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Long-term morphological change and its causes in the Mersey Estuary, NW England

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Abstract

Changes in the morphology of the Mersey Estuary, and their possible causes, have been investigated using Historical Trend Analysis and Expert Geomorphological Assessment. Historical bathymetric charts were digitised and analysed within a GIS to provide quantitative estimates of changes in areas and sediment volumes above and below selected elevation planes. The results show that the estuary experienced major changes over the last 150 years, notably between the late 19th century and ca. 1950. An analysis of data relating to possible natural and human factors which could have influenced these changes suggests that training wall construction and dredging in the Outer Estuary and Liverpool Bay was the most significant factor contributing to change during this period. These activities modified the hydrodynamic and sediment transport regime in a way which enhanced an existing natural tendency for movement of sediment from Liverpool Bay and the Outer Estuary into the Inner Estuary. Changes in other factors, including sea level, tidal range, wind/wave climate, freshwater flow and embanking/land reclamation, were of relatively minor importance. Between 1950 and 1977 the rate of sediment accumulation in the Inner Estuary declined as the estuary approached a new condition of dynamic equilibrium, and since 1977 there has been a slight net loss of sediment. Under these conditions the changes in natural forcing factors, such as sea level and storminess, are likely to have a relatively greater effect on the estuary than in the past.

Keywords: Estuaries; Morphology; Bathymetry; Sedimentation; Historical Trend Analysis; Expert Geomorphological Assessment; Mersey

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1. Introduction

There is increasing concern about the likely long-term effects of changes in natural environmental forcing factors, including wave climate, mean sea level and storm surge frequency, as well as of human activities such as training wall construction, channel dredging, sand mining and embanking, on estuarine environments. In order to predict possible future changes in estuary morphology, sedimentary characteristics, water quality and associated impacts on biota and human usages of estuaries, there is a need to understand the factors which have influenced the present morphology and process regime of the estuary. Estuary managers also require a range of evaluation and prediction tools which can be applied at different spatial and temporal scales. Short-term and more local scale changes can often be satisfactorily predicted using hydrodynamic and other

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process-based computer models (sometimes referred to as ‘bottom–up models’), but prediction of longer term changes, ranging from a few months to centuries, and those affecting broad-scale morphology, requires different approaches which are often referred to as ‘top–down’ and ‘hybrid’ models (Brew and Pye, 2002, Whitehouse, 2002; Townend, 2005). This paper presents the results of an investigation to quantify the magnitude and possible causes of morphological and sediment volume changes in the Mersey Estuary, northwest England, using a combination of two ‘top–down’ methods, Historical Trend Analysis (HTA) and Expert Geomorphological Assessment (EGA). HTA is principally concerned with the analysis of historical data sets to identify past and predict future trends, essentially independent of the causes of such changes, whereas EGA is an integrative exercise which may combine the outputs of HTA, results from ‘bottom–up modelling’, and information about geological constraints, sediment supply, natural processes and human activities which have, and may in future, affect sediment transport processes and morphological evolution (Pye and van der Wal, 2000a,b).

2. Physical setting and characteristics of the Mersey Estuary

The Mersey Estuary is located on the south-eastern margin of the Irish Sea in northwest England (Fig. 1). It consists of four distinct zones (Fig. 2): the Upper Estuary, which extends eastwards from Runcorn to the limit of tidal influence at Warrington; a bottle-shaped Inner Estuary, which has a maximum width of 5 km; the Narrows, with a minimum width of ca. 1 km near Liverpool; and a wide Outer Estuary, which forms part of Liverpool Bay. The plan form of the estuary is unusual, compared with the open funnel shape typical of many other estuaries, with a relatively large inner basin which is constricted at its seaward end by rock outcrops. The ‘Narrows,’ ca. 1.5 km wide, represent an ice-deepened trough cut into the surrounding and underlying Permo-Triassic sandstones, which rise to 60 m

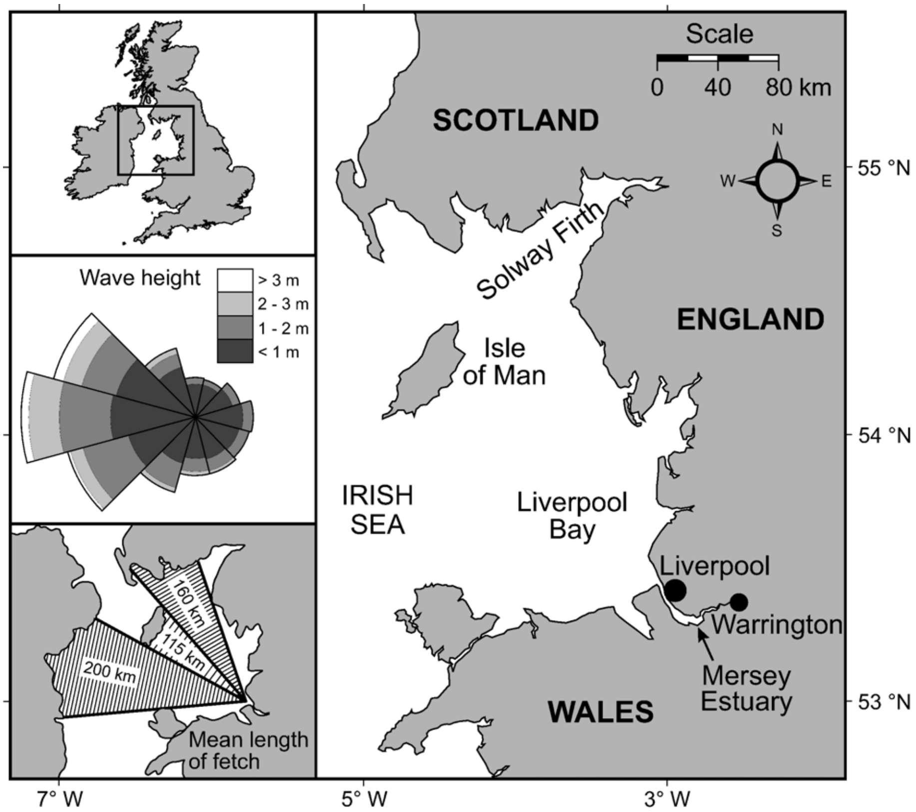


Fig. 1. Location map of the Irish Sea and the approaches to the Mersey Estuary. Inset are (bottom left) mean lengths of fetch from the estuary mouth and (centre left) a rose diagram of mean wave height and direction, calculated for an offshore point in Liverpool Bay (53°30′N 3°42′W) for June 1991 to April 2002, generated using the UK Meteorological Office European Waters Wave Model and redrawn from Associated British Ports (2002).

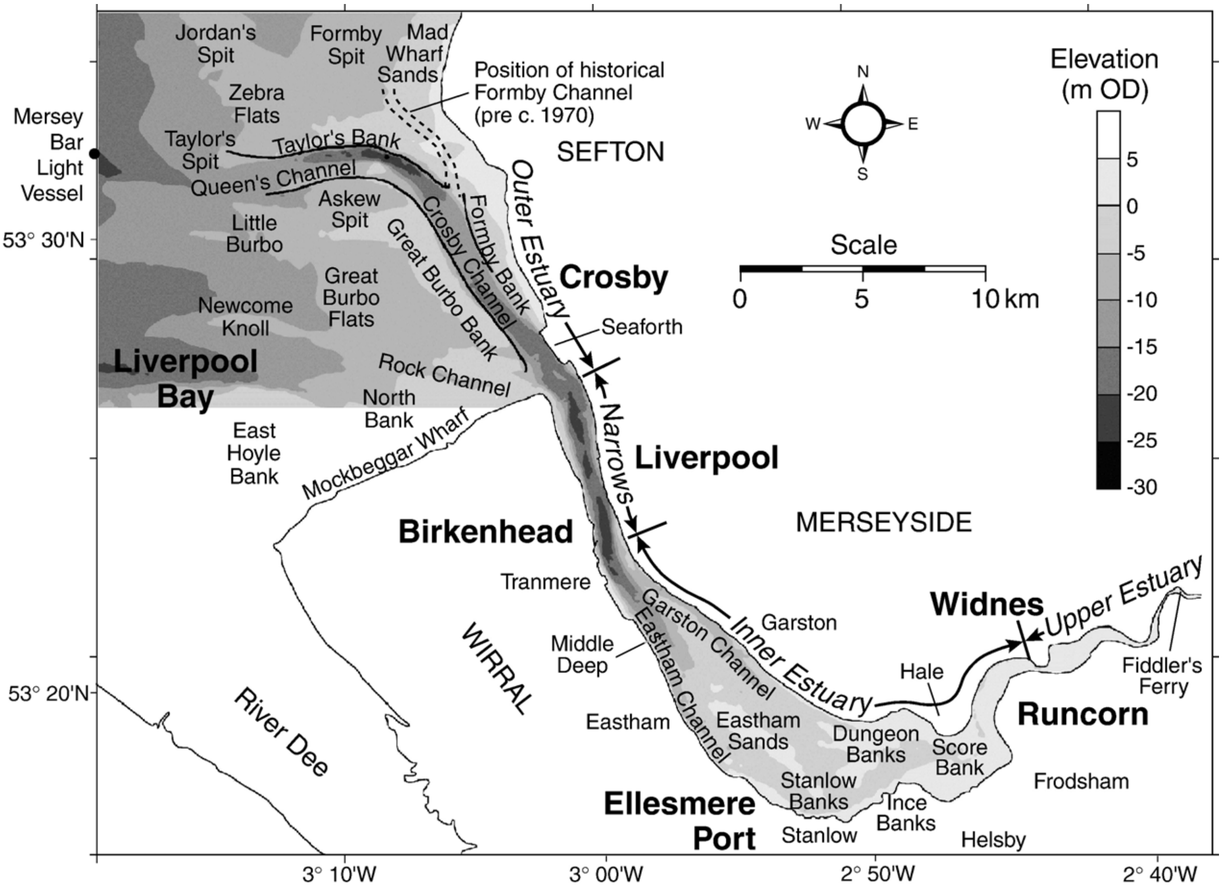


Fig. 2. Major divisions of the Mersey Estuary, showing the locations mentioned in the text. The solid black lines show the location of training walls.

above modern sea level (Gresswell, 1964). The margins of the Inner Estuary are formed mainly in Quaternary deposits up to 35 m thick, with solid rock outcrops at intervals, notably at Hale and Runcorn. The present estuary occupies a total area of about 11600 ha, of which 9700 ha is inter-tidal, with a total channel length of about 55 km (Comber et al., 1993).

The Mersey Estuary contains, and is fringed by, a range of important habitats, including coastal dune systems, inter-tidal sand and mudflats, rocky shores and saltmarsh, which support a range of bird and other species of international importance (Mersey Basin Campaign, 1995). Large parts of the Inner Estuary have been designated as Sites of Special Scientific Interest (SSSIs), as a RAMSAR site, and as a Special Protection Area (SPA). The estuary is also a major trade route leading to important industrial complexes around Ellesmere Port, Runcorn, Widnes and Manchester (via the Manchester Ship Canal). Liverpool and Birkenhead were formerly important centres of ship building; Seaforth remains a major container terminal, and there are other significant docks and terminals at Garston, Tranmere and Eastham (Fig. 2).

A high proportion of the shoreline of the estuary is fringed by embankments, with transitions to non-tidal habitats virtually non-existent (Doody, 1999). Decades of industrial effluent and sewage disposal have led to severe pollution of the estuary (DSIR, 1938; Best et al., 1973; National Rivers Authority, 1995; Fox et al., 1999, 2001), although recent initiatives have led to considerable improvements in water quality (Mersey Basin Campaign, 1995).

Saltmarshes and mudflats border the Inner Estuary, especially between Ellesmere Port and Runcorn on the southern shore, and on both banks upstream from Runcorn and Widnes. The Outer Estuary and Liverpool Bay also contain large sand banks (McDowell and O'Connor, 1977; British Geological Survey, 1984), with localised gravel (Sly, 1966).

The estuary experiences a macro-tidal regime (Table 1), with a mean spring tidal range of 8.4 m and mean neap tidal range of 4.5 m at Liverpool (Admiralty,

Table 1
Tidal levels at the standard port of Liverpool (Alfred Dock) and other secondary ports in the Mersey Estuary, given in metres OD (Admiralty, 2005)

Tide	LAT	MLWS	MLWN	MSL	MHWN	MHWS	HAT
Formby		− 3.93	− 2.03	0.22	2.37	4.07	
Gladstone Dock		− 4.13	− 2.03	0.22	2.37	4.27	
Liverpool	− 5.13	− 4.03	− 2.03	0.21	2.47	4.37	5.47
Eastham		− 4.33	− 2.13	0.24	2.57	4.67	
Hale Head					2.90	4.90	
Widnes		0.60	0.40		3.00	5.10	
Fiddler's Ferry		2.50	2.50		3.10	5.40	

2005). Maximum tidal current velocities are 1 m s^{-1} (on the flood tide) at the entrance to Queen's Channel and ca. 2.2 m s^{-1} (on ebb and flood) in the Narrows on spring tides (Admiralty, 2002). The strong tidal currents in the Narrows are slowed upstream as the estuary widens, leading to deposition of sand and mud which form extensive banks at low tide. The estuary is partially mixed. Mean freshwater flow of the River Mersey is about 66 m^3 s^{-1} (Shaw, 1975), compared with a tidal influx into the Narrows of, on average, 2000 m^3 s^{-1} during spring tides (McDowell and O'Connor, 1977). Average salinity ranges from 4 to 11 g l^{-1}, depending on river discharge (Dyer, 1997).

In view of its large tidal range and constricted entrance, the Mersey has been considered as a possible site for a tidal barrage, but no scheme has been implemented. More recently, two offshore wind farms have been constructed in the Outer Estuary (Associated British Ports, 2002).

Due to the constriction of the Narrows, there is very limited penetration of waves from the Irish Sea and wave energy is relatively low in the Inner Estuary compared with the Outer Estuary, which experiences moderate wave energy. Wave action is fetch-limited, preventing the formation of long period waves. In the eastern Irish Sea the largest waves come from the west (Sly, 1966; Pye and Neal, 1994), corresponding with a maximum fetch of ca. 200 km (Fig. 1). Some 52% of all waves approach from the south-west to north-west quadrants. The mean annual wave height is 0.8 m, but significant waves with heights of 5 m have been recorded at the entrance to Liverpool Bay during the winter months (McDowell and O'Connor, 1977). Wave activity from the prevailing south-westerly wind direction is restricted due to the shelter provided by North Wales and Anglesey. Similarly, the fetch from the north-west is restricted by the Isle of Man.

Owing to the importance of the Mersey for navigation, there are relatively good historical time series of bathymetric charts and surveyed cross-sections of the estuary, notably by the Mersey Docks and Harbour Company. Data relating to dredging volumes, sediment transport, bed sediment characteristics and water quality are also relatively abundant compared with many other UK estuaries. Summaries of activities within the river and estuary, including dredging, have been compiled for many years in the form of annual reports prepared by the Conservator of the Mersey.

3. Methods

In order to quantify the nature and magnitude of historical bathymetric change in the estuary, a number of charts from the ERP database (Associated British Ports, 1999) were digitised. The charts initially used for the Outer Estuary were Admiralty charts dating from 1912, 1949, 1988 and 2002 (Table 2). These charts, particularly the more recent ones, are based on survey data from a number of years and as such do not represent the bathymetry at a single point in time. Bathymetry for the Narrows and Inner Estuary was obtained from single surveys in 1906, 1936, 1956, 1977 and 1997 by the Mersey Docks and Harbour Company. The area investigated is shown in Fig. 2. Additional historical information about coastal change was obtained from Ordnance Survey maps, aerial photographic surveys,

Table 2
Bathymetric charts used as the main source for sediment volume calculations in the Outer Mersey Estuary and Liverpool Bay

Date	Chart title	Scale	Published	Surveyed
1912	Liverpool Bay; Chart Number 1951; British Admiralty	1:38,438	20/11/12	to 1911
1949	Liverpool Bay; Chart Number 1951; British Admiralty	1:38,440	22/04/49	to 1946
1988	Approaches to Liverpool; Chart number 1951; UK Hydrographic Office	1:25,000	19/02/88	1970–1987
2002	Approaches to Liverpool; Chart number 1951; UK Hydrographic Office	1:25,000	29/08/02	1970–2001

and airborne CASI imagery (see Associated British Ports, 1999).

The Admiralty chart data were digitized and analysed using *Map-Info* software. Additional analysis was performed using the *Surfer* mapping software package. Spot depths, spot heights, contours and estuary outlines, as defined by the Mean High Water Springs (MHWS) contour, were digitised on an A0 digitising tablet and geo-referenced using the latitude/longitude information on the charts. Data from charts and surveys were then transformed from their original projections to that of the British National Grid. Heights and depths were converted to metres and expressed relative to Ordnance Datum Newlyn (ODN). The bathymetric data were interpolated to a grid with 50 × 50-m cells. The grid was located in exactly the same position for all surveys. Kriging was selected as the most appropriate interpolation technique, as it provides a good interpolator for sparse data, when sufficient data points are available to compute variograms (Burrough and McDonnell, 1998; Webster and Oliver, 2001). Variogram models were fitted to each of the four data sets, yielding the appropriate parameters for kriging. Point kriging, with a linear variogram and best-fit slope, was applied.

Since the dates of surveys for the Inner and Outer Estuaries were different, the two areas were analysed separately. For each year studied, volumes were calculated within the most recent available estuary outline (1997 for the Inner Estuary and 2002 for the Outer Estuary), relative to an arbitrary lower plane of −30 m OD. These volumes are referred to as ‘sediment’ volumes, although the material is not necessarily unconsolidated in all places. In addition, sediment volumes above or below fixed planes corresponding to selected tidal levels were calculated. The tidal levels selected (Table 1) were applied to the whole area and the entire study period. The ‘inter-tidal area’ was defined as the area between the Lowest Astronomical Tide (LAT) and the Highest Astronomical Tide (HAT).

Tidal levels change both in time and space, but for purposes of comparison in this study it was assumed that the chosen tidal levels can be applied to the entire estuary and throughout the 90-year period of study. The errors associated with such assumptions and the use of bathymetric charts to calculate sediment (or tidal) volumes were assessed by van der Wal and Pye (2003), who concluded that the largest uncertainties arise from poor height data in the upper inter-tidal zone and datum inconsistencies. As in previous studies (e.g., van der Wal et al., 2002), a conservative approach was adopted, and only elevation changes greater than ± 0.5 m between subsequent surveys were considered to be significant. Although the estimated quantities for sediment volume, in particular, are unlikely to be truly accurate, it is considered that the data do provide a reliable indication of relative net accretion and erosion trends during different time periods.

4. Morphology and sediment volume change

4.1. Morphological changes in the Outer Estuary

A qualitative picture of changes in the pattern of banks and channels, and broad changes in the inter-tidal area of the Outer Estuary and Liverpool Bay, can be obtained from historical charts dating back to 1738 (Fig. 3), but the accuracy of the earlier surveys is questionable and quantitative comparisons can only be made from Admiralty surveys from the 1830s onwards. The main features on the Fearon and Eyes chart of 1738 (in Driscoll, 1970) are the Formby Channel, Rock Channel, Great Burbo Bank and Mad Wharf Sands. The channel of the River Alt, dividing Mad Wharf Sands and Formby Bank, was also a prominent feature which had evidently disappeared by 1766 according to a chart by Williamson (in Allison, 1949). The Great Burbo Bank was crossed by several shallow channels during this period. After an apparent decrease in inter-tidal area between 1738 and 1833, the area of sand flats west of Formby Point (including Mad Wharf, Jordan’s Spit, Taylor’s Bank and Askew Spit) increased significantly between 1833 and 1873, with Formby Channel dividing the banks. The Great Burbo Bank and Flats also increased in area and were separated from Taylor’s Bank by Crosby Channel. Between 1873 and 1912, Crosby Channel moved north, cutting into Taylor’s Bank, which moved east. Formby Channel was then a prominent feature, separating Taylor’s Bank from Formby Bank. A new training wall built in 1909 limited further northward movement of the Crosby Channel and caused it to curve towards the west. Further south, Great Burbo Bank had become dissected by a channel running southeast to northwest. South of this bank, the Rock Channel ran approximately east–west, separating Great Burbo Bank from Mockbeggar Wharf and the North Wirral coastline. Changes in the maximum depth of the main channels over time are shown in Fig. 4, and digitised extracts from the charts of 1912, 1949, 1988 and 2002 are shown in Fig. 5.

By 1949, training walls had been built along both sides of Crosby Channel for much of its length (Cashin, 1949; Agar and McDowell, 1971). Taylor’s Bank had eroded at its western end to a point coincident with the end of the training wall. Formby Channel still separated

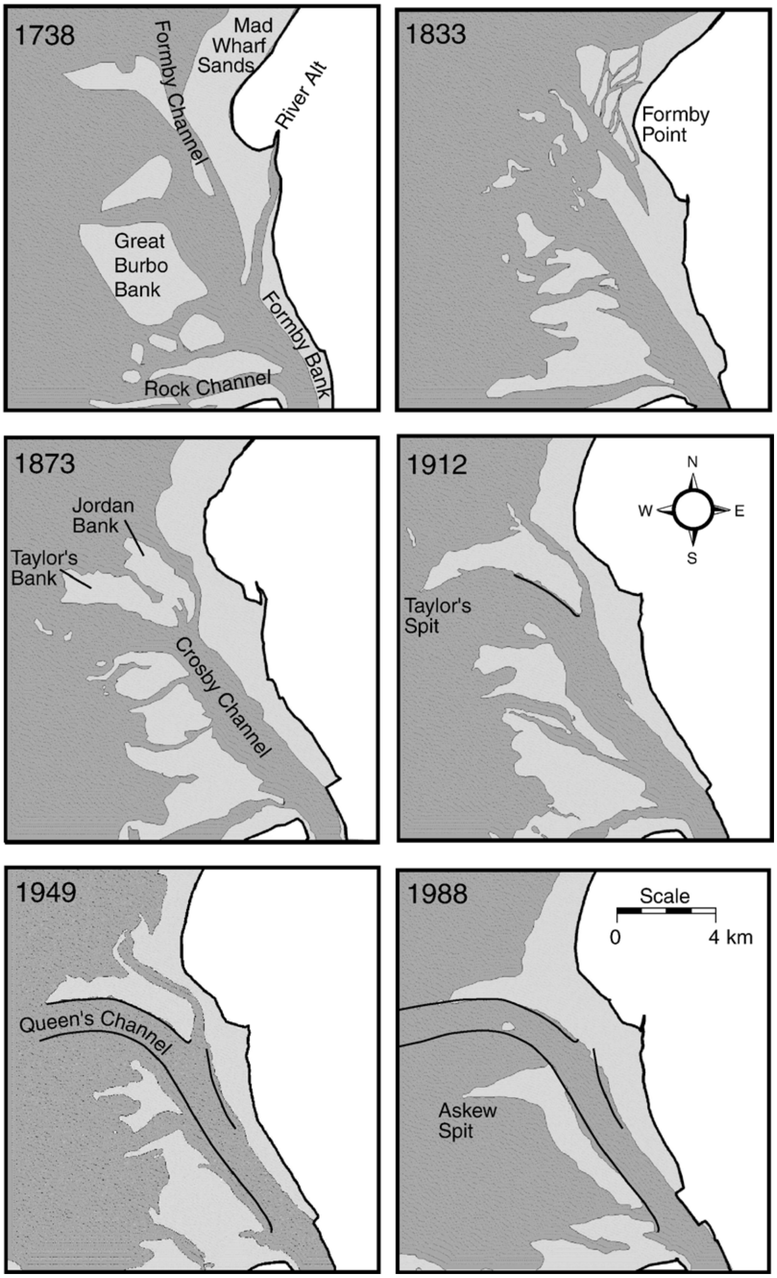


Fig. 3. Position and extent of inter-tidal sand banks and channels in the Outer Estuary, based on a chart by Fearon and Eyes published in 1738 (in Driscoll, 1970) and Admiralty charts (1833–1988). The solid black lines show the position of training walls.

Taylor's Bank from Formby Bank, but its northern end had moved further to the west and was slowly infilling. The channel which dissected Great Burbo Bank in 1912 had moved further north by 1949, and parts of the northern area of the Great Burbo Bank had eroded. The largest change was the complete infilling of the original Rock Channel. However, a separate channel further to the northwest was forming, leaving a larger 'North Bank' on its western side. This new channel is presently called the Rock Channel.

The 1988 chart shows that the depth of the Crosby Channel has been maintained, aided by dredging, but Formby Channel had completely infilled (by 1970), and Taylor's Bank had moved further to the east and become connected to the Sefton coast. The Great Burbo Bank had decreased significantly in size, and the channel

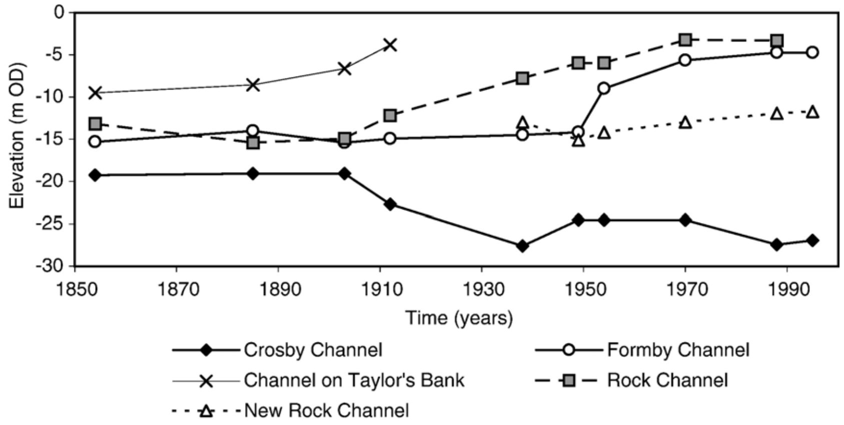


Fig. 4. Changes in maximum depth of sub-tidal channels in the Outer Estuary, based on data from historical Admiralty charts.

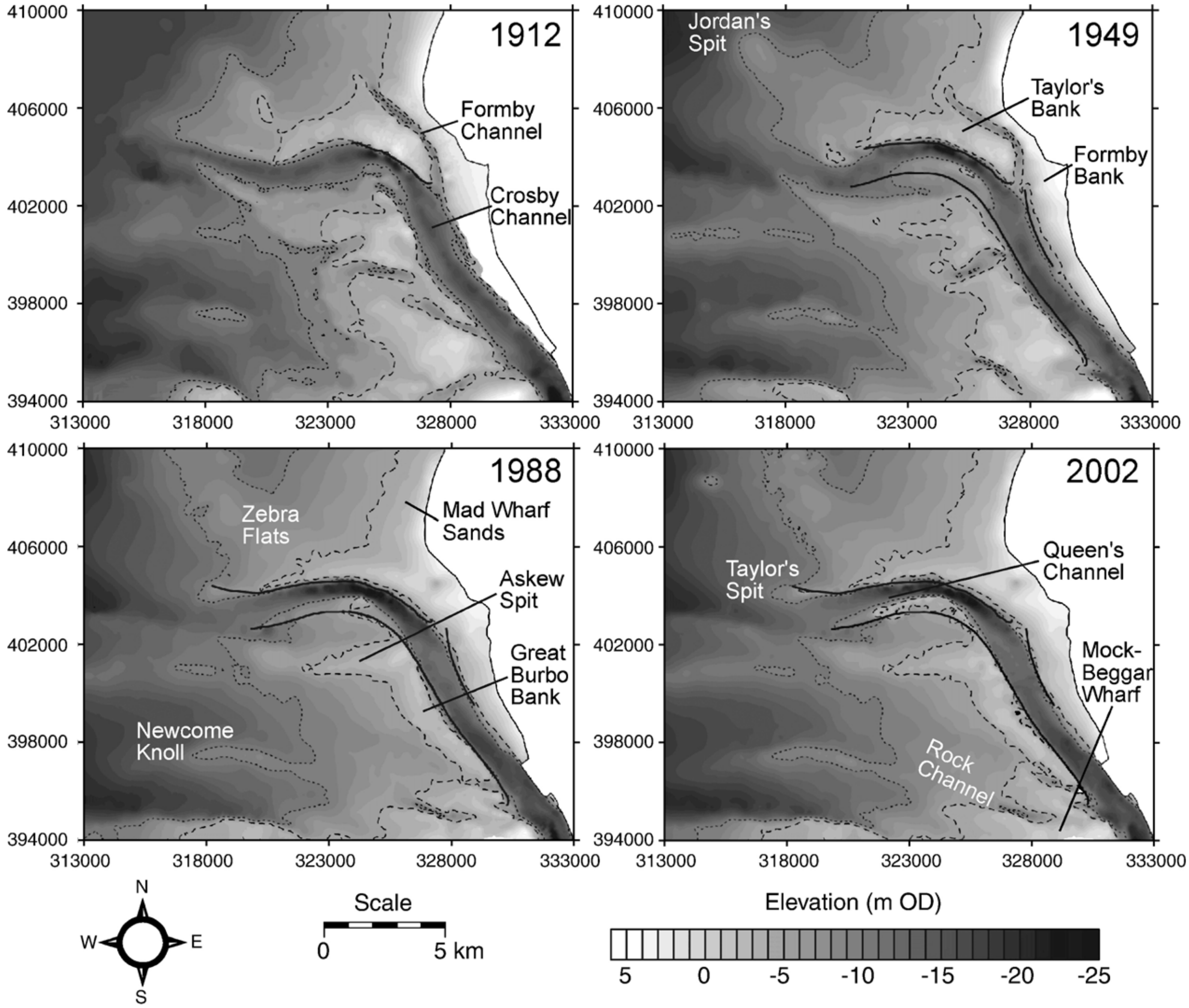


Fig. 5. Changes in the bathymetry of the Outer Estuary and Liverpool Bay, based on Admiralty charts. The dashed lines show the contours at −5 and −10 m OD. The solid black lines show the position of training walls.

which dissected it had infilled, although a new channel had formed to the south of the bank running westwards from Crosby Channel. The 2002 chart shows that Taylor's Bank had moved only slightly further to the east, indicating that the bank has reached an equilibrium position with respect to its retaining training wall. Askew Spit had accreted substantially, encroaching northwards beyond the training wall and into Queens Channel. Taylor's Spit, at the seaward end of Queen's North Training Wall, had also accreted. Great Burbo Bank and Formby Bank were not surveyed between 1988 and 2002.

Spatial patterns of net sediment accretion and erosion in the Outer Estuary between the different chart editions of 1912, 1949, 1988 and 2002, and over the whole period 1912–2002, are shown in Fig. 6, while total accretion and erosion in different areas are summarised in Table 3. The sub-tidal zone of the Outer Estuary experienced net accretion in all three time intervals, but especially during the period 1912–1949. By contrast, the inter-tidal zone experienced net loss of sediment in the first two periods and only slight net accretion between 1988 and 2002.

4.2. Morphological changes in the Narrows, Inner Estuary and Upper Estuary

In 1738 the Inner Estuary contained two main channels, one hugging the southern coastline, and one

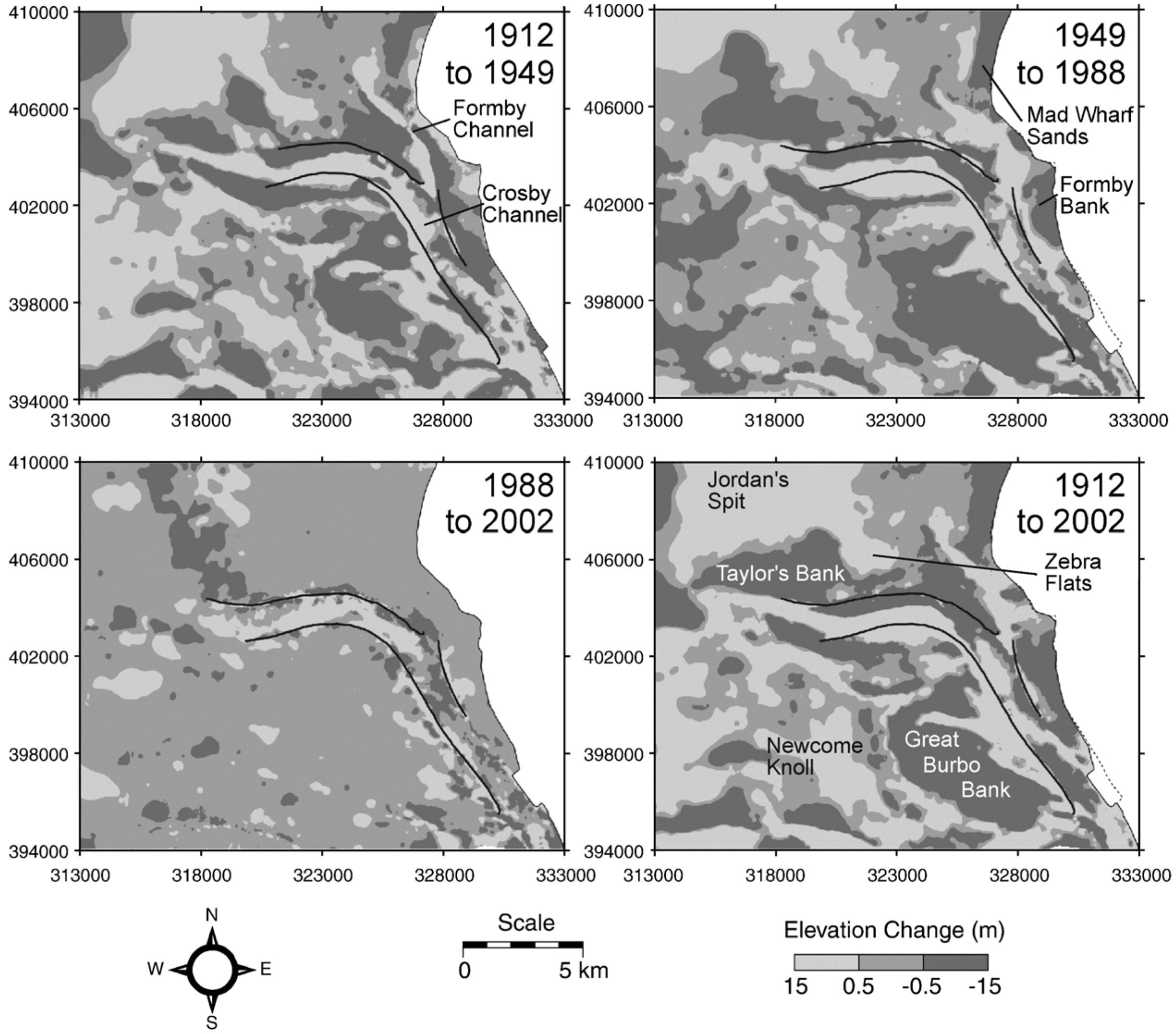


Fig. 6. Bathymetric change in the Outer Estuary and Liverpool Bay over three different time intervals. Positive values indicate net sediment accretion, negative values indicate net sediment erosion. The solid and dashed lines show the positions of the coastline in the recent and historical time periods, respectively.

Table 3
Net change in sediment volume within the sub-tidal zone (between LAT and − 30 m OD) and the inter-tidal zone (between LAT and HAT) in the Outer Estuary, Inner Estuary and Narrows for different time periods

Period	Net change in sediment volume within the sub-tidal zone		Net change in sediment volume within the inter-tidal zone		Net change within the sub-tidal and inter-tidal zones combined[a]		
	($\times 10^6$ m^3)	(% change)	($\times 10^6$ m^3)	(% change)	($\times 10^6$ m^3)	(% change)	(mm a^{-1})
Outer Estuary							
1912–1949	88.04	1.71	− 26.86	− 15.04	61.18	1.15	6.35
1949–1988	10.67	0.20	− 14.84	− 9.78	− 4.17	− 0.08	− 0.41
1988–2002	10.27	0.20	3.73	2.72	14.00	0.26	3.84
Inner Estuary and Narrows							
1906–1936[b]	2.41	0.12	24.29	7.82	26.70	1.15	10.67
1936–1956	18.33	0.90	25.69	7.68	44.02	1.87	26.33
1956–1977	2.92	0.14	0.13	0.04	3.05	0.12	1.67
1977–1997	0.99	0.05	− 7.31	− 2.03	− 6.32	− 0.21	− 3.04

[a] The combined change for the sub-tidal and inter-tidal zones is expressed both as a percentage volumetric change and as average change in bed level.

[b] Figures for the period 1906–1936 are partially estimated due to an incomplete survey in 1906 (see Fig. 7).

running in the north. It was not until about 1842 that three main channels developed in the seaward half (Allison, 1949), a pattern which has persisted to the present day. The 1906 chart (Fig. 7) shows three named channels: Eastham Channel in the south, Garston Channel in the north, and the Middle Deep in the centre. Between the channels, extensive inter-tidal sand banks were present. The Inner Estuary was fringed by flats and saltmarshes, notably around Stanlow, Ince and Score Banks in the south, and at Dungeon Bank in the north. The deepest point of the estuary was at the Narrows (−28.20 m OD). By 1936 the three main channels had become more distinct: Eastham Channel had deepened along its eastside, Garston Channel had narrowed and the Middle Deep had moved to the south. In the eastern half of the Inner Estuary, the main channel had migrated northwards, with significant erosion of Dungeon Bank and substantial accretion of Stanlow and Ince Banks on the southern side. The estuary experienced only minor changes up to 1956, with continued accretion on Ince Banks and Eastham Sands, but by 1977 the main channel had migrated south again, allowing accretion on Dungeon Bank. The southward movement led to erosion of the northern side of Stanlow and Ince Banks, although the marshes continued to accrete vertically. Eastham Sands continued to accrete and increase in area up to 1977, but by 1997 had eroded substantially. However, accretion continued on Stanlow Bank a little to the south. The Middle Deep had infilled to some extent, possibly aided by the dumping of dredge spoil, and the Garston Channel had enlarged, possibly aided by dredging of the approaches to the port of Garston.

4.3. Sediment volume changes in the Outer Estuary

Volume calculations show an average vertical sediment accumulation rate in the Outer Estuary of about 6 mm a^{-1} between 1912 and 1949 (Table 3). The sub-tidal zone (i.e., the zone between the lower plane of −30 m ODN and LAT) gained significant quantities of sediment (Figs. 8A and 8B). In the inter-tidal zone, there was net erosion between LAT and MHWS, with some accretion above MHWS (too small to be seen in Fig. 8A). Change after 1949 was much less marked, with the Outer Estuary experiencing a very slight overall loss of sediment. However, the sub-tidal zone continued to gain sediment.

Figs. 8C and 8D show changes in inter-tidal sediment volumes across the whole of the Outer Estuary and in three specific areas: the inter-tidal areas west of the training walls, including Great Burbo Bank, North Bank and Mockbeggar Wharf; the inter-tidal areas north and east of the training wall, including Taylor's Bank and Formby Bank; and the dredged navigation route through Queen's Channel and Crosby Channel. The inter-tidal areas in the west decreased rapidly in terms of both area and volume between 1912 and 1988, shrinking by ca. 36% of their volume in 1912. Changes between 1988 and 2002 are unknown due to the lack of re-survey data in this area. The inter-tidal areas in the north and east also decreased in volume between 1912 and 1949 (by around 16%), after which time the area showed very little change. Queen's and Crosby Channels experienced a dramatic reduction in sediment volumes between 1912 and 1949, due to training wall construction and dredging, although volumetric changes are small

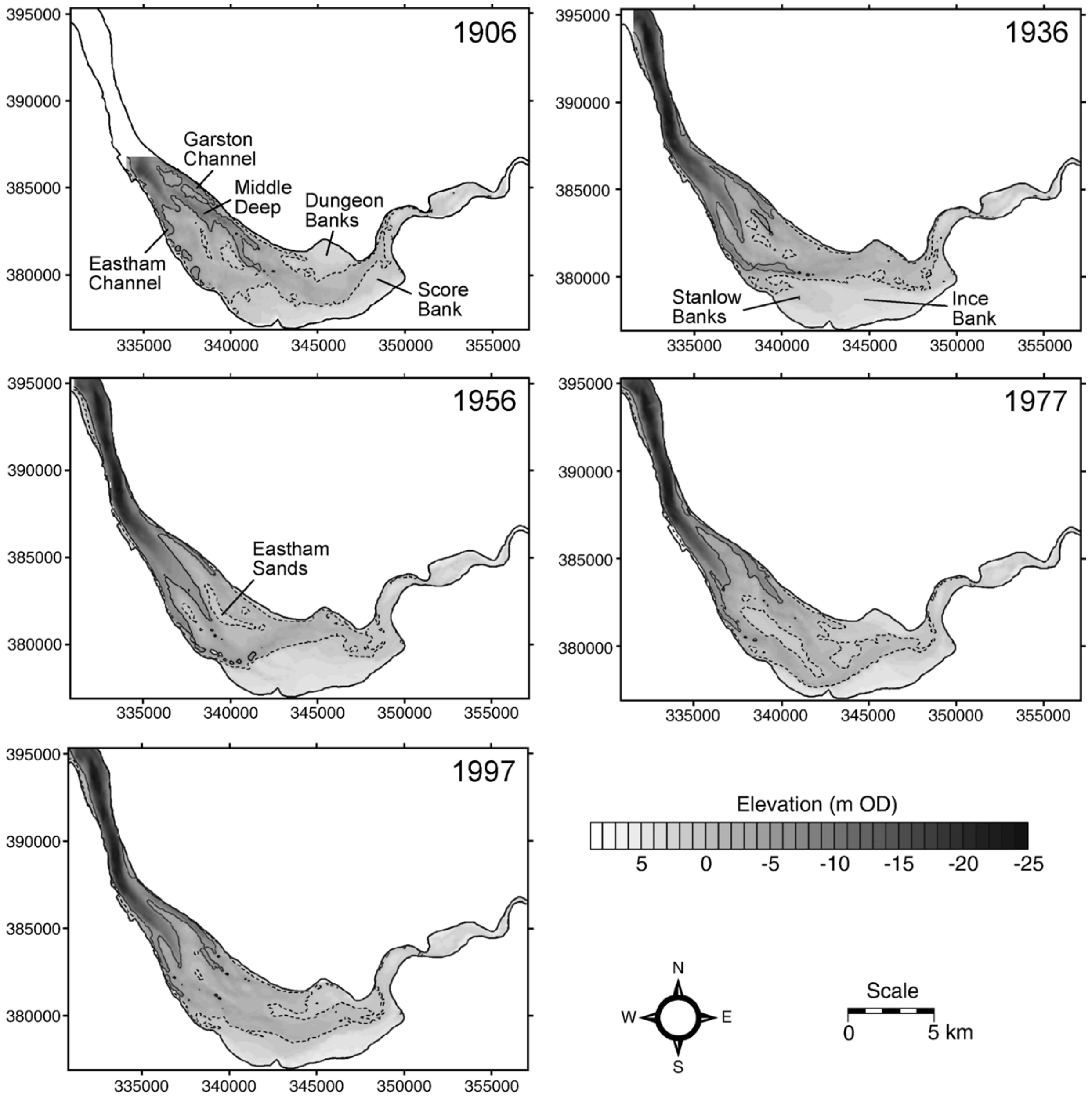


Fig. 7. Bathymetry of the Inner Estuary (including the Narrows), based on surveys by the Mersey Docks and Harbour Company between 1906 and 1997. The dashed and solid lines show the contours at 0 and −5 m OD, respectively.

compared to those outside the training walls. More recently the channels have experienced some infilling, mainly around Askew Spit, despite continued dredging.

4.4. Sediment volume changes in the Narrows, Inner Estuary and Upper Estuary

Figs. 8E and 8F show that between 1906 and 1997 sediment volumes increased in all zones of the Inner Estuary, but particularly in the sub-tidal zone. However, the trend was not constant. Using the data in Figs. 8E and 8F, sediment accumulation rates have been calculated for the inter-tidal and sub-tidal zones (Table 3). While accretion rates were modest at the start of the 20th century, there was significant accretion between 1936 and 1956 (average vertical sedimentation rate of almost 26 mm a^{-1}). This rapid accretion coincided with a marked reduction in channel dredging during the Second World War (see below). After 1956 the Inner

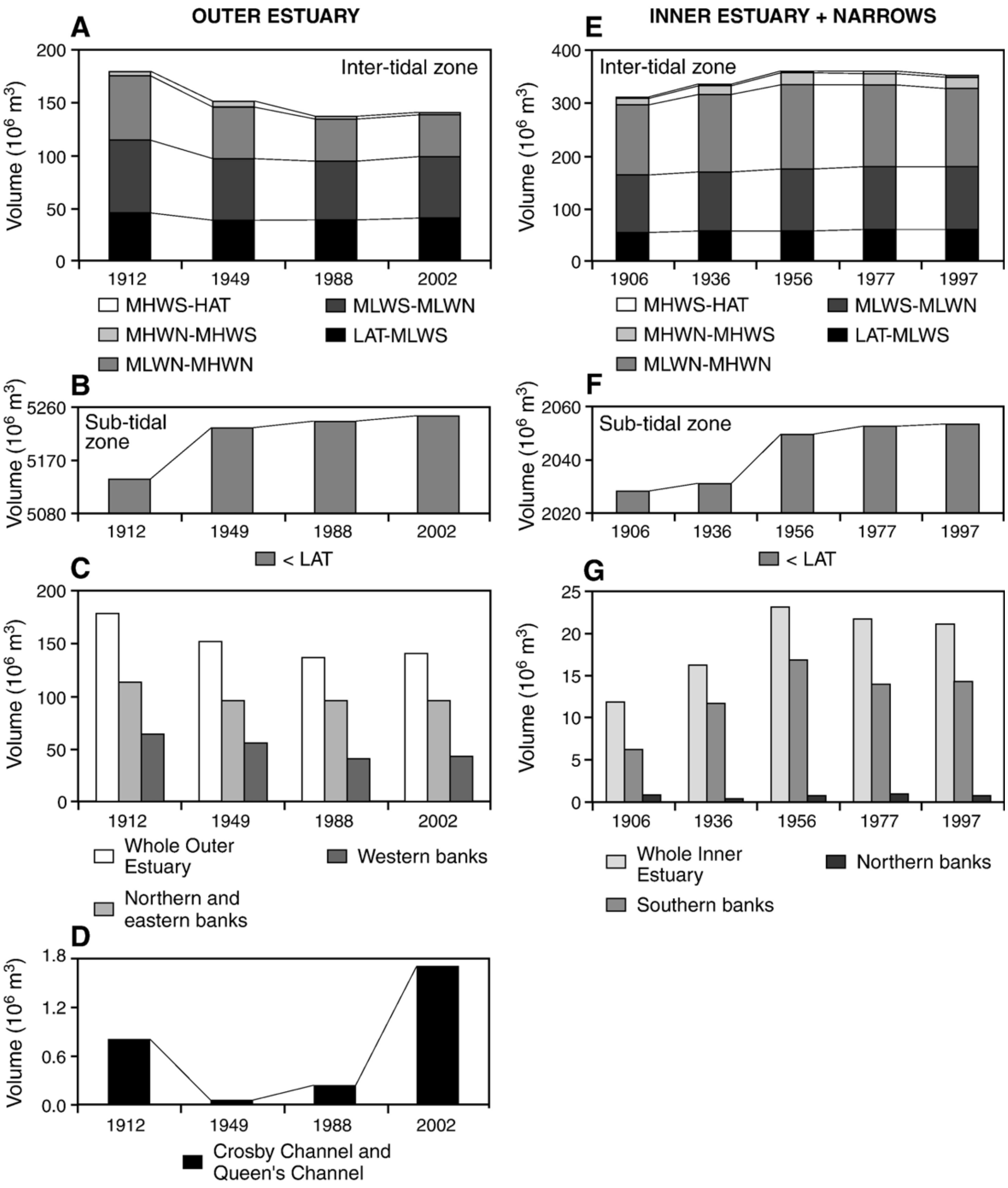


Fig. 8. Changes in sediment volumes in the Outer and Inner Estuary, based on survey data within the areas shown in Figs. 5 and 7. Sediment volumes in the Outer Estuary are calculated for (A) the inter-tidal zone, (B) the sub-tidal zone, (C) sand banks above LAT, and (D) navigation channels above LAT. Sediment volumes in the Inner Estuary and Narrows are calculated for (E) the inter-tidal zone, (F) the sub-tidal zone, and (G) banks between MHWN and MHWS.

Estuary continued to gain sediment in the sub-tidal zone, but the inter-tidal zone experienced slight erosion (average 3.7 mm a^{-1}), mainly in the mid-tide range. These trends are consistent with previous calculations using Empirical Orthogonal Function (EOF) analysis of tidal volumes (Lane, 2004), which indicate a 3.9% reduction in tidal volume between 1936 and 1977, followed by a 0.4% increase up to 1997.

Fig. 8G shows changes in sediment volume between MHWN and MHWS (which is approximately the zone for potential salt-marsh development) over the inter-tidal areas of Dungeon Bank on the northern shore of the estuary, Stanlow, Ince and Score Banks on the southern shore, and over the Inner Estuary as a whole. As discussed above, the southern banks of the Inner Estuary experienced accretion between 1906 and 1956, while the northern banks experienced substantial erosion up to 1936. Conversely, the southern side experienced erosion between 1956 and 1977 while the northern banks experienced accretion. These trends are

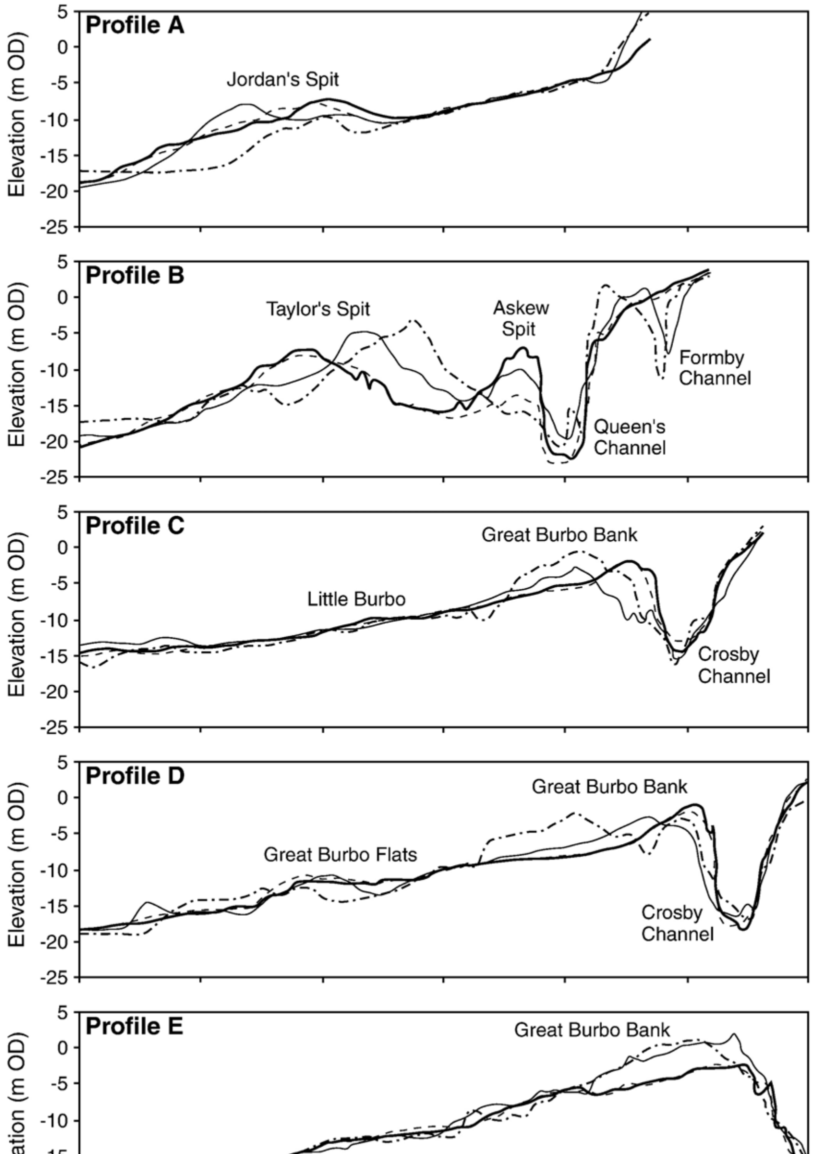


Fig. 9. Cross-sections across the Outer and Inner Estuary, based on bathymetric chart and survey data. Profiles are illustrated facing seaward (west–east or south–north).

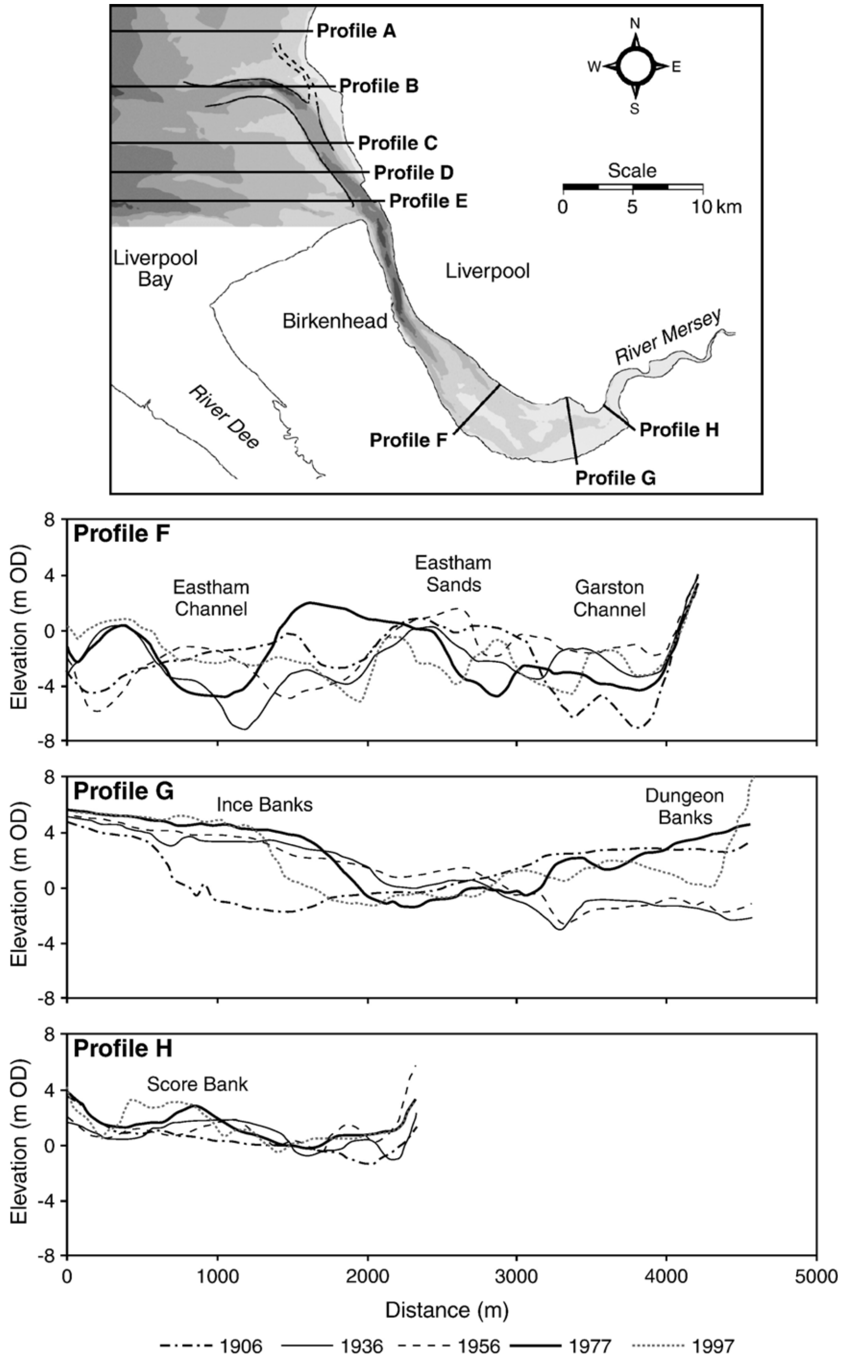


Fig. 9 (*continued*).

attributable to the migration of the main estuary channel which moved northwards between 1906 and 1956 and then southwards between 1956 and 1977. Although the Inner Estuary as a whole has experienced slight inter-tidal erosion since 1977, the southern banks have now stabilised and show recent slight accretion.

4.5. Changes in estuary cross-sections

Sections across both the Outer and Inner parts of the Estuary (Fig. 9) illustrate changes in the individual banks and channels in more detail. Cross-section A shows gradual accretion of Jordan's Spit between 1912 and 1949, and then an eastward migration until 2002.

Cross-section B clearly shows erosion and a westward migration of the top of Taylor's Spit, and substantial accretion of the northern part of Askew Spit. The position of Queen's Channel remained constant over the period, although it experienced some erosion. To the east, Formby Channel infilled and was almost unidentifiable by 1988. Cross-sections C, D and E show an eastward migration of Great Burbo Bank occurred until further movement was inhibited by the construction of the western training wall. This bank has experienced erosion and lowering over time, especially on its western side. The position and depth of Crosby Channel has remained relatively constant over time, as have the extensive sand flats to the west.

Cross-sections F to G in the Inner Estuary show a more complex pattern of morphological change. Cross-section F, in particular, shows large fluctuations in bed level due to lateral changes in the position of Eastham and Garston Channels. One feature to note is the substantial accretion on Eastham Sands between the channels by 1977, which then eroded by 1997. Cross-section G shows continuous accretion on the southern side of Ince Bank over the study period (ca. 2 cm a^{-1} since 1936). The largest increases occurred between 1906 and 1936, after which the northern edge of the banks retreated to the south and the area of the banks was reduced. The erosion of Dungeon Bank between 1906 and 1936 and its subsequent accretion after 1956 are also clearly illustrated on the northern side of the estuary. Temporal changes in morphology become less marked further upstream. Cross-section H shows modest changes to Score Bank, with gradual accretion throughout the study period. Likewise, the Narrows experienced relatively little change due to the underlying hard sandstone bed and the presence of dock walls.

5. Constraints and possible causes of morphological change

5.1. Possible causes of observed morphological changes

The available evidence suggests that, prior to the late 19th century, the Mersey Estuary, like others in northwest England, existed in a condition of dynamic equilibrium. Although there was slow net accretion of sediment in the Outer Estuary and Liverpool Bay, and significant coastal progradation around Formby Point, net changes in the Inner Estuary appear to have been fairly limited, with the capacity of the estuary being held more or less constant as a result of the periodic migrations of the channels (McDowell and O'Connor, 1977; O'Connor, 1987). This situation evidently began to change significantly in the later part of the 19th century, and particularly in the first half of the 20th century. After 1950, the estuary apparently approached a new condition of dynamic equilibrium (as reflected by sediment volume changes). However, since the 1970s a slight net loss of sediment from the Inner Estuary has occurred.

Several factors could have contributed to the observed morphological and sediment volume changes in the estuary. These include changes in natural environmental forcing factors, such as sea level, tidal regime, wave climate and storm surge frequency, or human activities such as training wall construction, channel dredging, embanking, reclamation and port development. Fig. 10 provides a conceptual summary, which is applicable to almost any estuary, of the linkages between environmental constraints, natural forcing factors, human activities and estuary morphology. An expert geomorphological assessment of past and possible future changes in an estuary requires that these constraints, forcing factors and potential linkages are identified and, where possible, quantified. The extent to which this is possible is dependent on the scope and quality of available data. In the case of the Mersey Estuary, the available data are more extensive than for many other estuaries, but there are still significant gaps which give rise to uncertainty. A full discussion of each of the geological constraints, environmental forcing factors and their interactions relevant to the Mersey Estuary is beyond the scope of this paper, but the more important aspects are discussed below.

5.2. Sensitivity of the system to morphological change

The geological framework, antecedent geomorphology and sedimentary characteristics of an estuary to a large extent determine its sensitivity to changes in forcing factors. The Outer Estuary is likely to be relatively sensitive to change because it is largely open to marine influences, although landward movements are restricted by the sedimentary rock framework of the Wirral and Liverpool areas. However, much of the coastline north of Crosby consists of unconsolidated Quaternary sediments which are more easily eroded. In the Narrows, morphological change is severely limited by the surrounding solid rock outcrops. In the Inner Estuary, the low water channels are free to migrate, but the margins of the estuary today are largely fixed by high ground at Helsby, Frodsham and Runcorn, by soft sediment cliffs (e.g., between Garston and Widnes), and by artificial sea walls. Overall, there is little scope for

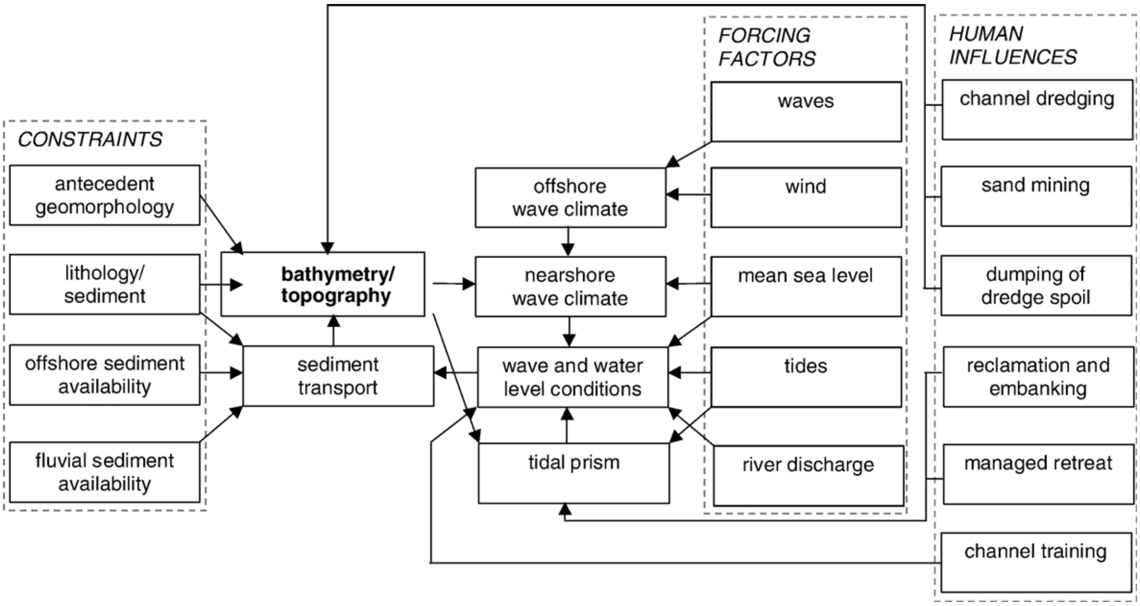


Fig. 10. Schematic representation of constraints and influencing factors on morphological change within an estuary.

broad-scale change in plan form of the estuary, but the pattern of sand banks, channels, tidal flats and saltmarshes is highly sensitive to changes in natural forcing factors or human activities.

5.3. Sediment availability

The floor of the eastern Irish Sea is extensively covered with glacial and fluvio-glacial deposits which have been reworked by tidal currents (Wright et al., 1971; British Geological Survey, 1984). Ramster and Hill (1969) found a long-term residual current movement in an offshore direction near the surface but onshore motion near the sea bed which encourages landward movement of sandy sediment. These patterns were also identified by Price and Kendrick (1963), and are reflected in the migration pattern of sedimentary bedforms in the eastern Irish Sea (Sly, 1966; Belderson and Stride, 1969). The long-term net transport of sediment into Liverpool Bay has resulted in a reduction in average depth (Pye, 1977; Neal, 1993) and has contributed to a net drift of sand into the Inner Estuary, identified by O'Connor (1987). A similar pattern of net landward transfer is also evident in the neighbouring Dee and Ribble estuaries (Pye, 1996; van der Wal et al., 2002). The fluvial supply of sediment to the Mersey has always been small compared to the supply from offshore sources (O'Connor, 1987), and the amount of sediment reaching the estuary was reduced further following construction of the Manchester Ship Canal in the early 1890s (Comber et al., 1993).

5.4. Freshwater discharge

The mean freshwater flow from the River Mersey is about 66 $m^3 s^{-1}$ (Shaw, 1975), compared with a tidal influx into the Narrows of, on average, 2000 $m^3 s^{-1}$ during a spring tide (McDowell and O'Connor, 1977). Despite the limited impact of freshwater discharge on the morphodynamics of the Mersey Estuary as a whole, low water channel movement may be related, at least partly, to the magnitude and duration of river flows. In the Upper Mersey, McDowell and O'Connor (1977) found that the low water channel meandered away from Hale Head during periods of low river flow, and remained close to it during high flows. Freshwater influx from the Mersey and surrounding areas also has an influence on salinity gradients and associated density-driven circulations within Liverpool Bay (Bowden and Sharaf El-Din, 1966). However, there is no evidence that major floods or longer term variations in river discharge have been responsible for major morphological changes within the main parts of the Inner or Outer Estuary.

5.5. Relative sea level

During the period 1860 to 1980, relative mean sea level rose by an average of about 1 mm a^{-1} at Liverpool

(Fig. 11) reflecting the combined effects of changes in mean eustatic sea level, tidal range, and vertical land movements (Shennan and Woodworth, 1992; Woodworth et al., 1999). If continued for any significant period and under unconfined conditions, sea level rise might be expected to cause a landward displacement of the estuary through a process of 'stratigraphic rollover'. However, the total magnitude of recorded sea level rise in the past century (ca. 10 cm) is sufficiently large to affect the elevation and vertical accretion rates on active saltmarshes, but is unlikely to have played a significant role in determining the major changes in the patterns of banks and channels, or sediment volume changes, reported in the earlier sections of this paper. The available data suggest that rapid morphological changes in the estuary began towards the end of the last century (Fig. 4) and were substantially complete by about 1950. The timescale and magnitudes of these changes show no identifiable correlation with recorded changes in mean sea level.

5.6. Tidal regime and density-driven currents

Changes in tidal regime, which may or may not be linked to changes in mean sea levels (Pugh, 1987; Woodworth et al., 1991), can involve variations in tidal levels, tidal volumes, tidal asymmetry and tidal currents. Woodworth et al. (1991) found a secular trend in mean tidal range of 1.30±0.18 mm a^{-1}, using data from Princes Pier, Liverpool, superimposed on a lunar nodal (18.61 years) variation with an amplitude of approximately 10 cm (Woodworth, 1999). The observed secular trend could, however, have been affected by anthropogenic modifications. Woodworth (1999) presented a time series of Mean High Water levels (adjusted for changes in the amplitude of the ocean tide) and found a secular trend for the period up to 1880 of 0.39±0.17 mm a^{-1}, a trend for the 20th century of 1.22±0.25 mm a^{-1}, and an overall low-frequency acceleration of 0.33±0.10 mm a^{-1} per century.

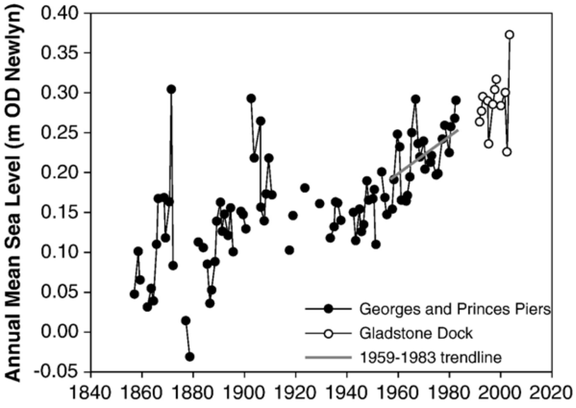


Fig. 11. Historical record of annual mean sea level at Liverpool from gauges at Georges and Princes Piers (1858–1983) and Gladstone Dock (1992–2004). The trendline is for the period of continuous record between 1959 and 1983, used by Woodworth et al. (1999) to calculate an average sea level rise of 2.58±0.88 mm/year. Data from the Permanent Service for Mean Sea Level data catalogue (PSMSL, 2006).

The tidal curve is almost symmetrical in the Narrows (e.g., at Liverpool Princes Pier tide gauge), becoming increasingly flood dominant with distance upstream. Thomas (1999) found that the Inner Mersey had become less flood dominant, especially between 1956 and 1977, and suggested that recent sedimentation changes in the Inner Estuary may be a response to changes in circulation patterns in Liverpool Bay. However, analysis of long-term (63 years) records led Lane (2004) to conclude there has been no significant change in the predominant M_2 and S_2 constituents.

Price and Kendrick (1963) concluded that changes in tidal propagation were not the triggering cause of accretion in the estuary in the later 19th century. Tidal currents in the upper levels of flow at the Narrows were found to be ebb dominant and, therefore, unlikely to be responsible for net transport of sediment into the Inner Estuary. They concluded that tidal residual currents in the Outer Estuary had been affected to a significant degree by the construction of training walls, which enhanced ebb flow in the trained channel and enhanced flood flow on either side of the trained channel. Bowden and Sharaf El-Din (1966) also suggested that the import of sediment into the Inner Estuary following the construction of training walls was accentuated by density currents. More recent hydrodynamic modelling work by Thomas et al. (2002), using historical bathymetries for the years 1906, 1936 and 1977, provided support for the hypothesis that there was a significant increase in the supply of sediment into the mouth of the Inner Estuary during the period of peak accretion, but that this increase was due not only to the direct effects of the training walls but also partly to the existence of a salinity-induced gravitational circulation within the estuary and wider Liverpool Bay system. However, this hypothesis cannot be considered to be fully proven.

5.7. Wind and wave climate

Pye and Neal (1994) found that strong winds along the coast of the southeastern Irish sea, which blow predominantly from the southwest and west, were relatively more frequent between 1914 and 1930, and that the late 1930s and 1940s were characterised by a low incidence of strong winds. There was an increase in windiness in the late 1940s until the early 1960s, followed by a further period of quiescence. The frequency of winter gales at Bidston Observatory on the Wirral was especially high between 1880 and 1905 and may have contributed to the onset of erosion at Formby Point around this time and to possible enhanced movement of sand towards the Mersey and Ribble estuaries. Periods of increased wind strength in this area generally correlate with an increase in the frequency of winds from the southwest. During the period 1861 and 1992, there was a rough cyclicity in the frequency of 'westerly weather type' (as defined by Lamb, 1982) across the British Isles, with an increase in the number of days of this weather type in the first half of the 20th century; however, studies have indicated only a poor correlation with wind data recorded at stations close to the Mersey Estuary (Jay, 1998).

The effects of changes in wind conditions on wave regime, currents and sediment transport are poorly quantified. The relative importance of changes in the frequency of extreme events, such as storm surges, relative to changes in longer term 'average' conditions, is an area of particular uncertainty. Individual storm events are known to have brought about significant erosion, leading to re-distribution of sediment, along the shorelines of both the Outer and Inner Estuary (e.g., Pye, 1991). However, their effect on long-term sediment movements at the whole estuary scale is much less clear.

5.8. Land reclamation

Compared with the neighbouring estuaries of the Dee and Ribble, there has been relatively little land reclamation in the Mersey Estuary. The main areas affected are dock developments close to Liverpool, including the container terminal at Seaforth, and the area around Ince Banks on the south side of the Inner Estuary affected by the building of the Manchester Ship Canal between 1887 and 1893. A total of 492 ha had been reclaimed by the end of the 19th century (Royal Commission on Coastal Erosion and Afforestation, 1911). However, these reclamations have had only a small effect on the tidal prism of the Mersey Estuary. O'Connor (1987) calculated that the direct loss of capacity of the estuary due to land reclamation since 1861 was about 12×10^6 m^3.

5.9. Channel training and dredging

The approaches to the River Mersey have been dredged since 1833. Prior to the 20th century, the main navigation route into the Port was via the Queen's and Crosby Channels, although smaller ships made use of Formby and Rock Channels. Competition for the Atlantic trade led to regular dredging of the Mersey Bar after 1890. By 1894 annual dredging rates reached

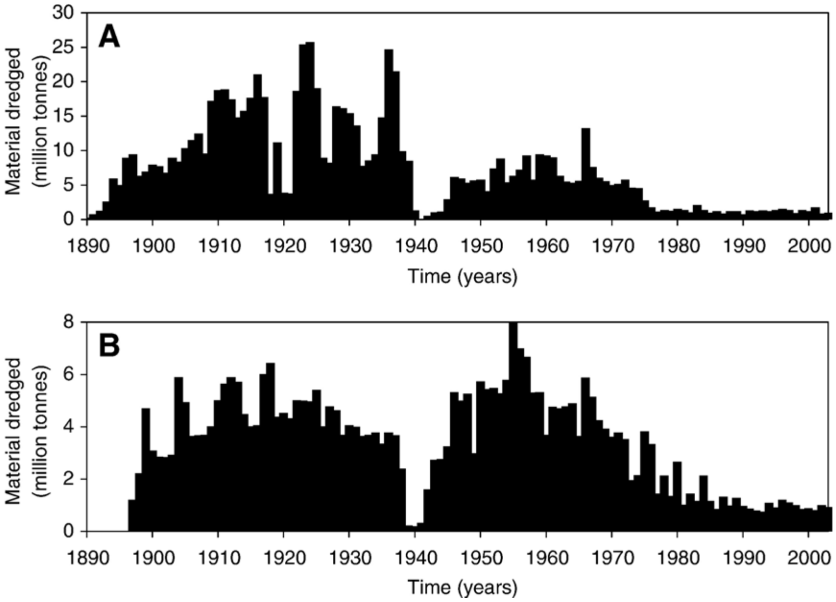
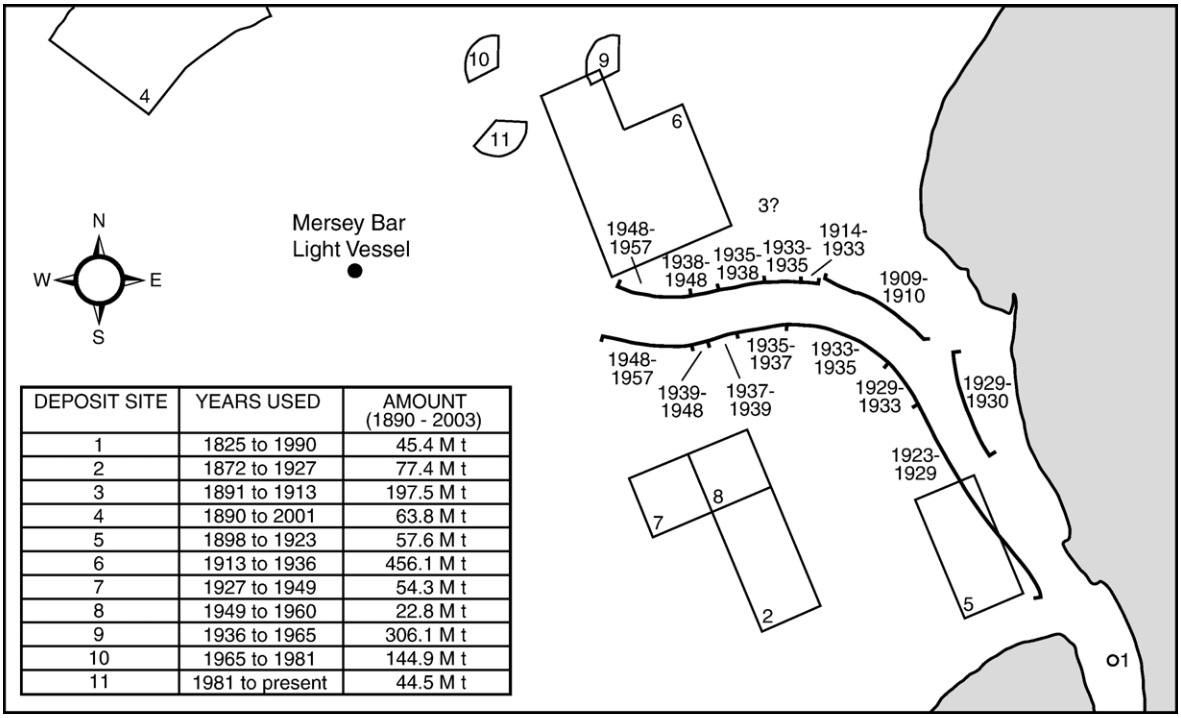


Fig. 12. Quantities of material dredged from (A) the Outer Estuary (Crosby and Formby Channels) between 1890 and 2003 and (B) the Inner Estuary and Narrows between 1897 and 2003, expressed in metric tonnes (wet weight). Data are collated from annual reports of the Conservator of the Mersey.

5 million tonnes (Fig. 12), and although the depth of the channel could be maintained at ca. −13.4 m OD, the position of the channels could not be stabilised. Consequently, in 1909, work began to construct a 3.6-km-long training wall along the face of Taylor's Bank on the outside of the Crosby Channel bend (Fig. 13). The intention was to prevent the continued northward movement of the channel and also to prevent a channel from breaking through Taylor's Bank (Agar and McDowell, 1971; McDowell and O'Connor, 1977). The wall was constructed from limestone blocks, 10–200 kg in weight, to a height of ca. −3 m OD. However, although erosion of Taylor's Bank was stabilised, continued dredging was required within the channel to counter accretion on Askew Spit (which was causing a narrowing of Crosby Channel) and on shoals closer to the Narrows. Between 1910 and 1957, the training walls were extended westwards, and new training walls were built to either side of Crosby Channel (Fig. 13). The walls succeeded in reducing the need for dredging, which declined from 25 million tonnes in 1924, to between 5 and 9 million tonnes after the Second World War (Fig. 12). Most of the dredged material was dumped at a number of sites in the Outer Estuary and Liverpool Bay (Fig. 13).

Dredging of the Inner Mersey began around 1897, although not on the same scale as in the Outer Mersey. Except during the war years, 3–6 million tonnes were extracted annually up to 1976, mainly from Eastham Channel which is the main approach to the Manchester Ship Canal. With the closure of many of the older docks and the seaward migration of the newer docks, the amount of dredged material in the Inner Estuary has been reduced in recent years to ca. 1 million tonnes/year. The combined total for the estuary (excluding the Manchester Ship Canal) is now ca. 2 million tonnes/year (Fig. 12). In recent years, dumping of dredge spoil has been restricted to one area in the Outer Estuary (site 11 on Fig. 13), at Garston Rocks and Middle Deep in the Inner Estuary, and ashore at Frodsham Marsh.

The available evidence strongly suggests that dredging, training wall construction and dredge spoil disposal were the most important factors affecting the morphology and distribution of sediment in the estuary in the last 100 years. As a result of these activities in the Outer Estuary, the ebb flow in the Rock Channel was reduced and the flood-dominated zones adjacent to the trained channel extended and moved inshore (Price and Kendrick, 1963; McDowell and O'Connor, 1977). Consequently, the Rock Channel and Formby Channel



DEPOSIT SITE	YEARS USED	AMOUNT (1890 - 2003)
1	1825 to 1990	45.4 M t
2	1872 to 1927	77.4 M t
3	1891 to 1913	197.5 M t
4	1890 to 2001	63.8 M t
5	1898 to 1923	57.6 M t
6	1913 to 1936	456.1 M t
7	1927 to 1949	54.3 M t
8	1949 to 1960	22.8 M t
9	1936 to 1965	306.1 M t
10	1965 to 1981	144.9 M t
11	1981 to present	44.5 M t

Fig. 13. Training wall construction and dredge spoil dumping sites in Liverpool Bay (modified after Smith, 1982). Quantities of material deposited are collated from annual reports of the Conservator of the Mersey and expressed in millions of metric tonnes (wet weight).

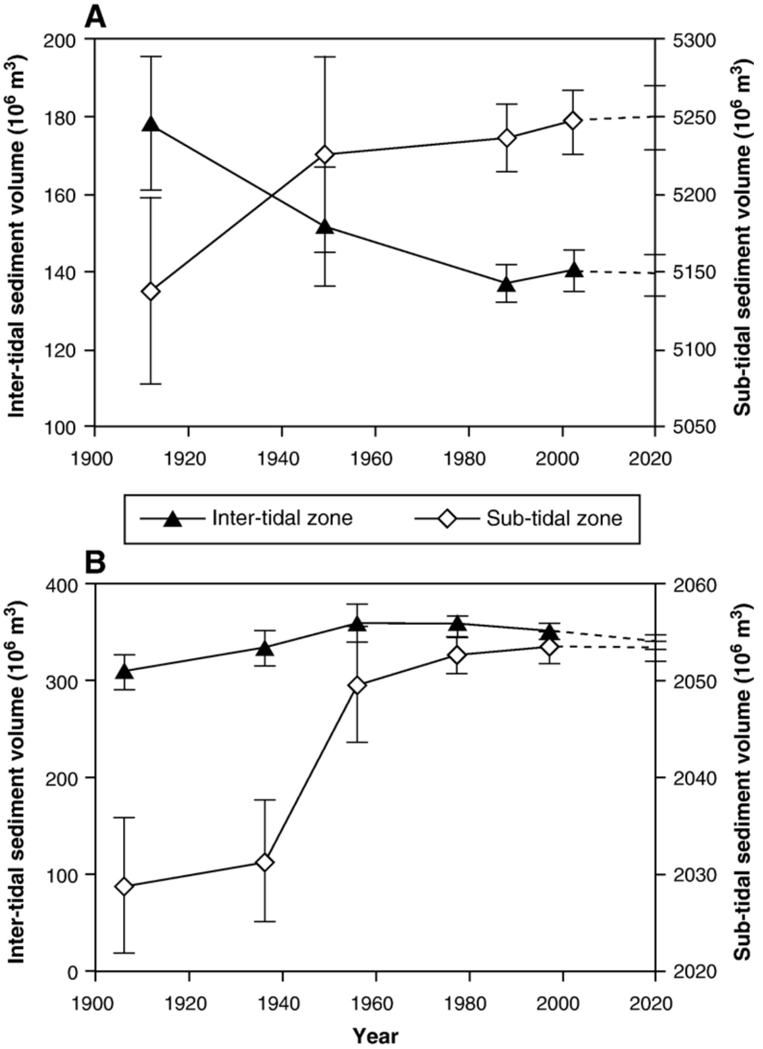


Fig. 14. Changes in inter-tidal and sub-tidal sediment volumes in (A) the Outer Estuary and Liverpool Bay between 1912 and 2002 and (B) the Inner Estuary and Narrows between 1906 and 1997, and predicted future changes in sediment volume to 2020 based on Expert Geomorphological Assessment.

filled in at an accelerated rate (Figs. 5 and 6). This infilling was further assisted by dredge spoil drifting into the channels from dump sites on Taylor's Bank and Great Burbo Bank (Halliwell, 1973). Reduced ebb flow also gave the strengthened flood tide a longer time period to move sediment inshore, causing an eastward migration of Taylor's Bank and Great Burbo Bank. While Taylor's Bank eventually amalgamated with Formby Bank, eastward migration of Great Burbo Bank was inhibited by the training wall, leading to erosion along its western flank. Some sediment overtopped the wall and entered the Inner Estuary (McDowell and O'Connor, 1977) until the height of the training wall was raised by 2 m in 1962 (Associated British Ports, 2002).

Dredging and dredge spoil dumping also altered the bathymetry, with likely implications for wave-induced sediment transport. Modelling by Pye and Neal (1994) suggested that increased water depths at the Mersey Bar and Crosby Channel, due to dredging, combined with decreased water depths at Jordan's Spit due to spoil dumping, and the infilling of Formby Channel, probably had a major effect on the wave regime around Formby Point, contributing to a change from frontal dune accretion to erosion in this area after 1900. While some of the eroded sand has moved southwards towards the Mersey Estuary, a greater proportion has moved towards the Ribble Estuary (Pye and Neal, 1994; van der Wal et al., 2002). A significant part of the sand moving south towards the Mersey has become trapped in the beach–dune system between Hightown and Seaforth.

6. Discussion and conclusions

The Mersey Estuary has experienced major changes during the last 150 years. The morphological changes have been especially apparent in the Outer Estuary, which is largely unconfined and has a high level of sensitivity to change. The Inner Estuary, upstream from the Narrows, is largely constrained by rock outcrops, sedimentary cliffs and artificial embankments, and most of the changes have occurred by way of re-distribution of sediments between and within the inter-tidal and sub-tidal zones, within a more or less fixed overall estuary plan form.

The main period of morphological change occurred between the late 19th century and ca. 1950. The most obvious feature of this period was large-scale movement of sediment into both the Outer Estuary and the Inner Estuary. In the period since 1950, and more particularly since the late 1970s, the estuary appears to have approached a new condition of dynamic equilibrium, and the rate of sediment movement into the estuary slowed markedly between 1950 and 1977; in the last 25 years the Inner Estuary has experienced a slight net loss of sediment. Fig. 14 presents a summary of the overall changes in inter-tidal and sub-tidal sediment volumes in the Outer Estuary and Inner Estuary between 1912 and 2002, based on the analysis undertaken in this study. Also shown in the figure are predicted future changes in sediment volumes based on expert geomorphological assessment, taking into account recent historical trends.

Analysis of the available evidence relating to constraining factors, environmental forcing factors and human interventions in the system strongly suggests that the main factors triggering the sudden changes after the late 19th century were dredging and training wall construction carried out to improve navigation access to the docks at Liverpool, Birkenhead and further up the estuary. These works had the effect of concentrating the ebb tidal flow in the main channel through the Outer Estuary, producing flood-dominated zones outside the trained area, and allowing sediment from dredge spoil disposal and further offshore to infill the adjacent channels. Dredging of the channels in the Inner Estuary, leading to the Manchester Ship Canal and docks such as Garston and Tranmere, also probably contributed to enhanced movement of sediment by creating 'accommodation space' within

Table 4
Quantities of sediment dredged from and deposited in the Outer Estuary, Narrows and Inner Estuary (excluding the Manchester Ship Canal), expressed in millions of metric tonnes (wet weight)

	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	Total
Total amount dredged from the Outer Estuary of which:	0.57	1.14	1.07	1.14	1.06	1.21	1.35	1.22	0.74	1.23	1.03	1.61	0.68	0.81	14.87
deposited in the Inner Estuary	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.00	0.08
deposited in the Outer Estuary	0.57	1.13	1.07	1.12	1.05	1.21	1.35	1.22	0.74	1.22	1.02	0.96	0.67	0.81	14.15
deposited ashore	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.64	0.00	0.00	0.64
Total amount dredged from the Inner Estuary and Narrows (including the docks) of which:	1.59	1.51	1.43	1.48	1.72	1.60	2.01	1.46	1.43	1.35	1.35	1.37	1.42	1.29	21.00
deposited in the Inner Estuary	0.23	0.21	0.24	0.23	0.43	0.30	0.55	0.42	0.42	0.37	0.42	0.39	0.56	0.53	5.31
deposited in the Outer Estuary	0.87	0.88	0.89	0.96	0.97	0.94	1.17	0.76	0.70	0.60	0.55	0.57	0.46	0.35	10.66
deposited ashore	0.49	0.42	0.30	0.29	0.32	0.35	0.29	0.28	0.31	0.38	0.38	0.41	0.40	0.42	5.03
Net change in the Outer Estuary	0.87	0.88	0.89	0.94	0.97	0.94	1.17	0.76	0.70	0.59	0.53	− 0.09	0.45	0.34	9.94
Net change in the Inner Estuary and Narrows	− 1.36	− 1.29	− 1.19	− 1.23	− 1.29	− 1.29	− 1.45	− 1.04	− 1.01	− 0.97	− 0.91	− 0.97	− 0.85	− 0.76	− 15.61

Data are collated from annual reports of the Conservator of the Mersey.

the Inner Estuary. While some of the material from the Eastham Channel, Garston Channel and associated docks has been (and still is) deposited within the Inner Estuary, most has been deposited in the Outer Estuary (Table 4), with some deposited onshore.

The slight reduction in sediment volumes in the Inner Estuary since 1977, and the corresponding increase in water volumes reported by Thomas et al. (2002), may be related to a combination of the effects of continued dredging, a reduced rate of sediment supply from the Outer Estuary to the Inner Estuary, and rising mean sea level. At the present time, the amount of sediment entering the system from all sources appears to be less than the amount leaving the system naturally or artificially as a result of dredged material disposal. Although the continued requirement for dredging in the Eastham and Garston Channels, and within the docks, reflects continuing sedimentation in these areas, the source of the material is likely to be inter-tidal banks and flats within the Inner Estuary.

Under these conditions the estuary is likely to be relatively more sensitive to the effects of changes in natural forcing factors, such as mean sea level, tides, waves and storm surges, than in the earlier period when adjustments to training wall construction and dredging in the Outer Estuary were dominant. Any significant remobilization of contaminated sediments within the estuary could have significant implications for water quality and habitat conservation. The Mersey Estuary has been a relatively polluted estuary for many decades, and its high-energy regime means that there is a high potential for erosion and re-distribution of contaminated sediments (Hartnett et al., 2005). Any acceleration in the rate of sea level rise in the coming decades would tend to favour an increase in water depths, tidal prism and current velocities, increasing the potential for sediment reworking both by waves and currents. For all these reasons, further work is required to investigate the potential sensitivity to erosion of different sediment bodies within the estuary, and to assess the likely impacts of further changes in both natural and anthropogenic forcing factors.

Acknowledgements

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