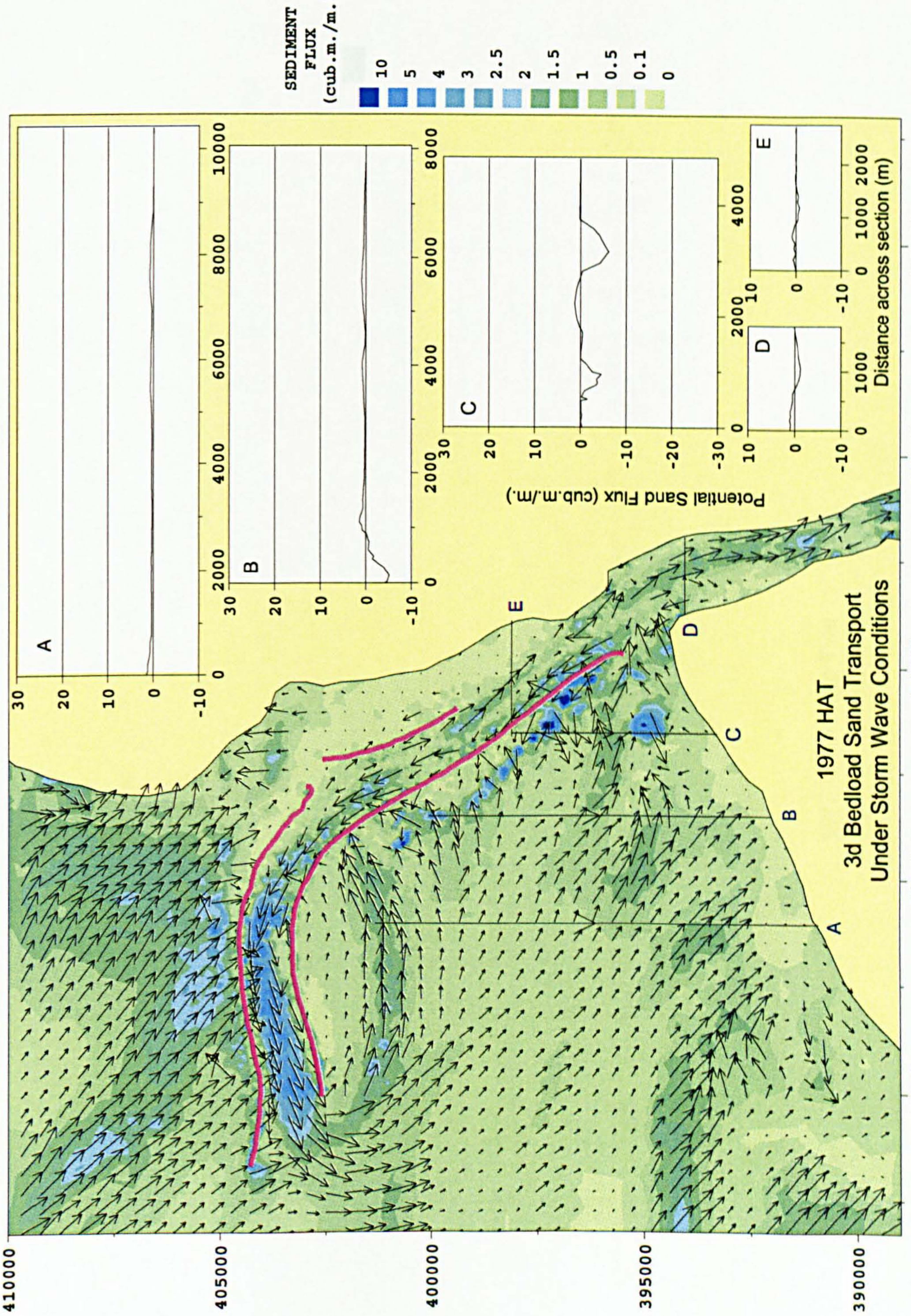


Figure 6.28 Potential non-cohesive bed load residual transport through a HAT for 1977 based upon 3D near bed flow simulation results and a storm wave forcing condition

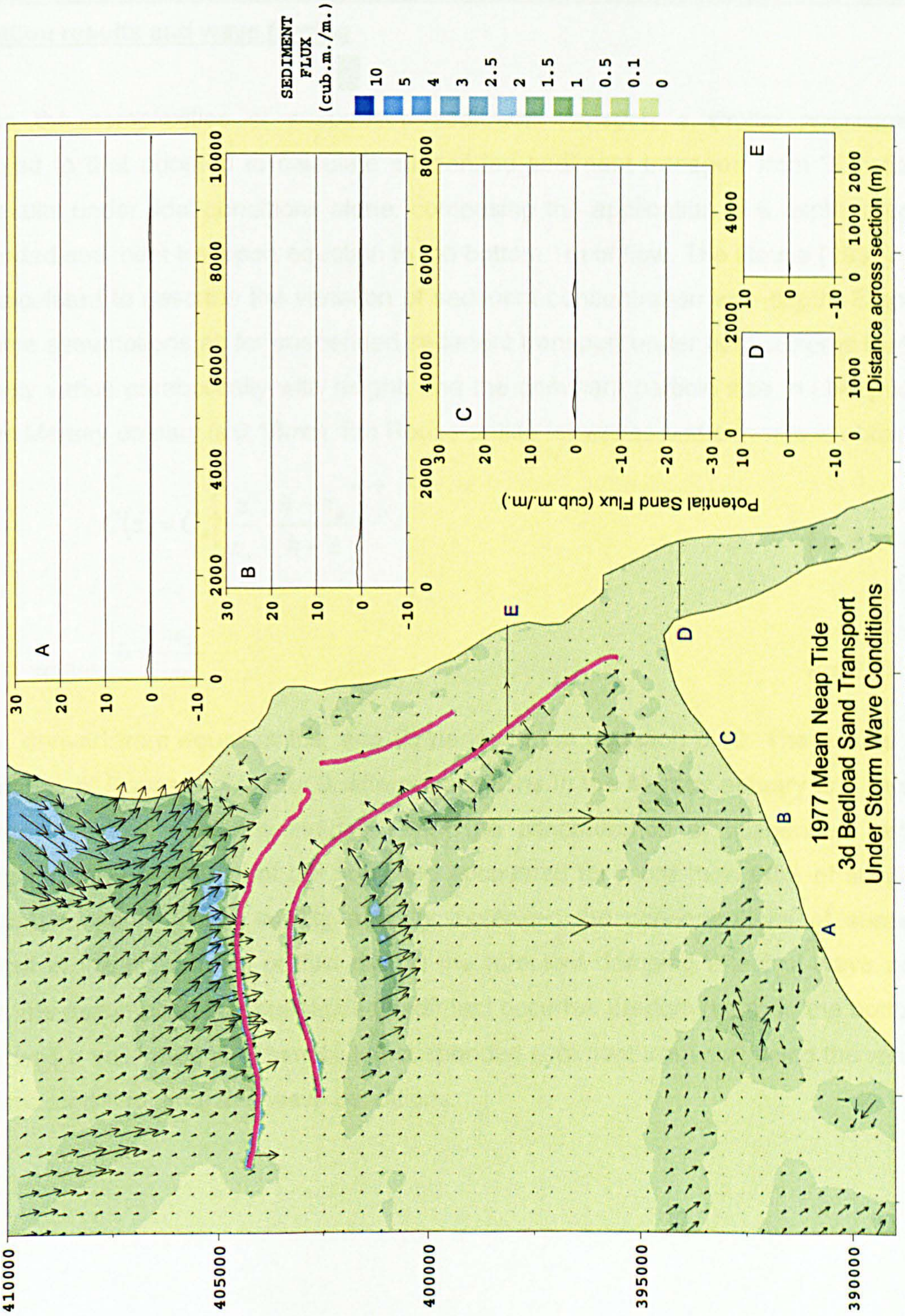


Figure 6.29 Potential non-cohesive bed load residual transport through a mean neap tide for 1977 based upon 3D near bed flow simulation results and a storm wave forcing condition

Potential non-cohesive suspended load transport based upon 3D near bed flow simulation results and wave forcing

Due to the complexities of suspended sediment transport a similar approach was employed to that adopted to calculate suspended sediment transport from 3D near bed flow results under tidal conditions alone, comprising the application of a depth integrated suspended sediment transport equation to the bottom 1m of flow. The Rouse (1937) profile was calculated to describe the variation of sediment concentration with depth. Employing the same assumptions as for suspended sediment transport under tidal currents that eddy diffusivity varies parabolically with height, and the dominant particle size in Liverpool Bay and the Mersey estuary is 0.18mm, the Rouse profile for waves and currents is obtained:

$$C(z) = C_a \left[\frac{z}{z_a} \cdot \frac{h - z_a}{h - z} \right]^{-b} \qquad \text{Eq. 6.24}$$

where, $b = \dfrac{w_s}{\kappa u_*}$ Eq. 6.25

with w_s derived from equation 6.9, and C_a derived from equation 6.10. The results of the calculations of Rouse profiles for 3 different positions in the Mersey estuary and Liverpool Bay shown below in clearly indicated that the concentration of suspended sediment transport in the bottom 1m of the flow field accounted for more than 90% of suspended sediment transport. Wave activity actually increased the concentrations of suspended sediment in the bottom 1m of flow due to the turbulent damping effect of wave activity. Hence, the assumption that suspended sediment occurred predominantly in the bottom 1m of flow was a valid means of simplifying suspended sediment transport using the results of a 3D flow model for tidal and wave conditions.

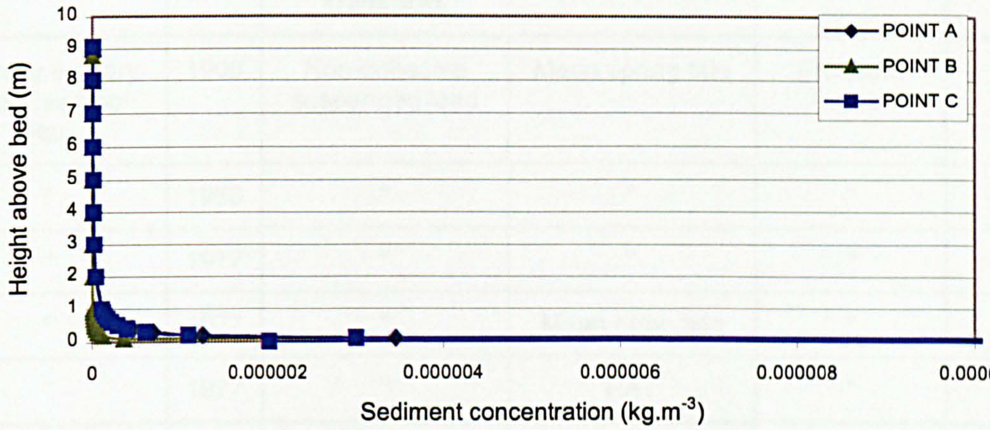


Figure 6.30 Suspended sediment concentrations with height above the bed under tidal and wave conditions

Current velocities were extracted at a height of 1m above the bed from the simulation results, and multiplied by equation 6.20 to derive a depth integrated velocity for the bottom 1m of flow. Calculated depth integrated flow velocities for the bottom 1m were then employed with wave parameter inputs for a frequent wave condition and a storm wave condition to calculate sediment transport using Soulsby's (1997) parameterisation of suspended sediment transport under tidal and wave conditions:

$$q_s = A_{ss}\overline{U}\left[\left(\overline{U} + \frac{0.018}{C_D}U^2{}_{rms}\right)^{0.5} - \overline{U}_{cr}\right]^{2.4} (1 - 1.6\tan\beta) \qquad \text{Eq. 6.26}$$

where, $$A_{ss} = \frac{0.012 d_{50} D_*^{-0.6}}{\left[(s-1)g d_{50}\right]^{1.2}} \qquad \text{Eq. 6.27}$$

where $\overline{U}$ is depth averaged velocity, $\overline{U}_{cr}$ is threshold depth-averaged current speed (derived from equation 6.3), h is water depth, s is the ratio of densities of grain and water (2.65), g is gravitational acceleration (9.81m/s^2), d_{50} is median grain diameter and D_* is a dimensionless grain size parameter. The approach assumed that the bottom 1m comprised a homogenous flow field with no significant variation in direction of residual transport, and that suspended sediment was predominantly transported in the bottom 1m of the water column, which was supported by the derivation of Rouse profiles for several areas of Liverpool Bay in the previous section. The scenarios for which sediment transport was calculated are summarised in Table 6.12.

Domain area	Year	Mode of sediment transport	Tidal condition	Wave conditions	Training wall
Mersey estuary and Liverpool Bay	1906	Non-cohesive suspended load	Mean spring tide	Frequent wave	No
"	1936	"	"	"	Yes
"	1977	"	"	"	"
"	1977	"	Mean neap tide	"	"
"	1977	"	HAT	"	"
Mersey estuary and Liverpool Bay	1906	Non-cohesive suspended load	Mean spring tide	Storm wave condition	No
"	1936	"	"	"	Yes
"	1977	"	"	"	"
"	1977	"	Mean neap tide	"	"
"	1977	"	HAT	"	"

Table 6.12 Summary of potential non-cohesive suspended load transport simulations undertaken based upon combined 3D near bed flow results and wave forcing

It was evident from the results of calculating sediment transport under combined tidal and wave forcing presented in Figures 6.31-6.40 and Tables 6.13 and 6.14 that wave activity significantly enhanced suspended load sediment transport when compared with suspended load sediment transport under tidal conditions alone. Both the spatial extent of residual sediment transport across Liverpool Bay and the strength of sediment transport fluxes increased for all bathymetric configurations under combined wave and tidal forcing. Furthermore, the transport of suspended load sediment calculated from the 3D near bed flow field under tidal and wave conditions was greater than that calculated under tidal conditions alone from a 2D depth integrated flow field. Suspended load sediment transport under tidal and wave forcing, caused the most significant transport of sediment over the extensive areas of Liverpool Bay exposed to waves propagating from offshore. Rates of sediment transport over exposed areas of Liverpool Bay were comparable with the highest rates of sediment transport calculated under tidal forcing alone in the low water channel and the Narrows, where tidal current velocities were greatest.

Year and tidal condition simulated	Net sediment flux across transect (m^3)				
	A	B	C	D	E
1906 Mean spring tide	21046	26912	3123	1066	230
1936 Mean spring tide	10751	19276	8892	447	1207
1977 Mean spring tide	12608	24177	3211	-395	-323
1977 HAT	20212	19922	-6656	-381	-76
1977 Mean neap tide	1517	3868	1916	-67	-3

Table 6.13 Net tide-residual sediment fluxes across transects in Figures 6.31-6.35

Year and tidal condition simulated	Net sediment flux across transect (m^3)				
	A	B	C	D	E
1906 Mean spring tide	87330	66684	9445	1063	31
1936 Mean spring tide	44360	71170	18159	451	2209
1977 Mean spring tide	54703	71497	23904	-388	568
1977 HAT	67681	65095	15013	-399	232
1977 Mean neap tide	10202	21014	8610	-67	71

Table 6.14 Net tide-residual sediment fluxes across transects in Figures 6.36-6.40

The results in Tables 6.13 and 6.14 demonstrated that significant landwards residual transport of sediment load across Transects A and B was induced for all bathymetric configurations by combined wave and tidal forcing under both frequent wave and storm wave conditions. The landwards transport of suspended sediment under wave and tidal forcing, for both frequent and storm wave conditions, represented a reversal of the net seaward transport of sediment as suspended load under mean spring tidal forcing with no wave activity across Transects A and B for the 1906 and 1936 bathymetric configurations. Furthermore, landwards transport of suspended sediment under wave and tidal forcing for both frequent and storm wave conditions was significantly larger for all bathymetric configurations than residual transport of sediment under any other scenario modelled. Fluxes across Transect A and B under mean spring tidal forcing with a frequent wave condition and a storm wave condition were at least 4.5 and 13 times greater respectively, than those calculated from mean spring tidal forcing alone. Calculations of large residual quantities of sediment indicated that landwards transport of suspended sediment across Transects A and B, resulting from combined wave and tidal action, was likely to have dominated the long-term sediment regime over the period studied. It is also probable that transport of sediment as suspended load caused considerably greater transport of sediment than bed load processes in outer areas of Liverpool Bay.

Similarities could be drawn between features of the results presented in Tables 6.12 and 6.13 and characteristics identified in examination of bed load sediment transport under combined tidal and wave activity. A particularly notable feature was that wave activity did not enhance suspended load sediment over the whole of the area studied. Suspended load residual transport fluxes across Transect D, at the mouth of the estuary, remained constant for all computations of sediment transport whether including wave activity or not. In a similar way to the characteristic trends in bed load transport, the sediment fluxes were comparable with fluxes under tidal forcing alone, even under storm wave conditions, indicating that the mouth of the estuary was sheltered from waves propagating from offshore by the banks of sediment in Liverpool Bay which induce waves to break. Thus in the Narrows area of the estuary it was apparent that tidal conditions were the dominant influence upon suspended load transport as well as bed load transport. This further accentuated the importance of representing gravitational circulation resulting from salinity induced stratification, which was shown to strongly influence both residual transport of bed load and suspended load transport.

Comparison of the patterns of residual suspended load transport across Transect C derived from calculations incorporating tidal forcing and combined tidal forcing with wave activity, demonstrated similarities with trends in bed load transport. From examination of residual sediment transport fluxes across Transect C presented in Tables 6.10 and 6.11 it was evident that although wave activity affected net sediment transport, the effects of wave forcing were not as significant as for Transects A and B. Wave activity increased the landward residual transport of suspended load sediment for the 1906, 1936 and 1977 bathymetric configurations under mean spring tidal forcing combined with both a frequent and a storm wave condition. However, despite a reversal of the net transport of bed load sediment across Transect C as a result of combining tidal and wave action, the magnitude of the residual suspended load sediment flux was less than the seaward residual transport of sediment for the 1977 bathymetric configuration under mean spring tide forcing alone. The results demonstrated that although wave effects influenced sediment transport in the vicinity of Transect C they were not as dominant as in seaward areas of Liverpool Bay.

Computations of sediment transport under neap tidal conditions, however, exhibited a significant difference from trends examined in bed load transport. Significantly larger quantities of sediment were transported landwards across Transect A under neap tidal conditions combined with a frequent wave condition and storm wave condition than was transported seawards across Transect A under mean spring tidal forcing alone. The landward fluxes of sediment transport across Transect A were approximately 13 and 90 times greater under a neap tidal condition combined with a frequent wave and a storm wave condition respectively than residual suspended load transport under a mean spring tidal condition alone. The residual transport of sediment across other transects under neap tidal conditions was not enhanced to the same extent when combined with wave activity, demonstrating that it was only in the outer areas of Liverpool Bay exposed to wave activity that wave forcing under a neap tidal condition could influence the sediment regime. Given the dominance of wave influenced sediment transport in the outer areas of Liverpool Bay under both neap and spring tidal conditions, the chronology of wave activity was of little significance and a general landward movement of sediment may be deduced. For the more complex inner areas of the estuary, however, the chronology of wave activity can have a significant impact upon sediment regime. It has been demonstrated that sediment transport under neap tidal conditions combined with wave activity has less significance to sediment regime than spring tidal forcing both alone and combined with wave activity. However, different patterns of residual transport can exist under mean spring tidal conditions compared with residual transport can exist under mean spring tidal combined with wave activity, particularly in the outer area of Liverpool Bay.

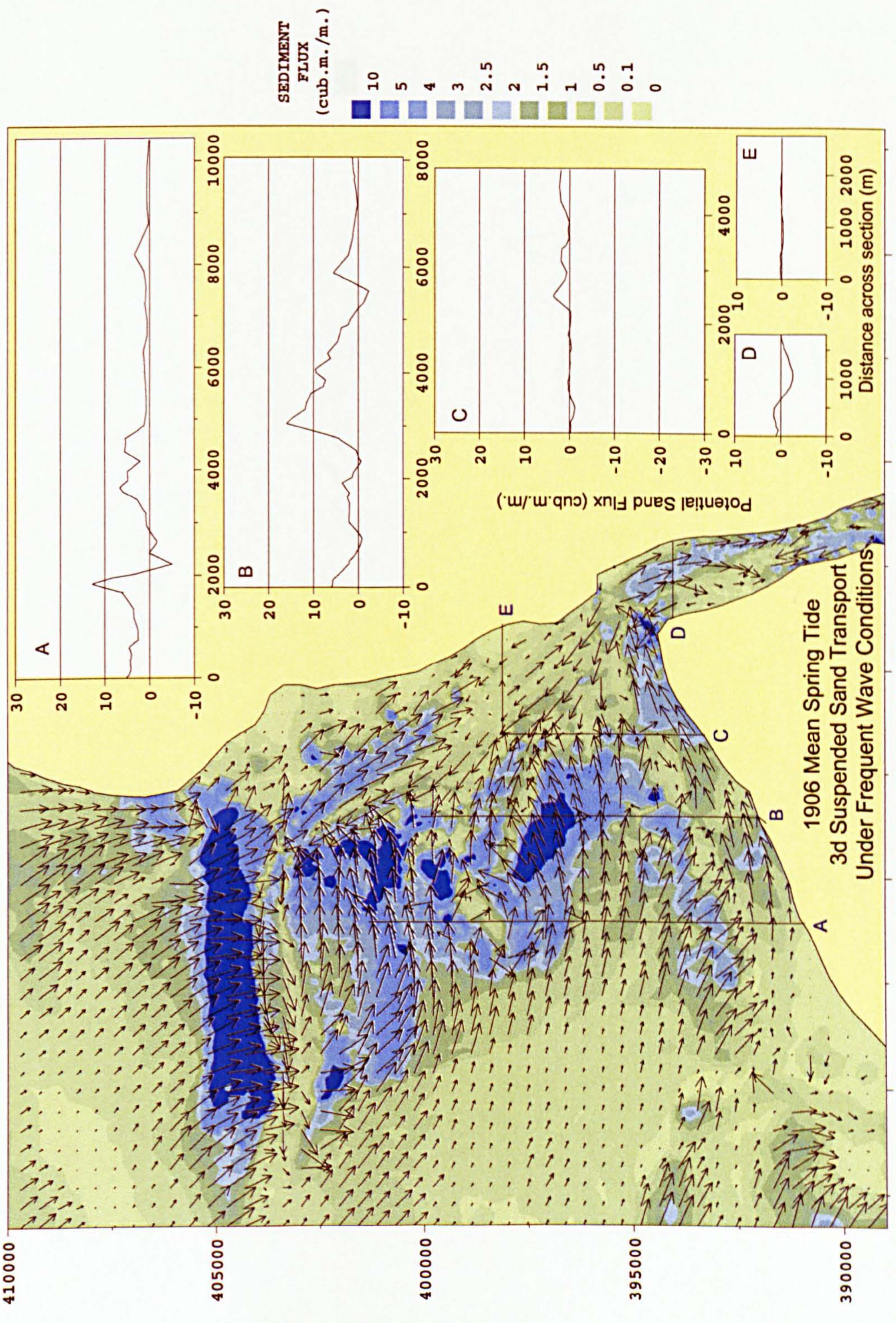


Figure 6.31 Potential non-cohesive suspended load residual transport through a mean spring tide for 1906 based upon 3D near bed flow simulation results and a frequent wave forcing condition

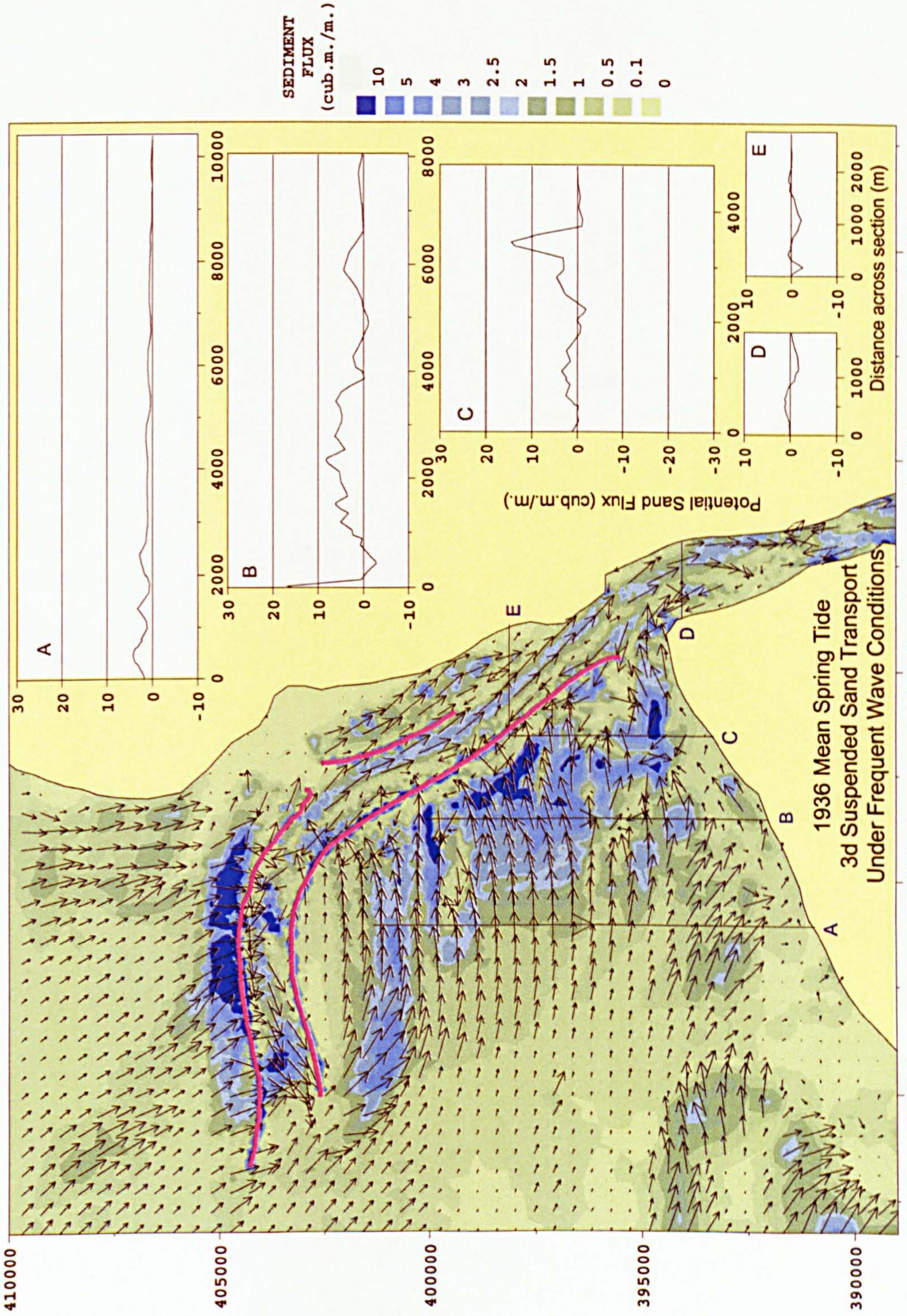


Figure 6.32 Potential non-cohesive suspended load residual transport through a mean spring tide for 1936 based upon 3D near bed flow simulation results and a frequent wave forcing condition

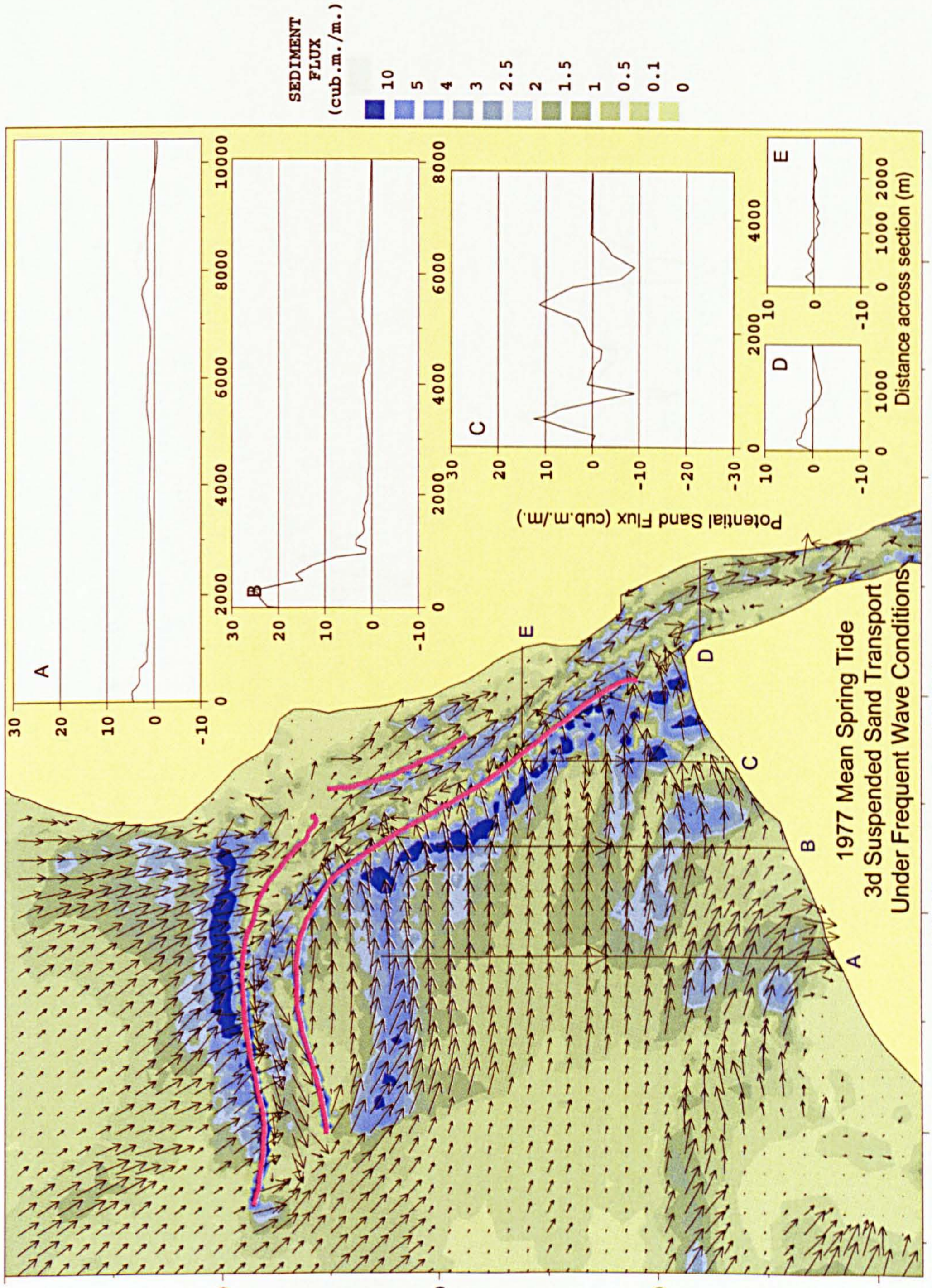


Figure 6.33 Potential non-cohesive suspended load residual transport through a mean spring tide for 1977 based upon 3D near bed flow simulation results and a frequent wave forcing condition

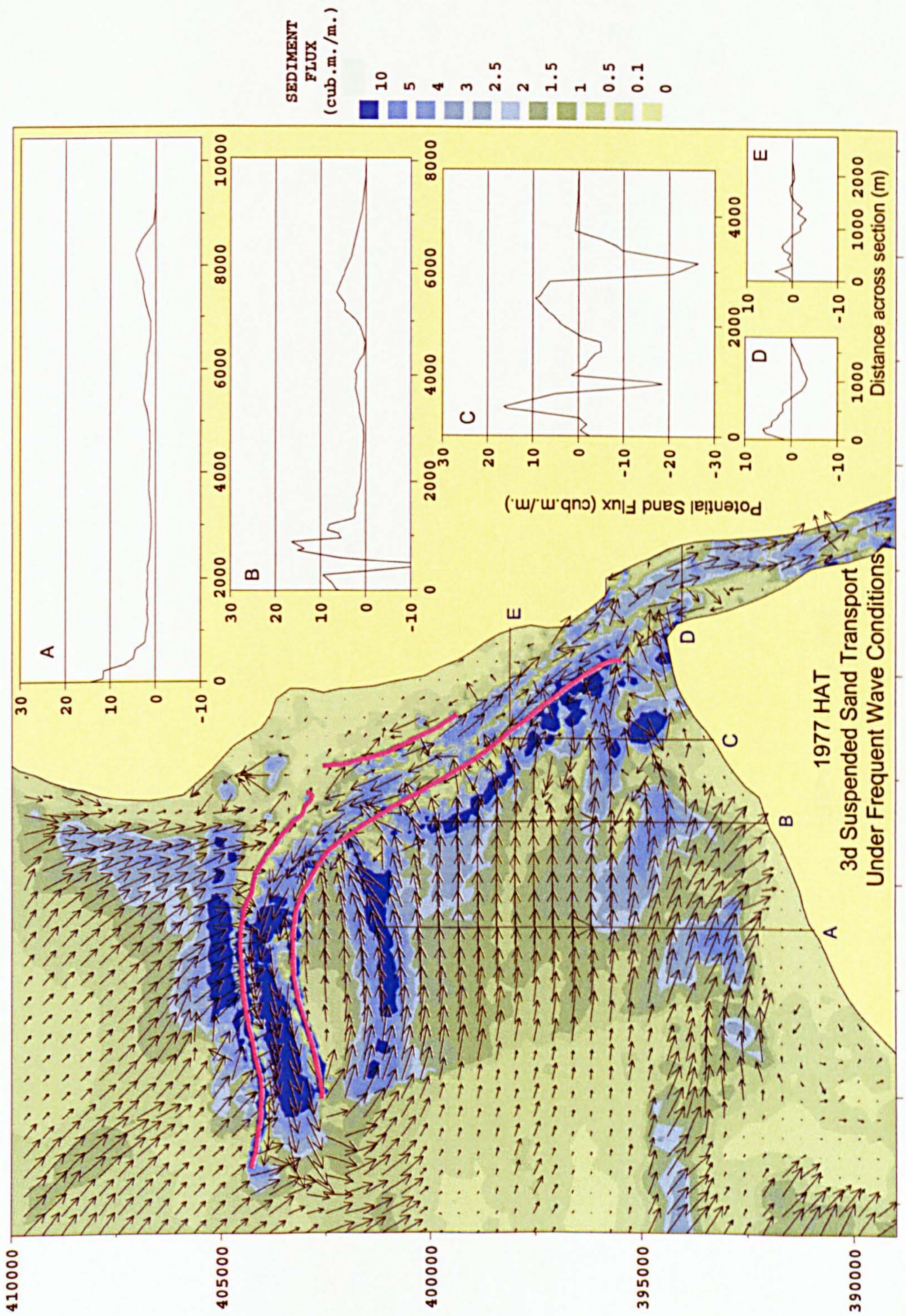


Figure 6.34 Potential non-cohesive suspended load residual transport through a HAT for 1977 based upon 3D near bed flow simulation results and a frequent wave forcing condition

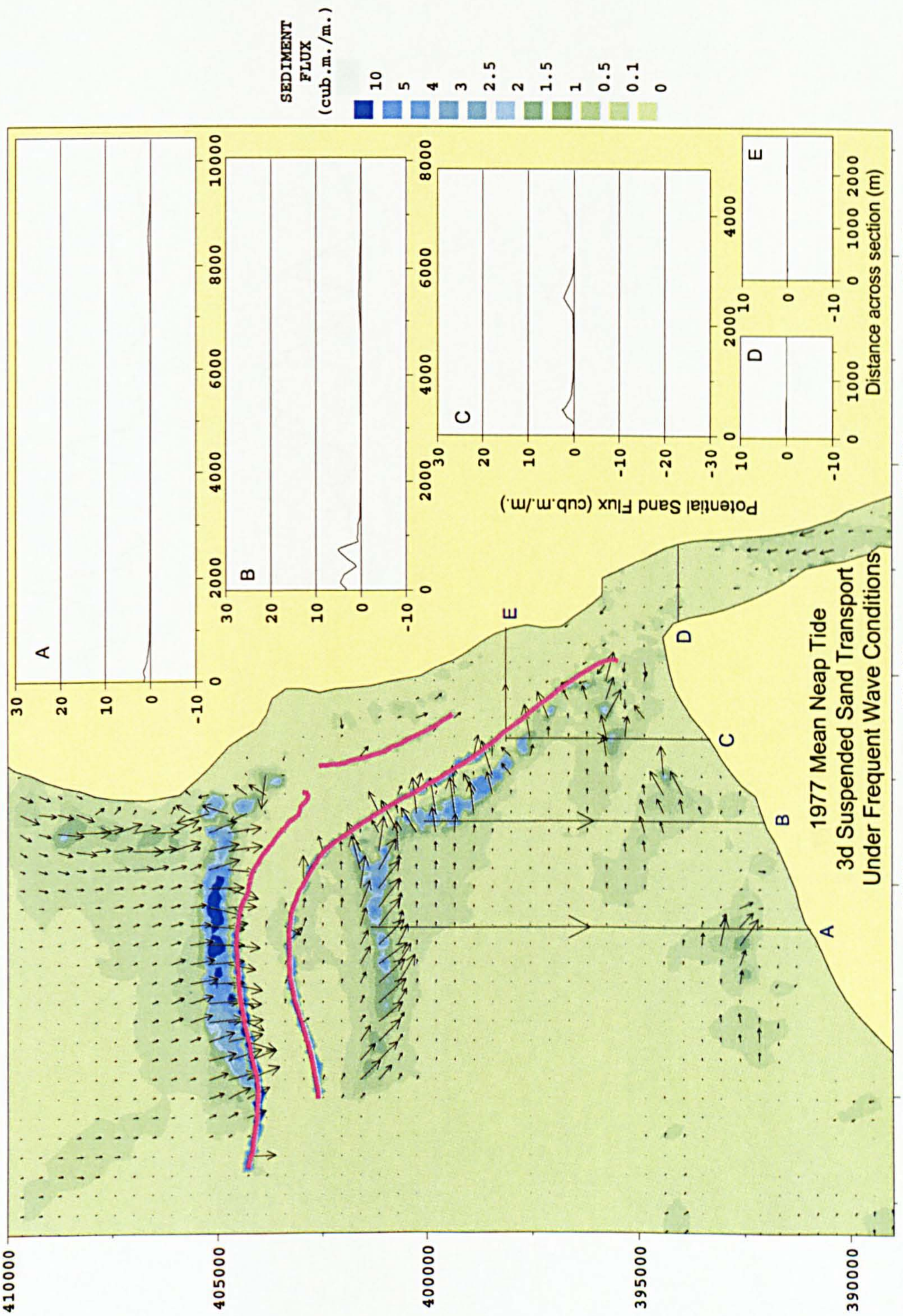


Figure 6.35 Potential non-cohesive suspended load residual transport through a mean neap tide for 1977 based upon 3D near bed flow simulation results and a frequent wave forcing condition

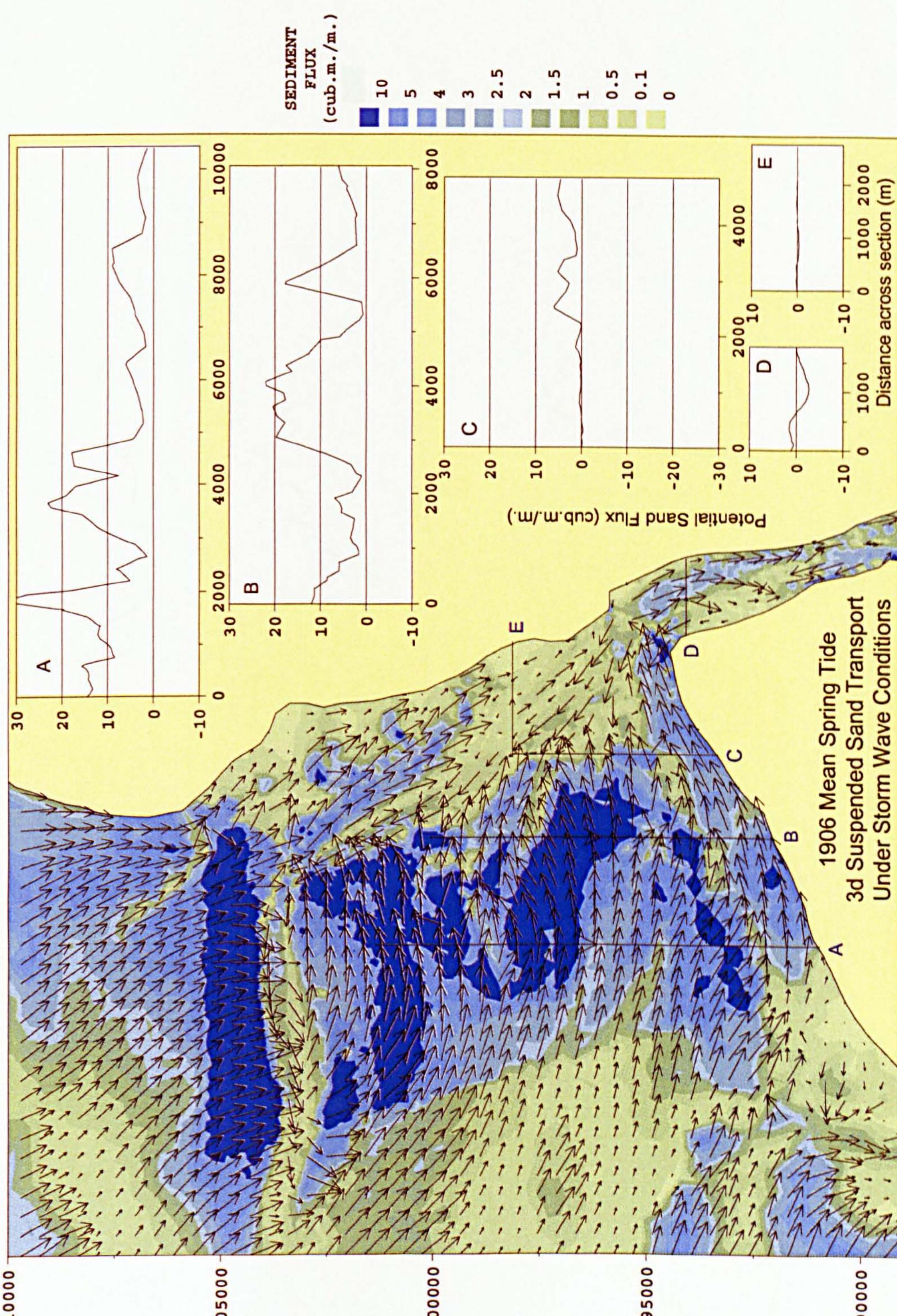


Figure 6.36 Potential non-cohesive suspended load residual transport through a mean spring tide for 1906 based upon 3D near bed flow simulation results and a storm wave forcing condition

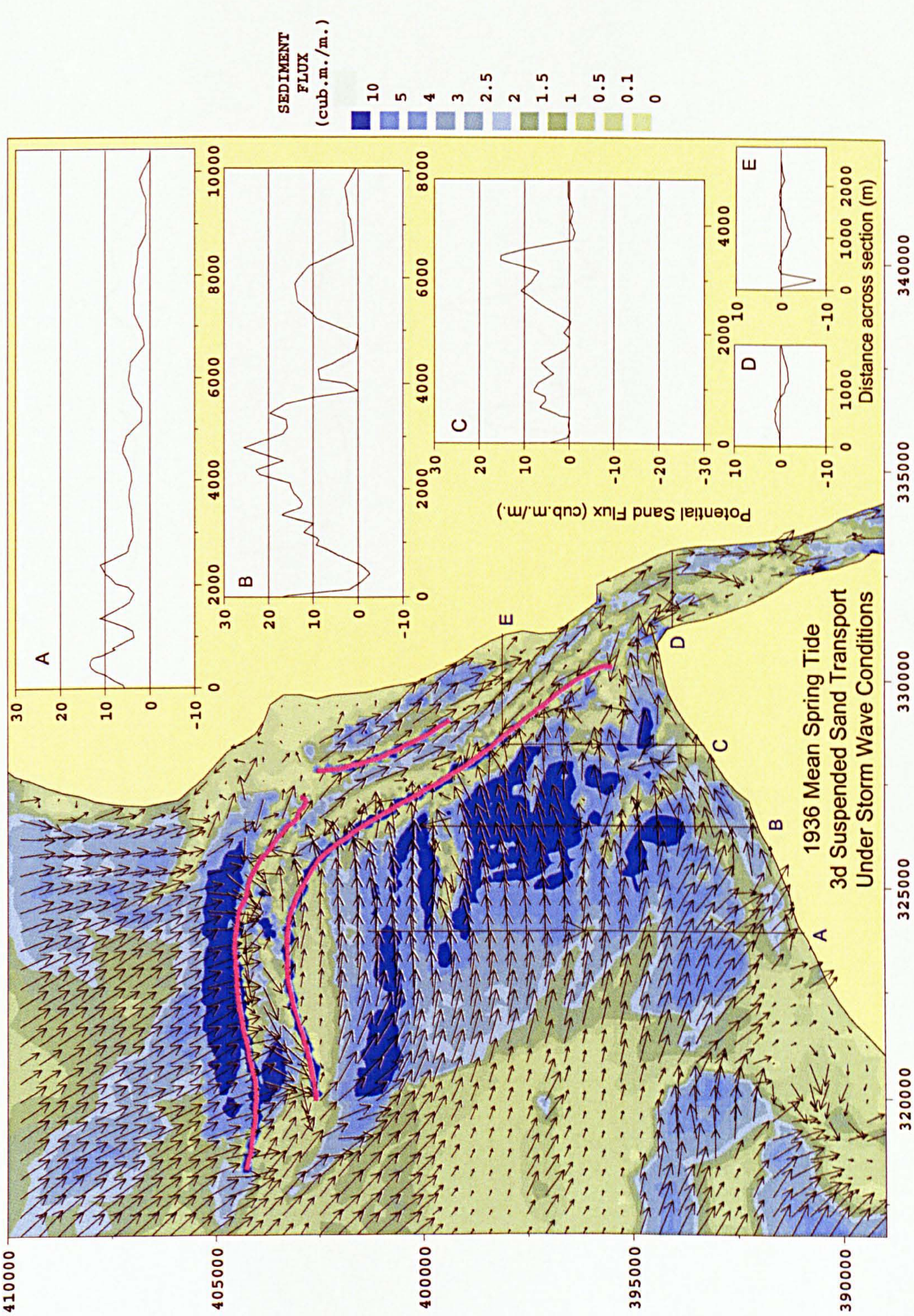


Figure 6.37 Potential non-cohesive suspended load residual transport through a mean spring tide for 1936 based upon 3D near bed flow simulation results and a storm wave forcing condition

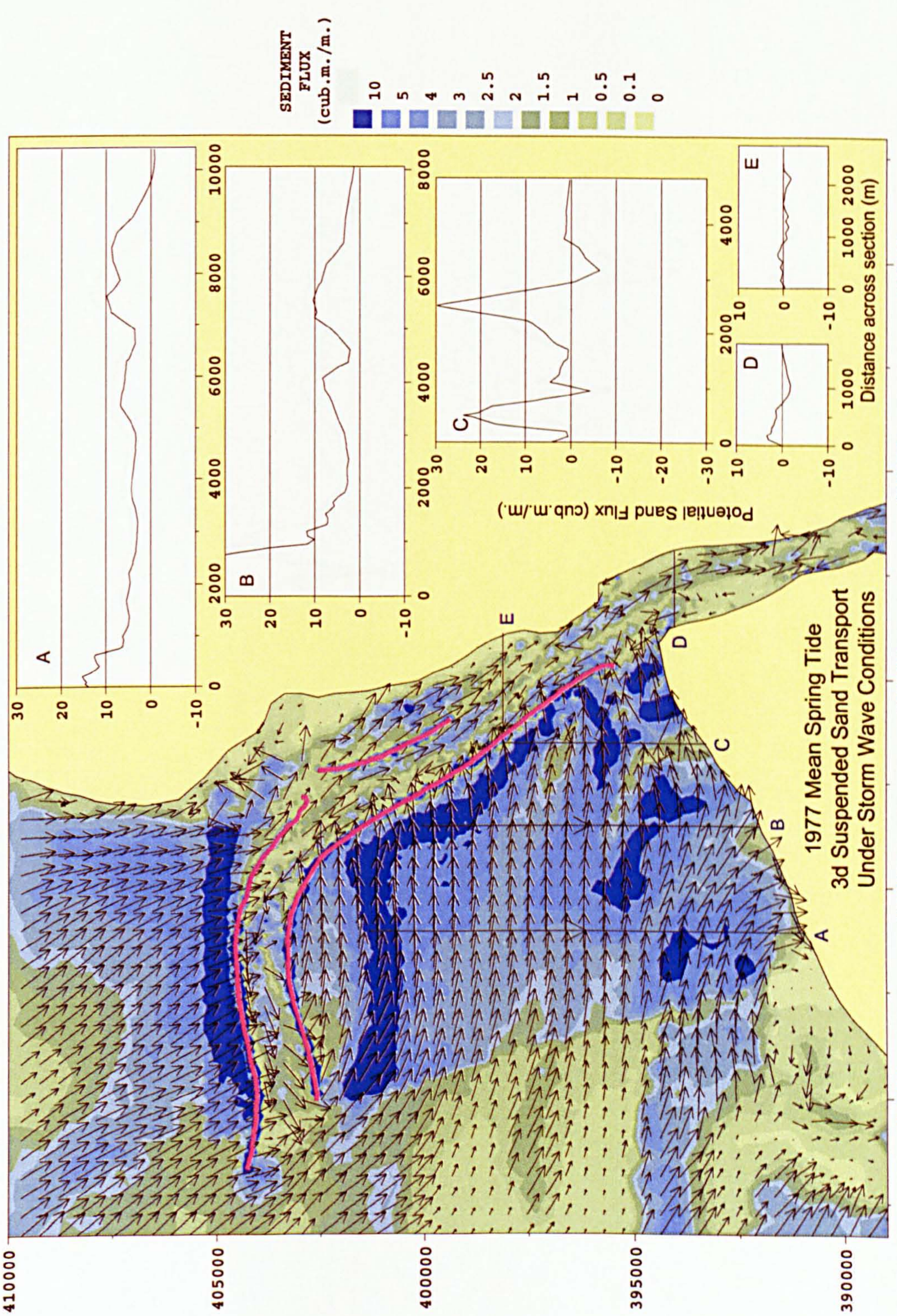


Figure 6.38 Potential non-cohesive suspended load residual transport through a mean spring tide for 1977 based upon 3D near bed flow simulation results and a storm wave forcing condition

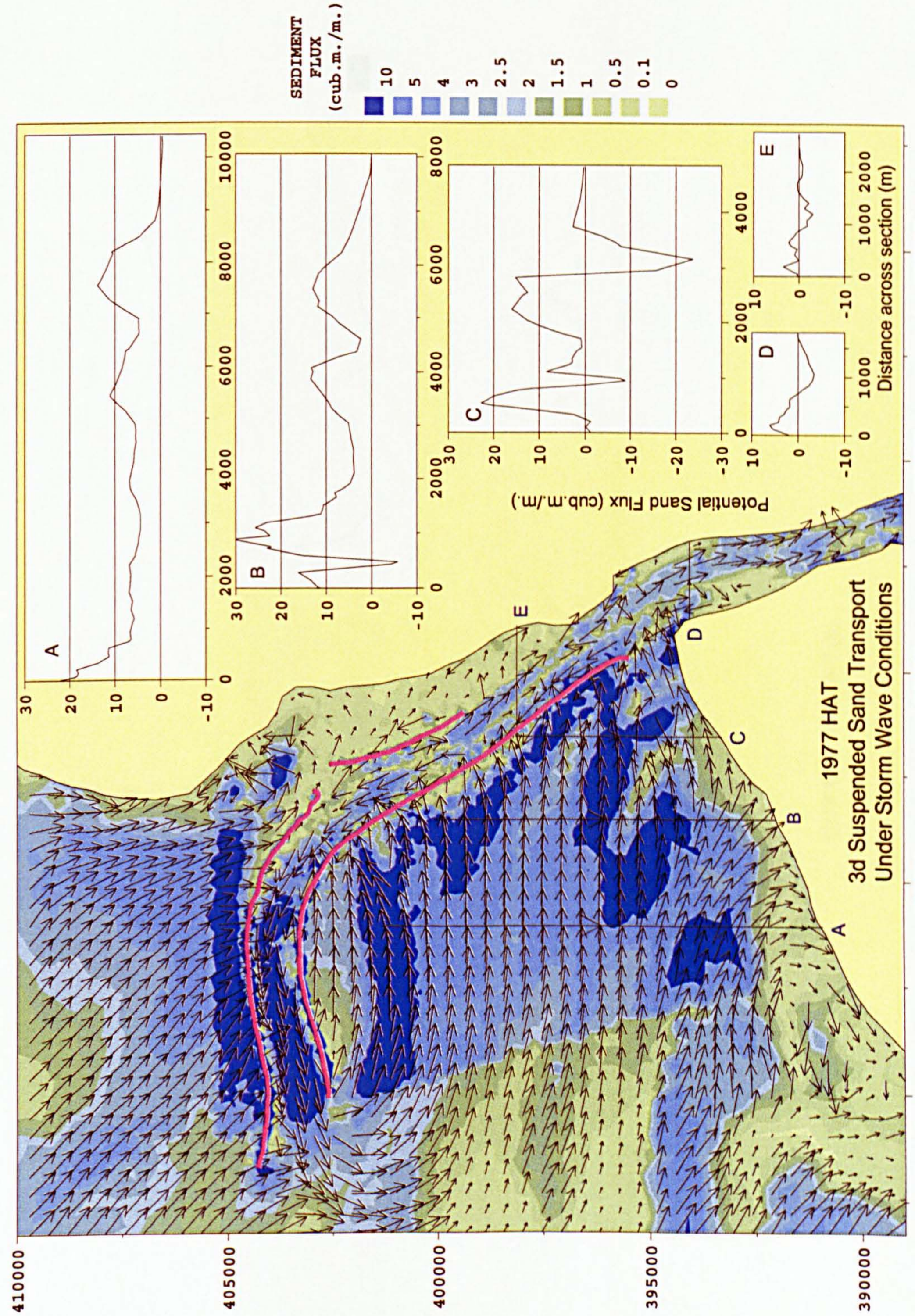


Figure 6.39 Potential non-cohesive suspended load residual transport through a HAT for 1977 based upon 3D near bed flow simulation results and a storm wave forcing condition

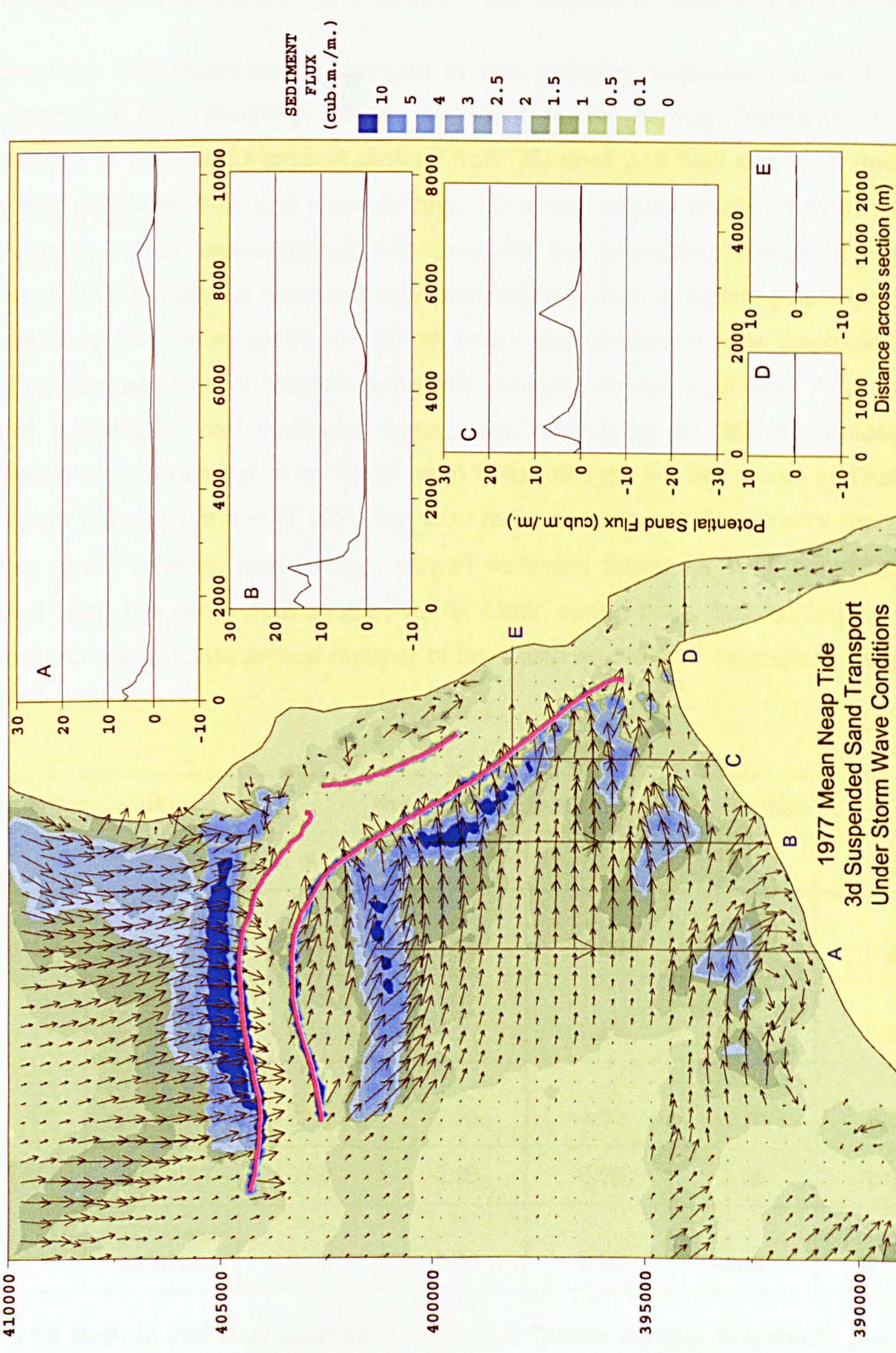


Figure 6.40 Potential non-cohesive suspended load residual transport through a mean neap tide for 1977 based upon 3D near bed flow simulation results and a storm wave forcing condition

6.5 Long-term consequences of changes in non-cohesive sediment transport regime

The long-term consequences of changes in non-cohesive sediment transport regimes were examined by estimating annual sediment fluxes across Transects A-E from computations of sediment transport derived from 3D near bed flow velocities under tidal forcing and combined tidal and wave forcing. 2D model results were not examined as it had previously been demonstrated that they did not accurately represent significant features of the tide-residual sediment transport resulting from stratification effects. Annual sediment fluxes for mean spring and mean neap tidal conditions were approximated by integrating computations of residual sediment transport across Transects A-E, summing bed and suspended load sediment fluxes, and multiplying by 350 to represent the approximate annual number of spring or neap tides, with the results shown in Table 6.15. To compare the effect of a HAT with long-term residual transport of sediment represented by mean spring or neap tidal forcing, annual sediment fluxes for HAT conditions were estimated using the same methodology as for mean spring tides, but multiplying by 2 to represent the approximate annual number of tides with an order of magnitude comparable to a HAT.

Simulation conditions		Net sediment flux across transect (Mm^3)				
		A	B	C	D	E
No wave condition	1906 Mean spring tide	-0.69	-1.20	-0.60	0.53	0.02
	1936 Mean spring tide	-0.06	-1.37	1.25	0.24	0.28
	1977 Mean spring tide	0.14	1.50	-4.32	-0.15	-0.20
	1977 HAT	0.00	-0.03	-0.06	0.00	0.00
	1977 Mean neap tide	0.00	-0.01	-0.02	-0.03	0.00

Table 6.15 Annual residual sediment transport fluxes across Transects A-E under tidal forcing alone

The approach adopted made the assumption that sediment transported under a mean spring or mean neap tidal condition was representative of the mean transport of sediment for all spring tides or all neap tides respectively. The potential transport of non-cohesive material as suspended load into the estuary accounted for greater quantities of sediment transport in Liverpool Bay and the Mersey estuary than bed load transport alone, and formed the dominant component of computations of annual sediment fluxes. The results shown in Table 6.15 for the annual sediment transport fluxes, calculated under neap tidal conditions for the 1977 bathymetric configuration, demonstrated negligible residual transport of sediment in comparison with mean spring tidal conditions. The results showed that neap tidal conditions contributed little to annual residual sediment fluxes under tidal conditions alone. Sediment fluxes calculated for mean spring tide forcing were more likely to be representative of annual residual sediment transport, although transport of sediment under neap tidal conditions combined with wave activity was significant for some areas. Although tide-residual fluxes were shown to be enhanced under HAT forcing in comparison with mean spring tide forcing in Section 6.4, when averaged over an annual duration, it was demonstrated that the significance of extreme tidal range flows was limited in comparison with the long-term average forcing, due to the low frequency of occurrence of extreme tides.

Plots of sediment transport vectors based upon hydrodynamic model results demonstrated little potential for sediment transport along the Formby coastline. Although the results did not accurately represent longshore drift, which required an approach simulating refraction of tidal and wave currents from the shoreline, studies of sediment transport patterns have shown that longshore drift is a localised effect, confined to the Formby coast. Transport north of Formby Point is predominantly in a direction away from the estuary mouth. The evidence presented in Sections 6.4.1-6.4.2 suggested that the most probable source of sediment causing large-scale accretion in the estuary was the east side of Liverpool Bay. However, the quantity of sediment transported eastwards across Liverpool Bay under tidal forcing alone was insufficient to account for the scale of morphological change observed. Furthermore, no pathway was evident in Table 6.15 for sediment to reach the Mersey estuary for any of the bathymetric configurations examined.

Gravitational circulation under tidal conditions represented the key process in the Narrows area of the estuary for morphological change, as a 3D representation of hydrodynamics accounted for movement of sediment landwards through the estuary mouth. It was evident from the sediment fluxes calculated across Transect D shown in Table 6.15 that potential fluxes of sediment into the estuary mouth varied over time. This phenomenon was probably the result of localised changes in patterns of sediment regime. Examination of fluxes further landwards in the Narrows exhibited landwards transport of for each of the bathymetric configurations examined (see Table 6.16), although the sediment fluxes were reduced in 1977. Changes in tidal propagation in the estuary were unlikely to account for the estuary attaining a hypothesised state of quasi-equilibrium, but localised changes in circulation patterns at the estuary mouth may have exerted a significant influence.

Simulation conditions	Net sediment flux across transects within the Narrows (Mm^3)
1906 Mean spring tide	0.77
1936 Mean spring tide	0.64
1977 Mean spring tide	0.39

Table 6.16 Fluxes of sediment through the Narrows at a location approximately 5km landwards of the estuary mouth

The values calculated for the annual residual flux of sediment through the estuary mouth under tidal forcing in the 3D hydrodynamic simulation (see Table 6.5) were significantly lower than the annual sediment flux derived from the sediment budget in Table 4.6. It was possible that there was no seaward transport of sediment through the estuary mouth in 1936, as residual fluxes across Transects C and E were landwards preventing sediment from leaving the area adjacent to the estuary mouth. However, even employing the assumption that sediment was transported landwards only through the estuary mouth, with no seaward transport contributing to net fluxes, the flux of sediment landwards through the estuary mouth was only $0.48Mm^3$ in 1936.

The underestimation of sediment fluxes could have resulted from several factors. Significant uncertainty is inherent in calculation of sediment rates. The correlation of flux calculations for other areas of Liverpool Bay with observed levels of morphological change indicated that sediment transport calculations were of the approximate order of magnitude. It was feasible, however, that calculations for all sediment fluxes computations were underestimations and that sediment transport in Liverpool Bay exceeded the quantities calculated in this study. The model representation of flood and ebb tidal flows for example was not exact, and although representative of the differences between bathymetric configurations imposed limitations which have been magnified by multiplying for an annual sediment flux. Alternatively, it is possible that the mechanism for transport of sediment into the estuary, although adequate to identify the processes responsible for transporting sediment into the estuary, was not represented with sufficient accuracy to derive an accurate sediment flux. Higher levels of freshwater flow for example may have increased stratification, strengthening the near bed landward residual flow. Flow in the bottom 1m was also assumed to be vertically homogenous, which was unlikely to have been the case with greater landwards flow near the bed, where sediment concentrations were greatest. Furthermore, the basic assumption employed of a relation between mean spring tide and annual sediment flux may not have been an accurate means of representing annual sediment flux.

A feature identified in the patterns of the calculated sediment fluxes across Transect C was that the annual sediment flux was greater for 1936 than 1906 and 1977. The landwards flux of sediment across Transect C was of a similar order of magnitude to that required to account for accretion in the estuary. Furthermore, by combining the calculated annual fluxes of sediment across Transects C and E, to represent the quantity of sediment entering the area adjacent to the estuary mouth, as shown in Table 6.17, a clear pattern of sediment supply to the estuary mouth was evident. The flux of sediment crossing Transect E was unlikely to have been transported along the Formby coast. However, sediment from the east of Liverpool Bay may have overtopped the training wall and been transported southwards towards the estuary, making it a valid route for sediment to enter the estuary.

Simulation conditions		**Net sediment flux across transects C+E (Mm^3)**
No wave condition	1906 Mean spring tide	-0.57
	1936 Mean spring tide	1.54
	1977 Mean spring tide	-4.52
	1977 HAT	-0.06
	1977 Mean neap tide	-0.02

Table 6.17 Annual combined residual sediment transport fluxes across Transects C and-E under tidal forcing alone

Analysis of the long-term consequences of changes in non-cohesive sediment transport regimes was developed further by estimating annual sediment fluxes across Transects A-E from computations of sediment transport derived from 3D near bed flow velocities under combined tidal and wave forcing. Annual sediment fluxes for mean spring and mean neap tidal conditions accounting for the occurrence of a frequent wave condition were approximated by assuming that frequent wave conditions affected sediment transport over 40% of tidal conditions annually with the remaining 60% being caused by tidal conditions alone. Computations of residual bed and suspended load transport under frequent wave conditions were integrated across Transects A-E, and multiplied by 140 to represent the approximate annual number of spring or neap tides coinciding with a frequent wave condition, and added to integrated computations of residual bed and suspended load transport under tidal forcing alone multiplied by 210 to represent the approximate annual number of spring or neap tides coinciding with no wave conditions. The results of sediment flux computations are shown in Table 6.18 To compare the effect of a HAT with long-term residual transport of sediment represented by mean spring or neap tidal forcing, annual sediment fluxes for HAT conditions were estimated using the same methodology as for mean spring tides, but multiplying by 2 to represent the approximate annual number of tides with an order of magnitude comparable to a HAT.

Simulation conditions		Net sediment flux across transect (Mm^3)				
		A	B	C	D	E
Frequent wave condition	1906 Mean spring tide	2.69	3.22	0.09	0.53	0.04
	1936 Mean spring tide	1.60	1.98	2.22	0.24	0.37
	1977 Mean spring tide	2.00	4.28	-2.43	-0.15	-0.17
	1977 HAT	0.04	0.04	-0.01	0.00	0.00
	1977 Mean neap tide	0.23	0.57	0.27	-0.03	0.00

Table 6.18 Annual residual sediment transport fluxes across Transects A-E under tidal forcing with a frequent wave condition

It was evident that waves played an important role in transporting sediment across Liverpool Bay towards the estuary mouth. The transport of sediment was significantly greater under combined tidal and wave forcing conditions examined, than under tidal forcing alone. Wave forcing predominated in the vicinity of Transects A and B for all bathymetric configurations examined. Under combined tidal and wave action, however, sediment transport was significantly enhanced, and under frequent wave conditions was sufficient to account for the observed scale of morphological change. Wave effects were therefore of significant importance in sediment regime in Liverpool Bay. Transport processes near the mouth of the estuary across Transects C and E, however, exhibited a more complex pattern of change. Wave effects upon these areas, although significant, were reduced in comparison with Transects A and B. Fluxes under a frequent wave forcing condition were similar to calculated fluxes under tidal forcing alone, indicating that wave propagating from offshore had little influence upon sediment transport in the Narrows.

Based upon the evidence it was possible to define three areas of physical process interaction within Liverpool Bay and the mouth of the Mersey estuary. Firstly, in the exposed seaward area along the west of Liverpool Bay where Transects A and B were positioned; wave processes dominated sediment transport causing a significant eastwards transport of sediment towards the estuary for all bathymetric configurations and all tidal forcing conditions when combined with wave activity. Although sediment transport was significantly reduced under neap tidal conditions, under combined wave and tidal forcing the net quantities of sediment transport were sufficient to account for the scale of observed morphological change. Secondly, the Narrows area of the estuary where tidal forcing dominates residual sediment transport processes and gravitational circulation induced by differences in salinity causes a net landward sediment transport. Thirdly, the area in Liverpool Bay around Great Burbo Bank to the west of the estuary mouth where patterns of sediment movement were complicated by the shallow water areas where waves break and which have exhibited significant bathymetric change over the timescale examined.

Simulation conditions		Net sediment flux across transects C+E (Mm^3)
Frequent wave condition	1906 Mean spring tide	0.13
	1936 Mean spring tide	2.60
	1977 Mean spring tide	-2.60
	1977 HAT	-0.01
	1977 Mean neap tide	0.27

Table 6.19 Annual combined residual sediment transport fluxes across Transects C and E under tidal forcing with a frequent wave condition

Analysis of the long-term effects of changes in non-cohesive sediment transport regimes was developed further by estimating the effects of a twice a year storm condition upon annual sediment fluxes across Transects A-E (see Table 6.20). The effects of storm wave conditions upon sediment transport fluxes calculated from previous computations of sediment transport under combined tidal and frequent wave forcing were examined. Annual sediment fluxes were approximated by assuming storm wave conditions occurred twice per year. Integrated computations of residual bed and suspended load transport under mean spring or neap tidal forcing combined with a storm wave condition were multiplied by 2 to represent the probability of potential annual occurrences of a storm wave condition, and were added to 99.4% of computed residual bed and suspended load transport fluxes across Transects A-E derived for combined tidal and frequent wave conditions (accounting for the remaining 348 spring or neap tides respectively that occur annually). The calculations employed the assumption that storm wave conditions coincided with the specified tidal condition to investigate the maximum potential impact of a storm wave condition upon net annual sediment transport under mean spring or mean neap tidal conditions respectively.

Computed residual sediment transport fluxes across Transects A-E were also calculated for forcing under a HAT combined with a storm wave condition. Residual sediment transport fluxes for forcing under a HAT combined with a storm wave condition were multiplied by 2 to account for the possible annual occurrence of extreme conditions in the event that HATs coincided with storm wave conditions. The sediment fluxes derived for a HAT and storm wave forcing enabled comparison to be drawn with the long-term trend demonstrated by assuming a mean spring tide to be representative of sediment transport conditions.

Simulation conditions		**Net sediment flux across transect (Mm^3)**				
		A	**B**	**C**	**D**	**E**
Storm wave condition	1906 Mean spring tide	2.86	3.35	0.11	0.53	0.04
	1936 Mean spring tide	1.69	2.13	2.25	0.24	0.38
	1977 Mean spring tide	2.11	4.41	-2.36	-0.15	-0.17
	1977 HAT	0.14	0.13	0.03	0.00	0.00
	1977 Mean neap tide	0.25	0.62	0.29	-0.03	0.00

Table 6.20 Annual residual sediment transport fluxes across Transects A-E under tidal forcing with a storm wave condition

It was demonstrated in previous sections that storm wave conditions significantly enhanced residual bed load and suspended load transport of sediment over a tidal cycle. This was particularly in evidence in the outer areas of Liverpool Bay, which were exposed to waves propagating from offshore. With the storm wave condition employed in this study occurring with a probability of two times per year, it was evident from Table 6.20, however, that the significance of storm wave conditions to the annual patterns of residual sediment transport due to the low frequency of storm waves was significantly less than wave conditions which were experienced with greater frequency. Thus the frequency of wave occurrence was of greater importance to morphological change than the magnitude of wave forcing when comparing a storm wave condition with a frequent wave condition. Liverpool Bay is, however, greatly exposed to waves propagating across the Irish Sea, resulting in a significant wave condition of considerable force. In other estuaries, which are not as exposed to wave activity the frequent wave conditions may not be as significant to morphological change, and storm waves may exert a greater influence.

A storm wave condition significantly enhanced sediment transport over a tidal cycle, demonstrating a significant short-term influence upon morphological change. When compared with long-term forcing processes in the system, however, it was evident that the influence of storm waves was not the dominant control upon morphological change. The effects of a storm wave condition upon sediment transport across Transects C and E, shown in Table 6.21, also demonstrated less effect than forcing under frequent wave conditions. Sediment fluxes were enhanced slightly with the effects of a frequent wave condition, but in comparison with outer areas of Liverpool Bay sediment fluxes were altered little by storm wave forcing. This illustrated that storm wave conditions did not penetrate significantly further towards the estuary mouth than a frequent wave condition.

Simulation conditions		Net sediment flux across transects C+E (Mm^3)
Storm wave condition	1906 Mean spring tide	0.15
	1936 Mean spring tide	2.63
	1977 Mean spring tide	-2.53
	1977 HAT	0.03
	1977 Mean neap tide	0.29

Table 6.21 Annual combined residual sediment transport fluxes across Transects C and E under tidal forcing with a storm wave condition

6.6 Analysis of changes in cohesive sediment transport patterns

Analysis of cohesive sediment transport is more complex than non-cohesive sediment due to the lagrangian nature of cohesive sediment behaviour, and the fact that particles can cover large distances and be deposited and then re-eroded through a tidal cycle. Moreover, cohesive sediment behaviour is dependent upon a combination of different factors including the size, settling velocity and strength of the settling units. Cohesive sediment can exist as either single particles or, more likely, aggregates or flocs, which may be loosely or strongly bound together. Flocs have larger settling velocity than their constituent particles, and the degree of flocculation depends on many parameters including mineralogy, size, pH and ionic strength of particles and the chemical composition of the water.

Only a 2D modelling tool was available at HR Wallingford to analyse cohesive sediment transport, and this was not considered suitable as it has been demonstrated that gravitational circulation is a significant process within the estuary. Instead a two stage approach was adopted to examine cohesive sediment transport schematically. Firstly, simple calculations of cohesive sediment erosion and deposition employing the 3D hydrodynamic flow computations of Liverpool Bay and the Mersey estuary described in 5.4 were undertaken. Secondly, the advection of material into the estuary was examined using a 3D particle tracking model to investigate whether the potential for sediment to enter the estuary has altered. Results of analysis of cohesive sediment transport patterns were examined to assess whether any trend in changes in deposition or advection of cohesive sediment may be identified over the period 1906-1977.

6.6.1 Changes in deposition patterns

The first element of study of cohesive sediment investigated the differences in the fate of cohesive material present in the estuary, employing 3D hydrodynamic flow computations of Liverpool Bay and the Mersey estuary at a height of 0.2m above the bed. The starting point for calculations was provided by basic sediment transport equations for cohesive sediments. Firstly, the rate of erosion was given by (Owen, 1970):

$$\frac{\partial m_E}{\partial t} = M(\tau - \tau_e) \qquad \text{Eq. 6.28}$$

where m_e is the mass of sediment eroded from the bed; M is an erosion constant; τ_e is the critical shear stress for erosion and τ is the total shear stress The erosion rate is dependent upon the excess shear i.e. the amount by which bed shear stress exceeds the critical shear stress for erosion. Secondly, the rate of deposition was given by Krone (1962):

$$\frac{\partial m_D}{\partial t} = w_s C\left(\frac{\tau_d - \tau}{\tau_d}\right) \qquad \text{Eq. 6.29}$$

where m_D is the mass of sediment deposited on the bed; w_s is the settling velocity; C is the concentration, τ_d is the critical shear stress for deposition and τ is the total shear stress. Equation 6.27 employs the implicit assumption that a value of bed shear stress may be defined below which all suspended sediment will be deposited at a rate defined by the settling velocity w_s. Given the same settling velocity and concentration the rate of deposition depends upon the bed shear stress, with the maximum rate occurring when the bed shear stress is zero, and the minimum (zero) rate occurring when the bed shear stress is equal to or greater than the critical shear stress.

In practice the critical shear stress for erosion varies with depth beneath the bed, thus as surface layers of sediment are removed from the bed the critical shear stress for erosion increases according to the strength profile of the sediment as increasingly consolidated sediment is exposed. Furthermore, the settling velocity of muddy sediment is not a simple function of concentration. The settling velocity increases with concentration because there are more particles present, thus more collisions occur between particles and the resulting larger flocs settle faster than the smaller, basic particles. At low concentrations there is relatively no interaction between the particles and the settling velocity tends to a constant value. However, detailed sediment parameter information was not available for this study, and is not normally available on an estuary-wide basis.

For the purposes of this study the assumption was made that cohesive sediment in the estuary could be characterised by single, constant values for critical shear stress for erosion, critical shear stress for deposition and settling velocity. The assumptions employed apply to uniformly flocculated sediments, which in reality are unlikely to exist, but provide a simple means of examining the relation between cohesive sediment behaviour and changes in hydrodynamic conditions in the estuary. The value of this test is that any change in the tendency for sediment to erode or deposit in different scenarios can be derived without having to ensure that the calculations are fully calibrated, as observational sediment transport data is sparse. Long run-in periods were eliminated, as were uncertainties due to mud density profiles, consolidation and observational error. The drawback to this approach is that the tests are schematic and care must be taken when relating the model predictions to observations, which are the result of a complex combination of a range of physical conditions.

Cohesive sediment transport is controlled by the variation of deposition and resuspension during a series of tides of varying magnitude. However the tests did not attempt to simulate the cycle of erosion and deposition that occur on a 15 day spring-neap tidal cycle because of the logistical problems of calculating flows and transport on intermediate tides. Simulating cohesive sediment transport over a spring-neap cycle presents specific problems, including, the difficulties of selecting a representative spring-neap cycle, difficulties of establishing a representative chronology for a spring-neap cycle, and the lack of observational data of suspended sediment concentrations covering a spring-neap cycle.

For practical reasons it was only possible to simulate conditions on mean spring tides. In some cases it is possible to have limited net siltation on a mean spring tide, but for a long-term build up of material to occur which is mostly due to net changes on a mean tide. However, a previous modelling study of the Mersey estuary indicated that the highest contribution to the yearly rate of cohesive sediment siltation resulted from mean spring tides of range 8.25-8.5m (HR Wallingford, 1991). For this study each model simulation started at high water, and continued for one mean spring tidal cycle. Suspended sediment concentrations were obtained from a study of simultaneously observed suspended concentrations at locations along the Mersey for a mean spring tide on 18th March 1989 (HR Wallingford, 1990c). Observed concentrations of suspended sediment were interpolated linearly between measurement points, and through time, to derive concentrations through a mean spring tide throughout the estuary. No information was available on historic changes in suspended mud concentrations in the estuary, so it was assumed that suspended sediment concentrations had not altered between 1906-1997.

Results

Three series of simulations were carried out to investigate the sensitivity of model results to the choice of values of the parameters describing the sediment properties. These properties are difficult to measure in the field and show considerable natural variability. The first series of simulations were carried out using a best estimate based upon values presented in field studies of sediments in the Mersey estuary as discussed in Section, and two further sets of simulations were conducted using parameters which increasingly favoured the deposition of sediment. The parameters used in the model are shown in Table 6.22.

Test	$\tau_e(N/m^2)$	$\tau_d(N/m^2)$	$w_s(mm/s)$	$M_e(mm/s)$
Best estimate	0.2	0.08	3.0	0.0005
Medium deposition	0.4	0.08	5.0	0.0005
High deposition	0.4	0.12	7.0	0.0005

Table 6.22 Parameter values employed in calculations of cohesive sediment deposition

The results for deposition over a single mean spring tide are shown in Figures 6.41-6.43. The results show considerable variation in the levels of accretion between the three scenarios, but the patterns of results are quantitatively similar. The greatest quantities of sediment were consistently deposited in 1936. The quantities deposited declined to 1977, which consistently represented the lowest quantities of sediment deposited for the scenarios modelled. The values calculated for the 1906 bathymetric configuration lay between the values calculated for 1906 and 1977. Based upon this evidence it could be inferred that flow patterns in the estuary have altered in such a way as to alter deposition patterns in the estuary.

A trend of increased deposition in 1936 indicated that cohesive sediment transport processes could have contributed to observed morphological change in the estuary. However, the amount of accretion in the estuary contributed by cohesive sediment processes could not be accurately quantified from a simple analysis, and required a study of greater complexity. Fundamental to deriving a more reliable quantification of cohesive sediment transport would be improved parameterisation of sediment properties based upon field analysis. Even if the sediment properties were accurately parameterised, however, it is unlikely that the analysis could accurately represent the complexity of physical process interaction with cohesive sediment transport. The effects of waves for example were not included in the model. Thus low velocities in the shallow water adjacent to the shoreline produced high deposition in these areas. In practice, however, localised wave action prevents high quantities of deposition by preventing material from being deposited or by resuspending it at low current velocities.

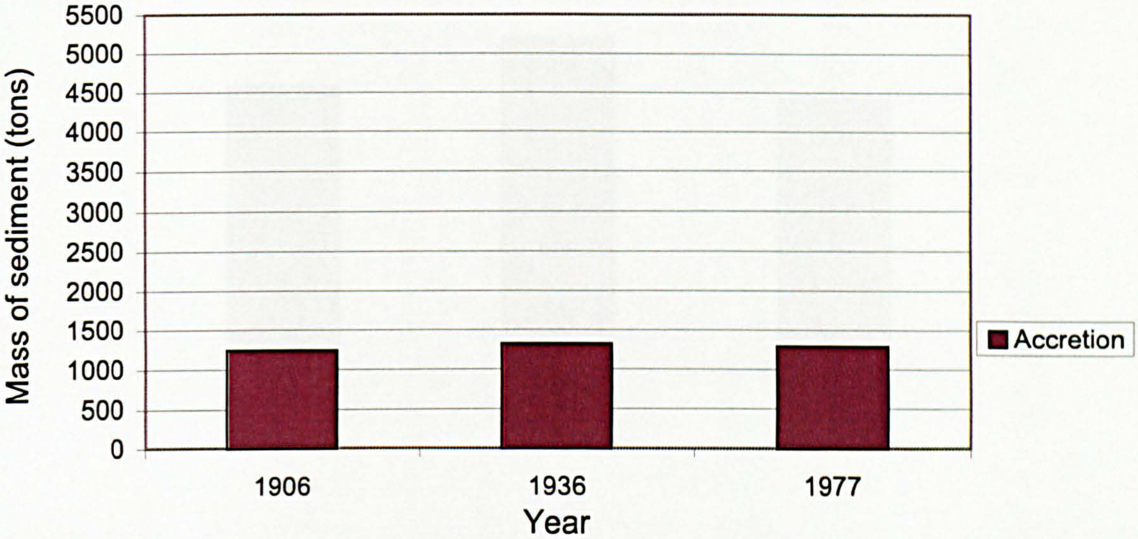


Figure 6.41 Predicted net sediment deposition and erosion through a mean spring tidal cycle with best estimate parameters

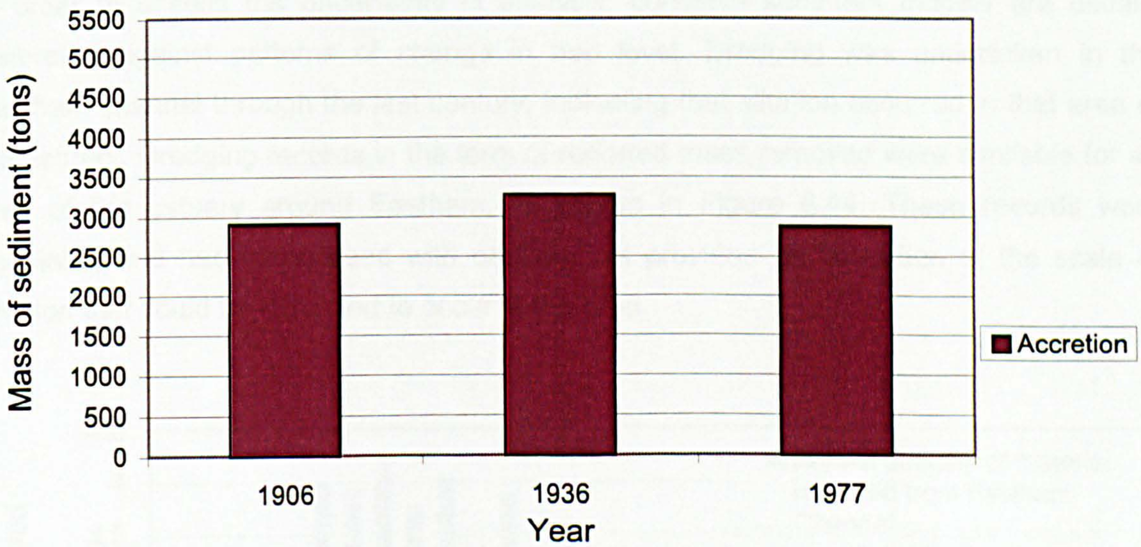


Figure 6.42 Predicted net sediment deposition and erosion through a mean spring tidal cycle with medium deposition parameters

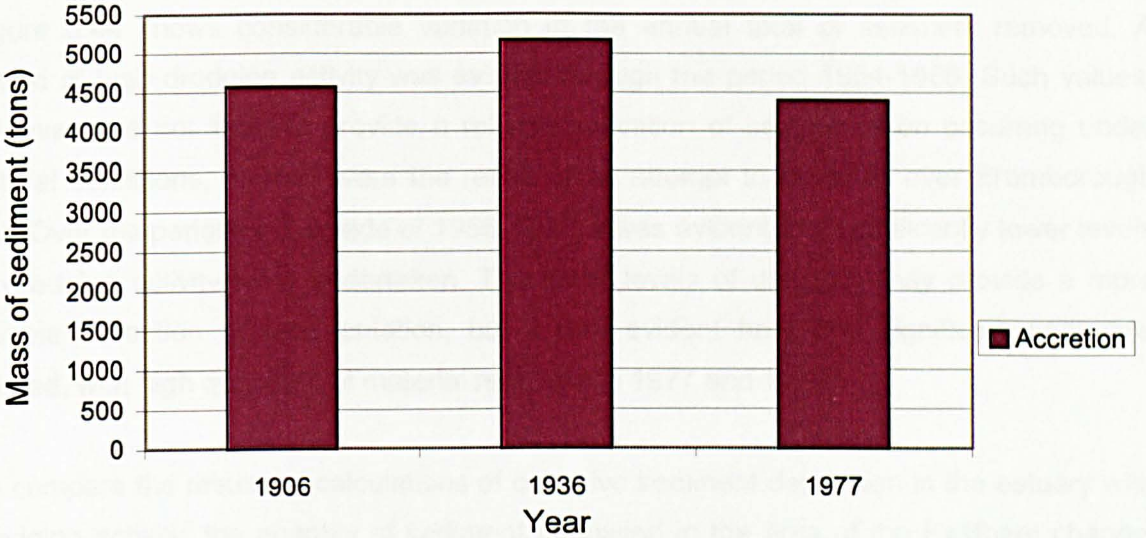


Figure 6.43 Predicted net sediment deposition and erosion through a mean spring tidal cycle with high deposition parameters

In order to assess the uncertainty in analysis, cohesive sediment models are usually calibrated against patterns of change in bed level. Dredging was undertaken in the Eastham channel through the last century, indicating that siltation occurred in that area of the estuary. Dredging records in the form of reported mass removed were available for an area of the estuary around Eastham, as shown in Figure 6.44. These records were unreliable and had to be used with caution, but provided an indication of the scale of siltation that could be expected to occur in the area.

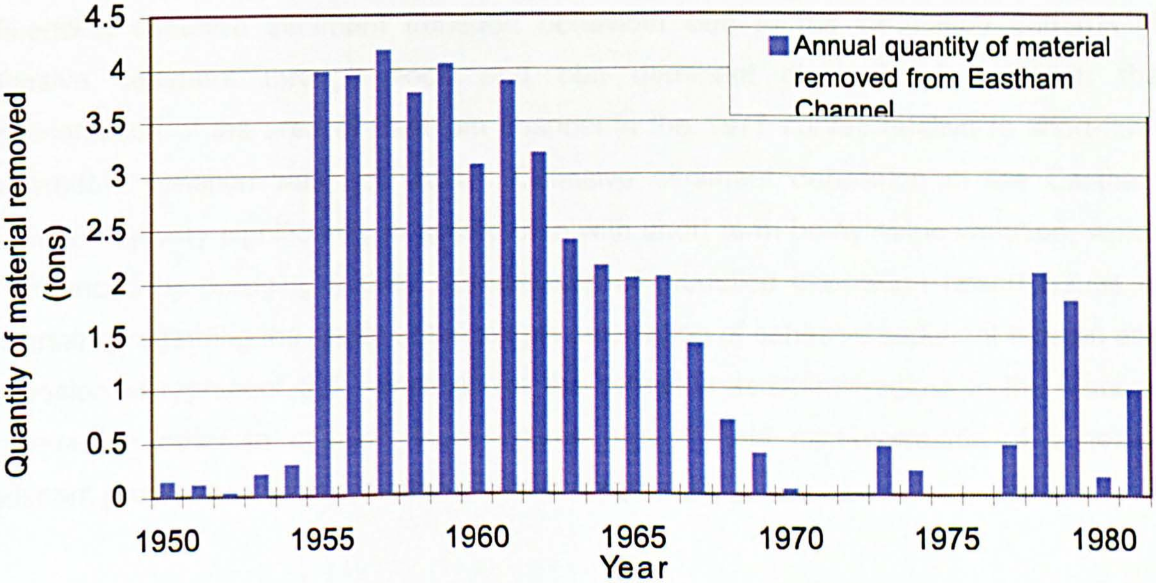


Figure 6.44 Annual quantities of sediment removed from Eastham channel between buoys E1 and E4 1950-1980

Figure 6.44 shows considerable variation in the annual total of sediment removed. A period of high dredging activity was evident through the period 1954-1966. Such values, however, are not likely to provide a reliable indication of sedimentation occurring under natural conditions, as they were the result of an attempt to increase over Bromborough Bar. Over the periods either side of 1956-1966, it was evident that significantly lower levels of dredging activity were undertaken. The lower levels of dredging may provide a more reliable indication of sedimentation, but it was evident here that significant variations existed, with high quantites of material removed in 1977 and 1978.

To compare the results of calculations of cohesive sediment deposition in the estuary with dredging activity, the quantity of sediment deposited in the area of the Eastham channel over a single tide was calculated. However, even for the conditions most condusive to deposition, no net deposition of sediment was calculated over a single mean spring tide for any of the bathymetric configurations examined. Although the limitations of the dredging records have been highlighted, it may be considered that they do represent a real trend of sedimentation in the Eastham Channel, and the failure of the analysis to account for any sedimentation in that area, even under conditions favourable for deposition, does raise issues regarding the ability of the model to represent the cohesive sediment regime within the estuary.

Price and Kendrick (1963) and McDowell and O'connor (1977) demonstrated that the area in the vicinity of Eastham Channel was subject to complex interaction between processes influencing cohesive sediment transport behaviour due to the circulation patterns of cohesive sediment through flood and ebb dominant channels. In addition the representation of the area of Eastham channel in the 1977 survey relative to short-term bathymetric variation was not known. Cohesive sediment deposition in the Eastham channel may vary significantly in accordance with short term bathymetric variation, which is enhanced by dredging activity. Comparison of modelled deposition raised issues of uncertainty regarding the ability of the simple calculation of cohesive sediment erosion and deposition to represent the complexity of the cohesive sediment regime in the Mersey. However, in order to address these issues greater field measurements of cohesive sediment processes and parameters would be required.

6.6.2 Particle tracking of cohesive sediment transport patterns

Calculations of changes in the deposition and erosion of cohesive sediment in the estuary provided a useful indication of changes in sediment regime. However, in the tests described in Section 6.6.1, it was not possible to determine the movement of cohesive sediment into and out of the estuary system. For that reason a series of simulations were undertaken using an additional computational modelling approach to examine of the paths of individual particles, and relative changes in the advection of cohesive sediment through the estuary system.

The particle-tracking model used study was SEDPLUME-3D, which uses 3D hydrodynamic data and a random walk approach to reproduce the advection, diffusion, settling and erosion of sediment particles under the action of tidal currents. The SEDPLUME software (see Appendix 8) calculates the transport of suspended sediment using a particle tracking method. Discrete particles, each representing a certain mass of sediment and assigned cohesive sediment characteristics, undergo advection by the tidal currents, with the mixing effects of turbulence represented by the particles making a random jump in each time step. The size of the random jump is related to the strength of the turbulent diffusion. In addition the particles experience gravitational settling and can be deposited on the bed and re-eroded from it, according to the value of the bed shear stress.

In this study the model was used primarily to investigate the advection of particles under the different tidal current fields corresponding to the three different historic bathymetric configurations. The conditions represented were dependent upon the processes that were significant in the area, and the availability of data on physical processes to validate and calibrate simulations. Since it had been demonstrated that 3D effects were important to the transport of sediment from Liverpool Bay into the estuary, the analysis was undertaken only for the 3D model results. As a consequence, input conditions to model simulations had to be reduced due to computational expense of running 3D simulations.

A reduction in the complexity of the simulation undertaken was achieved by dividing the area of interest into 4 zones (see Figure 6.45). A particle was released at high water from each of the grid nodes within the 4 designated zones, and its movement tracked for one tidal period beginning at high water. The final positions of particles were recorded and the movement of particles landwards and seawards were calculated as a percentage of the initial number of particles positioned within each zone.

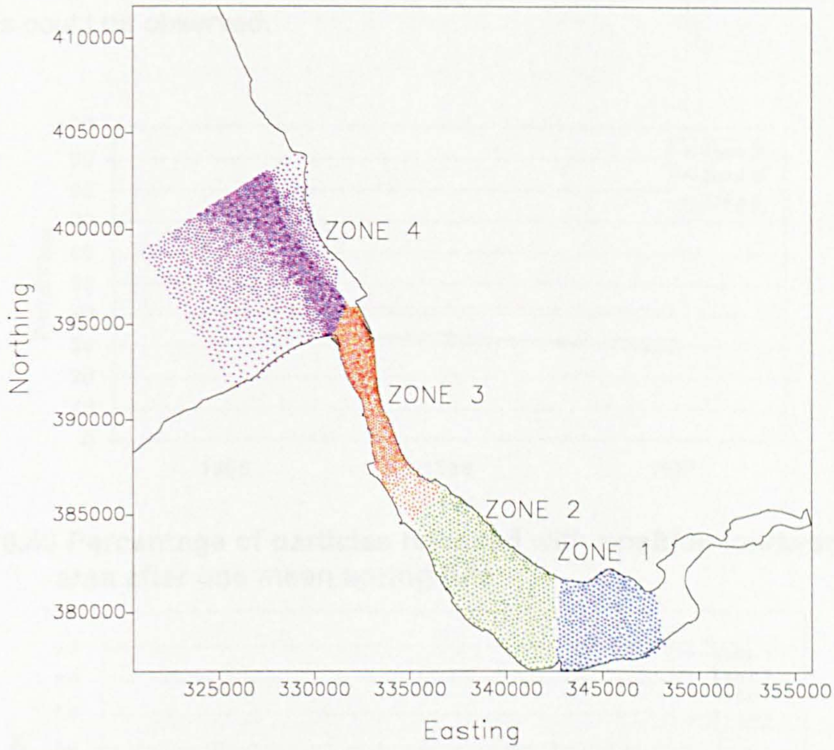


Figure 6.45 Initial positions of sediment particles tracked

Results

The difficulties of parameterising cohesive sediment properties for representation in computational modelling have been discussed in analysis of potential changes in deposition patterns. However, the findings of the previous study that temporal trends in bed exchange relations were relatively unaffected by the choice of sediment parameters, meant that a single set of parameter values was considered sufficient for analysis of advection processes using SEDPLUME. The sediment parameters employed were those reported in field studies of mud sediments in the Mersey estuary (see Section 6.3.1). The minimum settling velocity was taken as 0.0012mm/s, the erosion constant employed was 0.0005mm/s, the critical stress for deposition was 0.08N/m^2, and the critical stress for erosion was 0.2 N/m^2.

Results presented in Figures 6.46-6.47 for the advection of particles under a single mean spring tide forcing, show the movement of particles landwards or seawards respectively relative to their starting position. The calculated percentages were based on the final position of particles both in suspension and as bed deposits after one mean spring tide. Detailed analysis of the results was not justified because the simulation results were dependent upon the relatively arbitrary choice of release locations, but a number of general trends could be observed.

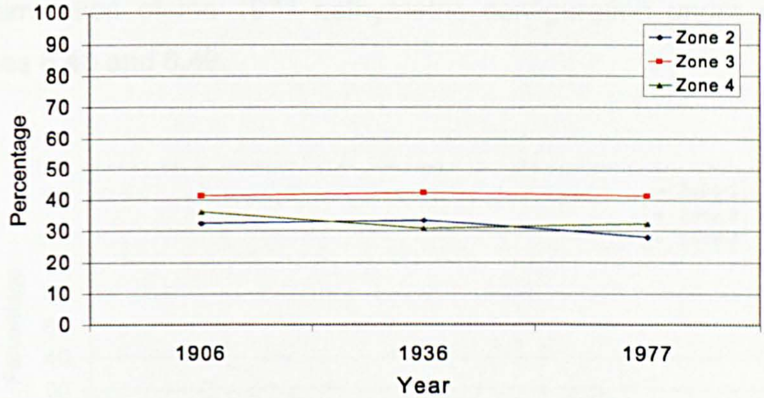


Figure 6.46 Percentage of particles released with position landwards of release area after one mean spring tide

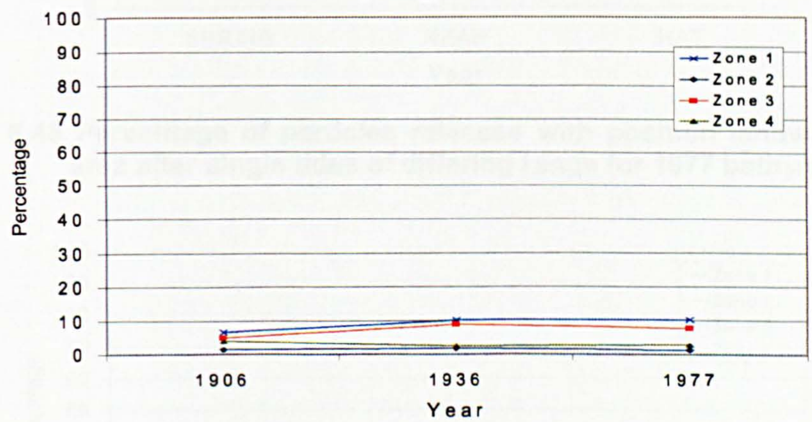


Figure 6.47 Percentage of particles released with position seawards of release area after one mean spring tide

For all three bathymetric configurations it was clear that the movement of particles was predominantly landwards for all four of the zones. The percentage of particles transported to landwards locations was consistently greater than 25%, whilst the seaward transport of particles was consistently less than 10%. Some temporal fluctuations were evident in the movement of particles, such as a decline in the landward movement of particles from Zone 2, and an increase in the seaward movement of sediment from Zone 1 between 1906-1977. Temporal variations in the advection of particles were, however, relatively insignificant in comparison with the net difference between seaward and landward transport of sediment for all bathymetric configurations examined.

In addition to analysis of patterns of particle advection under mean spring tide forcing, SEDPLUME was also applied to analyse, two further simulations comprising tides of differing magnitude. The additional simulations employed the same sediment parameters, but were undertaken using the 1977 bathymetric configuration with a HAT and a mean neap tidal boundary condition respectively. The results are shown in comparison with the results for a simulation of the 1977 bathymetric configuration under mean spring tide forcing in Figures 6.48 and 6.49.

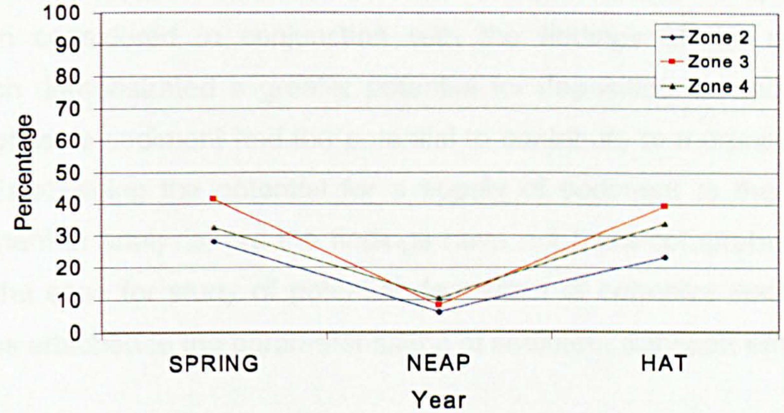


Figure 6.48 Percentage of particles released with position landwards of release area after single tides of differing range for 1977 bathymetry

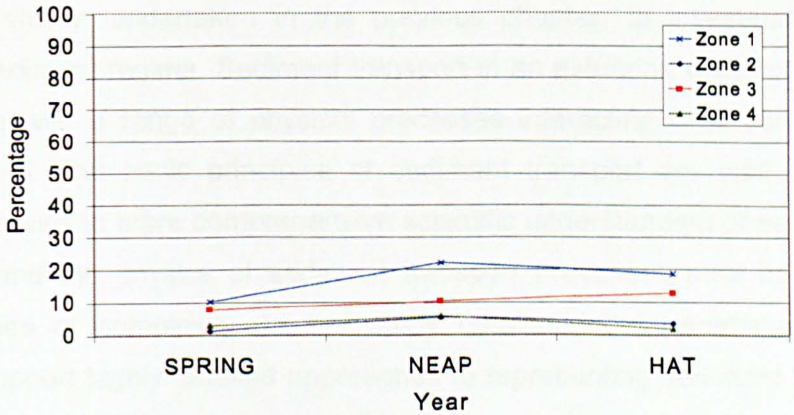


Figure 6.49 Percentage of particles released with position seaandwards of release area after single tides of differing range for 1977 bathymetry

From analysis of the relative transport of particles under spring, neap and HAT forcing presented in Figure 6.49, it was evident that the higher range mean spring and HAT tides induced a landwards movement of sediment. In contrast the values for transport under a neap tidal condition indicated that there was a greater balance between seaward and landward transport, with the potential for some seaward transport in sediment from Zone 1. Overall the greater difference between landward and seaward transport for spring and HAT tides indicated that landward transport of sediment was likely to be favoured.

Overall, the results of the SEDPLUME study showed that the Mersey estuary and Liverpool Bay forms a complicated system with exchange of sediment both between and within them. Advection formed an important issue for consideration in analysis of cohesive sediment behaviour. The exchange of cohesive sediment has, however, remained relatively unaffected by morphological change within the estuary system. This result implied that cohesive sediment transport processes had little influence upon morphological change. When considered in conjunction with the findings of the previous section, however, which demonstrated a greater potential for deposition existed in 1936, it was evident that cohesive sediment had the potential to contribute to morphological change in the estuary. Establishing the potential for a supply of sediment to the estuary was an important element in analysis, but the findings have not been comprehensively validated and, as was the case for study of potential deposition of cohesive sediment, significant uncertainty was attached to the parameterisation of sediment transport employed.

6.7 Chapter summary

This chapter has developed analysis of historical changes in the hydrodynamic regime of the Mersey estuary, undertaken in the previous chapter, to investigate the historical evolution of sediment regime. Sediment transport in an estuarine environment is clearly a complex issue with a range of physical processes interacting over varying spatial and temporal scales. The basic principles of sediment transport are well established, but uncertainty remains in more comprehensive scientific understanding of sediment transport phenomena, and the physics of sediment transport processes may be represented to varying degrees of complexity. In this study detailed input parameter data was not available to support highly detailed approaches to representing sediment transport. Given that the Mersey estuary has been studied intensively over a historic time period relative to other UK estuaries, this reflects scenarios facing studies of historical changes in sediment regimes in other estuaries. The approach adopted in this study involved applying established sediment transport formulae, combined with assumptions about input parameters based upon available information. Such an approach reduced the premium placed upon accurate prescription of input parameters and explored the utility of a schematised approach to examining relative trends in sediment behaviour.

Employing a structured approach to examine different historical and forcing scenarios for the estuary system conferred a more rigorous investigation of sediment transport than was previously possible using physical models. The application of instantaneous relationships between the transport rate and a number of hydrodynamic and sediment parameters have proved effective in developing understanding of the nature and causes of historical morphological change, where suitably applied. The results of analysis of non-cohesive sediment transport demonstrated that although similarities existed between computations derived from 2D depth integrated and 3D near bed flow fields, there were also significant differences which reduced the utility of a 2D depth integrated approach for interpreting the causes of morphological change in the physical environment examined.

Annual sediment fluxes were estimated by using a simple annual multiple to extrapolate from calculated values of tide residual sediment transport across transects based upon the assumption that sediment transport on a mean spring or mean neap tide was representative of sediment transport averaged over all spring or neap tides respectively. The results demonstrated that spring tidal effects dominated sediment regime, but the inclusion of wave effects as a frequent wave condition exerted a significant influence upon sediment transport in outer areas of Liverpool Bay when combined with tidal action. In the Narrows area of the estuary, however, wave activity had little effect upon annual residual fluxes of sediment. Although sediment fluxes through the mouth of the estuary varied closer inspection revealed this to be a localised feature with consistent landward fluxes of the same order of magnitude further landwards in the Narrows. More importantly calculated values of sediment transported into the estuary in 1936 were insufficient to account for the observed scale of morphological change in the estuary. Several possible reasons for this were identified, notably that significant uncertainty exists in calculations of sediment transport rates, and that the range of physical conditions analysed in simulations was not exhaustive. The area of Liverpool Bay adjacent to the mouth of the estuary was shown to exhibit considerable changes in net sediment flux that would have significantly influenced the morphological evolution of the estuary.

Analysis of cohesive sediment transport in the estuary was more complex than non-cohesive sediment in several respects. Representing integrated cohesive sediment transport through a water column for 3D model results presented significant difficulties, and parameterising calculations of cohesive sediment transport was complex due to the greater number of variables than for non-cohesive sediment transport. In order to derive a simplified examination of relative trends in cohesive sediment transport, analysis was subdivided to investigate changes in the advection of material into the estuary, and changes in the potential for deposition within the estuary. The results demonstrated that the advection of material into the estuary has remained relatively constant, with a net landward flux of cohesive material. The potential for deposition of cohesive sediment was, however, greater for the 1906 and 1936 bathymetric configurations than for the 1977 bathymetric configuration. This indicated that cohesive sediment may have contributed to the observed accretion in the estuary, although other studies have indicated that non-cohesive sediment was the dominant form of material transported into the estuary. A schematised approach to investigation of cohesive sediment transport could only provide information on relative changes in potential trends within the estuary. In order to examine and quantify changes in cohesive sediment transport in greater detail a more complex approach was necessary, but this required an increased provision of data to support analysis, which was not available for this study.

CHAPTER 7 DISCUSSION

7.1 Introduction

This chapter evaluates issues arising from a study of morphological change in the Mersey estuary. The principal research aim forms the central issue of discussion where the extent to which historical data and available computational methods can provide a coherent, reliable analysis of the causes of historical morphological change is examined. Broader implications are also assessed for applying historic data and computational methods to analyse long-term changes in other estuaries. The first section of discussion appraises the respective application of historic data and computational methods in a review of the approach adopted in the study. Following this is a conceptual interpretation of morphological change in the Mersey estuary where the different facets of estuary morphology studied (data, analytical parameters, computational methods) are synthesised to develop an understanding of the long-term behaviour of the estuary. The third section evaluates the implications for methods of predicting long-term morphological change in estuaries, and the fourth section assesses the limitations to the approach employed in this thesis with particular regard to the validity of its application to other estuaries.

7.2 Review of the approach

Three main analyses were undertaken in this study corresponding with the research presented in Chapters 4, 5 and 6, respectively. The approach to the analyses broadly paralleled a standardised six-stage approach to environmental modelling proposed by De Jongh (1988) comprising, scoping, data collation, model development, model application, model operation and interpretation of results. Although computational methods have been applied in a diagnostic sense in this study, the findings have significant implications for developing predictive tools to address management issues as the six stages are inherent in any modelling study and thus relate to stages of a potential predictive methodology.

For studies of long-term morphological change in estuaries to be of value, a judgement must be made of the uncertainty involved in analysis, which can originate from a variety of sources relating to the six stages of analysis (see Figure 7.1). Of particular relevance to this study are uncertainties associated with the scoping, data collation, application of computational procedures and interpretation stages. Operational errors have been assumed to be negligible as a range of tools have been satisfactorily calibrated with observed data where available and exhibit results within similar bounds, giving confidence that they do not contain significant operator errors. In addition detailed discussion of model physics is beyond the scope of this study as commercially available tools were employed which have established as capable of reliably simulating estuarine environments, although issues relating to model representation of physical processes are raised where relevant.

In practice there can be considerable overlap between the six stages identified in Figure 7.1, particularly with reference to use of historic data resources. Historic data on estuary morphological form and process is a finite resource and thus collation of available data is integral to decisions taken at the scoping stage of analysis. Computational simulation is a compromise between the degree of representation of physical process complexity against computational expense, with more complex approaches requiring a greater data resource for calibration and validation. The dependence of studies of long-term morphological change upon the availability of historic data presents particular difficulties, as the data may be disjoint and insufficient for reliable, robust analysis with difficulties in assessing error bounds. Assumptions may be required to enable analysis to be conducted where there are significant data constraints. It is important that these assumptions and their likely effect upon analysis findings are made explicit. Further constraints upon analysis are imposed by the requirement for analysis to be conducted within a framework permitting comparison of relative changes.

The hierarchical approach adopted in the three analyses conducted in this study creates a cumulative uncertainty, as analyses were reliant upon data or results from the previous analysis. It is therefore essential to assess uncertainty concomitant with each stage of analysis to enable an assessment of overall accuracy and confidence that may be attached to the final research findings. The issues are evaluated in the following sub-sections.

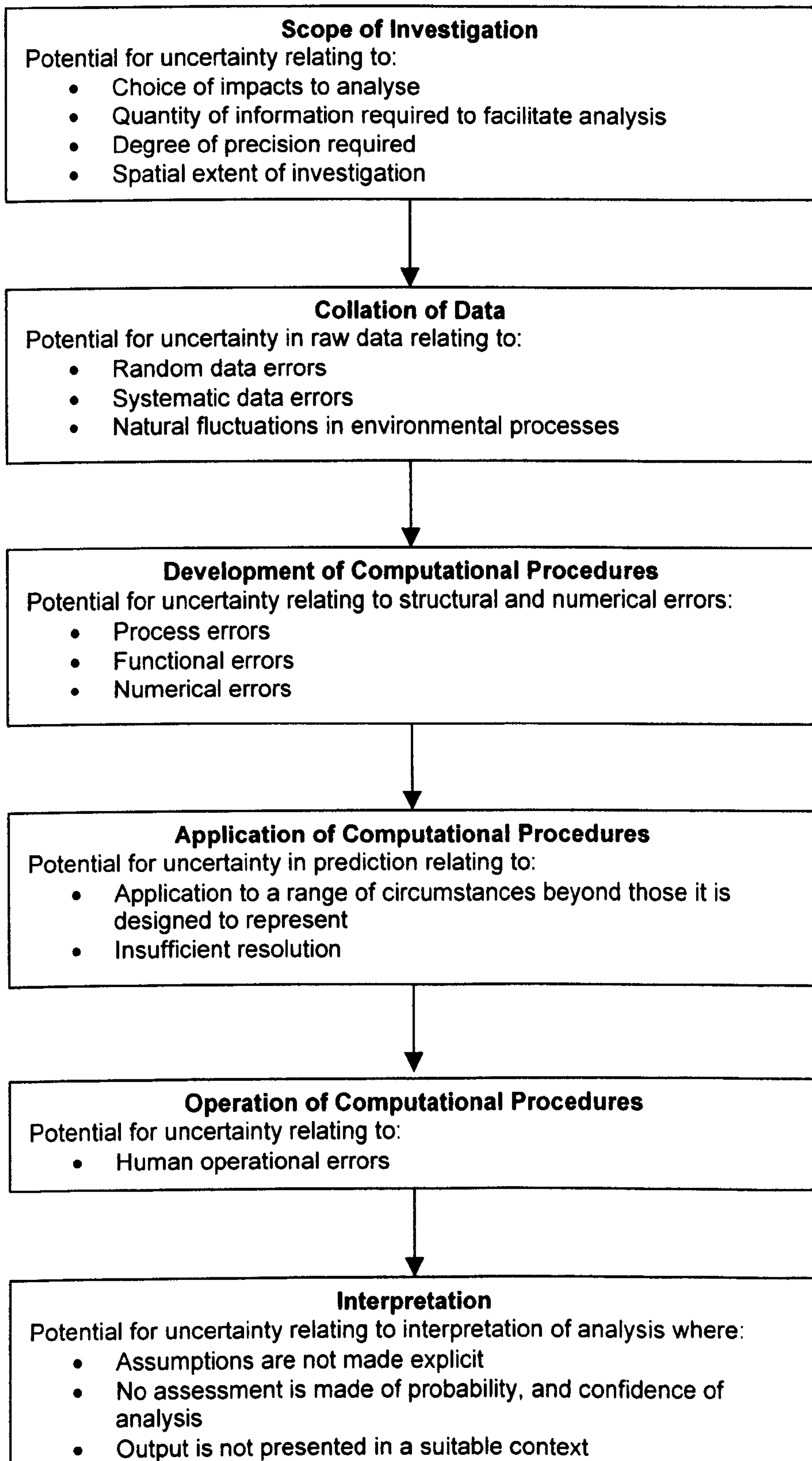


Figure 7.1 Uncertainty in stages of analysis of long-term morphological change, after De Jongh, (1988)

7.2.1 Analysis of historical bathymetric data

Detailed measurements of changes in estuary form represent the minimum requirement for analysing morphological change, as adjustments in estuary geometry cannot currently be accurately hindcast. Historical bathymetric data therefore proved to be of considerable value in this study as it provided one of the only sources of information on changes in estuary form, and was fundamental to analysis of the nature and causes of morphological change. Analysis of morphological change requires a minimum of two data sets of bathymetric measurement for comparison. Temporal coverage is dependent upon the nature of the study but should preferably cover a period of sufficient duration to encompass morphological change. Bathymetric data coverage of the Mersey provided significant benefits for analysis notably that it was estuary-wide, covered the majority of the intertidal area of the estuary and was recorded in a structured, replicated manner at regular intervals through a period of significant morphological change.

Uncertainty relating to scoping for historical bathymetric data analysis

Of particular importance to analysis of bathymetric data were decisions taken at the scoping stage of study, which included several issues for consideration in the analysis:

- The **range of estuary bathymetric data** analysed in Chapter 4 proved to be important in analysis of morphological change in the case of the Mersey. The bathymetric data coverage of high intertidal areas of the Mersey estuary, surveyed using land-surveying techniques, was particularly beneficial in this regard. The most substantial change in quantification of volume changes arose by adjusting computations to allow for variation in water level along the estuary, which indicated that intertidal volumes had a significant effect upon estuary capacity. Quantification of intertidal volume change substantiated the fact that intertidal volume exhibited greater change relative to overall volume change than the subtidal volume of the estuary. Many estuaries may only have data coverage of low intertidal areas and require reference to anecdotal evidence to estimate changes in intertidal areas such as saltmarsh extent. It is therefore important to measure and record changes in intertidal areas. The development of new measurement techniques such as remote sensing of topography with LIDAR will help quantify such changes in estuaries in the future.

- The **spatial extent of data** analysed was an important issue. Historic bathymetric data available for Liverpool Bay considerably enhanced the data resource. Although bathymetric data covering Liverpool Bay was not recorded simultaneously with measurement of the estuary, measurement of the estuary and Liverpool Bay broadly coincided and corresponded with the beginning mid-point and end of a period of significant morphological change. The bathymetric configuration of Liverpool Bay for 1977 was derived from an Admiralty Chart; this provided the principal bathymetric features but did not contain the detailed level of information in earlier charts of Liverpool Bay recorded by MDHC. To prioritise bathymetric surveying for the purposes of monitoring and analysing morphological change the evidence of this study suggests that it is more effective to survey at a lower resolution over a broader area.

- The **temporal coverage of data** must be considered at the scoping stage both in terms of the overall period analysed and the frequency at which data is analysed. Limitations were imposed upon this study by the availability of data and practical issues of manipulation. Although bathymetric data was collected from the estuary as often as each year through parts of the period studied, converting it into a digital format for manipulation was a time-consuming task, and limited the application of all available data. Furthermore, the data employed had to be compatible with bathymetric data for Liverpool Bay, which was only available for the years 1904, 1933, and the late 1970's/early 1980's. Implicit in the use of this temporal coverage of data was the assumption that snapshots of estuary form are representative of long-term trends in estuary behaviour. The use of the temporal intervals employed was justified by consideration of analysis of changes in estuary volume based upon MDHC's computation of all available bathymetric data, which demonstrated that the years analysed in this study are consistent with a long-term trend. Although analysis of all available data may prove more reliable, it is rarely practical, and consideration must be given to the broad context of morphological change for selection of representative temporal intervals for analysis.

- The **quantity of information analysed** can have a significant effect upon analysis. The value of bathymetric data in the Mersey was significantly augmented by the addition of data to derive a sediment budget in Section 4.8. The sediment budget enabled an examination of the net morphological trends and the determination of the relative contribution of natural and anthropogenic factors to estuary volume change. A sediment budget was of particular value in attempting to establish the stability or otherwise of an estuary system by indicating the net flux of sediment into the estuary. In the case of the Mersey the sediment budget presented a different perspective on estuary behaviour to volume change for the period 1977-1997, with a very small net sediment flux into the estuary despite an increase in estuary volume change. This difference could be attributed to dredging activity. However, significant difficulties remained with establishing fluvial input to the Mersey estuary, as records of changes in fluvial flow were disjoint. Fluvial input of sediment was assumed to be negligible as it was likely to be several orders of magnitude less than marine sediment exchange. Dredging records also needed to be treated with caution as measurements were unreliable and methods of converting hopper tons to cubic metres or dry tonnes were an approximation. Furthermore, no data existed for the deposition of dredged material within the estuary for the period 1871-1956. Where no data was available, deposition in the estuary was assumed to be negligible. A sediment budget did indicate net trends in the estuary with greater clarity and it was a useful tool in morphological analysis, although regard must be given to the limitations of the data on which it was based.

Uncertainty relating to collation of historical bathymetric data

- The **resolution of bathymetric data** coverage could potentially affect analysis, and was examined in Section 4.5.1. The main limits imposed by bathymetric data from the Mersey estuary were the relatively low resolution of data coverage between surveyed cross-sections, and the restricted number of bathymetric configurations that could be analysed due to the time taken to digitise historic charts. Modern surveying techniques mean data can be recorded and stored in digital format at higher levels of resolution, as in 1997, overcoming the limitations of analysing bathymetric surveys stored as hard paper copy.

- **Random bathymetric data measurement errors** was proposed as a factor which could affect analysis in Section 4.5.2, and depth measurements recorded in the 19^{th} Century were likely to exhibit significantly greater error margins than present day measurements. However, when averaged over depth measurements which cover the whole of the estuary system, random error had a significantly reduced impact upon volume calculations. Overall the change in estuary volume between 1906-1977 was significantly greater than would be expected to arise from random errors in measurement.

- **Systematic bathymetric data measurement errors** had the potential to distort analysis. Calculated trends may be altered in situations where systematic measurement errors differed between surveys, for example due to a change in measurement device. It was shown in the case of the Mersey, however, that the change from leadline measurements to echo-sounded measurements did not lead to a significant distortion in the overall trend of volume change in the estuary. Although volume change between 1977-1997 was relatively small and would be distorted to a greater degree by measurement error, these two surveys were both undertaken using modern echo-sounding equipment to measure the same survey lines, thus reducing the potential for significant differences in systematic error between the two surveys.

- **Environmental variability** was shown to have little effect upon the identified trends of net morphological behaviour of the estuary in Section 4.5.4. The effect of sea level rise upon volume calculations was examined. Correcting volume calculations to represent a sea level rise of 1mm/year identified by Woodworth (1999) did not have a significant effect upon volume calculations.

- The **accuracy of additional data** employed to derive a sediment budget was an issue considered in Section 4.8. Dredging records for example were difficult to use in a quantitative fashion. Dredging was recorded in hopper tonnes, an imprecise unit of measurement based upon changes in dredger or barge displacement which was not easily converted into a sediment mass or volume. In the case of the Mersey, dredging records were maintained in the same form for an extensive period, which added a degree of reliability to the trends that they exhibited, but overall dredging records were unreliable and required a statement of uncertainty to be attached to their application.

<u>Uncertainty relating to application of computational methods to analyse historical bathymetric data</u>

- Several **interpolation and differencing methods** were applied to bathymetric data to create directly comparable regular spaced grids in Section 4.5.1. The sensitivity of geometric parameter calculations to the interpolation method was shown to be of little significance in this study. Analysis of raw data by plotting cross-sectional data substantiated identified patterns of change. Differences in the resolution of data collection and distribution of data measurements between surveys was of less importance with modern interpolation techniques, which enabled data to be interpolated onto directly comparable regular spaced grids. An increased longitudinal resolution of data would have been beneficial to accurately calculate estuary volume, but was not available as surveys had been consistently surveyed on replicated survey lines.

Uncertainty relating to interpretation of results from historical bathymetric data analysis

- It was important to give consideration in analysis to the **context of findings**, recognising the potential effects of other factors that could influence morphology. If analysis results were used in an unsuitable context it was possible to draw misleading conclusions. Examination of volume change in the estuary for example indicated that volume increased between 1977-1997 which may be interpreted as a morphological trend of erosion in the estuary, representing a reversal of the previous trend of accretion in the estuary. Examination of dredging records indicated that this may be attributed to the quantity of material removed from the estuary through dredging activity exceeding sediment transported into the estuary from Liverpool Bay. In fact Table 4.6 demonstrated that there was actually a small flux of sediment seawards from the estuary after adjustment to account for dredging activity, although the flux may not not be regarded as definitive due to the uncertainty over the accuracy of dredging figures employed. Although it could be argued on the basis of Table 4.6 that increased dredging activity leads to an increased sediment impact, the fact that volume change was significantly greater than the quantities of sediment removed through dredging during the period 1906-1977 indicates that some other factor was having a greater influence upon sediment movement and volume change in the estuary. During the period 1977-1997 however dredging activity corresponds to a much greater extent with volume change and there is little evidence on this basis of other factors influencing sediment transport on a large scale within the estuary. Examination of changes in geometric parameters in the estuary also indicated that estuary form did not adjust in a manner that could induce change in non-linear tidal distortion. Subsequent analysis of changes in potential sediment transport through the Narrows indicated that the estuary exhibited a continuous capacity to transport sediment in a landwards direction through the Narrows through the period 1906-1977. The results of analyses therefore needed to be qualified in terms of their likely overall impact upon morphological change.

Implications for other studies of bathymetric data

Many other estuaries may not have such comprehensive bathymetric data coverage as the Mersey. The measurement of only certain spatial elements of an estuary raises issues about how data is analysed and employed. Intertidal areas in particular are less likely to have been measured in many estuaries as surveys have historically concentrated upon subtidal areas due to their importance to navigation. The evolution of subtidal areas is frequently of less interest, as they are more likely to have been subjected to dredging activity, which may conceal natural morphological behaviour. Intertidal areas are also of increasing significance from a management perspective due to their ecological value as habitats. In estuaries with less comprehensive data coverage assumptions may have to be made, involving for example means of combining data from different surveys. This reduces the accuracy of computations but may provide the only means for deriving global estimates of change.

Additional data could further enhance the value of the bathymetric data resource. It is possible, for example, to draw preliminary conclusions on net changes in habitat types in the estuary based upon intertidal exposure. However, habitat type is also highly dependent upon sediment type for which little data exists. Instigating a data collection campaign of future long-term changes in sediment type may take a significant time to provide usable results. In the meantime assessment of changes in habitat types would have to employ assumptions about the nature of previous changes in sediment types unless a means of examining historical changes is derived. The development of sediment core analysis may be able to provide valuable information on the nature of sediment changes in the estuary considerably enhancing interpretation of changes in habitat type to provide a baseline for assessing the significance of future change.

7.2.2 Examination of historical changes in hydrodynamic regime

A number of issues pertinent to the accurate simulation of changes in historical hydrodynamic regime were examined. Theoretically estuarine hydrodynamics can be accurately reproduced by resolving flow calculations analytically in computational models. Accurate simulations are, however, dependent upon substantial user input and decision-making that can have a considerable bearing upon the results obtained. The general aim of applying hydrodynamic computational models is to adequately represent governing physical processes within an area of interest by including an appropriate physical representation of the system within a model. Applying computational models in this study to examine historic changes in estuary hydrodynamics created an additional element of complexity by requiring that governing physical processes were represented within a framework permitting assessment of relative changes in physical processes between bathymetric configurations. Several criteria relating to different stages of analysis may thus be identified against which the reliability and coherence of simulation of historical changes in estuary hydrodynamic flow regime could be evaluated.

Uncertainty relating to scoping for analysis of changes in hydrodynamic regime

- The **spatial extent of the model domain** was an important issue for consideration in scoping in Chapter 5. In an ideal situation the model should represent a quasi-autonomous morphological unit, such that a contiguous area of interaction is represented in the model enabling a thorough analysis of the relative contribution of changes in form and physical processes to be assessed. This may be determined to a significant extent by the availability of data constraining the model domain to areas for which bathymetric data is available. For the purposes of this study historical bathymetric data was available covering a large area. Extending the model domain to incorporate Liverpool Bay enabled simulation of changes in boundary conditions at the estuary mouth due to the shallow water effects of changing bathymetry in Liverpool Bay. This raised the issue of the extent to which the model domain needed to be increased until there was no longer a significant impact upon model results. A shortage of physical process data required a more extensive modelled domain to examine potential changes in boundary conditions, although this necessarily required greater spatial coverage of historic bathymetric data coverage. Ideally a balance may be achieved between bathymetric data covering areas with a significant impact upon morphological change in the estuary and physical process data of changes in boundary conditions for the area of interest, which limits the need for extensive bathymetric data measurement.

Uncertainty relating to collation of data for analysis of changes in hydrodynamic regime

- Through simulating estuary processes using computational methods, requirements for physical process data were reduced and became inextricably linked to modelling requirements and applications. Physical process data was required in this study to **calibrate model representations** and data required to force model simulations (see Section 5.3. Model simulations were reliant on observed data for calibration and validation and therefore incorporated limitations of these observed data. The most suitable calibration data comprises Eulerian measurements recorded simultaneously with a temporal resolution at least equivalent to the model output of approximately thirty-minute intervals covering at least two distinct tidal cycles. The spatial distribution of data should provide calibration points covering the area of interest within the model domain. Ideally data observations should coincide with the period of bathymetric surveying to provide observations corresponding with the bathymetric configuration of the estuary. Data employed to calibrate hydrodynamic models in this study was the best available data and suitable for reproducing representative conditions within the estuary to simulate general physical process characteristics. The water level data recorded in 1980 comprised simultaneously measured water levels but the observed velocity data was not recorded simultaneously and did not coincide with water level measurements. Improving the quality of data employed in calibration would increase confidence in the approach. Hydrodynamic modelling was calibrated to provide satisfactory reproduction of the principal features of flow for sediment transport.

<u>Uncertainty relating to application of computational methods to examine changes in hydrodynamic regime</u>

- The **level of representation of physical processes** required represented a significant area of uncertainty. Varying levels of representation of physical complexity were employed in this study (see Section 5.2) involving a range of implicit assumptions to justify different modelling approaches. 1D modelling provided the simplest level of representation of estuarine processes, and was particularly effective at simulating tidal elevation amplitudes in the upper estuary where calibration with 1977 water level data was superior to that attained in a 2D simulation of the estuary. However, a 1D approach could only resolve cross-sectionally averaged flows and could not resolve flow velocities as accurately as a 2D or 3D model as it could not represent the effects of water draining from intertidal areas, which are extensive in the upper estuary. 1D models were also not well suited to simulation of coarse sediment transport, which was sensitive to near-bed current profiles, or to resolving lateral variations in flow, which are significant in the Mersey where a system of ebb and flood dominated channels, existed within the basin of the estuary.

- Of particular importance to this study was the **provision of boundary conditions** (see Section 5.4). Although tidal level data has been collected in the

Mersey estuary and has been processed, it was not possible to obtain it for use in this study. Model simulations were heavily reliant upon the specification of boundary conditions. Due to lack of information on changes in boundary conditions in the estuary and Liverpool Bay, implicit assumptions were employed in analysis that conditions at the offshore boundary had not changed over time for both Mersey estuary and Liverpool Bay and Mersey estuary models. The results showed that assuming no changes in boundary conditions at the mouth of the Mersey estuary provided little information on the net causes of morphological change in the estuary. A similar situation is likely to exist in most estuaries, which are unlikely to have long-term physical process data sets, other than tidal records, from which to elicit changes in boundary forcing. Even with tidal records analysis is not straightforward. The records may be disjoint having been collected at different sites or to different reference levels. Where tidal records are available, the most practical approach to determining changes in tidal forcing is through tidal harmonic analysis to define changes in tidal harmonic constituents that may then be employed to generate boundary tides representing different tidal conditions. However, defining changes in tidal constituents is an involved process requiring careful analysis. In particular the duration of the tidal record analysed must be sufficient that identified changes are real and not the result of cyclical, long period harmonics that have been identified as occurring over intervals of up to 18.9 years.

- Analysis of historic changes in physical processes required a **transferable framework** enabling inter-comparison between historic bathymetric configurations (see Section 5.4). In the case of a 1D simulation this was relatively straightforward as bathymetric survey lines were used to represent cross-sections across the estuary for computing cross-sectionally averaged flow. The application of 1D models may be complicated where bathymetric data is not available as measured survey lines, raising issues over a suitable form of representing the estuary as a sequence of cross-sections. Representing estuary bathymetry as a finite element mesh for computing 2D and 3D flow patterns presented greater complexity. Representation of the subtidal channel in the upper estuary was a significant issue as the channel became disjoint where bathymetric measurements did not include the deepest part of the channel or where depths were interpolated between measurements. Improved model calibration of neap tidal flow with observed data, compared with spring tidal flow in the upper area of the estuary, indicated that model resolution of the low water channel was not sufficiently detailed to allow conveyance of water into the upper estuary at low water on a spring tide. The simulation of flow characteristics could have been improved by adapting model meshes to represent specific estuary bathymetric with greater accuracy as discussed by French and Clifford (2000). Such an approach was, however, unsuitable for this study as a consistent modelling representation was required to examine relative changes in physical processes for different bathymetric configurations.

Uncertainty relating to interpretation of results from analysis of changes in hydrodynamic regime

- Beyond calibration of a single bathymetric configuration, the performance of the modelling system was assessed by addressing the broader issue of the **representation of historic changes in flow properties** (see Section 5.6). Flow conditions can be examined in a number of ways, which in this study included a simple comparison at a single point of tidal velocities through a tidal cycle for modelled scenarios. For more accurate analysis of changes in flow properties, the phase and amplitude of M2 and M4, representing the dominant tidal harmonic constituents, were compared, providing a useful means of interpreting results quantitatively. This analysis demonstrated that bathymetric changes in Liverpool Bay had a significant effect upon tidal propagation through the Narrows, which represented an important transition area for sediment entering the Mersey estuary from Liverpool Bay.

- **Relating changes in flow properties to potential changes in sediment transport regime** may be undertaken by examining features of changes in hydrodynamic regime. Sequences of flow vectors at intervals through a tidal cycle were analysed (see Section 5.6.2). These provided an indication of the net effect of training wall construction and bathymetric change in Liverpool Bay upon changes in hydrodynamic regime that could affect sediment transport regime. In addition residual velocity patterns were examined (see Section 0), and in this study provided a useful insight into the potential nature and causes of changes in sediment transport. However, uncertainty was involved in interpreting changes in hydrodynamic regime relevant to sediment transport as sediment could behave in a manner that deviates significantly from flow patterns, particularly due to the influence of thresholds for sediment transport. It was important that recognition is given to this uncertainty, and that changes in hydrodynamic flow patterns were employed only as a basic context for sediment transport issues.

Implications for application of hydrodynamic simulations to other estuaries

The utility of the different modelling schematisations examined depends upon the nature of flow and the spatial domain examined. 3D simulations are the most accurate and best suited to problems of sediment transport as they resolve bed shear stresses with greatest precision. However, a 3D model is computationally expensive rendering it unwieldy for certain applications, and also requires greater data input for calibration and validation. 1D and 2D simulations may be suitable for examining localised hydrodynamics in estuaries where stratification effects are not significant. For the purposes of examining estuary-wide morphological change, particularly where information on historical changes in forcing characteristics is not available, a model domain extending seaward of the estuary mouth may be required as it was demonstrated seaward changes in bathymetry influenced hydrodynamic flow in the Mersey. To represent the expanse of a seaward area a 2D or 3D approach is required. The potential for examining historical morphological change in an estuary is therefore limited by the requirements for detailed information on changes in estuary forcing, or the availability of historical data on bathymetric changes in seaward areas, which does not exist for many estuaries at present.

7.2.3 Examination of historical changes in sediment regime

Computations of estuary hydrodynamics were of considerable importance as a basis for examining sediment transport phenomenon. Calculations of sediment transport were, however, inexact as no analytical solutions for sediment transport rate exist. As a result, computations of sediment transport rates employed a number of assumptions to enable analysis. The emphasis was placed upon identifying and representing processes that had a significant impact upon the behaviour of the sediment regime. A significant element of analysis involved comparing findings from different modelling representations of the estuary to examine the effect of including different physical processes.

Data resources were insufficient to validate complex methods of quantifying sediment transport processes such as probabilistic approaches to modelling long-term tide and wave effects. This study therefore concentrated upon simulating a single mean spring tide condition for different bathymetric configurations, and examined the sensitivity of results to variations in tidal conditions with regard to the main trends represented. By employing assumptions concerning the nature of change in the estuary, the limitations of data coverage of historic change in the estuary may be overcome. This study employed the implicit assumption that boundary conditions and physical parameters have not altered significantly over time.

Non-cohesive sediment transport patterns

A simple approach to examination of non-cohesive sediment transport processes was adopted in this study of applying instantaneous relationships between sediment transport rate and hydrodynamic and sediment transport parameters. Considerable effort was expended upon ensuring that hydrodynamic conditions were representative of historical changes in flow regime. The aim of examining non-cohesive sediment transport patterns was to address in a straightforward, transparent manner the effective of relative changes in hydrodynamics upon sediment transport. Although more complex approaches could be employed, insufficient data was available to validate them, and for the purposes of this study they were unlikely to enhance conceptual understanding of changes in the behaviour of non-cohesive sediment.

This study represented a test of the capabilities of short term modelling tools that schematised and simplified representation of the estuary system, by applying them to investigate relative long-term trends in physical process behaviour in the Mersey estuary. Although short-term physical processes could be represented in model simulations to a satisfactory degree given adequate data for calibration and validation, analysing historical evolution presented significant difficulties due to shortages of relevant data and a lack of scientific understanding of interactions between the processes driving estuary morphology over timescales of the order of 100 years. The approach relied on implicit assumptions to a greater extent than analyses of bathymetric data and hydrodynamic regime, which are important to recognise at the interpretation stage of study.

Uncertainty relating to scoping for analysis of changes in non-cohesive sediment regime

- At the scoping stage of study it was important to consider the **physical sediment transport processes** to be represented in the model (see Section 6.2). Total load transport is comprised of bed load and suspended load, and may be influenced by tidal currents and wave action. The choice of process depends to a significant degree upon the area being examined and the nature of sediment in this area. In the case of this study, Liverpool Bay was exposed to wave activity and had a large tidal range, so it was important to examine the effects of both tidal forcing and the combined forcing of waves and tides. Furthermore, the median sediment size employed in this study, based upon evidence derived from other studies, indicated that suspended load transport would form a significant component of total load transport. However, due to gravitational induced residual flows bed load transport could exhibit different characteristics to suspended load transport.

- The choice of **spatial area** examined was of significant importance and was dependent upon initial assumptions of the source of sediment. In this study the supply of sediment from a marine source formed the focus of attention, so coverage of the estuary mouth and Liverpool Bay area has been of primary importance. However, the extent of model domain in the case of this study was defined by the spatial extent of the hydrodynamic model domain. Thus decisions about the area of interest had to be made at an early stage of analysis.

<u>**Uncertainty relating to collation of data for analysis of changes in non-cohesive sediment regime**</u>

- **Data requirements for calibration of sediment transport calculations** were dependent upon the approach adopted in the study (see Section 6.2). To represent sediment transport precisely, data is required for a known set of hydrodynamic conditions covering two distinct periods for calibration and validation of sediment transport calculations. In cases where such data is not available, alternative information may be employed for a more approximate calibration, such as comparing areas of known erosion with model results. However, significant difficulties are encountered in measurement of sediment transport in coastal areas due to the dynamic nature of the environment. Van Rijn (1993) emphasises that the selection and operation of instruments is critical to accurate measurement for the required purpose, but a degree of error is always present with measurements of sediment transport, limiting the accuracy of studies. Measurements may be affected by the number of measurements taken, the sampling method employed, the location of measurement sites and the means of analysis. Obtaining representative sediment transport data from an estuary for the purposes of calibrating a model, presents significant difficulties due to the inherent variability within an estuary system. A range of processes induces changes in estuary sedimentary behaviour due to tidal effects, variations in freshwater flow and variations in wave activity. In this study detailed calibration was not undertaken as the purpose of the study was to compare the effects of changes in hydrodynamics upon sediment transport. Although uncertainty was implicit in the approach, the principal requirement was that data was sufficient to support investigation of the study objective. Employing a comparative element of study reduced the need for precise calibration and validation, provided that the underlying forcing processes are adequately represented.

- Of particular importance to calculations of sediment transport was the specification of a **sediment size parameter** (see Section 6.3.1). No detailed analysis of sediment size characteristics was available for this study, so, based upon evidence from other studies, a characteristic median grain size of 0.18mm, representing fine sand was employed throughout. Furthermore, no information was available concerning changes in sediment characteristics over time, so the research was conducted with the implicit assumption that sediment characteristics had remained constant throughout the period examined. In the absence of detailed data on sediment characteristics, these assumptions permitted analysis of the effects of relative changes of physical processes upon sediment transport patterns, although it was important to recognise the assumptions made at the interpretation stage of analysis.

Uncertainty relating to application of computational methods for analysis of changes in non-cohesive sediment regime

- Calculation of sediment transport rates is an inexact science and significant **error bounds** are attached to sediment transport algorithms (see Section 6.4.1). Soulsby (1997) suggested, for example, that in complicated marine environments, the best methods of calculating non-cohesive sediment transport rates may not be able to achieve much better than an accuracy of a factor of 5 in 70% of cases. The margins of error in calculations need to be recognised and explicitly stated. In this study a consistent set of parameterisations derived by the same researcher based upon the same empirical data were applied to represent the physical process phenomena. The results were therefore comparable and valid for examining relative changes in physical process behaviour and influence upon sediment transport patterns, despite uncertainty attached to the absolute values calculated.

- The **dimensionality of hydrodynamic process representation** was shown to have a significant effect upon interpretation of the causes of morphological evolution (see Section 6.4.1). A 2D representation of hydrodynamics was shown to represent some of the features of changes in flow in Liverpool Bay, but could not represent a mechanism for transporting sediment into the estuary. Despite the relatively weak stratification in the system, gravitational circulation had a significant effect upon sediment transport patterns, and was fundamental to developing a conceptual understanding of morphological evolution. This study indicated that although representation of sediment mechanics may beneficially be simplified and schematised in complex systems, the complexity of underlying forcing factors must be represented to understand the causes of long-term evolution. This is the particularly the case in systems where stratification occurs.

- The **specification of tidal boundary conditions** was an issue of significant importance for representing the causes of morphological change (see Section 6.3.2). Input sequences of tidal forcing can be predicted accurately over periods up to decades. However, the modelling requirements for detailed tidal sequences are extensive and impractical for most studies. Representative tides based upon long-term sediment transport fluxes may be derived to reduce model inputs. In this study, however, data was not available to validate such an approach, so mean spring tides were examined, which have been shown to dominate sediment transport elsewhere (e.g. Dutch Wadden coast; de Vriend *et al.*, 1994). In this study it was shown that tidal conditions at the upper end of the range did dominate sediment transport in the estuary. However, wave effects enhanced sediment transport even at low flows and were fundamental to accounting for the magnitude of morphological change. In consequence it was more important to examine combined wave and tidal effects than to specify precisely a representative tidal condition.

- The **specification of wave conditions** examined is an issue of considerable uncertainty in situations such as this study where no data on historical changes in wave climate was available (see Section 6.3.3). Complex approaches to calculating representative wave conditions require considerable data and analysis, and could not be supported where no information was available on historic changes in wave climate, which may have had a significant effect upon sediment transport. Furthermore, short-term bathymetric data was not available to support detailed analysis of the variability wave patterns. In this study two general wave conditions were examined. Uncertainty was inherent in this approach, but it provided a valid means of examining the general interaction of wave activity with tidal flow, which was shown to be influential for morphological change.

__Uncertainty relating to interpretation of analysis of changes in non-cohesive sediment regime__

- In the absence of detailed information on the sediment properties it was possible examine sediment transport by applying some suitable **assumptions regarding the nature of sediment characteristics**. It was important in analysis to give consideration to the effect of these assumptions upon calculations. Firstly it was assumed that sediment type was uniform, and a definitive threshold for sediment erosion and deposition could be calculated based upon a uniform particle size. This was unlikely to be the case as sediment within the system was found to vary significantly see Section 3.3. Secondly it was assumed that sediment characteristics have not changed over the period examined. This assumption represented a simplification as evidence existed for an increase in non-cohesive sediment in the system (see Section 6.3.1). Despite the assumptions, the simulations undertaken provided a basis for examining the relative changes in the system, and sediment transport computations were analysed within this context.

- The analysis undertaken relied on **assumptions regarding the behaviour of sediment in the system**. The rates of sediment transport calculated were potential rates and relied on the assumption that there was an unlimited supply of uniform material present in Liverpool Bay for transportation according to the hydrodynamic conditions. In reality this is unlikely to be the case, as there are spatial variations in the availability of sediment. Assuming that the system was saturated, i.e. that an unlimited supply of sediment existed, would have led to an overestimation of sediment transport calculations. In this study, however, several processes such as fetch limited wave action within the estuary and longshore drift of sediment along the coast. The uncertainty induced by simplifying assumptions must be balanced against the limitations of scientific understanding of sediment transport, and considered relative to the complexity of a range of interacting physical processes. Increasingly complex analyses may not yield any greater accuracy in sediment transport computations when considered relative to the system behaviour as a whole. Complex analyses also require increasingly detailed data which is rarely available covering a historic period for estuarine systems to represent for example unsaturated i.e. not potential sediment transport.

- The representation of **physical process interaction with sediment transport** represents a further area of uncertainty for consideration in analysis. The processes examined in this study represented the most probable physical processes to dominate sediment regime. However, the study was not exhaustive, processes such as radiative wave stresses, longshore drift, and internally generated waves in the estuary which can all influence sediment transport were not examined. In localised areas of the system such processes may have exerted a significant influence upon sediment transport. The processes that were examined were not examined exhaustively either. Although stratification effects were found to exert a significant influence upon residual patterns of sediment transport in the Narrows, the relative effects of changes in the degree of stratification induced by high freshwater flow events for example were not examined. Furthermore, the simple relation applied between mean spring tide residual sediment transport and annual residual sediment transport may not have been an accurate representation of the relation between sediment behaviour and physical processes.

Cohesive sediment transport patterns

Detailed information regarding cohesive sediment properties was not available for the Mersey estuary, so a schematised analysis was undertaken using sediment transport relations. This permitted basic analysis with employed to explain conceptually the causes of morphological change in the estuary. The results of the investigation of the cohesive sediment transport results exhibited different outcomes dependent upon the assumptions employed in analysis of sediment behaviour. Overall it was evident that greater complexity was inherent in studies cohesive sediment transport than non-cohesive sediment transport due to the greater physical complexity of cohesive sediment behaviour.

Uncertainty relating to scoping for analysis of changes in cohesive sediment regime

- At the scoping stage of study it was important to consider the **physical sediment transport processes** relevant to the study (see Section 6.2). Cohesive sediment transport may be influenced by a range of processes including tidal currents and wave action. The choice of process depended to a significant degree upon the area being examined and the nature of sediment in this area. In the case of this study, cohesive sediment processes were examined predominantly within the Mersey estuary, which had a large tidal range, but was sheltered from waves propagating from offshore. Although internally generated fetch-limited waves could influence sediment transport, a basic analysis of cohesive sediment behaviour under tidal forcing was considered adequate to gain a general understanding of relative trends in the deposition patterns and the advection of material into the estuary.

- Due to gravitational induced residual flows the **dimensionality of hydrodynamic process representation** was an important issue for consideration in scoping. A 2D representation of hydrodynamics was shown to represent some of the features of changes in flow in Liverpool Bay, but could not represent a mechanism for transporting non-cohesive sediment into the estuary (see Section 6.4). Despite the relatively weak stratification in the system, gravitational circulation can have a significant effect upon cohesive sediment transport patterns, and was fundamental to developing a conceptual understanding of morphological evolution. This study therefore employed 3D model results. Employing a 3D flow field increased the potential complexity of representing integrated cohesive sediment transport through the water column. In order to simplify examination of changes in cohesive sediment regime, analysis was schematised to examine changes in depositional regime and changes in the advection of cohesive material into the estuary system separately. Although this increased the uncertainty inherent in analysis, it improved the representation of the underlying forcing processes producing a relatively transparent analysis for investigating changes in cohesive sediment regime. It was important to consider the balance between the accuracy of physical process representation, and the accuracy of representation of the underlying forcing mechanism, which is fundamental to the credibility of the analysis.

<u>Uncertainty relating to collation of data for analysis of changes in cohesive sediment regime</u>

- **Data requirements for parameterising cohesive sediment transport calculations** were more complex than non-cohesive sediment parameters (see Section 6.3.1). Although studies have examined the properties of cohesive sediment in the Mersey, significant issues were raised concerning the degree to which the parameters were representative of cohesive sediment throughout the estuary system, and over the period examined. Methods of measuring cohesive sediment transport processes have been the subject of recent research, which has improved estimation of sediment parameters. The parameters measured for the Mersey were recorded prior to significant advances in means of measuring cohesive sediment parameters (Dearnaley *et al.*, 1995), raising questions over their validity. Although a schematic approach was able to indicate potential trends in the estuary, uncertainty were its ability to represent features of sediment regime within the estuary, resulting from uncertainty over sediment parameters. Accurate estimation of cohesive sediment parameters is a fundamental requirement for analysis, and poorly specified parameters can significantly limit the reliability of analysis at all levels of complexity.

- The **specification of suspended sediment concentrations** was an issue of significant importance for representing the causes of morphological change (see Section 6.3.2). Suspended sediment concentrations in the Mersey estuary have been found to vary linearly with tidal range by Halliwell and O'Dell (1969). However, concentrations were also found to vary along and across the estuary, and can also vary with season. Specifying representative suspended sediment within an estuary system for the purposes of modelling sediment regime therefore presents significant difficulties. Suspended sediment concentrations employed in this study varied through the tide, and also with distance into the estuary. However, the model was unable to reproduce some basic features of sediment regime within the estuary, which may have been due to inadequate representation of local variations in suspended sediment concentrations. Erosion of intertidal areas by wave activity can generate considerable localised increases in suspended sediment concentrations.

Uncertainty relating to application of computational methods for analysis of changes in cohesive sediment regime

- Calculation of sediment transport is an inexact science and significant **gaps exist in scientific understanding of cohesive sediment transport processes**. These include uncertainty regarding the influence of organic material upon settling velocity, bed consolidation processes, fluid mud processes, erosion and re-suspension within boundary layers, and cohesive sediment transport processes on slopes. This necessarily hinders the representation of the physics of cohesive sediment transport behaviour in modelling approaches. The physics of cohesive sediment transport are essentially, a significant degree more complex than for non-cohesive sediment transport. A simple approach to representation of cohesive sediment transport was shown to exhibit considerable elements of unreliability. Even a highly complex representation of cohesive sediment transport, however, will exhibit uncertainty due to the gaps that exist in scientific knowledge of cohesive sediment processes.

- The **calibration of cohesive sediment transport studies** represented an issue of uncertainty (see Section 6.6.1). Calibration of cohesive sediment models is usually made against patterns of change in bed level. In this study dredging records in the form of reported mass removed were available for an area of the estuary around Eastham. These records were unreliable and had to be used with caution, but did provide information upon the scale of siltation that could be expected in the area. A simple representation of cohesive sediment deposition in the estuary was, however, unable to reproduce patterns indicative of sedimentation where dredging was known to have occurred. This indicated that a basic analysis, as undertaken in this study cannot resolve important features of cohesive sediment regime without improved parameterisation and representation of cohesive sediment processes.

Uncertainty relating to interpretation of analysis of changes in cohesive sediment regime

- In the absence of detailed information on the sediment properties it was possible to examine sediment transport by applying similar **assumptions regarding the nature of sediment characteristics** to those employed in study of non-cohesive sediment transport. It was important in analysis to give consideration to the effect of these assumptions upon calculations. Firstly it was assumed that sediment type was uniform, and a definitive threshold for sediment erosion and deposition could be calculated. This was unlikely to be the case as sediment within the system was found to vary significantly see Section 3.3. Secondly it was assumed that sediment characteristics have not changed over the period examined. This assumption represented a simplification as evidence existed for an increase in non-cohesive sediment in the system (see Section 6.3.1). Additional uncertainty arose in analysis of cohesive sediment, as the similar sized cohesive sediment particles could exhibit significantly different characteristics in different locations according to factors such as the consolidation of the material at the bed. In instances where consolidation occurs, the threshold shear stress for erosion is increased significantly, resulting in greater variations in erosion and deposition of cohesive sediment than for non-cohesive sediment. Assumptions regarding a uniform nature of cohesive sediment can, therefore, induce greater uncertainty than the application of the same assumption to studies of non-cohesive sediment.

- The representation of **physical process interaction with sediment transport** represented a further area of uncertainty for consideration in analysis. Cohesive sediment transport is the result of interaction with a range of physical processes. Although tidal forcing represents one of the dominant controls upon cohesive sediment, to develop a more comprehensive understanding of the sediment regime within the Mersey. Fetch-generated waves, can have a significant influence upon erosion of intertidal areas for example, generating increased concentrations of suspended sediment. Episodic events of high freshwater flow, can also influence cohesive sediment regime, as stratification effects are responsible for determining the position of the turbidity maximum. In order to support examination of these processes and reduce the uncertainty of model representations to derive a credible analysis, however, greater provision of data is required pertaining to both cohesive sediment parameters, and the magnitude and variations in physical forcing that may occur.

Implications for analysis of sediment regime in other estuaries

Estuaries exist under a range of conditions, and the physical processes influencing morphology in a particular system, may be unique to that location. Data coverage of physical processes can vary considerably between and within systems. The nature of historical morphological change may also differ considerably between and within systems, according to the exposure to physical processes, and the history of anthropogenic interference. The selection of an appropriate approach for examination of historical changes in sediment regimes is, therefore, dependent upon the specific study requirements.

A particular limitation for most studies of historical morphological change in estuaries is the availability of historical data on sediment behaviour and forcing mechanisms. In the absence of a comprehensive field data set computational models can be employed as diagnostic tools to assist in examination of different processes. By applying computational models with assumptions to simplify data requirements for study, a coherent analysis of non-cohesive sediment transport, which was considered to have contributed predominantly to morphological change, was derived. In estuaries dominated by non-cohesive sediment transport, therefore, the approaches outlined could be applied to develop an understanding of the mechanisms responsible for long-term morphological change. Greater provision of historic data on sediment characteristics and behaviour would, however, be required to support a more detailed analysis where improved quantification of non-cohesive sediment transport was required. In comparison a simplified approach to cohesive sediment transport was less satisfactory, and further investigation would be required to derive a reliable understanding of cohesive sediment transport behaviour. Studies of estuaries dominated by cohesive sediment transport would, therefore be subject to a greater degree of uncertainty, and greater data resources would be required than those employed in this study, to derive a reliable understanding of the mechanisms for long-term morphological evolution.

7.3 Interpretation of morphological change in the Mersey estuary

Morphological change in the Mersey estuary through the period 1871-1997 was complex. The findings of Chapters 4, 5, and 6 are synthesised in the following sections to develop a consistent interpretation of the nature and causes of morphological evolution in the estuary.

7.3.1 The nature of morphological change

The Mersey estuary exhibited a largely consistent, continuous trend of accretion between 1906–1977 followed by a relatively small increase in estuary capacity, indicative of erosion, between 1977-1997. Derivation of a sediment budget accounting for the effects of dredging and reclamation activity in the estuary in Table 4.6 indicated with greater clarity morphological trends in the estuary. The annual flux of sediment into the estuary was consistently greater than 1.5Mm^3 between 1906-1977. Between 1977-1997, however, annual sediment fluxes declined dramatically to 0.2Mm^3 which could reflect an increased influence of dredging activity upon large scale morphological change, because it was one factor which appeared to correspond with the scale and trend of estuary volume change. Attributing a casual relationship between dredging activity and estuary volume, underestimates the complexity of estuary processes. It is clear for example that such a relationship did not exist for the period 1871-1906, although engineering activity was undertaken in the sea approaches during that period (Leighton, 1950) and may have caused perturbations to the functioning of the estuary system.

It appeared the estuary attained a near stable state regarding net sediment flux during the period 1977-1997, although localised erosion and accretion within the estuary may have occurred. Although the quantities of dredged material deposited within the estuary were not available for flux calculations for years prior to 1956, they were unlikely to be greater than 25% of the total volume of material dredged from within the estuary, so annual sediment fluxes into the estuary would remain significantly higher than for 1977-1997.

Analysis of estuary geometrical parameters indicated that Dronkers γ parameter, increased through the period 1906-1997 to a value significantly greater than 1, representing a potential increase in flood dominance and a reduction in the balance between flood and ebb tidal flow. Analysis of geometric parameters Vs/Vc and a/h identified by Friedrichs and Aubrey (1988) as being indicative of trends in non-linear tidal propagation also indicated an increase in flood dominance in the estuary between 1907-1977. However, the Narrows are largely inerodible and there was little adjustment of system geometry in this area. Morphological change in the estuary was concentrated in the inner estuary. Changes in tidal flow characteristics within the Narrows, represented in 2D and 3D computations of hydrodynamics, most probably resulted from changes in boundary forcing caused by bathymetric changes in Liverpool Bay distorting the progression of the shallow water tidal wave into the estuary.

7.3.2 The causes of morphological change

Calculation of net non-cohesive sediment fluxes indicated that the estuary exhibited a continuous potential to import sediment base upon calculation of fluxes, although changes in sediment transport patterns at the estuary mouth may have restricted the import of sediment into the estuary. The geological constriction of the Narrows and the existence of gravitational circulation as a mechanism for importing sediment remained relatively unaltered by anthropogenic activity and morphological change, which prevented the adaptation of the sediment regime within the estuary to achieve a new equilibrium state. The estuary instead appeared to have attained a new equilibrium state due to a restriction of sediment supplied to the estuary mouth. Feedback between hydrodynamic conditions and bathymetric configuration in Liverpool Bay controlling the supply of sediment to the estuary acted as a dominant control upon morphological change and was responsible for causing and ending accretion.

The sustained nature of morphological change between 1906-1977 suggested that perturbation and subsequent recovery associated with anthropogenic activity at the end of the nineteenth and beginning of the twentieth century had the single most important influence on the estuary over the last 100 years. Although morphological evolution in the Mersey was linked to the construction of training walls along the navigation channel, the onset of morphological change cannot be definitively attributed to training wall construction. The construction of the training walls was itself a response to changes in sediment transport patterns in Liverpool Bay that may have been related to the onset of morphological change in the Mersey estuary, since they were constructed to stabilise the position of the low water channel. Earlier anthropogenic activity represented a possible cause of morphological perturbation in Liverpool Bay prior to training wall construction, particularly dredging of the bar at the seaward end of the navigation channel in 1890 from a depth of 4m below Low Water Springs to 10m below Low Water Springs (Cashin, 1949). The probable impact of dredging in the navigation channel was to increase the ebb tidal flow over the bar resulting in gyres to the north and south of the seaward entrance to the channel (HR Wallingford, 2000). Changes in flow at the mouth of the navigation channel were associated with the formation of sandbanks, i.e. Taylors Spit and Askew Spit, at the entrance to the navigation channel, which were evident on historical charts.

Following construction of the training walls, however, it was evident that there were significant changes in sediment transport patterns in Liverpool Bay. The changes were related to the effect of the training walls constraining ebb flow from the estuary and concentrating the flow of water leaving the estuary within the trained low water channel. Ebb flow in the Rock Channel, and flow over Burbo Bank, was thus reduced and the subsidiary channels became more flood dominant as reflected in changes in sediment transport patterns presented in Chapter 6. As a result sediment accreted in these channels as demonstrated in bathymetric changes presented in Figure 4.15. The resulting expansion and increase in height of Great Burbo Bank caused sediment to overtop the training wall locally and also increased the supply of sediment to the mouth of the estuary. Density currents in the Narrows extending into a trained area of the Crosby Channel then transported material into the estuary.

7.3.3 Sediment source

The source of sediment entering the Mersey estuary represented a key issue for developing a conceptual understanding of the morphological functioning of the system. The scale of sedimentation experienced in the Mersey estuary indicated it was most probable that sediment entered the estuary system from seaward sources. Making the assumption that sediment was only transported on spring tides, approximate annual sediment fluxes into the estuary under different forcing conditions were calculated in Section 6.5, to examine relative changes in the sediment regime, and hence identify the possible of source of sediment that contributed to observed accretion within the estuary. Calculations were based upon the integration of sediment transport calculated from 3D simulation, adding computed bed and suspended load transport residual sediment fluxes across transects, and multiplied by 350 to represent the annual number of spring tides. The values were approximate as sediment transport calculations have significant error bounds; Soulsby (1997) suggested, for example, that in complicated marine environments, the best methods of calculating non-cohesive sediment transport rates may not be able to achieve much better than an accuracy of a factor of 5 in 70% of cases.

The values calculated for annual flux of sediment eastwards across Liverpool Bay in a landward direction under tidal forcing alone did not correlate with the annual sediment flux required to account for the observed morphological change derived from the sediment budget in Table 4.6. The results indicated bed and suspended load transport of non-cohesive sediment under tidal forcing alone could not account for the quantity of sediment transported into the estuary. Examination of wave effects, however, indicated hydrodynamic conditions altered changing the potential for sediment to be transported towards the estuary mouth in the outer areas of Liverpool Bay. Following the inclusion of a frequent wave condition to sediment transport computations, there was a clear eastward movement of sediment through Liverpool Bay across Transects A and B towards the mouth of the Mersey estuary for all bathymetric configurations. Examination of changes in the bathymetry of Liverpool Bay Figure 4.15 indicated significant erosion of Great Burbo Bank between 1906-1977, providing a substantial source of sediment for transportation into the estuary. Furthermore, plots of sediment transport vectors based upon hydrodynamic model results in Chapter 6 demonstrated little potential for sediment transport along the Formby coastline, indicating the most probable source of sediment causing large-scale accretion in the estuary was the west side of Liverpool Bay. The model did not represent longshore drift, however, which requires an approach simulating refraction of tidal and wave currents at the shoreline and may have been a significant sediment transport process along the Formby coast.

The effects of storm wave conditions were examined, and over a single tide, substantial increases in residual transport of sediment were calculated. In comparison with the long-term average trend of forcing under tidal and wave conditions however storm events had little impact upon sediment regime, although the movement of sediment towards the estuary mouth from outer areas of Liverpool Bay was enhanced slightly. To further develop analysis of the combined effects of wave and tidal activity upon sediment regime, increasingly detailed data would be required, to examine changes in the historic changes in the wave climate and changes in the chronology of wave occurrence relative to tidal activity. From this study, however, it was established that wave activity had a substantial influence upon the sediment regime in the outer areas of Liverpool Bay, and strongly influenced a landward movement of sediment from the west side of Liverpool Bay, making this the likely source of sediment that accreted in the estuary.

Net annual flux calculations of sediment crossing Transects C and E in Chapter 6 in the direction of the estuary, based upon integration of sediment transport calculated from 3D simulations of bed and suspended load transport across the transect multiplied by 350, were presented in Section 6.5. Under tidal forcing alone, it was evident that sediment flux varied considerably between 1906-1977. The bathymetric configuration of 1936 exhibited a significantly larger annual sediment flux than 1906 and 1977 indicating that transport of sediment upon the flood tide was significantly greater in 1936, most probably due to a reduction in ebb flow across the eastern side of Liverpool Bay as ebb tidal flow became constrained within the trained channel. By 1977 it appeared that the bathymetry of Liverpool Bay had adjusted to induce a reduction of flood tidal velocities due to the erosion of Great Burbo Bank evident in Figure 4.15, reducing flood tidal velocities. Under wave forcing conditions there was a slight increase in the quantity of sediment transported landwards, but a similar trend of a large landward flux of sediment was evident for the 1936 bathymetric configuration. In comparison with computations for Transects A and B, wave forcing was of less significance to the sediment transport regimes examined. The calculated annual landward sediment flux across Transects C and E was sufficient to account for the net annual sediment flux calculated in the sediment budget in Table 4.6 for the observed period of accretion in the estuary. The flux across Transect C was greater than across Transect E, which indicated that sediment most likely to be transported into the estuary through the gap between the training wall and the estuary mouth. A landwards flux of sediment across Transect E did, however, indicate that sediment could have been transported to the estuary mouth through the trained channel where overtopping of the west side of the training wall occurred.

Price and Kendrick (1963), suggested that the deposition of dredged material in an area of Liverpool Bay that was dominated by the landwards movement of sediment, resulting from combined tidal and wave forcing according to this study, provided a source of readily erodible sediment for transport into the estuary. Although the sediment budget for Liverpool Bay calculated in Section 4.9, indicated a relative balance between the quantities of material dredged and deposited, an important issue for consideration in studying morphological change is the location of dredged material deposition. The deposition of sediment at Site 53 was not capable of causing morphological change, but was a contributing factor that was dependent upon the specific set of physical process condition that existed. Although the deposition of dredged material at Site 53 was discontinued following the study of Price and Kendrick (1963), the changes in sediment fluxes across Transects C and E in this study indicated that the material would not have been transported into the estuary under the conditions demonstrated for the 1977 bathymetric configuration. Furthermore a significant influx of sediment into Liverpool Bay from offshore between 1904-1955 (see Section 4.9) indicated that a supply of material for transportation into the estuary was readily available in Liverpool Bay, and that the deposition of dredged material at Site 53 only enhanced this trend.

The most probable mechanism for sediment import into the estuary itself was via the salinity induced gravitational circulation in the Narrows. Potential annual sediment flux at the estuary mouth, calculated from 3D results, indicated a potential net annual flux of sediment into the estuary for 1906 and 1936, in contrast with seaward fluxes of sediment calculated from 2D results. It was evident from the sediment fluxes calculated across the mouth of the estuary, howver, that potential fluxes of sediment into the estuary mouth varied over time. This phenomenon was probably the result of localised changes in patterns of sediment regime. Examination of fluxes further landwards in the Narrows exhibited landwards transport of for each of the bathymetric configurations examined (see Table 6.16), although the sediment fluxes were reduced in 1977. Changes in tidal propagation in the estuary were unlikely to account for the estuary attaining a hypothesised state of quasi-equilibrium, but localised changes in circulation patterns at the estuary mouth may have exerted a significant influence. The values calculated for the annual residual flux of sediment through the estuary mouth under tidal forcing in the 3D hydrodynamic simulation were significantly lower than the annual sediment flux derived from the sediment budget in Table 4.6. It was possible that seaward transport of sediment through the estuary mouth in 1936 was negligible, as residual fluxes across Transects C and E were landwards preventing sediment from leaving the area adjacent to the estuary mouth. However, even employing the assumption that sediment was transported landwards only through the estuary mouth, with no seaward transport contributing to net fluxes, the flux of sediment landwards through the estuary mouth was only $0.48Mm^3$ in 1936. Several reasons for an possible underestimation of non-cohesive sediment fluxes through the estuary mouth were discussed in Section 6.5.

7.4 Limitations to the approach used in this thesis

Several limitations were evident in the analyses undertaken in this study. Although use has been made of available data resources to develop a valid understanding of the causes of long-term morphological change, several issues require consideration. The limitations of this study may be divided into several categories including; the quality of bathymetric data, the accuracy of model parameters, the validation of long-term changes in forcing factors, the representation of a contiguous morphological unit and the effects of processes beyond the scope of this study.

The fundamental data employed in this study comprised bathymetric surveys. However, the data was not recorded specifically for monitoring and analysing morphological change. Rather it was recorded primarily for navigational purposes, and may be skewed towards measuring the shallowest depths. Furthermore, data coverage of the Mersey estuary and Liverpool Bay does not coincide precisely and there is no information on short-term bathymetric fluctuations. Nevertheless, the data set represented one of the most suitable available for long-term study, and was invaluable for analysis as bathymetric changes cannot be accurately hindcast.

Modelling representation of forcing processes and sediment transport was dependent to a significant extent upon available data. The availability of data, particularly for sediment transport restricted the calibration and validation of the model. Hydrodynamic calibration also exhibited limitations for a larger model domain extending seawards. However, it was demonstrated that a compromise was required upon the accuracy of calibration in order to improve representation of historic changes in flow properties. The validity of computations was enhanced by ensuring the underlying forces were representative of historic changes in the estuary although the precision of sediment transport calculations was reduced.

A distinction can be made between data employed in model calibration for calibrating model performance covering a single measurement period and data that from a continuous programme informing on long term changes in forcing. One of the most significant limitations of this study was the lack of available data covering long-term changes in model parameters and forcing processes. Data on changes in tidal flow conditions, wave climate, storminess and sediment characteristics would enable a more detailed analysis to be undertaken. In some instances it may be possible to hindcast some of these changes, for example by employing model simulations of wave climates based upon long-term wind records. Analysis of data such as tidal records may be undertaken to inform on changes in tidal flow conditions. Data from field studies may also be employed to inform on long-term changes in the estuary, such as sediment core analysis providing information on long-term changes in sediment parameters.

The spatial domain influencing the behaviour of the Mersey estuary has not been definitively identified in this study. The modelled area was extended to examine a broader seaward area, which was shown to influence the behaviour of the estuary significantly. However, there is no certainty that the area affecting morphological change in the Mersey has been comprehensively represented. The possibility exists that the study area interacts with a broader coastal environment than represented in this study, for example on the scale of a littoral cell comprising interaction with the Dee and Ribble estuaries, which have also experienced significant morphological change. A more complex modelling approach and significant data resources would be required to examine this possibility.

The morphological behaviour of the estuary system is more complex than the representation undertaken in this study. Although the schematisation may have been appropriate for examining certain aspects of the system, natural sediments rarely consist of exclusively cohesive or non-cohesive material. Natural aquatic sediments are likely to consist of a mixture of mud/sand/gravel in varying proportion and with a specific 3D structure (Soulsby, 1997). In consequence sediment properties result from a combination of physical, chemical and environmental conditions. The approach applied in this study employed well-established sediment transport formulae based on the treatment of sediment as sand or mud. However, a more comprehensive study would require the application of more complex methods to represent the behaviour of non-homogenous sediment. To facilitate a more detailed approach, comprehensive information on the properties of sediment in the study area would be required, which were not available to support such analysis in this study.

The action of wave processes upon sediment transport is complex, and has not been fully explored. For the purposes of this study wave processes were simplified as "typical" wave conditions; representing the most frequent wave and a storm wave condition. To develop a more detailed understanding of the potential influence of waves upon sediment transport patterns requires examination of comprehensive representative wave conditions. However, no wave or short-term bathymetric data was available to justify this approach.

Furthermore, wave processes influence sediment transport through radiative stresses induced by wave action in areas of wave breaking and wind stresses, and internally fetch-limited waves generated within the estuary. It was not possible to examine the effects of radiation stress forces or global wind stresses as no information was available. This is not a serious limitation for the Liverpool Bay area because both the wave breaking force and the wind stress are acting in the general onshore direction. Under these circumstances the main response would be increase of onshore mean water levels, which would tend to oppose and effectively cancel the imposed wind and wave forces without generating any significant longshore currents. It would be misleading under these circumstances to include wind and wave breaking as overall driving forces in the model since analogous mean water level changes outside the model could not be represented leading to appreciable water level differences near the model open boundaries with the erroneous generation of longshore currents. Wave fetch calculations within the estuary may have had a significant effect upon sediment transport regime, due to the effects of feedback processes. Accretion in the estuary causes feedback by reducing the wave fetch, resulting in reduced wave energy leading to further accretion. The inverse processes occur where erosion is prevalent. The direction of the maximum fetch length is of significant importance to determining the influence of internally generated waves upon sediment transport within the estuary.

Other factors may also have contributed to net patterns of sediment transport, including littoral drift processes along coastlines, freshwater flow and ecological effects. These processes are likely to be an order of magnitude less important to sediment transport in the study area than tidal and wave stirring and tidal processes, which formed the focus for investigation. Given the strong currents in the area, it is probable physical estuary processes exerted the dominant influence upon morphology.

7.5 Implications for estuary management decision-making

Several points may be made regarding the implications of this research for decision-making in the Mersey and other estuarine environments. Firstly it is evident that several anthropogenic impacts may be superimposed upon a system. One impact may dominate the morphological behaviour of the system and take precedence, as the accretion of sediment in the estuary due to changes in hydrodynamic flow regime in Liverpool Bay has for the Mersey estuary between 1906-1977. When the impact declines, however, other anthropogenic activity may assume a position of greater importance in terms of net morphological behaviour of the estuary system. The increased influence of dredging activity upon volume change between 1977-1997 may mean dredging policy needs to be reviewed, although it is probable that dredging is being undertaken in response to localised morphological impacts.

Secondly the time-scale of morphological response to perturbation can have significant implications for decision-making. The secondary effects of training wall construction and dredging in Liverpool Bay have been shown to affect the morphological behaviour of the Mersey estuary for a period of approximately 70 years. Residual impacts may last significantly longer than the direct impact of activities, and the response to perturbation is complex. When assessing the implications of plans careful consideration of the potential impact of anthropogenic activity upon factors forcing estuary morphology must be undertaken. A simple exponential response to perturbation cannot be assumed, as O'Connor (1987) overestimated the duration of response to perturbation of 250 years for the Mersey estuary.

O'Connor (1987) does not specify a mechanism for estuary response to perturbation, but recovery appears to be based upon the assumption that the estuary has adjusted its form in a manner that induces negative feedback. The implications of this thesis are that the interaction of the estuary with a broader morphological unit is fundamental to both perturbation and subsequent recovery. It is important to understand the underlying processes forcing morphological evolution over a spatial area broader than the estuarine environment itself. To predict future morphological change it may be necessary to include the complexity of morphological process interaction evident in this study. However, the Mersey exists in a set of physical conditions that may cause its morphological behaviour to differ substantially from other estuaries. For example the Mersey experiences a high tidal flow regime, has a geological constriction and has been subjected to substantial anthropogenic activity. Thus it may be more suitable to study estuaries on an individual basis to understand the specific complexity of morphological processes relevant to long-term evolution.

7.6 Chapter summary

Historic data and computational methods have been applied to examine the nature and cause of long-term morphological change in the Mersey estuary. However, estuaries are complex environments with a range of interacting forces occurring over varying temporal and spatial scales. Considerable uncertainty exists regarding the behaviour of estuary processes with incomplete or incompatible data coverage presenting analysis difficulties. Defining the precise impact of specific events and activities upon the estuarine system, which are superimposed upon the natural regime of the estuary represented a complex task. This chapter has evaluated points of interest arising from the study, and it is clear that significant uncertainty was inherent in the various stages of analysis. Due to the considerable uncertainty involved in studying physical process change in estuaries the significance of changes in physical process characteristics was assessed by comparing relative changes over time. Accurate representation of sediment transport processes is the ultimate goal of analysing estuary systems, but this was not possible in this study given the data resources available. Instead a schematic representation reproducing key trends was established employing existing understanding of system and available data for validation. The limits of the study were imposed by available data and the requirement for data for the purposes of analysing long-term change was demonstrated.

Bathymetric data formed a fundamental requirement for analysis and represented the minimum routinely collected data requirement for analysing morphological change. Modern interpolation and gridding methods mean that differences between the resolution and distribution of bathymetric measurements for different eras have little discernible effect upon calculated changes in geometric parameters. Of greater importance was the spatial extent of measurements. Bathymetric data was of greatest value where it covered the intertidal area of the estuary, which has been shown to exhibit greater changes than the subtidal area. Bathymetric surveying of the area seaward of the estuary significantly augmented bathymetric data covering the estuary by enabling examination of the interaction of the estuary with the seaward environment. The data available for the Mersey estuary comprised comprehensive spatial and temporal coverage of the estuary and other estuaries may not have such comprehensive coverage requiring assumptions to be made concerning changes in estuary form base upon anecdotal information which assumes greater importance. The value of geometrical parameters calculated from bathymetric data was be considerably enhanced by additional data to derive a sediment budget enabling morphological change to be analysed with greater clarity and assessment of the relative contribution of natural and anthropogenic factors to evolution.

Computational methods were applied to bathymetric representations of estuary geometry to examine changes in physical processes. Requirements for physical process data were therefore reduced and became inextricably linked to the needs of computational models. As a result it was not necessary to collate routinely collected physical process data relating to each bathymetric configuration. Although data on changes in boundary conditions would have reduced uncertainty in modelling simulations, data corresponding to a single bathymetric configuration proved sufficient to calibrate the model. The same calibration parameters were then applied to examine relative changes in physical process behaviour. For the purposes of examining historical evolution a transferable mesh was required to examine different bathymetries, to achieve this it is necessary to sacrifice some resolution reducing the accuracy of simulation. The approach adopted demonstrated several advantages of computational models over physical models employed in previous studies of long-term change in the Mersey estuary, particularly the scaling of sediment, and a more flexible representation of the estuary allowing a greater range of scenarios to be examined. However, the analysis undertaken was not comprehensive with significant scope remaining to improve analysis, principally through greater data recording and analysis, improved representation of sediment processes, and examination of other processes relevant to morphological change.

CHAPTER 8 CONCLUSIONS

8.1 Introduction

A comprehensive analysis of historic data and computational methods has been undertaken in an attempt to examine the nature and causes of long-term morphological change in the Mersey estuary. The study evaluated the application of available data and computational methods to provide an understanding of the long term functioning of an estuary system. Data and modelling requirements for representing factors forcing evolution have been identified, and implications for the development of tools to predict long-term morphological change in estuarine environments assessed. Analysis of morphological change over a historical timescale presented specific difficulties due to:

- Scarcity and uncertainty of environmental data
- Unknown margins of error associated with analysis techniques
- Ambiguity in assessment of impacts for informing decision makers

This thesis focused upon evaluating the outcomes of research within a structured, coherent framework to assess the reliability of findings and analysis techniques for representing the causes of long-term change. As such, the research serves to identify areas of uncertainty associated with particular techniques.

8.2 Conclusions relating to research aims and objectives

This research has been conducted without an overall hypothesis for evaluation, an approach adopted for several reasons. Firstly, the use of a limited number of hypotheses, with the necessary rejection or acceptance implied, would detract from the diversity of findings and insights identified. Secondly, given the inductive nature of the research, the use of hypotheses places artificial restraints upon the exploratory development of the research. Thirdly, the testing of one or more hypotheses would not add significantly to the validity of the approach or the scientific strength of the findings.

In place of a set of hypotheses for evaluation, a series of research aims and objectives was specified in Chapter 1 to guide the direction and structure of the thesis. These conclusions are employed as a framework for discussing the conclusions to the research.

8.2.1 Conclusions relating to the principal research aim

- **To assess the use of historic data and computational method requirements for investigation of the behaviour of long-term physical processes in estuaries.**

It has been established that there is a need to understand morphological change in estuaries, and that scientific understanding and tools based upon this understanding are available to assist this. A body of literature has been identified dealing with issues relevant to analysing long-term changes in estuary morphology. However, the research area is at present in its infancy and only limited information on quantifying or predicting morphological change is available. Although knowledge of individual processes may be well developed, the interaction of these processes over varying spatial and temporal scales, and the means of representing this is not well developed. A number of issues pertinent to practical application of historic data and computational method requirements have been identified and addressed in this study, including:

- The interaction of processes that influence morphology and appropriate means of representing them.
- The difficulties and uncertainties that arise in practical applications with regard to specifying the boundary or forcing conditions of the physical processes.
- The likely accuracy of simulations that can be achieved with site-specific calibration.
- The most effective means of operating models to account for the inevitable uncertainties and inaccuracies in an efficient manner.

The principal conclusion drawn from the study is that historical data and computational methods are useful tools for developing an understanding of the long-term evolution of an estuarine system and a context for its present morphological state, provided that they are utilised with care. A thorough insight into the physical background of the constituent models and their interactions is required. The application of computational methods also requires a structured approach to software application and data transfer, and is not suitable for incidental use. Despite the utility of the approach adopted in this study more research and development is required on morphodynamic models, which present distinct limitations and complexities, particularly regarding their theoretical basis, interpretation, and extrapolation to long-term behaviour.

The findings demonstrate the complexity of estuarine systems, and the importance of representing physical parameters relevant to the physical setting of the estuary, which can vary significantly between and within estuary systems. Key management issues and pressures within estuaries are hugely varied and may cover a range of spatial scales within an estuary system. However, it has been demonstrated in this study that there is a strong interrelationship between different aspects of the estuary system. An estuary-wide approach is proposed as an important component of the decision-making processes, although determining the extent of a contiguous area of interaction is a complex task. In the context of the Mersey estuary, interaction with Liverpool Bay was of fundamental importance to morphological change, although it is not clear that the area examined constituted a quasi-autonomous area, as a significant quantity of sediment also accreted in Liverpool Bay. The sediment may have been derived from littoral sources, but is more probably accounted for by a marine supply due to the scale of sediment movement. A larger littoral cell between natural sediment boundaries at the headland of the Great Orme and the northern end of the Wyre peninsula (Motyka and Brampton, 1993) represents a suitable unit for investigation, and provides a basis for examining the interaction of morphological change in the Mersey in conjunction with the evolution of the Ribble and Dee estuaries.

As a basis for examining historical morphological change, data collection has been a pre-requisite. Of primary importance was data on changes in estuary form, as there are no means at present of accurately hindcasting changes in estuary form over a timescale of approximately 100 years using proxy sources. Data covering changes in estuary form was only available for a historic period in the form of hydrographic survey measurements, although new techniques are being introduced for measuring changes in estuary form that may prove of use to future studies. Technological developments which may prove beneficial include remote sensing using Lidar, which has been employed in hydrodynamic modelling by Thomas and Chesher (submitted), and Synthetic Aperture Radar (SAR) satellite images which have been applied to hydrodynamic modelling by Mason and Garg (2001). The ability to measure satisfactorily changes in estuary form was central to scientific explanation of the nature and causes of changes in estuary morphology. In the case of the Mersey estuary uncertainty in analysis of changes in estuary morphology resulting from data errors and bias and analysis technique, was shown to be of limited significance to the identified trends in estuary volume calculations.

To examine the interaction of short-term observations of physical process behaviour with changes in estuary form, computational modelling techniques were employed. In an assessment of the requirements of data sets for developing and verifying models Lane *et al.* (2000) specify a number of criteria for a 'comprehensive' data set:

- Completeness, requiring overlapping in range of parameters and duration of spatial extent.
- Consistency, inferring compatibility in accuracy and in both spatial and temporal resolution.
- Adequacy of documentation, indicating suitability, usability including details of information on how the data was obtained and error bounds.
- Accessibility, ensuring data is available in a form suitable for application to modelling studies.

These requirements are suggested as guidelines for the planning of observational experiments and data recording. The guidelines are valid for the application of historic data to modelling tools, but specific difficulties are encountered when investigating historic evolution because use has to be made of an existing data resource with little potential for hindcasting changes in physical process parameters relevant to morphological change. As a result studies must be conducted within a framework that enables elucidation of the main features of changes in physical processes relevant to morphological change, i.e. the approach must be transferable between bathymetric configurations. In this study assumptions were made that calibration parameters were appropriate for previous bathymetric configurations. For a more detailed study it would be beneficial to include information on changes in physical process parameters, which may be obtained from techniques, such as investigation of sediment cores, to examine changes in sediment characteristics.

Modelling simulation of physical processes was undertaken within a composite structure; a sub-model for hydrodynamics providing results for subsequent modelling of sediment transport processes. A major requirement for modelling efforts was the identification and reduction of uncertainty at each stage of analysis. Four main areas of uncertainty existed in each analysis of hydrodynamic and sediment transport processes undertaken. Firstly, two areas of uncertainty associated with model inputs were identified:

i. Model assumptions

ii. Interaction of physical process events

Secondly, two areas of uncertainty associated with model outputs were identified:

i. Comparison of results
ii. Interpretation of results

Overall in the case of the Mersey estuary it was demonstrated that it was necessary to examine the interaction of the estuary with Liverpool Bay using a 3D model to provide the most satisfactory representation of changes in historical physical processes responsible for morphological change. In addition it was clear that wave activity exerted a significant influence upon sediment transport.

As the complexity of the model simulation increased it was increasingly constrained to a set of conditions relevant to the Mersey estuary and Liverpool Bay. In consequence the validity of the model simulation for application as a generic model to other estuarine situations decreased, i.e. the transportability of the modelling approach was reduced. From the analysis conducted in this study a complex approach was required to represent historical changes in morphology that occurred within a physical environment defined by a unique set of conditions. Although estuaries are in essence the same, in detail they exhibit significant differences in terms of their hydrodynamic and sediment regimes, which can have a significant effect upon morphological evolution. For studies of other estuaries a different set of conditions will exist and a different modelling approach may be valid to develop a conceptual understanding of the nature and causes of morphological change.

8.2.2 Conclusions relating to detailed research aim 1

- **To examine the validity of a theoretical morphological equilibrium state and investigate the principal physical processes governing estuary behaviour.**

A theoretical morphological equilibrium concept infers that estuaries exist in a state of quasi-equilibrium over a timescale greater than that of short-term process behaviour where an approximate balance may exist between the net flux of sediment into and out of the system. Perturbations, whether anthropogenically or naturally induced, may cause the estuary to deviate from this state, with the response of the estuary being to seek a new quasi-equilibrium state.

The Mersey is clearly a complex system with an extensive history of anthropogenic interference, and an initial difficulty with examining changes in morphodynamic stability centres around defining the state of the estuary at the beginning of the period investigated.

Although the derivation of a sediment budget indicated that the net flux of sediment through the estuary mouth between 1871-1906 was significantly smaller than between 1906-1936, analysis of volume change between 1871-1906 by Price and Kendrick (1963) demonstrated that the volume of the estuary exhibited significant fluctuations. The error bounds for surveys from this period may be significant, but given that the surveys were conducted in the same manner it is probable that the trends identified were representative of changes in the estuary. Moreover, the estuary was subject to significant engineering work prior to training wall construction, particularly the construction of the Manchester Ship Canal which removed a significant amount of the shoreline at the end of the nineteenth century. In addition extensive engineering work such as the canalisation of the estuary banks had been undertaken in the nineteenth century, and the residual impacts of this work may have continued to exist within the estuarine system.

Despite limitations of defining the initial state of the estuary prior to training wall construction, it was clear from the analysis conducted that the estuary has experienced a sustained trend of accretion between 1906-1977. Derivation of a sediment budget of the estuary substantially enhanced interpretation of bathymetric data indicating that the estuary attained a state of stability between 1977-1997 in terms of a net sediment flux through the estuary mouth of approximately zero. Although Table 4.6 actually shows a small net seaward flux from the estuary, this cannot be definitive due to the uncertainty regarding to the dredging figures, and the results from analyses undertaken in Chapters 5 and 6 demonstrated that it is more probable that the net flux of sediment through the Narrows became approximately zero. The evidence analysed indicates that the estuary has undergone a period of morphological change followed by the establishment of a relatively stable state. However, estuary volume increased between 1977-1997 as a result of dredging activity within the estuary, which is indicative of localised erosion and accretion, so the estuary cannot be regarded as completely stable.

Spatially, the extent of morphological change has not been consistent throughout the estuary system. The adjustment in system geometry has been greatest in the inner estuary, which has adjusted more readily to changes in forcing processes. The Narrows in contrast have altered little throughout the period examined due to their inerodible nature, and the fact that this area represents a geological constriction with high flow velocities and significant potential for scour restricting sediment deposition. The conditions and behaviour of the Mersey may well vary from the behaviour of other estuaries that do not have a geological constriction and can adapt their bathymetry more readily to respond to perturbations. However, the mechanisms of morphological change may be relevant.

The causes of morphological change in an estuary are an issue of considerable interest, and particularly the conditions that lead to the establishment of a quasi-equilibrium state. The evolution of estuary morphology over periods of approximately 100 years results from changes in sediment transport patterns determined by forcing factors operating at a range of temporal and spatial scales. Several studies (Fitzgerald *et al.*, 1976; Friedrichs and Aubrey, 1994; Dronkers, 1998) have shown that morphodynamic stability may be attained by a change in physical processes, particularly tidal propagation, in response to perturbation such that the average ebb and flood sediment fluxes become unbalanced and restore an equilibrium state. Thus a pattern of negative feedback may be experienced within the system maintaining a balance, and preventing self-destructive change from occurring. However, interaction between the estuary and the seaward environment also influences morphology. In a situation where the marine supply of sediment is limited, an estuary may exist in a theoretical equilibrium state where tidal propagation is such that the estuary has the potential to import or export sediment, if it were available, but ebb and flood sediment fluxes are both very small.

In the case of the Mersey estuary changes in geometric parameters devised by Dronkers (1998) and Friedrichs and Aubrey (1988) covering the estuary as a whole were not reconcilable with a morphological response to perturbation. The results of analysis did not support the theory that estuaries respond to perturbation by altering geometric parameters to adjust non-linear tidal processes in order to attain a stable state. Analysis of hydrodynamic model results did, however, indicate that changes in tidal flow through the Narrows may have contributed to a reduction in sediment transported into the estuary. However, sediment transported into the estuary has been dominated by the influence of the Narrows. Although changes in circulation patterns were identified at the mouth of the estuary, residual fluxes further landwards within the Narrows exhibited a continuous potential to import sediment, both as cohesive and non-cohesive sediment. Changes in tidal flow velocities do not appear to have been the dominant cause of morphological change in the estuary, and probably represent a response rather than a controlling mechanism. The adjustment of estuarine system geometry has therefore not been a dominant control upon net morphological behaviour.

The interaction of the estuary with the broader seaward environment, as demonstrated in the interaction of the Mersey estuary with Liverpool Bay in this study, may exert a significant control upon morphological behaviour in other estuaries where identifiable mechanisms exist for transporting sediment into the estuary. Changes in movement of sediment across Liverpool Bay in response to changes in hydrodynamic regime were found to be the principal cause and controlling influence upon accretion in the Mersey estuary, indicating that sediment supply to the estuary mouth is an important component of study. The effects of training wall construction and dredging of the Crosby Channel were to increase ebb tidal flow through the Crosby Channel and reduce ebb tidal flow over the Great Burbo Bank. As a result flood tidal flow over Great Burbo Bank became increasingly dominant enhancing the movement of non-cohesive sediment towards the estuary mouth. Stability was attained as a result of bathymetric adjustment in Liverpool Bay changing hydrodynamic flow patterns and reducing the dominance of flood tide non-cohesive sediment transport over Great Burbo Bank, thus reducing the supply of sediment to the estuary mouth. In 1906 it is proposed that the estuary existed in a supply-limited state, where morphological evolution was restricted due to lack of sediment supply to the estuary. The driving force for the observed accretion in the Mersey estuary is changes in sediment transport pathways in Liverpool Bay, outside of the estuary itself. The study highlights the significance of estuary interaction with offshore areas particularly in terms of sediment exchange, as well as relations between estuary hydrodynamics and system geometry as factors controlling morphological evolution. Differences between 2D and 3D results also demonstrate the importance of salinity-induced gravitational circulation in an area of relatively weak salinity stratification.

8.2.3 Conclusions relating to detailed research aim 2

- **To examine whether schematising estuary process behaviour in computational models to represent differing levels of physical reality can have a significant effect upon the interpretation of causes of long-term morphological change.**
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A key element in the analysis and prediction of long-tem morphological change in estuaries is the reduction of inputs, models, outputs and measured data (de Vriend *et al.*, 1993). In some cases this may be an imposed need for schematising representation of the system, for example due to a lack of information on a particular parameter. Alternatively it may be due to a desire to reduce the complexity of the simulation to examine a specific feature of estuary behaviour. Whatever the reasons for schematising representation of an estuary system there are several areas in which it may justifiably be undertaken:

- Specification of spatial area of interest
- Model input parameters and boundary conditions
- Representation of forcing factors i.e. tidal and wave processes
- Sediment transport mechanics

It is imperative that the effects of these different means of schematising estuary behaviour are carefully considered and investigated in order to achieve an adequate representation of the system under investigation

An integral component of investigation is the formulation of an objective of the study; an analysis strategy may then be devised based upon consideration of the available data and specification of the elements of physical processes that may be considered important. The objective of this study was to represent historical changes in sediment transport processes for different bathymetric configurations and hence develop understanding of the interaction of physical processes within a contiguous morphological unit. To attain this objective the investigation adopted a practical approach by representing short-term sediment transport descriptions for different tidal flow and wave conditions.

The specification of a model domain is a task undertaken at the scoping stage of study and in this study was found to have a potentially significant effect upon the choice of simulation approach and interpretation of causes of morphological change. Analysis of changes in sediment transport processes outside the estuary in Liverpool Bay was of fundamental importance to developing understanding of the causes of morphological change. Representation of an extensive model domain was significantly more informative, but considerably increased the computational requirements. In order that computational requirements do not become excessive, the spatial resolution of the simulation is frequently increased as the model domain is increased. In many instances, however, data from areas beyond the estuary mouth may not be available to support the representation of more extensive model domains. In practice the modelling simulation represents a compromise, which needs to make the most appropriate use of available data; more extensive models can increase understanding of the behaviour of the estuary system, provided they are undertaken at a resolution that provides sufficient detail of physical process characteristics in areas of interest.

The formulation of a consistent set of model input conditions appropriate for representing relative changes in historic forcing has proved a complex task. Tidal and wave boundary conditions create problems of instabilities and disturbances originating from lateral boundaries. Consistency problems can be overcome by specifying a boundary of uniform water levels such as the mouth of the estuary, by moving the boundary away from the area of interest, and by employing regional and local area models. In this thesis it was demonstrated that the shallow water effects of the bathymetry of Liverpool Bay exerted a significant control upon changes in tidal propagation through the Mersey estuary. The most appropriate means of deriving a boundary condition involved specifying an offshore boundary where the tidal condition was derived from a larger model of the Irish Sea. The tidal cycle examined consisted of a spring tide. Likewise no evidence of changes in wave climate was available, so the utility of a representative wave condition was reduced. In the absence of knowledge of changes in wave climate a simple approach to simulating wave conditions was adopted.

A structured step-wise approach was adopted to represent estuary physical processes. The modelling of hydrodynamic processes is generally better validated and a more mature science than the modelling of sediment transport and morphological changes. However, there are inevitably errors in predicting current conditions even in the most accurate models, and these can create significant errors in subsequent calculations of sediment transport. Initial decisions concerning the degree of schematisation of physical process representation can have significant affects upon subsequent sediment transport computations. Specific difficulties were encountered with representing historic changes in tidal flow in the Mersey estuary due to limited data coverage of historical changes for calibrating and validating simulations. Employing a range of simulations to schematise physical processes according to dimensionality, and with different model domains, the effectiveness of modelling representations were analysed by comparing the representation of physical processes. Investigation of the requirements for accurately representing changes in estuary hydrodynamics demonstrated that the 2D and 3D hydrodynamic simulations of a model domain comprising the estuary and Liverpool Bay were the most reliable representation of historical changes in hydrodynamics.

The effect of schematising representations of changes in historical hydrodynamics was emphasised in the case of the Mersey, by examination of residual velocity patterns. Although a greater quantity and quality of field data is required for validating and calibrating three-dimensional representations of estuary processes, the approach was justified as it illustrated the existence of a gravitational driven residual circulation in the Narrows. 1D and 2D schematisations of physical processes were adequate for certain areas of the system; a 1D simulation of the estuary accurately represented bathymetry by employing bathymetric measurement data instead of interpolated values and accurately reproduced water levels, and a 2D simulation was adequate for areas of the estuary and Liverpool Bay where stratification effects were not significant. However, to represent the area and processes significant to morphological change a 3D representation of the estuary and Liverpool Bay was required; a 1D simulation was unable to represent the spatial area and physical processes of interest, and a 2D simulation was unable to represent important features of the physical processes. The assumptions implicit in more schematised modelling approaches such as 1D and 2D modelling simulations of estuarine hydrodynamics were appropriate for representing localised processes within the estuary, although it has been demonstrated that localised issues should be studied in a context of the broader functioning of the estuary and Liverpool Bay system.

A schematised approach to non-cohesive sediment transport problems has been shown to be very informative for examining issues of historical change in estuaries, provided it is based upon suitable physical processes. It was demonstrated in this study for example that 3D processes were fundamental to understanding the interaction of the estuary with Liverpool Bay. The differences between 2D and 3D results demonstrated the importance of salinity-induced gravitational circulation in the Narrows and provided the only identified means of transporting sediment into the estuary. A 3D representation of the flow field also improved representation of bed shear stress, which was important to calculation of sediment transport rates. In terms of accounting for the scale of morphological change, the study demonstrated that it was necessary to account for the role of sediment transport as suspended load as well as bed load and also the effects of wave activity. A schematised approach to cohesive sediment transport issues has also proved beneficial, although not as informative as for non-cohesive sediment transport. Greater parameterisation is required for representation of the behaviour of cohesive sediment, and the mechanics of cohesive sediment transport processes are more complex.

Overall schematising the representation of estuary processes has been an essential means of facilitating examination of morphological change. However, it was important that this was not undertaken at the expense of representing relevant processes. To analyse morphological change in the Mersey estuary, a combination of modelling approaches was required to examine the processes responsible. Significant benefits were realised from analysing the nature and causes of morphological change in the estuary using a combination of approaches including, analysis of bathymetric data, calculation of analytical parameters and hydrodynamic simulation, and developing a consistent interpretation of morphological evolution. Fundamental to addressing the objective of study to develop an understanding of the nature and causes of historical morphological change, was defining a spatial and temporal scale of study, and the interaction of complex physical processes determining net sediment transport processes. Models were employed as diagnostic analytical tools, placing emphasis upon critical evaluation of the ability of the model to represent the processes underlying morphological change as opposed to the precise representation of sediment transport rates. Schematising estuary processes has proved useful to examining morphological change, although it is clear that the functioning of the system is complex. Although different levels of schematisation may be appropriate to different areas of the estuary, to develop an understanding of nature and causes of change through the estuary as a whole a 3D representation covering a spatial scale extending seawards beyond the area of interest was required. However, even in the most complex representation of the estuary system undertaken, uncertainty is implicit in the methods employed. More detailed approaches can provide more information, but in practice limitations are imposed by the availability of data to support them.

8.2.4 Conclusions relating to detailed research aim 3

- **To examine whether the influence of anthropogenic activity upon morphological change in an estuary can be clearly identified and distinguished from natural estuary functioning.**

Morphological evolution in the Mersey estuary between 1906-1977 has been coincident with the construction of training walls along the navigation channel to the estuary. Following training wall construction the estuary exhibited a sustained morphological trend of accretion that has been interpreted as a response to perturbation. Estuarine response to perturbation induced by anthropogenic activity in Liverpool Bay occurred over a period of approximately 70 years. The response to perturbation was the dominant impact between 1906-1977 and was superimposed upon the effects of other anthropogenic activity such as dredging in the estuary. Although areas within the estuary have been dredged continuously between 1906-1997, dredging activity has only had a dominant impact upon the net behaviour of the system as net sediment flux into the estuary has declined. From the sediment budget it was therefore possible to distinguish between the effects of different anthropogenic activity. However, over shorter periods the impact of these activities may have differed from the long-term trends. In 1953-1954 for example, dredging at Bromborough Bar was increased significantly (McDowell and O'Connor, 1977), and as a result the volume of the estuary increased. For certain situations therefore careful consideration must be given to the time intervals at which analysis is undertaken.

It has only been possible to identify factors contributing to gross morphological change in the estuary i.e. changes in volume and more specifically sedimentation. The causes and mechanisms controlling more detailed features of morphological change in the estuary are more complex. For example, the causes of relative changes in intertidal and subtidal areas of the estuary and changes in the position of the low water channel have not been identified. Although the gross changes in estuary morphology may have been caused by anthropogenic activity, the mechanisms controlling detailed changes in estuary morphology have been determined by localised processes. To develop a more thorough understanding of the factors controlling estuary morphology there is a need to understand the interaction of anthropogenic activity with processes controlling smaller scale morphological units within the estuary system and their natural behaviour. It has not been possible in this study to distinguish between the effect of anthropogenic and natural causes of more detailed changes in the bathymetry of the estuary.

As a result of the analysis undertaken in this thesis and the work of Price and Kendrick (1963), the cause of sedimentation in the estuary through the period 1906-1977 has been related to changes in hydrodynamic flow patterns in Liverpool Bay subsequent to training wall construction. Changes in sediment transport patterns outside the estuary have been identified, which increased supply of sediment to the estuary mouth. This thesis has assessed the utility of representing short-term processes using modern computational methods, and the findings have been synthesised and interpreted in a context that builds on the study of Price and Kendrick (1963), by developing understanding of the processes relevant to morphological change. Applying computational models has enabled more accurate study of sediment transport phenomena than the use of physical models and developed a better understanding of the complex interaction of physical process variables and their effect upon changes in the sediment transport regime. As a result of this a mechanism that accounts for the scale of morphological change identified has been identified through the interaction of tidal and wave processes upon non-cohesive sediment transport.

Despite the identification of a clear morphological trend and mechanism for morphological change being identified as a consequence of training wall construction, the onset of morphological change cannot be definitively attributed to the training walls. Liverpool Bay has experienced other anthropogenic activity linked to changes in the hydrodynamic regime in Liverpool Bay. The precise impact of training wall construction cannot be differentiated from these impacts, and changes in the Mersey estuary cannot be definitively attributed to training wall construction; these changes are most probably the result of cumulative impacts of anthropogenic activity in Liverpool Bay. Morphological evolution may have been induced by earlier perturbations such as the construction of the Ship Canal, the canalisation of the estuary, or the dredging of the bar at the seaward end of the navigation channel in 1890 from a depth of 4m below Low Water Springs to 10m below Low Water Springs (Cashin, 1949). The probable impact of dredging in the navigation channel was to increase the ebb tidal flow over the bar resulting in gyres to the north and south of the seaward entrance to the channel (HR Wallingford, 2000). Changes in flow at the mouth of the navigation channel is associated with the formation of sandbanks, Taylors Spit and Askew Spit, at the entrance to the navigation channel evident on historical charts. The construction of the training walls was itself a response to changes in sediment transport patterns in Liverpool Bay, and the effects of different anthropogenic activities cannot in this instance be clearly distinguished from one another.

The scenarios examined in this thesis were concerned with investigating the effects of changes in the bathymetry of Liverpool Bay. It is probable that changes in hydrodynamic flow patterns in Liverpool Bay, ensuing from the construction of training walls, caused adjustments in the bathymetry of Liverpool Bay. Implicit in this study has been the assumption that changes in the bathymetry of Liverpool Bay were directly determined by the presence of the training walls. However, Liverpool Bay is a complex environment, and changes in bathymetry may be induced by a number of factors. For example, the bathymetry may evolve in response to changes in natural forcing factors such as changes in wave climate, or changes in storminess. Distinguishing the effects of natural and anthropogenic induced changes in this instance represents a difficult task, particularly due to the lack of long term information on changes in physical forcing factors. Furthermore, understanding of the extent of fluctuations in forcing and functioning of the morphological system under natural conditions is limited as a result of the lack of data covering a historical period where there were no anthropogenic effects, either direct or residual, upon the estuary system.

Overall it is possible to identify both a cause and a mechanism for the trend of gross morphological change in the estuary associated with the construction of a training wall in Liverpool Bay that has induced morphological change in the Mersey estuary. However, there are difficulties in distinguishing between the role of anthropogenic activity as the effects of several activities have been present within the estuary at the same time. Furthermore, there are difficulties distinguishing between the effects of natural and anthropogenic processes, which could both have contributed to changes in the bathymetry of Liverpool Bay. Particular difficulties are associated with distinguishing natural and anthropogenic induced morphological change due to a lack of data on changes in natural forcing processes and a lack of knowledge of the bounds of fluctuations in natural processes. Nevertheless, it is probable that training wall construction exerted the dominant influence upon morphological change in the estuary. Moreover, an order of impact dominance was identified for dredging in the estuary and accretion in response to changes in the bathymetry of Liverpool Bay. The effects of dredging were of secondary importance, except for a period between 1953-1954, until 1977 when they became the dominant impact, as sediment transport patterns across Liverpool Bay had altered reducing the supply of sediment to the estuary mouth.

8.3 Areas for further research

As a consequence of undertaking the research in this thesis a number of issues have arisen which were beyond the scope of investigation, but provide significant areas for developing complementary future research. These may be grouped into two related but distinct sections pertaining to: areas of research relevant to developing an understanding of historical morphological change in estuaries, and secondly to developing a more detailed understanding and means of representing the nature and causes of historical change in the Mersey estuary. A number of areas for further research on estuary morphology that are complementary to those identified in this study are set out in EMPHASYS (2000c), with this study focusing on areas of potential development that are beneficial to analysis of large-scale morphological change over historic periods.

8.3.1 Further research on morphological change in estuaries

To place this study of the Mersey in a wider context, and develop understanding of the processes and mechanisms controlling the morphological evolution of estuaries it would be beneficial to analyse morphological change in other estuaries. There would be specific value in investigating a number of issues including:

- Analysis of estuaries that exist within a different set of physical conditions to investigate whether the processes influencing sediment transport differ.
- Assessment of whether it is appropriate to represent estuary processes in a more schematised manner for different systems.
- Analysis of estuaries that have not been subject to significant anthropogenic activity to examine the extent of natural fluctuations that may occur within the morphological system.
- Analysis of estuaries without significant geological constrictions, to examine whether they are capable of inducing negative feedback in terms of tidal propagation to evolve to a state of quasi-equilibrium in response to a perturbation.
- Examination of the extent of contiguous morphological units for estuaries in terms of their interaction with nearshore, offshore and adjacent coastal areas, and examination of the effects of changes in bathymetry beyond the mouth of an estuary upon tidal distortion.

However, there are few estuaries as well documented as the Mersey in terms of historical data coverage. In the UK only a few datasets exist which fit the requirements for morphological study of providing sufficient data coverage of a period of morphological change to enable the processes responsible for morphological change to elucidate the processes responsible for morphological change, these include:

- Lune estuary 1847-1891 (Inglis and Kestner, 1958).
- Thames estuary 1830's (Inglis and Allen, 1957).
- Humber estuary, 1900's to present (ABP Research and Consultancy, 1999).
- Harwich and Felixstowe, 1900's to present (HR Wallingford, 1997c).

There is little data coverage of estuaries that have not experienced significant anthropogenic activity, as the principal reason for measuring and documenting estuaries has been to facilitate their commercial use. Furthermore, bathymetric change over a period as long as the 100-year period examined in this thesis has not been recorded in many estuaries, although the findings of this research demonstrate that anthropogenic impacts can reside in systems for this order of time. Where bathymetric data has been collected it may not be in a comparable form as was the case in this study, and may not cover the whole estuary, particularly the intertidal area. Data coverage of extensive areas seaward of estuary mouths is also rare.

A number of issues must be addressed before it is possible to examine the issues raised concerning placing the study of the Mersey estuary in a wider context, including:

- Examination of means of analysing estuaries where the data coverage of the estuary is not as comprehensive as for the Mersey. The means of obtaining an accurate representation of morphological change where bathymetric surveys have not been repeated in the same manner or comprise measurements in differing points within the estuary is a particular area for investigation.
- Examination of the influence upon morphological behaviour as a whole, and response to perturbation of morphological sub-units within an estuary system, such as intertidal areas.
- Development and investigation of new methods of measuring changes in estuary form, such as remote sensing and examination of its application to studies of morphological change.
- Improvements in measuring physical processes within estuaries, using modern equipment such as Acoustic Doppler Current Profilers (ADCP), and development of methods for manipulating the large quantities of data produced.
- Development of means of hindcasting changes in physical parameters of estuaries, which may require integration of different aspects of studying long-term changes in estuaries. Multi-disciplinary research could incorporate methods such as examination of sediment cores to examine changes in sediment parameters, seismic surveys to examine changes in estuary form, and evidence of ecological change.

In addition to these factors, research on a number of theoretical issues could prove beneficial to improving methods of examining long-term morphological change in estuaries, including:

- Reducing the computational requirements for 3D simulations of estuary processes. The development of computational tools is continuous both through improved hardware and more efficient computational algorithms. As 3D simulations become less computationally expensive their range of application increases, and the need for schematising model representation of an estuary, and input conditions is reduced.

- Improved techniques for measuring and representing the physics of mixed sediment transport i.e. a combination of cohesive and non-cohesive sediment transported under the same conditions.
- Improved techniques for measuring suspended sediment transport processes, which could be applied to improve and develop simulations of cohesive sediment transport.
- Improved parameterisation of sediment transport relations. At present significant margins of error are associated with sediment transport. Although significant research effort has been expended in this area, further improvements are still required for more precise quantification to be achieved.

Ultimately, the objective of this research area as a whole is to develop a comprehensive understanding of nature and causes of morphological change in estuaries, and to be able to represent these in a form that enables reliable prediction of future change to be achieved. One of the key requirements to facilitate this is to translate understanding of estuary systems into a conceptual understanding of their evolution over time-scales of the order of 100 years. However, at present there is clearly a considerable need for research in several areas before this stage may be reached.

8.3.2 Further research on historical morphological change in the Mersey estuary

In addition to examining issues of interest to the generic study of the long-term morphological evolution of estuaries, the research undertaken in this thesis has developed understanding relating specifically to the long-term behaviour of the Mersey estuary. To achieve this, available historic data from the Mersey estuary was employed combined with several computational methods. Developing a detailed understanding of the causes of the long-term evolution of the system was, however, complex due to the limitations of the available data, and difficulties of accurately representing and interpreting the interaction of physical processes, which vary over a range of spatial and temporal scales. A number of areas for further research can be identified to build upon the findings of this research, and improve understanding of the morphological functioning of the Mersey estuary system.

The shortcomings of available data represents the most significant limitation to developing a more detailed understanding of the long-term behaviour of the Mersey estuary. To develop a comprehensive understanding of the nature and causes of long-term morphological change in the Mersey estuary various data collection and analysis studies would be beneficial. The historic nature of several processes may be obtained from an existing data record, but have not been included in this study due the disjoint nature of the data record, or difficulties of accessing the data:

- Long-term changes in tidal propagation in the estuary have been measured at tide level gauges within the estuary, and compiled into a complete synchronised record by Woodworth (1999). Harmonic analysis of this record would provide significant information on the nature of changes in tidal characteristics within the estuary. Such analysis would provide a useful comparison with the modelling of changes in tidal propagation undertaken in this study, and demonstrate the utility or limitations of employing short-term models of hydrodynamics to indicate long-term trends in an estuary. However, harmonic analysis of a long-term tidal record is a complex task, and the tidal data was not available for analysis in this study.

Studies of certain estuary processes that are restricted by the limitations of historic data, may be overcome by examining proxy data sources, to establish the nature of changes in physical processes within the area of interest:

- Long-term changes in the wave climate in Liverpool Bay have not been studied in detail, but would be of benefit to examine the nature of long-term changes in wave forcing in Liverpool Bay. Although no data on waves in the estuary exists covering the period of time examined, long-term wind records exist for several stations around the Irish Sea. The wind records may be used as a proxy record to drive computational wave simulation models to examine changes in the wave climate in Liverpool Bay.
- Changes in freshwater flow in the Mersey estuary have not been studied in detail, and these can affect fluvial input of sediment into the estuary and gravitational circulation within the estuary. No accessible long-term record of fluvial flow in the Mersey estuary exists, although records maintained by the Centre for Ecology and Hydrology exist for the complex network of tributaries flowing into the estuary through the Weaver. This record could be studied to provide an indication of relative changes in freshwater flow in the estuary. Alternatively rainfall records are available for several stations with close proximity to the Mersey estuary, and these could be employed with computational modelling of the basin catchment to calculate relative changes in freshwater flow in the estuary.

For some issues of interest to studies of long-term morphological change, no historical data record exists, although it may be possible for contemporary studies to provide information on historic changes:

- Detailed analysis of the distribution of sediment types and characteristics within Liverpool Bay and the Mersey estuary would be beneficial to improve parameterisation of sediment characteristics in computational modelling. To develop further understanding of the historic nature of changes in sediment characteristics within the estuary, analysis of sediment cores derived from the estuarine environment could be undertaken. This approach has already been adopted by the British Geological Survey on the Humber, and data is to be compiled for the Mersey estuary under the British Geological Survey's Coastal and Estuarine Evolution Project.

In some instances, however, there is no means of examining further data on historical changes in the estuary, nevertheless further studies could provide a context for examination of the available historic data.

- Overall bathymetric data has proved to be of fundamental importance to studying long-term morphological change, providing a basis for examination of the nature and causes of evolution. There is at present no means of hindcasting changes in the bathymetry of the estuary, accentuating the value of the available bathymetric data. Although further bathymetric data of the estuary is available for analysis, the data resource covering Liverpool Bay is limited. To develop understanding of the nature of morphological change in the estuary and Liverpool Bay in the long-term, it is beneficial to continue conducting bathymetric surveys at comparable time intervals of approximately 20 years. In the short-term recording and analysis of short-term bathymetric change would be of value to verify that data examined is representative of long-term trends in the estuary.
- The data employed in calibration of computational models of physical processes within the estuary and Liverpool Bay is another area where further studies could provide a context for examination of the available historic data. Considerable variation can occur in short-term measurements employed to calibrate and validate model performance of hydrodynamic and sediment transport simulation. More detailed analysis of physical process data, over an extended period could increase the precision of physical process representation in the computational models employed in analysis.

In addition to extending understanding of the Mersey estuary system by addressing the limitations imposed by available data, the study could also be developed through improving representation of the physical processes forcing morphological evolution.

Further research to develop analysis tools as outlined in Section 8.3.1, and the development of computational tools outlined as areas for further research in EMPHASYS (2000c) could be applied to improve analysis of the Mersey estuary. Some of the key areas which could be developed from this study include:

- Examination of processes relevant to sediment transport that were not examined in this study, such as longshore drift, and the effects of changes in freshwater flow.
- Examination of non-homogenous sediment types and mixed sediments.
- The interaction of the Liverpool Bay and Mersey estuary system with a larger morphological unit, including the Dee and Ribble estuaries.
- The selection and sequencing of representative of tide and wave conditions for probabilistic approach to analysis of sediment transport.

8.4 Contribution to research on estuary morphology

This study has contributed to the research field of estuary morphology by establishing the utility of studying estuaries holistically. An approach was developed that enabled understanding of linkages between large-scale estuary form and process to be investigated over a historical period. The changes exhibited by an estuary over a long time-scale are complex, as physical components and controlling processes of an estuary encompass a range of temporal and spatial scales. Nevertheless, careful application of available historical data and computational methods produced a coherent, reliable analysis of the causes of historical morphological change in the Mersey estuary. The research findings have implications for examination of other estuaries, and applying techniques to investigate complex morphological change under different sets of physical conditions.

An estuary wide historical bathymetric data set covering a period greater than 100 years for the Mersey estuary formed the basis of the study. Data requirements and the utility of methods of computational spatial interpolation for interpreting historical change in an estuary and its morphological sub-units were established as a result of critically evaluating historic bathymetric data variability in terms of spatial resolution of surveys, method of measurement and geographical coverage. The findings of the study emphasised the benefit of sequential recording of estuary bathymetry. The study developed existing understanding of the Mersey estuary by improving the accuracy of computations of volumetric change in the estuary, and employing historic data from other sources such as dredging records to derive a sediment budget for the estuary over the period 1871-1997. The temporal extension of bathymetric data coverage of the Mersey estuary enabled its evolution to be examined over a longer timescale than previous studies, placing the behaviour of the estuary within a broader long-term context, and providing an improved perspective for analysis of the response of the estuary to an inferred perturbation event.

A major shortcoming of the data resource for studying morphological change in the Mersey estuary was the limited data coverage of changes in physical forcing factors over a historic time-scale. To address this limitation, which is common to the majority of UK estuaries, the study developed practical means of applying computational tools and methods for characterising morphological change and associated process behaviour. Computational modelling techniques combined short-term field observations with one-dimensional (1D), two-dimensional (2D) and three-dimensional (3D) spatial scale modelling techniques. Employing historic bathymetries as temporal snapshots applied to models in a diagnostic analytical capacity provided a suitable means to reproduce physical process behaviour where no historical data was available. The different dimensions in which estuary processes were resolved represented different levels of compromise in diagnostic modelling tools between reality and practicality, and the accuracy of hydrodynamic process simulation and the adequacy of tools to achieve satisfactory representation was critically assessed.

The study developed investigation of the applicability of generic hydrodynamic models to simulate relative changes for historical bathymetric configurations with an approach that was transferable between different bathymetric configurations and permitted examination of unmeasured parameters. The ability of available data and assumptions to support reliable representation of physical process behaviour was examined, and hydrodynamic results were employed as a basis for examining relative changes in sediment behaviour. Through analysing historical snapshots of estuary form and physical process behaviour using diagnostic modelling tools, the interaction of physical processes of tidal movement and wave action was examined in terms of influence on sediment transport. By applying computational models with a greater ability to resolve complex sediment transport phenomena and interactions between current and wave processes the study examined means of developing previous studies of historical change in the Mersey estuary which employed physical model simulations.

With the evolution of increasingly reliable and accurate modelling tools, greater emphasis is being placed upon their application to problem solving, which can in turn provide feedback to drive the future development of computational techniques. Several issues were explored which are relevant to generic investigation of estuaries, including means of determining the compound effects of multiple development activities in estuaries, the spatial extent of linkages that can exist between an estuary and its seaward area, the factors determining the stability or otherwise of an estuary system, and the timescales over which responses to perturbation can occur. The increased rigour of computational methods of simulating sediment transport issues enabled linkages between different physical forcing processes to be examined, and the influence upon long-term sediment regime to be quantified. As a result concepts relating to long-term estuary evolution in the Mersey developed by Price and Kendrick (1963) based upon study of two physical models to investigate causes of morphological change between 1911-1957 were developed.

Significant limitations are imposed upon studies of estuary morphology, and these are exacerbated when examining long-term evolution due to a lack of routinely collected historical data in even the best documented estuaries, and gaps in scientific understanding of the long-term morphological behaviour of estuary systems. Of fundamental importance to improving scientific understanding of long-term estuary morphology is the maintenance and extension of existing data resources covering a historical period, as this study has clearly shown the benefit of continuing and extending such data resources, particularly bathymetric data. In addition, the tools available for analysing estuarine systems have progressed significantly with the development of computational methods, which enable sediment transport problems to be addressed in greater detail, and more quantitatively, than could previously be attained using physical models. Studying the long-term evolution of estuaries to develop a conceptual understanding of an estuary system represents a significant challenge to current understanding and analysis tools and techniques. Nevertheless, provided the uncertainty resulting from by gaps in scientific understanding and data limitations are recognised, existing data and computational methods can be applied to develop understanding of an estuary system through a structured approach to analysis. Despite considerable uncertainty being inherent at several stages of analysis in this study, the application of several different strands of investigation derived a credible understanding of the long-term interaction of morphological form and function in the estuary system, and illustrated how the available observational evidence could be built upon in different ways to derive a comprehensive analysis.

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APPENDIX 1

Calibration of 1D Mersey estuary hydrodynamic flow model

APPENDIX 1 Calibration of 1D Mersey estuary hydrodynamic flow model

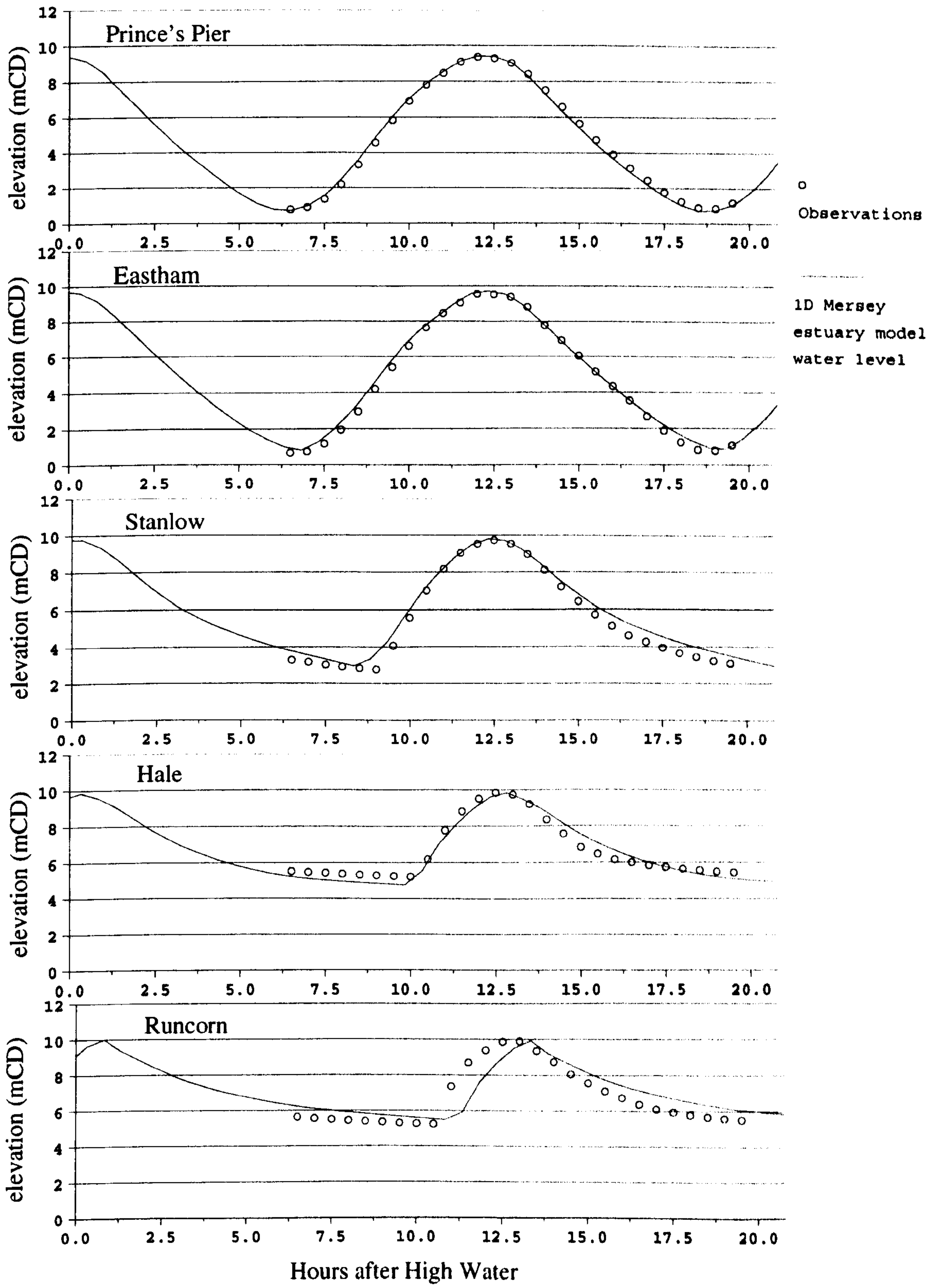

Figure A.1 Comparison of 1D simulated mean spring tidal levels with observed data (West data 1980)

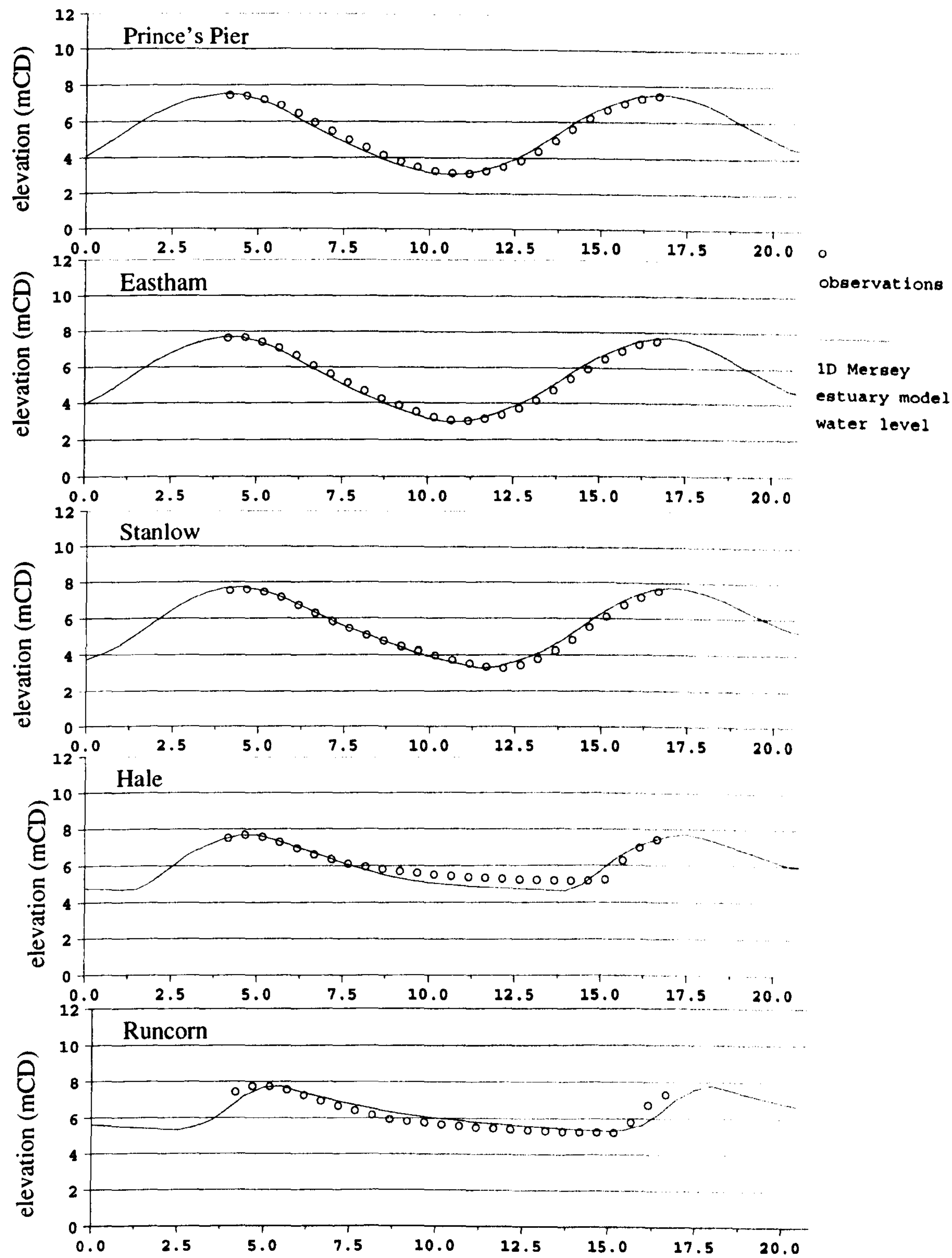

Figure A.2 Comparison of 1D simulated mean neap tidal levels with observed data (West data 1980)

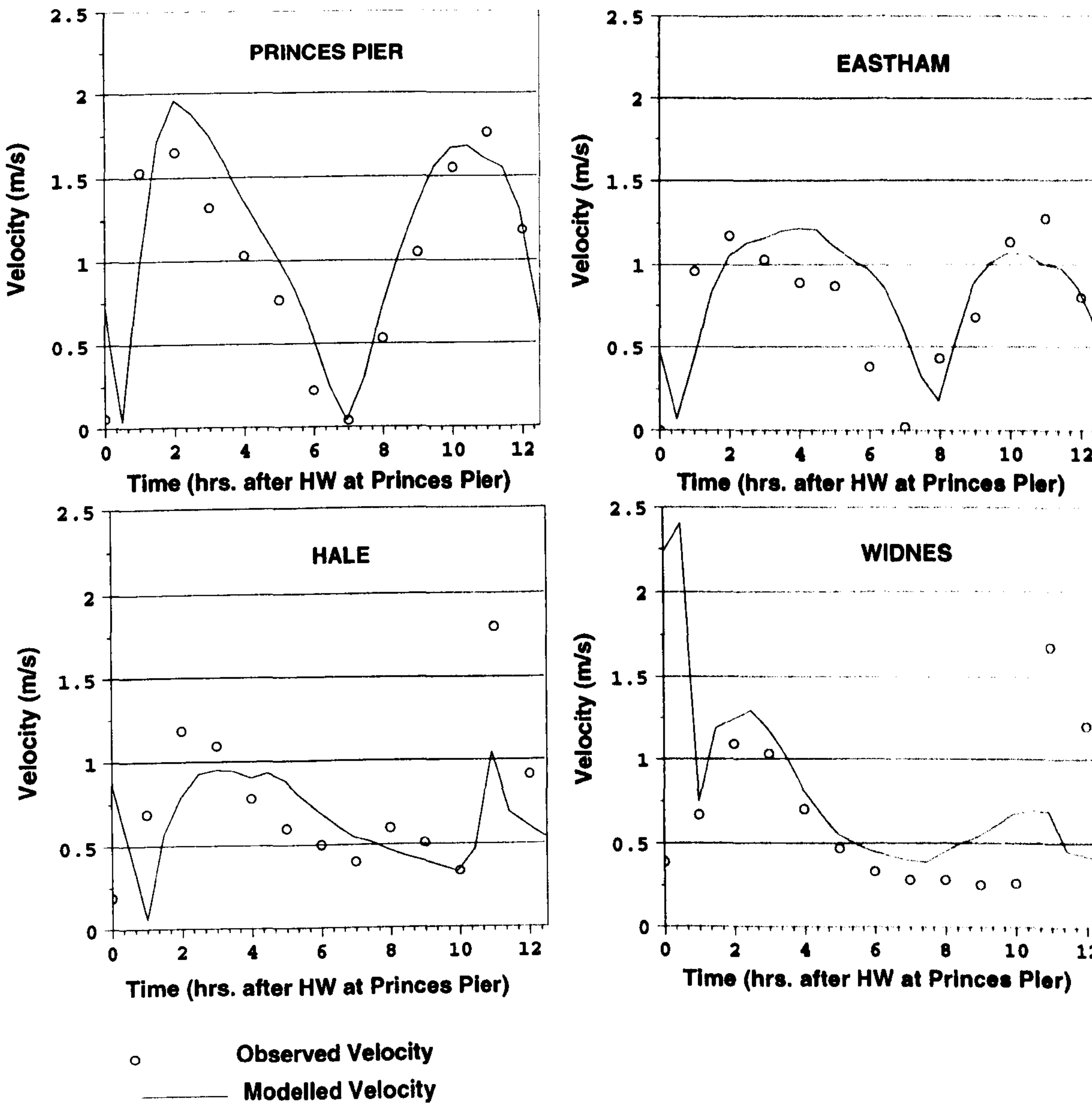

Figure A.3 Comparison of 1D simulated mean spring tidal velocities with observed data (West data 1980)

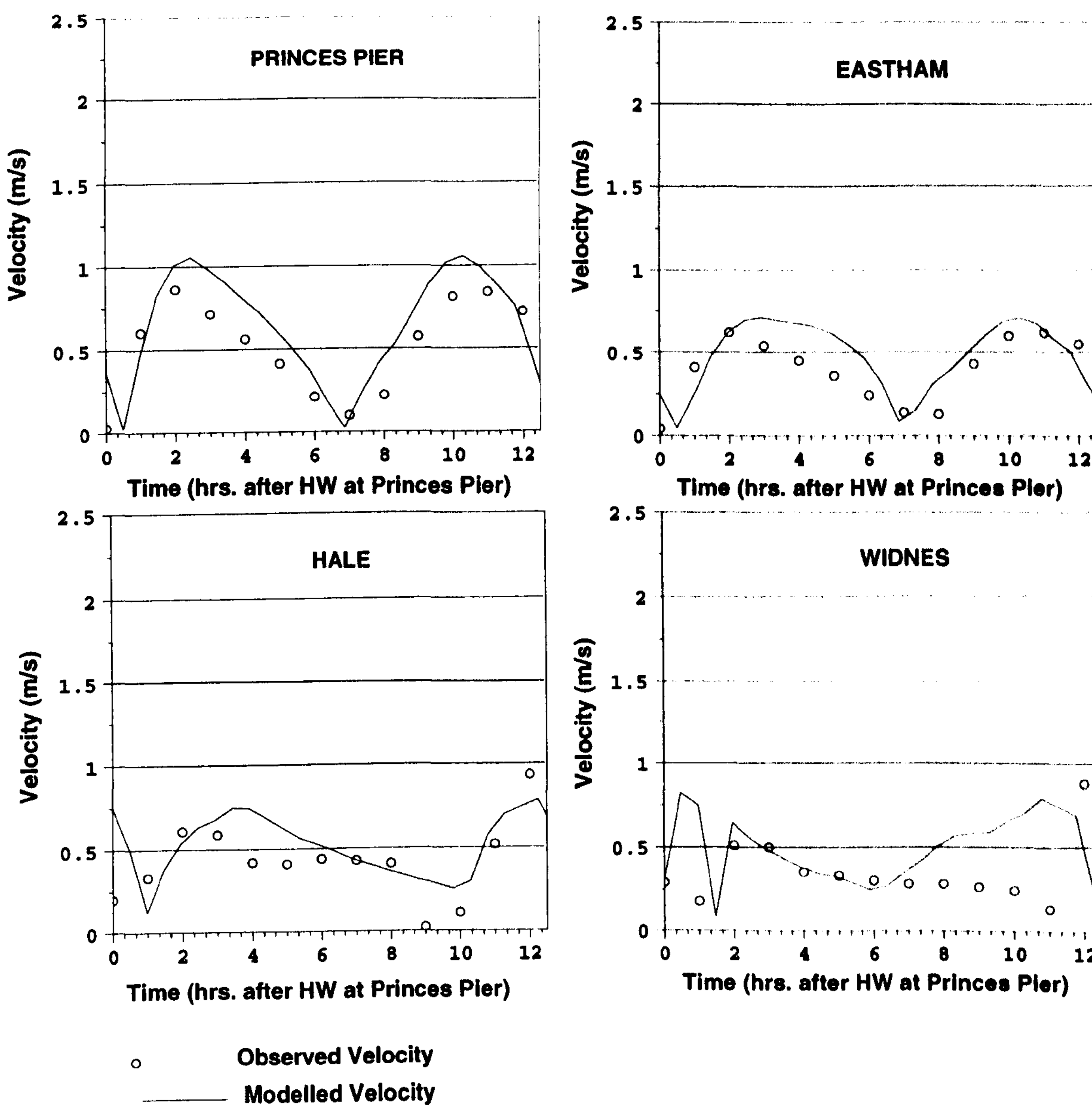

Figure A.4 Comparison of 1D simulated mean spring tidal velocities with observed data (West data 1980)

APPENDIX 2

Irish Sea harmonic constants

APPENDIX 2 Irish Sea harmonic constants

Harmonic constant	Holyhead		Belfast		Dublin		Liverpool	
	Amp (m)	Phase (°)	Amp (m)	Phase (°)	Amp (m)	Phase (°)	Amp (m)	Phase (°)
J(1)	0.007	253.9	0.008	260.9	0.008	260.9	0.01	268.4
K(1)	0.107	181	0.105	187	0.098	190	0.13	193
K(2)	0.161	330.9	0.079	355	0.11	359.5	0.275	12.7
L(2)	0.051	317	0.032	345	0.039	355	0.083	343
M(1)	0.007	107.5	0.007	112.5	0	0	0.009	117
M(2)	1.788	292	1.196	315	1.342	326	3.131	323
M(3)	0	0	0	0	0	0	0	0
M(4)	0.029	39	0.024	47	0.096	53	0.223	215
M(6)	0	0	0	0	0	0	0	0
M(8)	0	0	0	0	0	0	0	0
N(2)	0.36	267	0.226	285	0.271	297	0.58	303
2N(2)	0.048	242	0.03	255	0.036	268	0.077	283
O(1)	0.094	34	0.095	38	0.107	47	0.121	41
OO(1)	0.004	328	0.004	336	0.005	333	0.005	345
P(1)	0.035	170	0.035	175.8	0.032	179.3	0.043	181.6
Q(1)	0.026	325	0.028	5	0.029	352	0.034	358
2Q(1)	0.002	-111.8	0.002	-109.8	0.003	-94.9	0.003	-109.8
R(2)	0.005	329.4	0.002	353.5	0.003	358.2	0.008	10.8
S(1)	0	0	0	0	0	0	0	0
S(2)	0.591	328	0.29	352	0.404	357	1.011	9
S(4)	0	0	0	0	0	0	0	0
S(6)	0	0	0	0	0	0	0	0
T(2)	0.035	326.6	0.017	350.5	0.024	355.8	0.06	7.2
LAMBDA(2)	0.013	308.7	0.008	332.2	0.009	340.4	0.022	-15.7
MU(2)	0.043	256	0.029	278	0.032	295	0.075	-83
NU(2)	0.07	270.4	0.044	289	0.053	300.9	0.113	305.7
RHO(1)	0.004	-29.1	0.004	-25.9	0.004	-14.3	0.005	-24.2
MK(3)	0	0	0	0	0	0	0	0
2MK(3)	0	0	0	0	0	0	0	0
MN(4)	0.011	2	0.005	62	0.035	21	0.084	186
MS(4)	0.009	105	0.018	74	0.052	110	0.135	259
2SM(2)	0	0	0	0	0	0	0	0

MF	0	0	0	0	0	0	0	0
MSF	0	0	0	0	0	0	0	0
MM	0	0	0	0	0	0	0	0
SA	0.101	261	0.082	229	0.102	212	0.039	258
SSA	0	0	0	0	0	0	0	0

Table A.1 Irish Sea harmonic data; obtained from internet address: http://gatekeep.cs.utah.edu/hpp.d/cgi-bin/wwwtar?/hpux/Physics/xtide-2.2/xtide-2.2-ss-11.00.tar.gz+xtide-2.2/harmonics on 20/03/2001

APPENDIX 3

Calibration of 2D Irish Sea hydrodynamic flow model

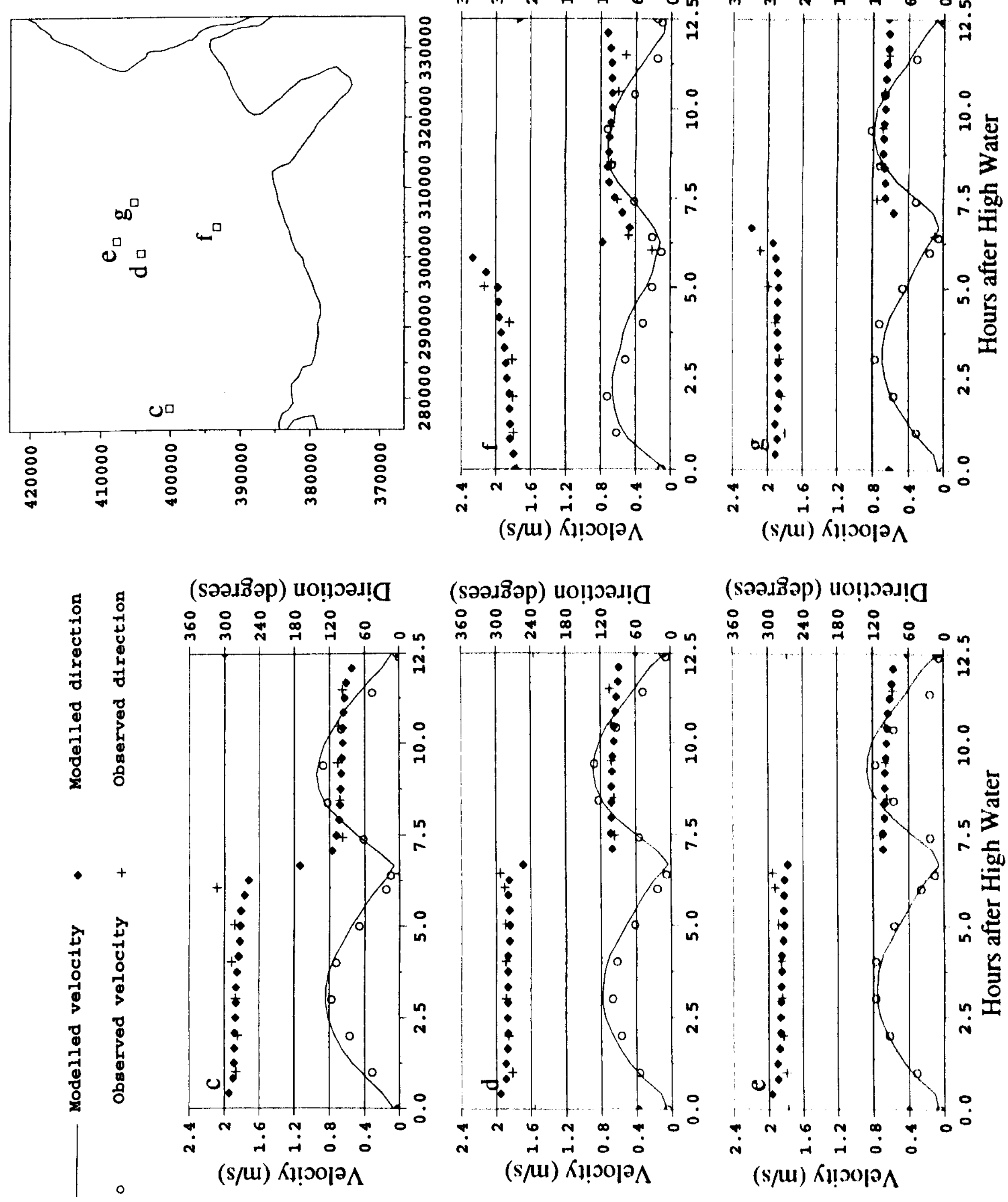

Figure A.5 Comparison of 2D Irish Sea model simulated mean spring tidal velocities with observed data (Hydrographer of the Navy data, 1977)

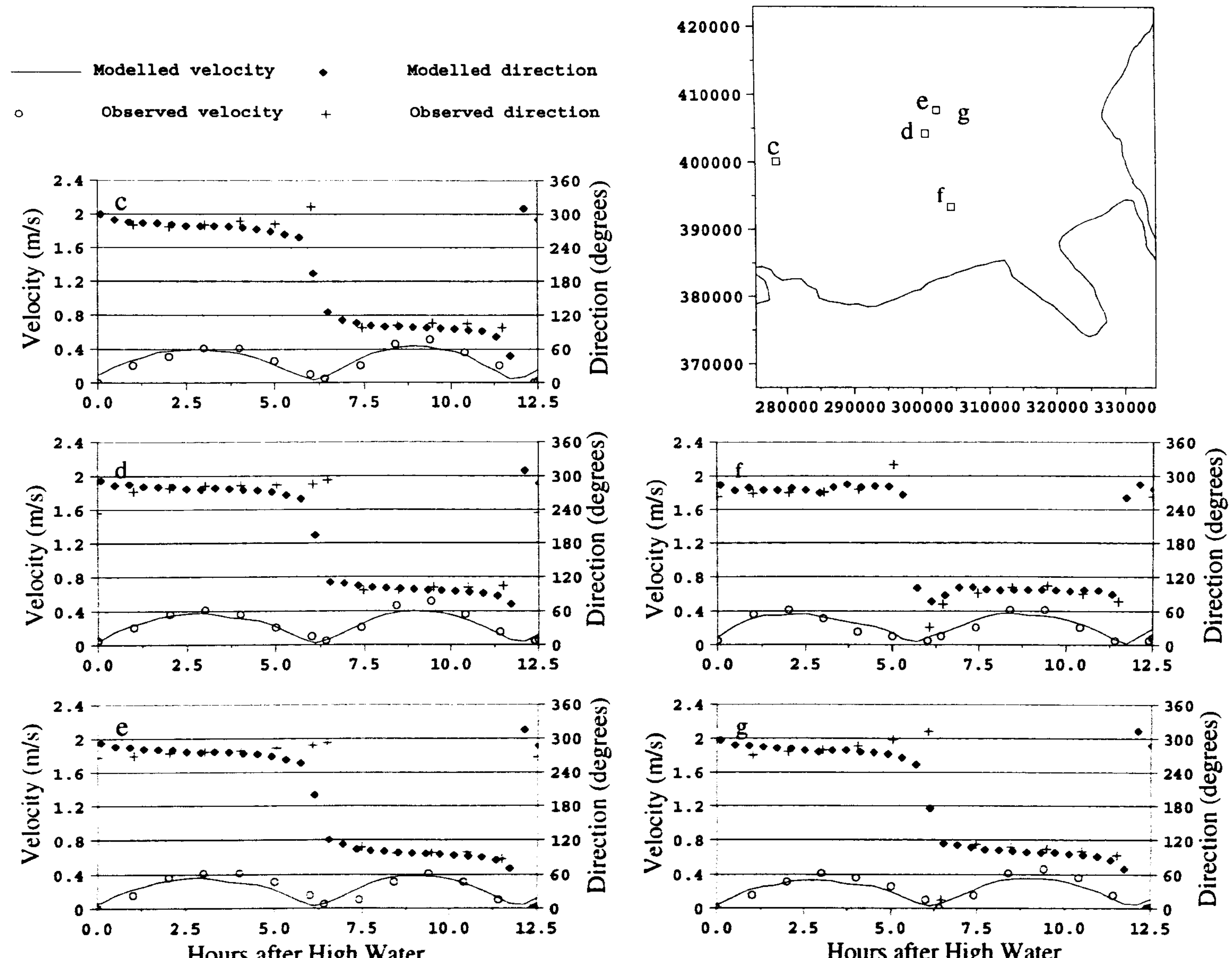

Figure A.6 Comparison of 2D Irish Sea model simulated mean neap tidal velocities with observed data (Hydrographer of the Navy data, 1977)

APPENDIX 4

Calibration of 2D Mersey estuary hydrodynamic flow model

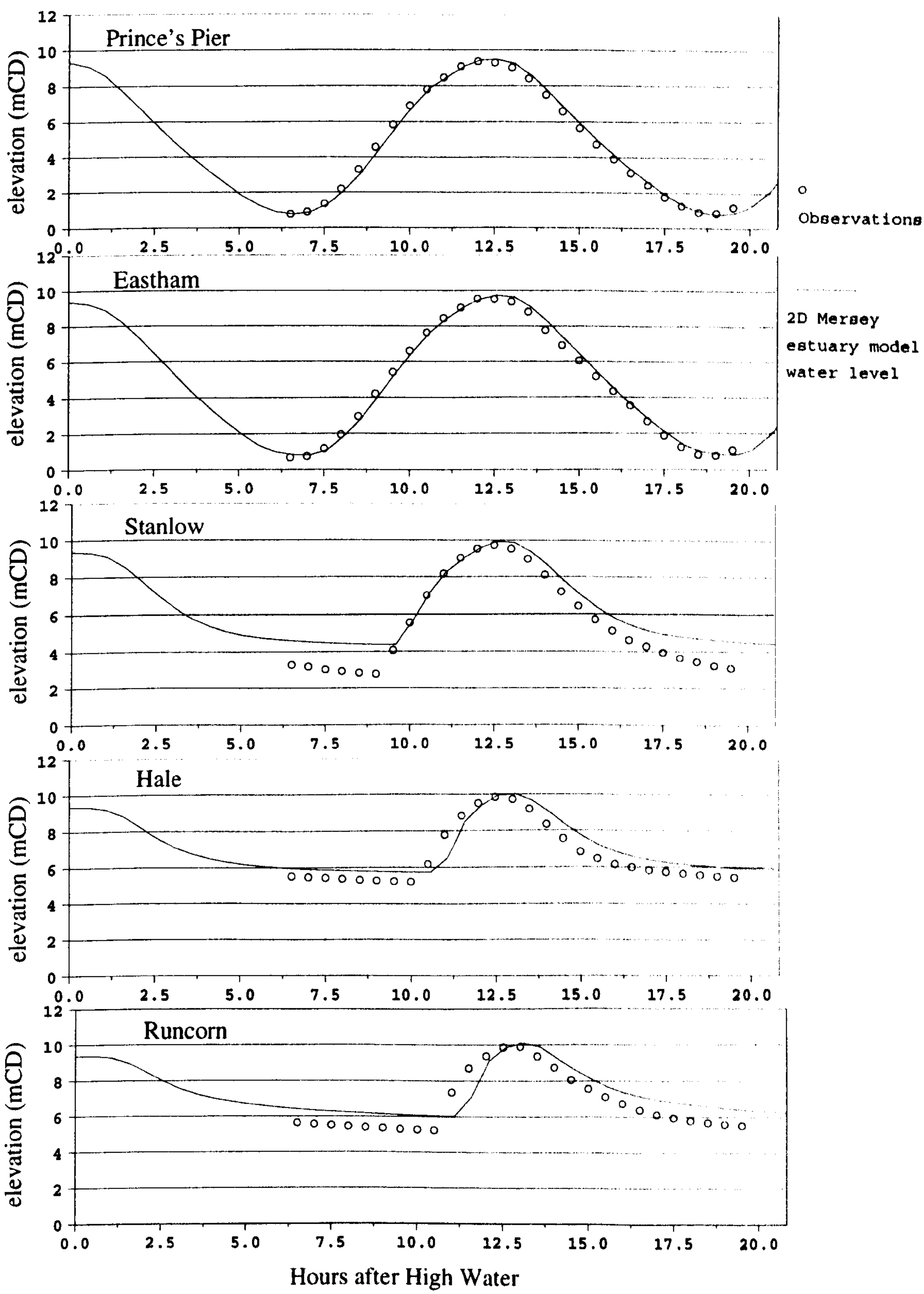

Figure A.7 Comparison of 2D Mersey estuary model simulated mean spring tidal levels with observed data (West data 1980)

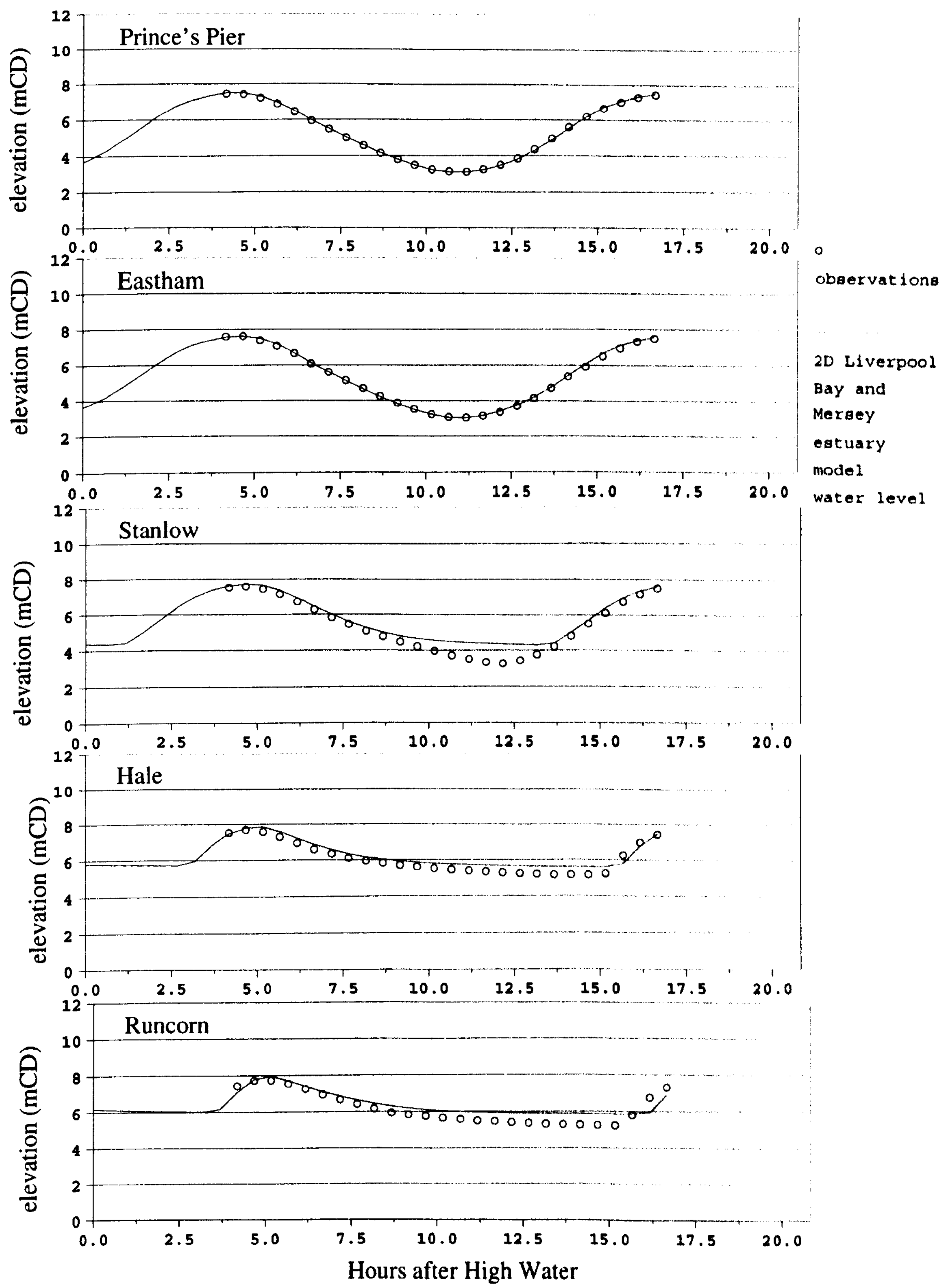

Figure A.8 Comparison of 2D Mersey estuary model simulated mean spring tidal levels with observed data (West data 1980)

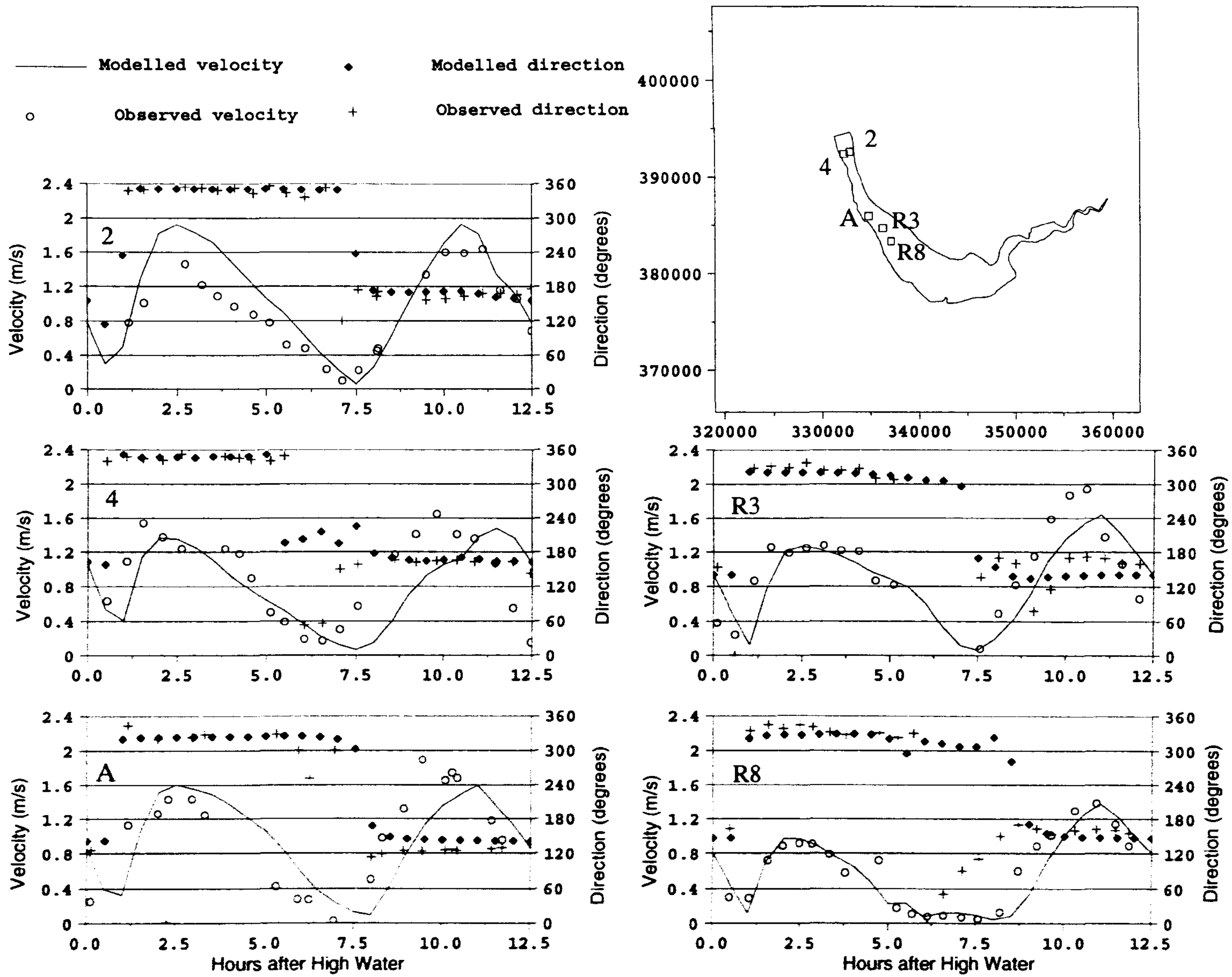

Figure A.9 Comparison of 2D Mersey estuary model simulated mean spring tidal velocities with observed data (source: R3,R8 = HR Wallingford, 1983; A = HR Wallingford, 1990; 2,4 = Mersey Barrage Company, 1990)

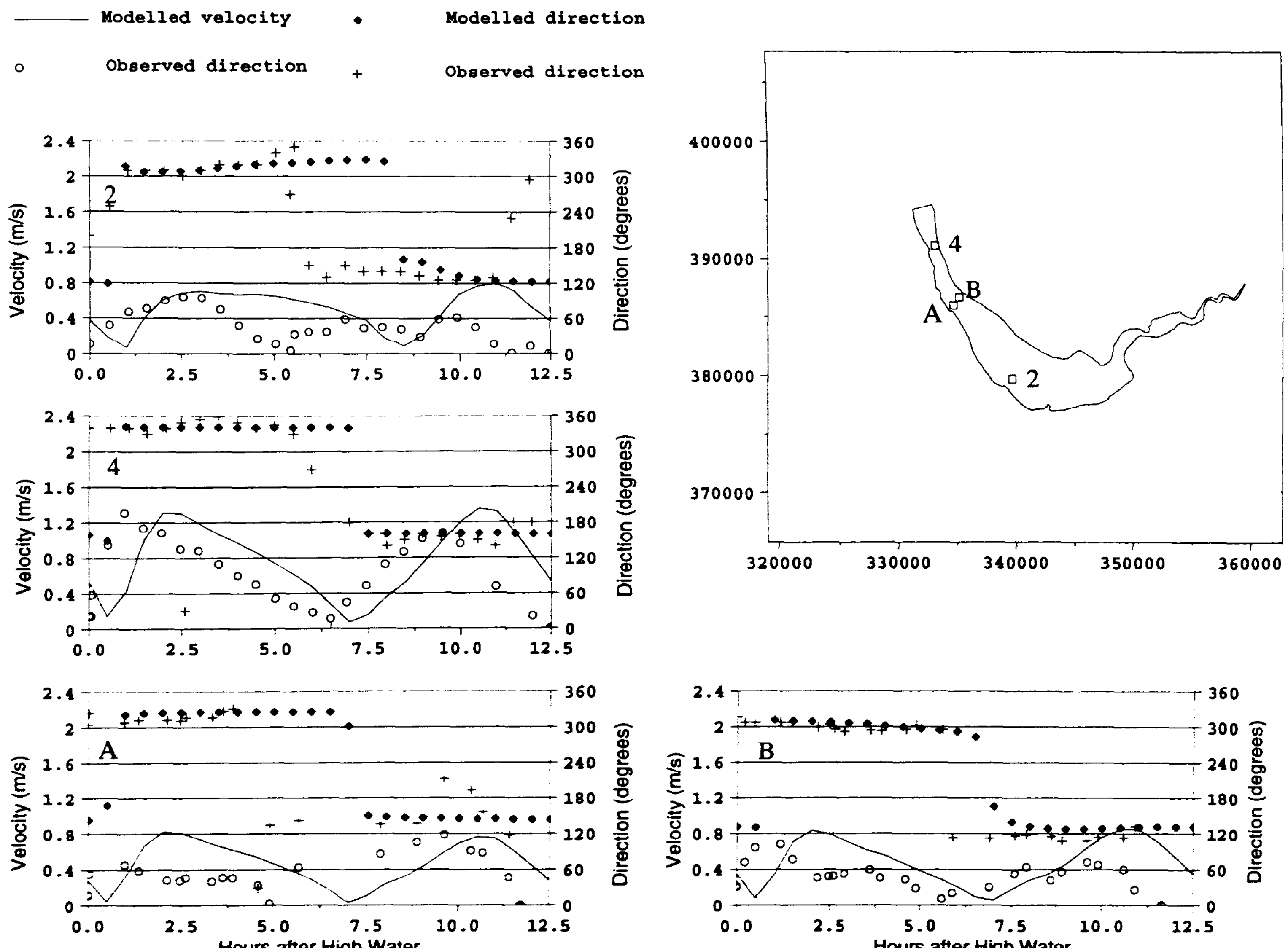

Figure A.10 Comparison of 2D Mersey estuary model simulated mean neap tidal velocities with observed data (source: A,B = HR Wallingford, 1990; 2,4 = Mersey Barrage Company, 1990)

APPENDIX 5

Calibration of 2D Mersey estuary and Liverpool Bay hydrodynamic flow model

APPENDIX 5 Calibration of 2D Mersey estuary and Liverpool Bay hydrodynamic flow model

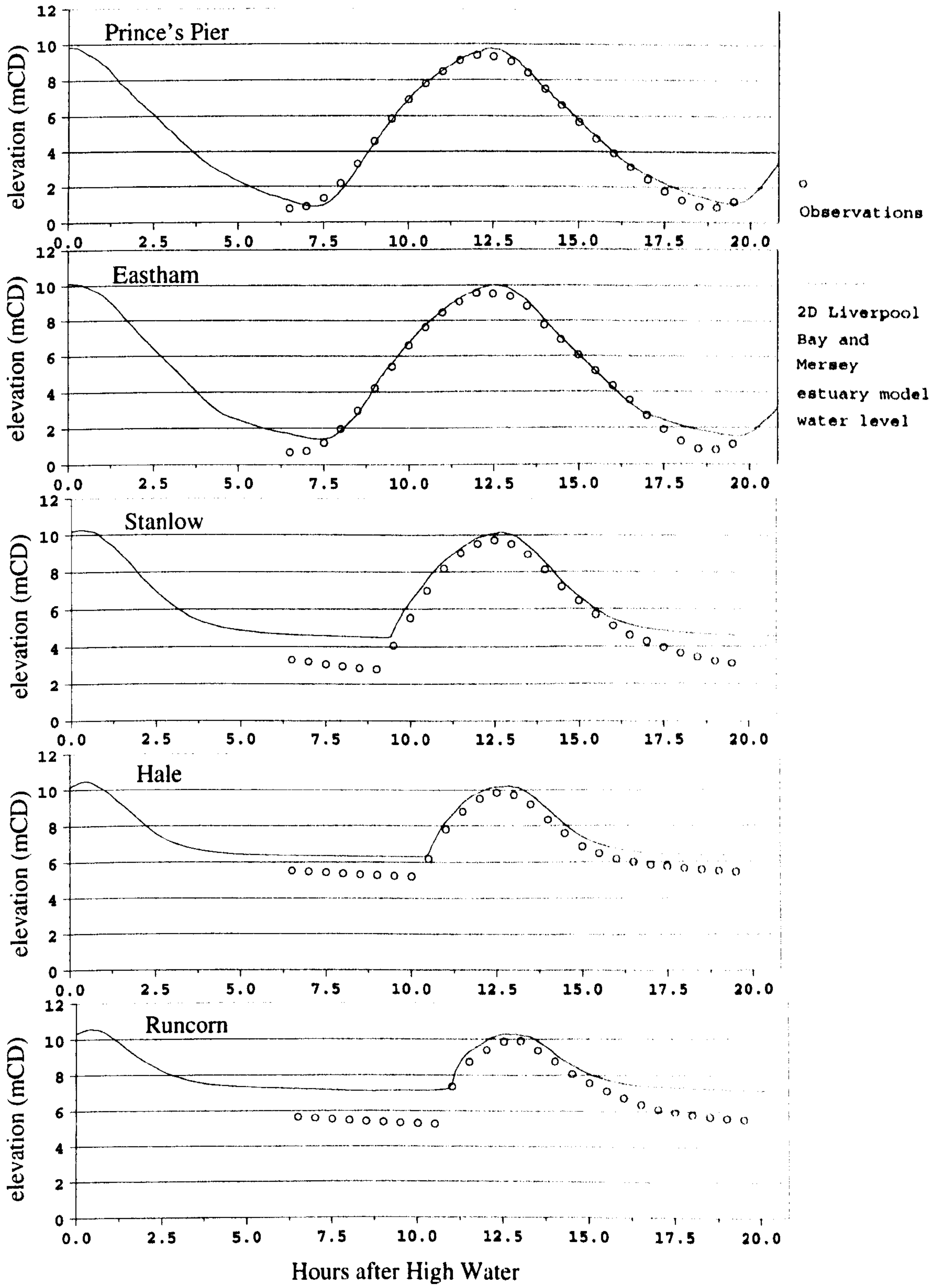

Figure A.11 Comparison of 2D Liverpool Bay and Mersey estuary model simulated mean spring tidal levels with observed data (West data 1980)

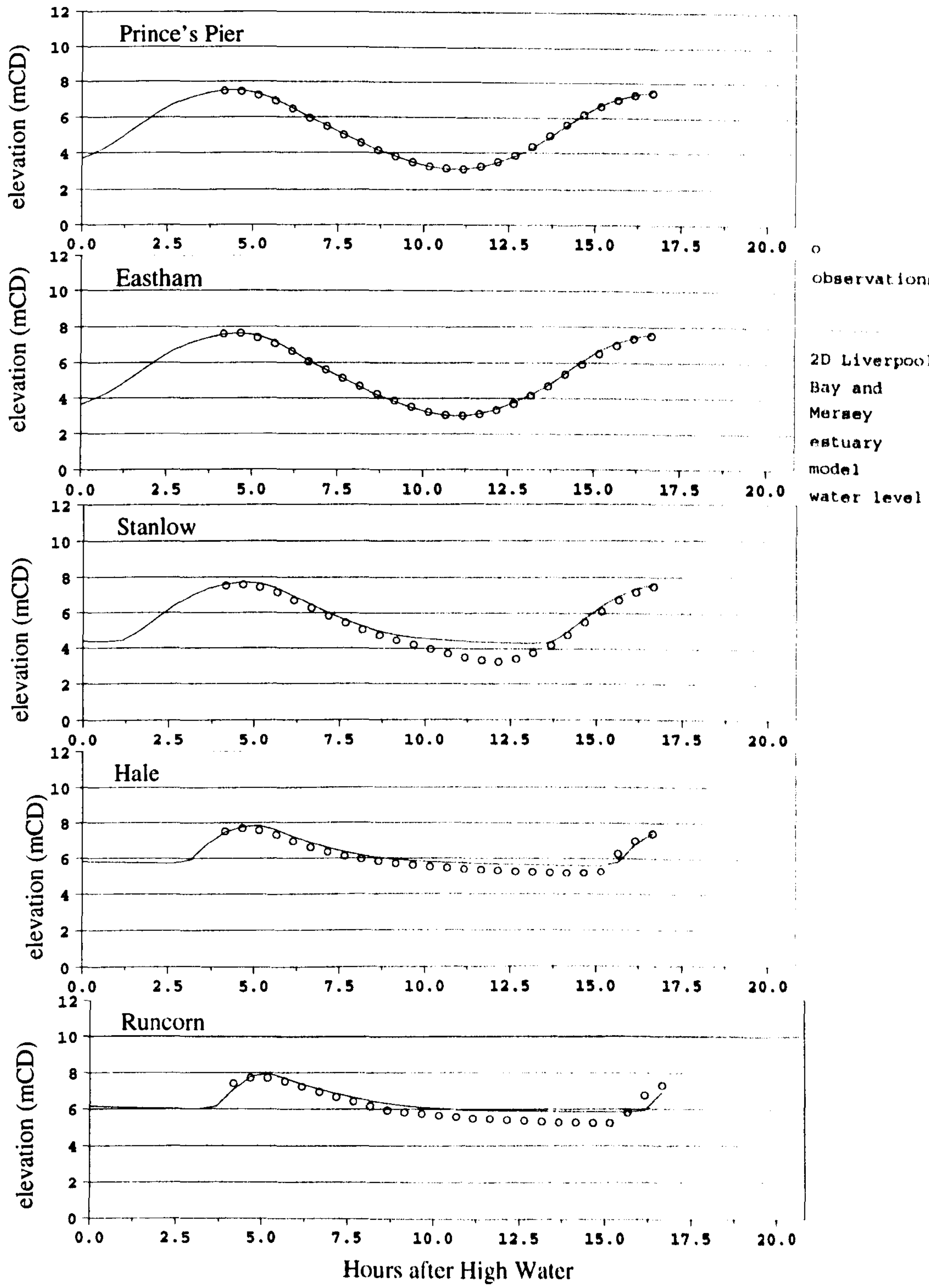

Figure A.12 Comparison of 2D Liverpool Bay and Mersey estuary model simulated mean neap tidal levels with observed data (West data 1980)

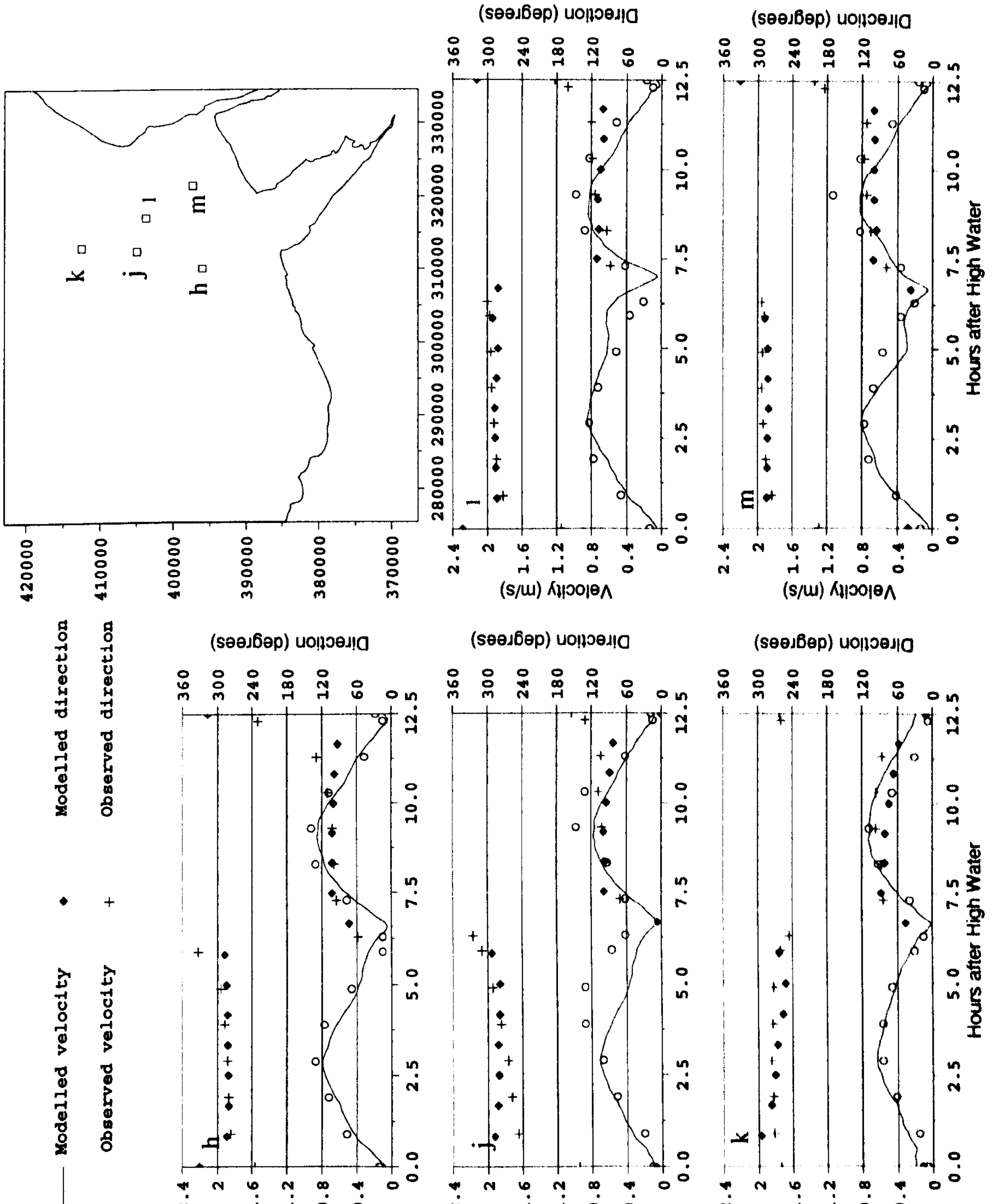

Figure A.13 Comparison of 2D Liverpool Bay and Mersey estuary model simulated mean spring tidal velocities with observed data (Hydrographer of the Navy data, 1977)

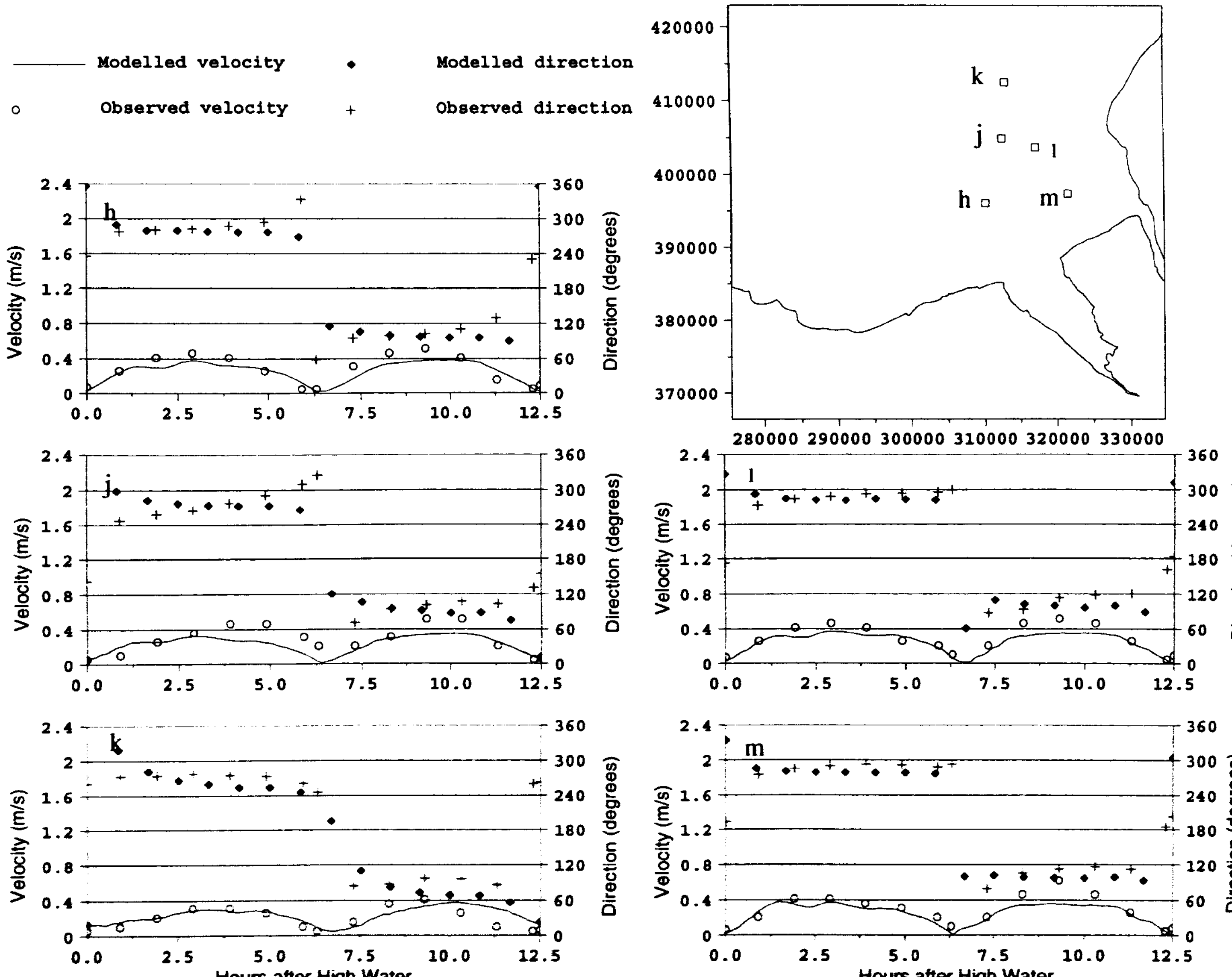

Figure A.14 Comparison of 2D Liverpool Bay and Mersey estuary model simulated mean neap tidal velocities with observed data (Hydrographer of the Navy data, 1977)

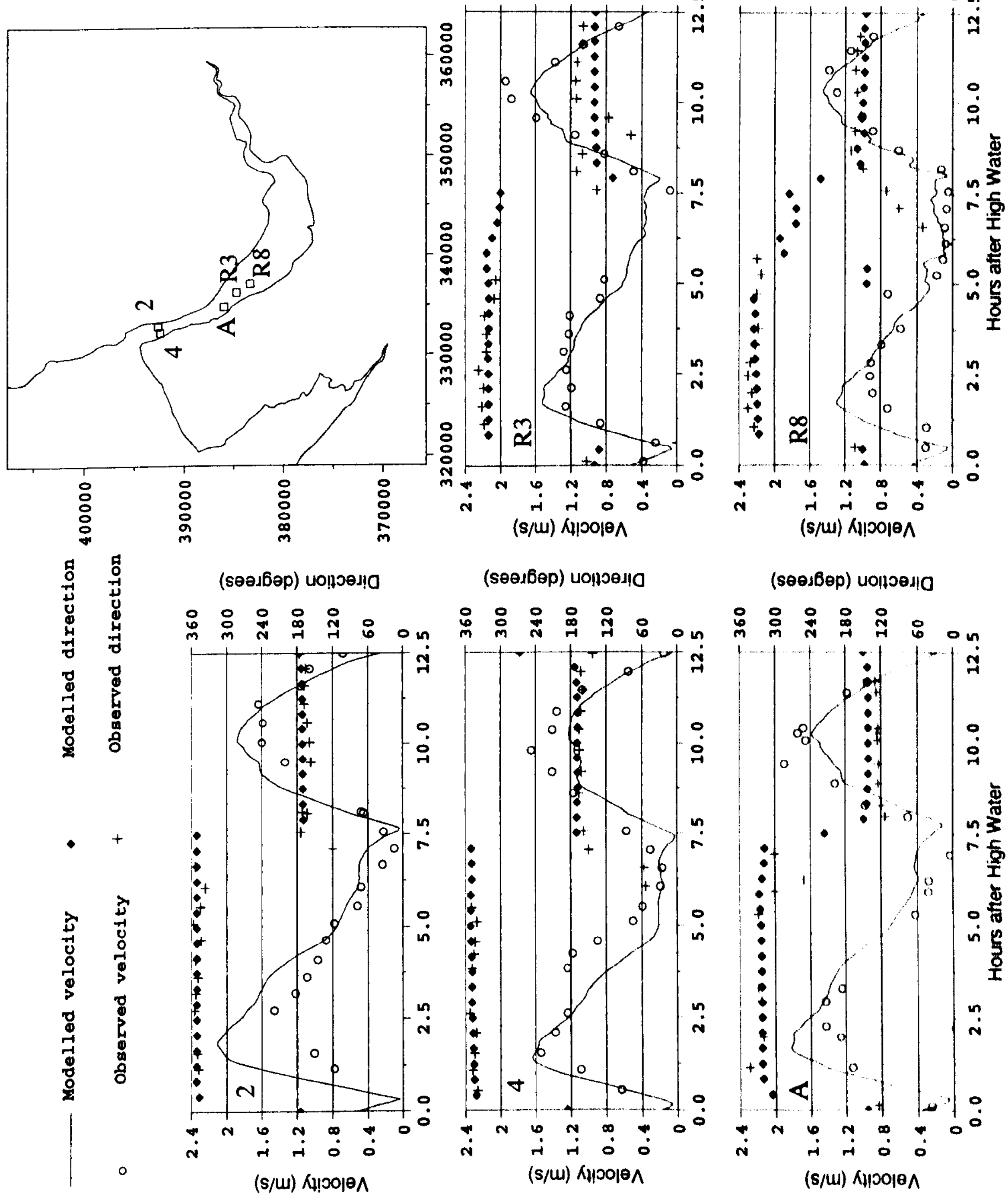

Figure A.15 Comparison of 2D Liverpool Bay and Mersey estuary model simulated mean spring tidal velocities with observed data (source: R3,R8 = HR Wallingford, 1983; A = HR Wallingford, 1990; 2,4 = Mersey Barrage Company, 1990)

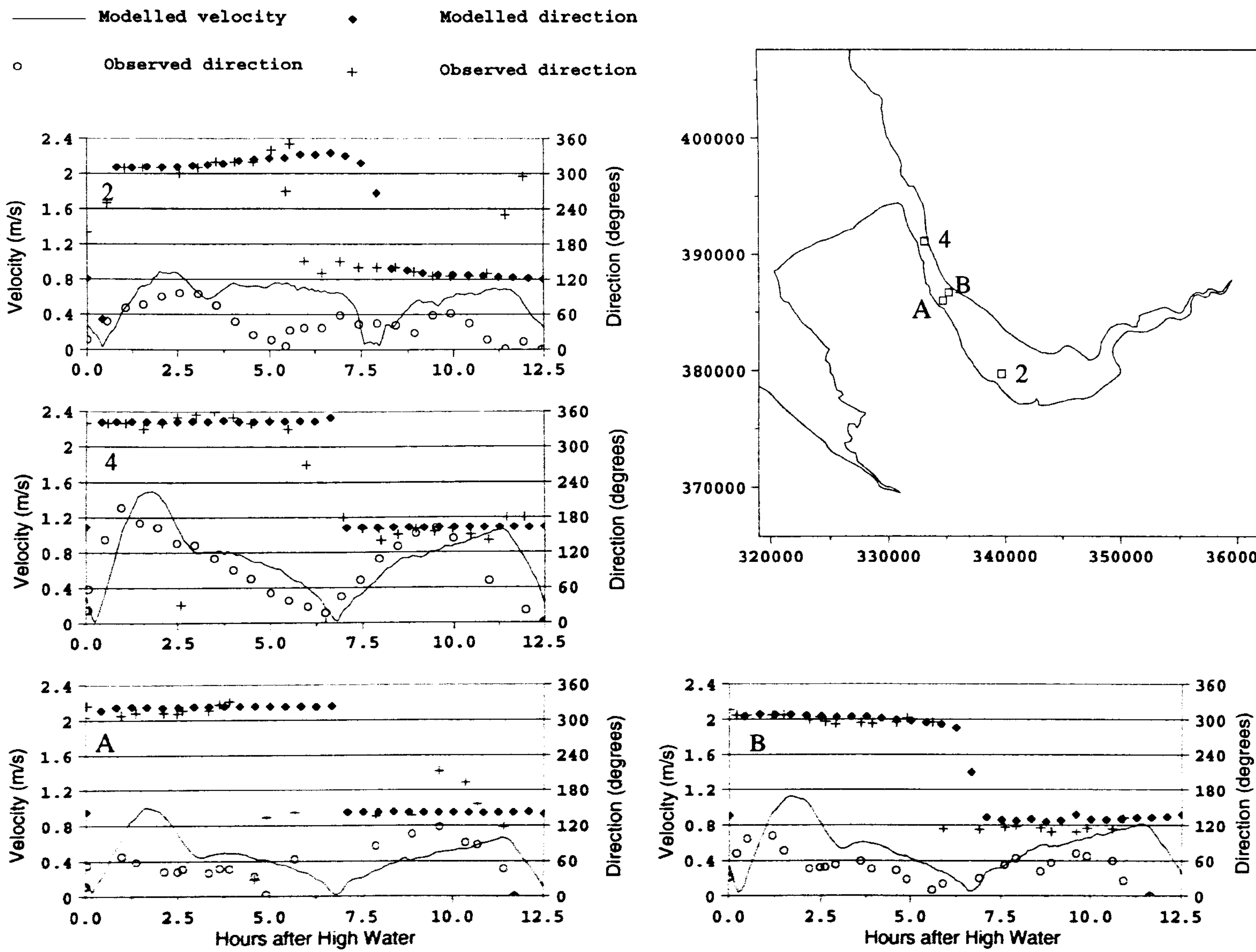

Figure A.16 Comparison of 2D Liverpool Bay and Mersey estuary model simulated mean neap tidal velocities with observed data (source: A,B = HR Wallingford, 1990; 2,4 = Mersey Barrage Company, 1990)

APPENDIX 6

Calibration of 3D Mersey estuary and Liverpool Bay hydrodynamic flow model

APPENDIX 6 Calibration of 3D Mersey estuary and Liverpool Bay hydrodynamic flow model

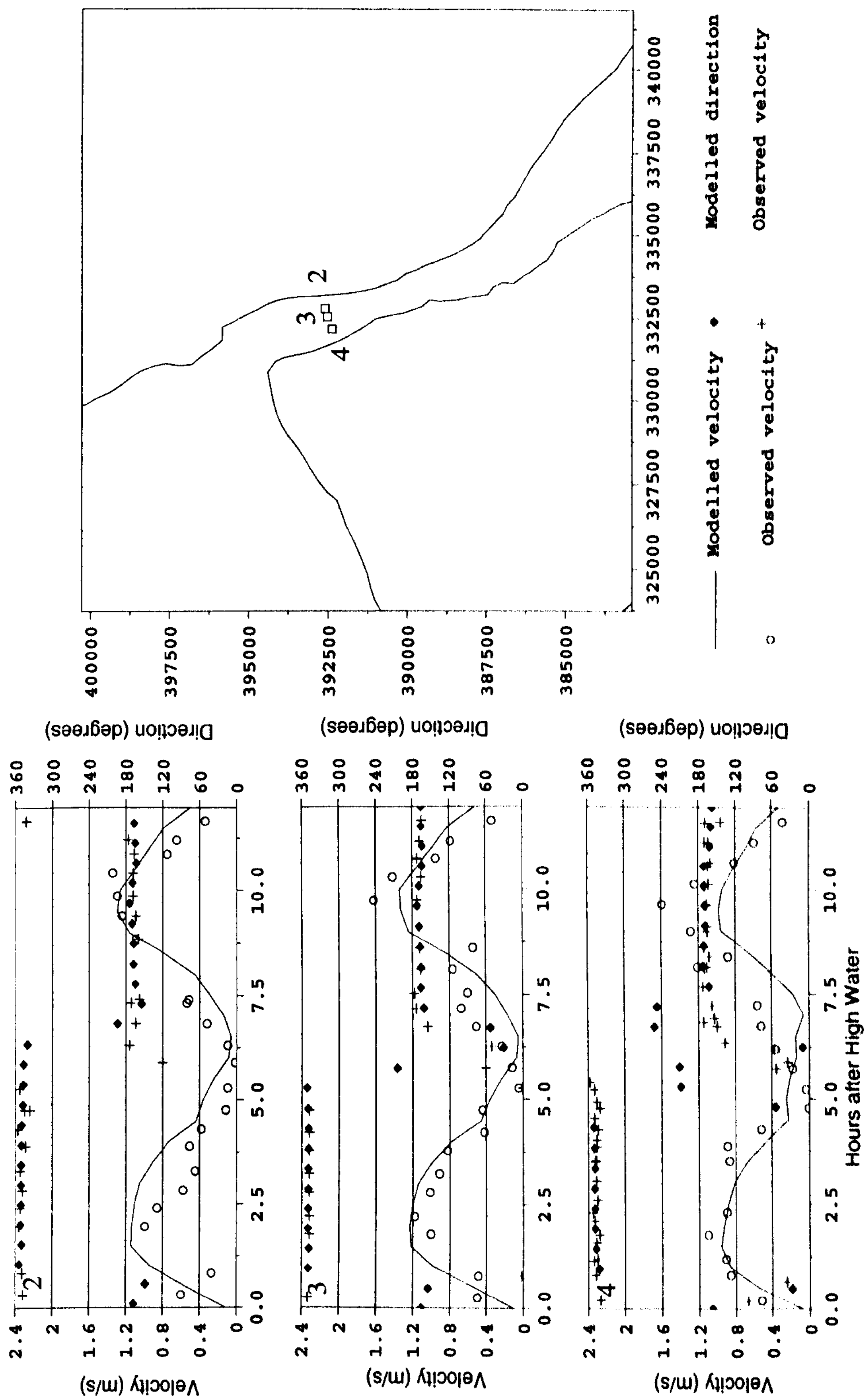

Figure A.17 Comparison of 3D Liverpool Bay and Mersey estuary model simulated mean spring near bed tidal velocities with observed data (source: 2,3,4 = Mersey Barrage Company, 1990)

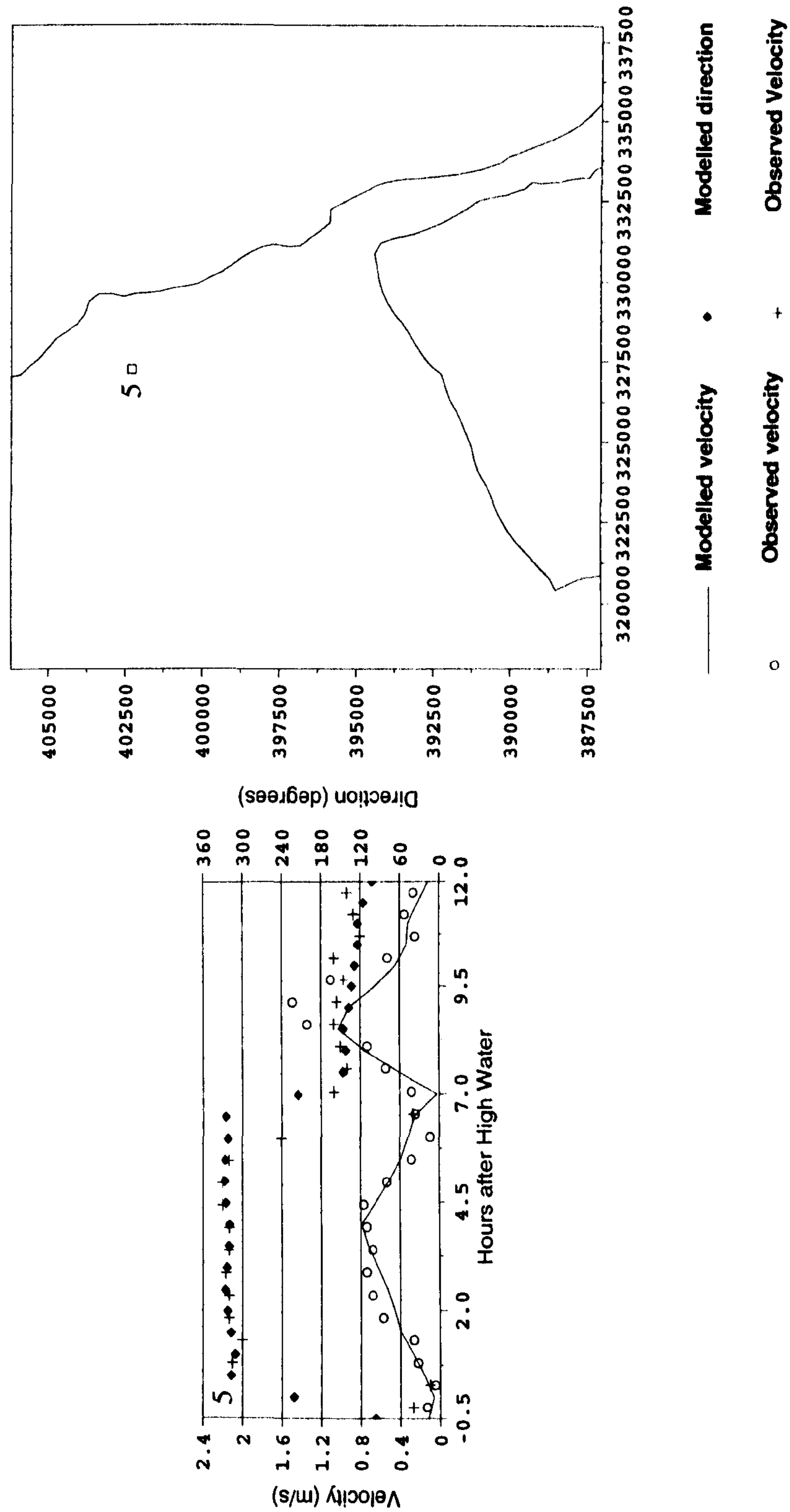

Figure A.18 Comparison of 3D Liverpool Bay and Mersey estuary model simulated mean spring near bed tidal velocities with observed data (source: 5 = Mersey Barrage Company, 1990)

APPENDIX 7

Wave climate data for Liverpool Bay

APPENDIX 7 Wave climate data for Liverpool Bay

H1	H2	P(H>H1)	Wave angles in degrees									
			-10	$f.H^{2.4}$	10	$f.H^{2.4}$	30	$f.H^{2.4}$	50	$f.H^{2.4}$	70	$f.H^{2.4}$
			10		30		50		70		90	
0	0.2	0.9985	59	0.23	90	0.36	400	1.59	446	1.78	710	2.83
0.2	0.4	0.9502	596	33.14	574	31.92	793	44.09	967	53.77	1748	97.19
0.4	0.6	0.7852	731	138.5	673	127.5	138	26.15	734	139.07	1520	287.99
0.6	0.8	0.6197	313	132.98	523	222.2	662	281.25	880	373.87	1241	527.24
0.8	1	0.4604	622	483.03	360	279.6	383	297.43	546	424.01	649	504
1	1.2	0.3549	296	372.08	94	118.2	234	294.14	361	453.78	432	543.03
1.2	1.4	0.2495	151	283.43	186	349.1	152	285.3	213	399.8	193	362.26
1.4	1.6	0.2059	142	375.76	149	394.3	74	195.82	106	280.49	82	216.99
1.6	1.8	0.1482	107	382.35	103	368.1	42	150.08	47	167.95	57	203.68
1.8	2	0.1035	48	224	57	266	35	163.33	18	84	15	70
2	2.2	0.0765	38	225.48	16	94.94	14	83.07	3	17.8	6	35.6
2.2	2.4	0.057	20	147.63	25	184.5	1	7.38	0	0	0	0
2.4	2.6	0.0375	5	45.08	3	27.05	2	18.03	0	0	0	0
2.6	2.8	0.0301	17	184.38	5	54.23	2	21.69	0	0	0	0
2.8	3	0.0202	8	103	1	12.88	0	0	0	0	0	0
3	3.2	0.0146	2	30.22	0	0	0	0	0	0	0	0
3.2	3.4	0.0079	5	87.78	0	0	0	0	0	0	0	0
3.4	3.6	0.0064	0	0	0	0	0	0	0	0	0	0
3.6	3.8	0.0028	0	0	0	0	0	0	0	0	0	0
3.8	4	0.002	0	0	0	0	0	0	0	0	0	0
4	4.2	0.0012	0	0	0	0	0	0	0	0	0	0
4.2	4.4	0.0009	0	0	0	0	0	0	0	0	0	0
4.4	4.6	0.0004	0	0	0	0	0	0	0	0	0	0
4.6	4.8	0.0002	0	0	0	0	0	0	0	0	0	0
4.8	5	0.00005	0	0	0	0	0	0	0	0	0	0
5	5.2	0.00003	0	0	0	0	0	0	0	0	0	0
5.2	5.4	0.00002	0	0	0	0	0	0	0	0	0	0
5.4	5.6	0.00001	0	0	0	0	0	0	0	0	0	0
$\sum f.H^{2.4}$				3249.1		2531		1869.4		2396.3		2850.8
$\sum f$			3160		2859		2932		4321		6653	
$(\sum f.H^{2.4}/\sum f)^{1/2.4}$			1.01		0.95		0.83		0.78		0.70	

90	f.H$^{2.4}$	110	f.H$^{2.4}$	130	f.H$^{2.4}$	150	f.H$^{2.4}$	170	f.H$^{2.4}$	190	f.H$^{2.4}$	210	f.H$^{2.4}$
110		130		150		170		190		210		230	
697	2.77	180	0.72	92	0.37	199	0.79	247	0.98	135	0.54	136	0.54
1622	90.19	1434	79.73	1161	64.55	497	27.63	319	17.74	411	22.85	737	40.98
1695	324.14	1551	293.86	988	187.19	994	188.3	582	110.3	404	76.54	497	94.16
977	415.08	1470	624.53	1434	609.23	558	237.1	156	66.28	252	107.1	649	275.7
668	518.75	765	594.08	338	262.48	321	249.3	63	48.92	54	41.93	157	121.9
168	211.18	320	402.25	219	275.29	122	153.4	11	13.83	17	21.37	94	118.2
67	125.76	82	153.91	44	82.59	6	11.26	2	3.75	9	16.89	25	46.92
37	97.91	13	34.4	6	15.88	1	2.65	0	0	1	2.65	10	26.46
24	85.76	2	7.15	1	3.57	0	0	0	0	0	0	5	17.87
0	0	0	0	0	0	0	0	0	0	0	0	2	9.33
0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0
	1868.5		2190.6		1501.2		870.4		261.8		289.8		752.1
5955		5817		4283		2698		1380		1283		2312	
0.62		0.67		0.65		0.62		0.50		0.54		0.63	

230	$f.H^{2.4}$	250	$f.H^{2.4}$	270	$f.H^{2.4}$	290	$f.H^{2.4}$	310	$f.H^{2.4}$	330	$f.H^{2.4}$
250		270		290		310		330		350	
229	0.91	416	1.66	348	1.39	181	0.72	173	0.69	96	0.38
535	29.75	722	40.14	1110	61.72	1290	71.73	1236	68.72	747	41.53
605	114.63	903	171.09	1709	323.79	1443	273.4	918	173.93	462	87.53
874	371.32	1300	552.3	1251	531.49	1225	520.44	1400	594.79	764	324.6
645	500.89	1531	118.93	2063	1602.07	595	462.06	411	319.17	375	291.2
379	476.41	1206	1516	2899	3644.1	2097	2636	1209	1519.74	386	485.2
222	416.69	841	1578	1170	2196.09	562	1054.9	288	540.58	143	268.4
61	161.42	257	680.07	1994	5276.48	1690	472.04	897	2373.62	250	661.5
20	71.47	436	1558	2270	8111.54	849	3033.8	260	929.07	253	904.1
13	60.67	122	569.34	540	2520.01	1263	5894	544	2538.68	48	224
4	23.73	59	350.09	1067	6331.27	459	2723.6	164	973.13	114	676.4
0	0	43	317.41	692	5108.02	814	6008.6	343	2531.87	10	73.82
0	0	14	126.24	287	2587.84	306	2759.2	72	649.21	57	514
0	0	5	54.23	353	3828.67	443	4804.8	166	1800.45	0	0
0	0	3	38.63	269	3463.44	211	2716.7	31	399.13	38	489.3
0	0	0	0	241	3641.54	316	4774.8	112	1692.33	0	0
0	0	1	17.56	68	1193.83	57	1000.7	10	175.56	10	175.6
0	0	0	0	136	2749.81	177	3578.8	44	889.64	0	0
0	0	0	0	7	161.73	61	1409.3	8	184.83	3	69.31
0	0	0	0	42	1101.04	37	969.97	4	104.86	2	52.43
0	0	0	0	5	147.79	19	561.61	3	88.68	0	0
0	0	0	0	27	894.72	17	563.34	2	66.28	1	33.14
0	0	0	0	17	628.29	8	295.67	2	73.92	0	0
0	0	0	0	5	205.12	4	164.09	2	82.05	0	0
0	0	0	0	2	90.68	1	45.34	0	0	0	0
0	0	0	0	1	49.91	0	0	0	0	0	0
0	0	0	0	1	54.73	0	0	0	0	0	0
0	0	0	0	1	59.82	0	0	0	0	0	0
	2227.9		8760.2		56566.9		50796		18770.9		5372
3587		7859		18575		14125		8299		3759	
0.82		1.05		1.59		1.70		1.41		1.16	

APPENDIX 8

Description of SEDPLUME-3D model

APPENDIX 8 Description of SEDPLUME-3D model

Flow in a coastal region consists of large-scale tidal motion, wind-driven currents and small-scale turbulent eddies. In order to model the dispersal of suspended mud in such a region, the effects of these flows on suspended mud plumes must be simulated. The random walk dispersal model, SEDPLUME-3D, represents turbulent diffusion as random displacements from the purely advective motion described by the turbulent mean velocities computed by the three dimensional free surface flow model, TELEMAC-3D.

1.1 Representation of mud disturbance

In SEDPLUME-3D, the release of suspended mud in coastal waters is represented as a regular or intermittent discharge of discrete particles. Particles are released throughout a model run to simulate continuous mud disturbance or for part of the run to simulate mud disturbance over an interval during the tidal cycle, for instance to represent the resuspension of fine sediment during dredging operations. At specified sites a number of particles are released in each model time-step and, in order to simulate the release of suspended mud, the total mud released at each site during a given time interval is divided equally between the released particles. Particles can be released either at the precise coordinates of the specified sites, or distributed randomly, centred on the specified release sites. The particles can be released at the surface or evenly distributed through the water column. This allows the representation of the initial spreading of plumes of material released by, for example, a dredger.

1.2 Large scale advection

TELEMAC-3D simulates tidal flows in coastal waters, including the effects of any thermal or saline stratification and any three dimensional structure induced by bed friction or wind stress. Three components of current speed are calculated at a number of points through the depth and these values are interpolated to establish the precise current at the position of each SEDPLUME particle. Each particle is then advected by the local flow conditions. Because the three dimensional structure of the flow is calculated by TELEMAC-3D, effects such as shear dispersion of plumes are automatically represented.

1.3 Turbulent diffusion

In order to simulate the effects of turbulent eddies on suspended mud plumes in coastal waters, particles in SEDPLUME-3D are subjected to random displacements in addition to the ordered movements which represent advection by mean currents. The motion of simulated plumes is, therefore, a random walk, being the resultant of ordered and random movements. Provided the lengths of the turbulent displacements are correctly chosen, the random step procedure is analogous to the use of turbulent diffusivity in depth-averaged mud transport models. This is discussed in more detail below.

(a) Lateral diffusion

The horizontal random movement of each particle during a time-step of SEDPLUME-RW consists of a displacement derived from the parameters of the simulation. The displacement of the particle in each of the orthogonal horizontal directions is calculated from a Gaussian distribution, with zero mean and a variance determined from the specified lateral diffusivity. The relationship between the standard deviation of the displacement, the time-step and the diffusivity is defined in Reference 1 as:

$$\frac{\Delta^2}{\Delta t} = 2D \tag{1}$$

where, Δ is the standard deviation of the turbulent lateral displacement (m), Δt is the time-step (s) and D= lateral diffusivity (m^2s^{-1}).

In a SEDPLUME-3D simulation, a lateral diffusivity is specified, which the model reduces to a turbulent displacement using Equation (1). No directional bias is required for the turbulent movements, as the effects of shear diffusion are effectively included through the calculated depth structure in the mean current profile.

(b) Vertical diffusion

Whilst lateral movements associated with turbulent eddies are satisfactorily represented by the specification of a constant diffusivity, vertical turbulent motions can vary significantly horizontally and over the water depth, so that vertical diffusivities must be computed from the characteristics of the mean flow field, rather than specified as constants. In neutral conditions, the vertical diffusivity, K_z, is given by:

$$K_z = 0.16\, h^2 \left(1 - \frac{h}{d} \right) \frac{\partial u}{\partial z} \tag{2}$$

where, h is height of particle above the bed, d is water depth, 0.16 is (von Karman constant)^2, u is current speed, and z is vertical coordinate

The value of the vertical diffusivity is calculated at each particle position, then a vertical turbulent displacement is derived for each particle from its K_z value using an equation analogous to (1) for the lateral turbulent displacement.

If the water density varies in the vertical, then stable stratification can occur, whereby the turbulence is damped by buoyancy effects. In this case the mixing length is adapted by a function of the Richardson number, based on field measurements (Reference 2).

(c) Drift velocities

A particle undergoes a random walk as follows:

$$x^n = x^{n-1} + A(x^{n-1}, t^{n-1})\Delta t + B(x^{n-1}, t^{n-1})\sqrt{\Delta t}\ \xi^n \tag{3}$$

where x^n is the position of the particle at time t^n, A is the advection velocity at timestep $n-1$ and B is a matrix giving the diffusivity. ξ is a vector of three random numbers, each drawn from a normal distribution with unit variance and zero mean. In the case of SEDPLUME-3D,

B is diagonal, with the first two entries equal to $\sqrt{(2D)}$ (as introduced in the previous section)

and the third diagonal entry being equal to the local value of $\sqrt{(2K_z)}$.

The movement of a particle undergoing a random walk as described in equation (3) can be described by the Fokker-Planck equation in the limit of a very large number of particles and a very short timestep, where we introduce subscripts i,j and k running over the three coordinate directions:

$$\frac{\partial f}{\partial t}+\frac{\partial}{\partial x_i}(A_i f)=\frac{\partial^2}{\partial x_i \partial x_j}(\frac{1}{2}B_{ik}B_{jk}f) \tag{4}$$

The probability density function $f(x,t|x_0,t_0)$ is the probability of a particle which starts at position x_0 at time t_0 being at position x at time t.

Equation (4) can be compared with the advection-diffusion equation for the concentration of a pollutant, c:

$$\frac{\partial c}{\partial t}+\frac{\partial}{\partial x_i}(u_i c)=\frac{\partial}{\partial x_i}(K_{ik}\frac{\partial}{\partial x_k}c) \tag{5}$$

where K_{ik} is the eddy diffusion matrix, diagonal in our case but not necessarily so. Thus identifying f with c, we can see that the two equations are equivalent provided that we take the advection velocity as:

$$A_i = u_i + \frac{\partial}{\partial x_k}K_{ik} \tag{6}$$

In the case of SEDPLUME-3D, the diffusivity varies only in the vertical and is constant in the horizontal, so the horizontal advection velocity is simply the flow velocity (assuming that the relatively small effects of changing water depth can be neglected). However, when considering the movement of particles in the vertical it is important to include the gradient of the diffusivity (often referred to as a drift velocity) in the advection step. If this term is omitted then particles tend to accumulate in regions of low diffusivity, which in our case means at the surface and at the bed.

This subject is discussed in considerably more detail in References 3,4,5 and 6.

1.4 Sedimentation processes

(a) <u>Settling</u>

In SEDPLUME-RW, the settling velocity (w_s) of suspended mud is assumed to be related to the mud concentration (c) through an equation of the form:

$$w_s = \max(w_{min}, Pc^Q) \tag{7}$$

where w_{min}, P and Q are empirical constants. Having computed a suspended mud concentration field, as described subsequently in this section, a settling velocity can be computed in each output grid cell from Equation (7) and used to derive a downward displacement for each particle during each time-step of a model simulation. This displacement is added vectorially to the other computed ordered and random particle displacements. Note that there is a specified minimum value of w_s. This results in settling velocities being constant at low suspended mud concentrations, as indicated by recent research at HR. (Reference 7).

(b) Deposition

SEDPLUME-3D computes bed shear stresses from the input tidal flow fields using the rough turbulent, based on a bed roughness length input by the user. If the effects of storm waves on mud deposition and erosion at the sea bed are to be included in a model simulation, a bed shear stress associated with wave orbital motions, computed from the results of mathematical wave model simulations, is added to that resulting from the simulated tidal currents (Reference 8). Where the computed bed stress, τ_b, falls below a specified critical value, τ_d, and the water is sufficiently deep, then deposition is assumed to occur. Mud deposition is represented in SEDPLUME-3D by particles approaching the sea bed becoming inactive when τ_b is below τ_d. Whilst active particles in the water column contribute to the computed suspended mud concentration field, as described subsequently in this appendix, inactive particles contribute to the mud deposit field.

In shallow areas, where tidal currents are sufficiently weak to allow mud accretion, normal wave action can prevent mud deposition. This effect is included empirically in SEDPLUME-3D, by specifying a minimum water depth below which deposition does not occur.

(c) Erosion

The erosion of mud deposits from the sea bed is represented in SEDPLUME-3D by inactive particles returning to the water column (becoming active) when τ_b exceeds a specified erosional shear strength, τ_e. The number of particles which become re-suspended in each cell of the output grid in each time-step of a simulation is determined by the equation:

$$\text{Erosion Rate} = M(\tau_b - \tau_e) \tag{8}$$

where M is an empirical erosion constant.

1.5 Computation of suspended mud concentrations

In SEDPLUME-3D, suspended mud concentrations are computed on a multi-layer square grid designed to resolve the essential features of relatively small-scale plumes. The layers of the output grid are separated by the element planes of the TELEMAC-3D grid, so that if there are N planes in the TELEMAC-3D mesh, there are N-1 layers in the SEDPLUME-3D output grid. In each SEDPLUME-3D grid cell a concentration is derived by dividing the total suspended mud represented by all the active particles in that cell by the volume of the cell.

1.6 Computation of mud deposit distributions

SEDPLUME-3D computes mud deposit distributions by summing the mass of mud represented by the inactive particles in each cell of the output grid, and assuming that the resulting mass is evenly distributed over the cell area.

The model is usually used to simulate the dispersal of mud released by dredging-related activity in one of the following three ways:

(a) Dredging in shallow areas releases small quantities of mud into the water column close to the sea bed.

(b) When dredging for marine fill, the coarse sediment content of dredged material may be increased by over-filling of the receiving barge; with coarse material settling rapidly in the barge and the fine mud component remaining in suspension and re-entering the water column.

(c) The disposal of dredged spoil in deep water results in a dense column of sediment descending rapidly to the sea bed. Entrainment of water into this column results in some of the fine mud component entering the water column.

The model is most suited to simulating detailed distributions of suspended mud and mud deposits near areas of dredging-related activity over a few tidal cycles. The far-field effects of dredging-related activity can be simulated using other models in use at HR Wallingford.

1.7 References

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