HISTORICAL TRENDS ANALYSIS

Method Indicator		
Bottom-Up	Hybrid	Top-Down
		YES

Summary of key issues

Issue	**Description**
Description	Data assessment from different periods in time, in order to identify directional trends and possibly rates of change of morphological features or physical processes within an estuary.
Temporal Applicability	Medium-term depending on data availability.
Spatial Applicability	Whole estuary or specific geomorphological features / geographical locations within an estuary, depending on data availability.
Links with Other Tools	• Complements longer-term geological analysis approaches. • Can provide useful data to inform regime analyses. • Provides key input to establishing a conceptual understanding of the longer-term estuary behaviour during synthesis of results or Expert Geomorphological Assessment (EGA).
Data Sources	Published papers, parliamentary records, land registry archives, anecdotal evidence, maps and charts, aerial photography, topographic and bathymetric surveys, remote sensing imagery.
Necessary Software Tools / Skills	• Identifying, collating and reviewing relevant data / information sources. • GIS / image processing software / photogrammetry. • Cartography / digital ground measurement. • Geomorphological interpretation of output.
Typical Analyses	• Changes in shoreline position (e.g. MHW, MLW). • Changes in channel/bank morphology or position. • Changes in sediment volumes above specified datums. • Identification of areas of 'cut' and 'fill' or erosion/recession, or deposition/progradation over time.
Limitations	• Availability of historical data can be limited in some areas. • Accuracy of some historical datasets can be questionable. • Different measurement techniques, specifications, datums, units, density of data points in successive datasets. • Identifies net change between successive datasets, but not the scale of variability over shorter timescales. • Need information on anthropogenic intervention which is often not well documented. • Many estuaries can exhibit long relaxation (lag) times before changes are apparent, making cause-consequence assessments difficult. • Past trends are not always a good indicator of future behaviour.
Example Applications	• Humber Estuary • Ribble Estuary • Mersey Estuary • Southampton Water

Introduction

Historical Tends Analysis (HTA) is a geomorphological tool which utilises the analysis of data relating to a particular physical process or morphological feature from different time periods, in order to identify directional trends and, if quantifiable, rates of changes in that process or feature. HTA focuses on temporal morphological variation within estuaries, and complements Holocene Analysis, considering morphological change over historical rather than geological times, typically the last 1-200 years.

Whilst the approach can relate specifically to physical processes, such as long-term sea level trends, it more frequently relates to many different aspects of historical and ongoing estuarine morphological behaviour, such as erosion or progradation of intertidal saltmarshes, changes in the position or morphology of estuarine channels and banks, or changes in the location of spits across estuary mouths.

It is also important that historical changes are attributed, in so far as is possible, to likely causes of morphological change in terms of the historical and ongoing forcing or constraints imposed on the system. This could take the form of trends or changes in natural forcing (such as sea level rise, changes in rainfall, wind or wave patterns, changes in current speed and direction, natural changes in rates of sediment supply as stocks become extinguished, etc.) or perturbations to the estuary system caused by anthropogenic activities (such as estuary-scale responses to major engineering works like training walls, reclamation, dredging, water abstraction, flood defences, re-alignment, barrages, etc.). If the causes of historical and ongoing morphological change can be identified, then a good understanding can be developed of the cause-consequence or process-response relationships in the estuary, which can in turn provide a useful indicator of possible directions and rates of future morphological responses. If such causes cannot be identified, then the data can be misleading. In addition, responses to some changes can occur over long timescales.

Forms of HTA have been applied, with varying degrees of sophistication, to estuarine environments for many years for the purposes of both research and management. Within the UK Estuaries Research Programme Phase 1 (ERP1), HTA was applied to several UK estuaries leading to a degree of formalisation of the approach (EMPHASYS Consortium, 2000a; 2000b; 2000c).

Data requirements

The key limitation to the application of HTA is the availability of historical data covering the estuary under consideration. Data quality and quantity will determine more precisely the application of the technique, the extent to which the assessment can be quantified, and the degree of confidence that can be placed in the results. Commonly, data coverage for a particular estuary is available at irregular time intervals and with incomplete spatial coverage. Nonetheless, there will be at least some historical data for most estuaries in the UK that can be used for purposes of HTA. This may involve qualitative assessment of the first and most recent edition Ordnance Survey maps to identify broad changes (or otherwise) in features.

A historical time series is required to apply the technique more thoroughly. For estuary morphology, navigational charts are the main source of such data although there are some limitations associated with these datasets. In many cases, charts will be available, either from the Admiralty or local port authority, spanning a long period of time providing suitable records for assessing and quantifying morphological change. Navigational charts can be supplemented with other data sources, such as aerial photographs, LiDAR or CASI data, Environment Agency or local authority surveys, etc.

To correlate recorded morphological change with potential causes of change, data is also required defining both processes and anthropogenic change. This may include time series data relating to water levels, waves, flows (tidal and freshwater), sediment types, etc. Data on anthropogenic influence may include records relating to land reclamation, maintenance and capital dredging, aggregate dredging, dredged spoil disposal, flood defence / coast protection, training wall construction and anecdotal evidence.

Further supporting information (e.g. significant changes such as channels switching, sealing or opening, bank crests altering, key erosion or flooding events, abstraction, construction of major engineering works, etc.) can be derived from newspaper articles, published papers, parliamentary records, land registry records, local and county archives, archaeological records, studies by local historians and local anecdotal evidence. Output from the ERP1 Uptake Project (FD2110) provides some historical data for a selected sample of UK estuaries (Defra, 2003).

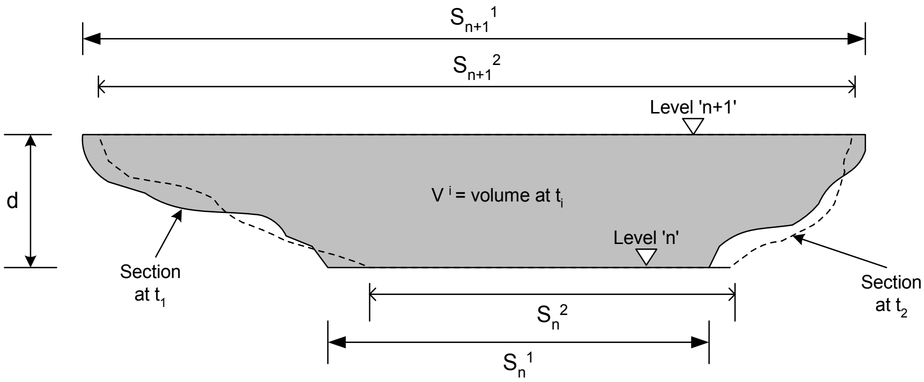
The reliance of the technique on an adequate historical data coverage (most essentially covering bathymetry and anthropogenic intervention) acts to restrict the extent to which HTA can be applied in certain estuaries. Reference should also be made to the Data Requirements supporting document.

Application

The following section provides details of a generalised procedure for applying HTA, with specific examples of its application to assess changes in estuary bathymetry presented in Box 1.

Box 1. Use of hypsometry data to identify specific changes

Ignoring sea level rise and the need to take account of moving surfaces, within a fixed vertical frame changes are a result of movements of the channel bed as illustrated below, for time intervals, t_1 and t_2 and a channel cross-section between level 'n' and level 'n+1'.



The volume of water over the channel side: $v_n^i = V_n^i - S_n^i{*}d$

From which the change in volume over the channel side: $\Delta v = v_n^1 - v_n^2$ (+ve=accretion of bed)

Area over the channel side: $s_n^i = S_{n+1}^i - S_n^i$

And again the change in are over the channel side: $\Delta s = s_n^1 - s_n^2$ (+ve=reduction in area)

So that the "average" depth change over the channel side is: $\delta = \frac{v_n^1}{s_n^1} - \frac{v_n^2}{s_n^2}$ (+ve=accretion of bed)

Given the time interval between surveys, the associated rates of change can be calculated.

Data processing

Most historical datasets are unavailable in a digital format and consequently a degree of digitisation is to be anticipated if the data is to be used for anything other than visual comparative assessments. This stage may require key skills in cartography and/or GIS and, if required, is likely to be one of the most time-consuming elements of the procedure.

Data analysis

Historical data can be analysed in several ways including visual comparisons of successive datasets to identify broad changes in morphology, such as the location of channels and banks, the extent of intertidal area, and changes in shoreline alignment (e.g. due to reclamation). Further information can be yielded by digitally overlaying successive surveys and computing changes, for example in saltmarsh area or bed levels. These datasets can also be used to determine additional parameters to support other assessment tools. For example, a digital ground model of a historical estuary bathymetry can be used to extract planimetric values or estuary cross-sectional areas to inform various types of regime analyses.

Quantitative means of assessing estuarine morphological changes include:

- 'Standard' statistical methods (e.g. mean and variance in a particular parameter over time);
- Direct observation of changes (e.g. volumetric analysis, changes in plan form position, etc.); and
- Advanced statistical methods (e.g. Empirical Orthogonal Function (EOF) analysis based on eigenfunctions).

Each analytical approach has its own advantages and limitations and often a more complete picture of historical change can be determined by using a number of these HTA approaches in combination.

Data Interpretation

Output from HTA needs to be interpreted with due care and full awareness of the limitations of the supporting data and associated processing/analytical approaches. Interpretation should be related to the observed trends or rates of change to causative effects, such as altered forcing conditions (e.g. due to long-term sea level changes) or constraints to the estuary system (e.g. anthropogenic intervention). It is important that output from HTA, with its associated limitations and scales of error explicitly noted, are incorporated within the synthesis of results (Expert Geomorphological Assessment).

Data issues

Potential issues arising from using historical data to assess historical change are likely to introduce errors when using sequential datasets to quantify temporal variability. Issues can arise due to several factors including changing survey techniques; variations in sampling density over time and across different areas of an estuary; and, the use of different datums in surveys.

There are several possible ways in which each data issue can be considered when applying the HTA technique. These fall into three generic categories:

- Qualitative Assessment: making a qualitative assessment of the likely importance of a particular data issue on a study-specific basis;

- Error Assessment: quantifying the likely magnitude of the error introduced by the issue; and,
- Data Corrections: correcting the data to remove any error introduced by a particular data issue.

The degree to which any data issue will require addressing using any one of the three above approaches will vary between studies and issues but is dependent on the following:

- The nature and purpose of the study;
- The nature of the data;
- The perceived sensitivity of recorded morphological change to each issue; and
- The nature of the particular data issue.

Standard correction levels or error limits cannot be applied to each of the data issues; they have to be applied to each dataset being utilised. Each issue requires consideration on an individual and site-specific basis.

Survey techniques

Technological advances have allowed survey techniques (e.g. bathymetry) to become more accurate. This has implications for temporal variation in both the vertical and horizontal accuracy of the resulting charts. Additionally, the resolution and coverage of data points collected in surveys has changed with the ways in which survey techniques have progressed.

Error in the method of vertical measurement

Systematic errors

Data on early hydrographic charts was collected using a lead line, with a correction to the depths obtained to account for the effects of flows. This technique had the potential to introduce errors particularly in fine sediments where the lead line could settle below the bed level; and (ii) the lead line may not settle to record an accurate depth on a slope, therefore overestimating depths.

Lead lining was replaced in the 1930’s by single beam echo-sounders. This was more accurate, although data errors were still common. The subsonic frequency of early echo-sounders led to some penetration through soft muddy sea beds prior to signal reflection (van der Wal and Pye, 2003). The introduction of ultra-sonic echo-sounders meant reflection occurred at the top of fluid mud overlying the actual solid bed (Wilkinson *et al.*, 1973). Modern multi-frequency equipment is now capable of overcoming this problem.

Variation in the data’s vertical accuracy used to compile navigational charts over time could potentially introduce errors into the analysis of changes between successive charts, as the errors will be transferred through to the volume calculations.

A dataset-specific assessment is required to determine if and how the issue should be addressed. A qualitative assessment can first be undertaken to assess the need for a correction to be applied. This requires knowledge of the survey techniques used to compile each chart, i.e. at what time a change in technique occurred. This knowledge can be used to assess if the historical analysis demonstrates a marked change or step that coincides with a change in survey technique. If the change is beyond what would be expected then it might be necessary to investigate determining a correction.

Within a historical analysis of the Humber (ABP Research, 1999), a correction to bed levels was produced to account for the difference between data collected via a lead line and that from echo-sounders. A 10% correction was initially applied to all of the pre-1930 data, following advice from surveying sources. To assess how the correction had performed in removing the difference introduced by the different survey techniques, the datasets immediately either side of the correction (1925-1936) were compared both with and without the 10% adjustment, in terms of intertidal and subtidal sediment volumes. A marked 'step' in sediment volumes (especially in the subtidal data) was observed between the two dates both with and without the correction, but each in opposite directions. This provides an important illustration of the sensitivity of the results produced by a historical analysis to such corrections. In this example the correction was refined by using a time series from 1920-1986 to assess the natural variability in the data and to provide an upper and lower band of change over the period of transition in survey technique. A change of 3.5% was derived and the application of a 3.5% correction to the data provided more consistency in terms of subtidal sediment volumes.

At other locations, using different survey regimes, other corrections will be appropriate. A comparison of lead lining measurements with echo-sounder measurements in a 1946 survey of the Mersey Estuary (Thomas, 2002) suggests that errors from lead lining measurements are normally distributed but with a non-zero mean (this is a result of the lead line not being fully vertical, increasing the depth relative to the true measurement. In the case of the Mersey the mean error was 0.9% of the average depth (with an absolute value of approximately 0.1m). In modern surveys, the magnitude of bias error is generally insignificant (Byrne *et al*., 2002).

Random errors

Any method of depth measurement can be thought of as having a random, normally distributed, error, such that repeated (and averaged) measurements of the depth at the same point should converge upon the true depth. This has both a fixed component and a depth-dependent component, but the latter is generally negligible in the range of depths occurring around the coast and in estuaries. Standards for the allowable magnitude of depth measurement error have been published since the late 1800's and are now defined internationally by S44 (4^{th} edition) (IHO, 1998).

When estimating changes in estuary morphology, it is important to note that volume changes are calculated from a large number of measurements with random error and that the average expected error associated with each measurement is reduced. In fact (assuming the data points are evenly distributed), the standard deviation of the error, ε, will generally reduce as $^{\varepsilon}/n^{1/2}$ where n is the total number of survey points (i.e. from both surveys). Sufficient survey data resolution in surveys can reduce the volumetric error associated with comparison of two surveys to acceptable limits.

Error in the method of horizontal measurement

The accuracy of the position fix at the time a depth sample is taken is another source of potential error that requires accounting for when applying HTA. The accuracy of positional data has changed over time, with early lead line surveys positioned using triangulation, later replaced by transponders that could fix positions to within accuracy of ±3m (ABP Research, 2001). Modern GPS utilises a number of satellites to provide fixes with an accuracy of ±0.5-1m.

Positional errors could potentially introduce errors into sequential assessments when two depth values over different years are assumed to be located in the same position. Positional errors will have the most pronounced influence on the historical analysis process in areas of an estuary with marked slopes. An error assessment can be made to quantify the error introduced into any volume calculations due to positional errors during data collection. A constant offset can be applied to the raw co-ordinate data equal to the accuracy of that data, in a random direction (e.g. 0.5m for GPS positioned data). Calculation of sediment volumes both with and without this offset can be compared to provide an error estimate.

Data resolution

Improved survey techniques have increased the density of sample points. Byrnes *et al.* (2002) describe the primary factors that impact accuracy of volume computations: terrain irregularity, data density, depth measurement bias errors and deviations in depth observations. Of these the terrain irregularity and data density have the greatest influence on overall accuracy of volume change.

The error introduced into a survey volume through coarse data resolution is proportional to $^{1}/_{n}$ where n is the number of survey data points (HR Wallingford, 2001). An estimate of the volume error associated with a volumetric comparison can be made by computing the volume change twice: once as normal and a second time with half as many data points (chosen by selecting every other point in both surveys). The error in the volumetric comparison will then be approximately equal to the difference between the 'data-rich' and 'data-sparse' estimates.

Lower resolution raw data may prevent the digital ground model fully representing bathymetric features of a certain scale (e.g. sand waves), which higher resolution raw data is likely to resolve. If datasets are comprised of different densities of survey points the error in the volumetric comparison will be at least equal to the error associated with the lowest resolution data set. Spatial variation of coverage is also important. Coverage of intertidal areas is likely to be far less comprehensive in bathymetric surveys, particularly on older surveys because the focus was on subtidal navigable channels and surrounding areas. Recent complementary data may be available to provide improved resolution of the intertidal, including cross-sectional estuary surveys or LiDAR data, which provides a means of obtaining higher resolution coverage of intertidal if reliably 'ground truthed' against topographic survey data. However, such data is unlikely to extend back further than the 1990s.

Intertidal coverage of raw data should be considered when interpreting the changes illustrated on charts, principally consisting of a qualitative assessment relating any recorded changes between charts to the raw data coverage. This will allow an understanding to be developed of where actual changes are recorded and where data resolution is too poor to permit an interpretation of change. In some cases this may mean the data only permits a longer time period assessment of changes. Poor data resolution has implications in terms of errors translating into the historical analysis. Firstly, due to the lack of generally available data there will be a tendency for studies to utilise intertidal bathymetric data derived from charts created for nautical purposes (such as Admiralty Charts, Port Authority charts, etc). These charts are deliberately biased towards recording high spots on the sea bed and so the data they present does not represent other areas accurately. This can have significant consequences for comparison of variable intertidal areas such as those with saltmarsh.

Additionally, assuming raw (rather than navigation-biased) data is available, there are two particular features of the upper intertidal that may not be resolved if raw data on intertidal elevations are sparse: (i) a step at the seaward edge of saltmarsh; and/or (ii) the crest and toe of the line of sea defence at the upper margin of the intertidal. Both these features have the potential to propagate significant error into the historical analysis, particularly if they are represented in one (more recent) dataset but not in other (older) datasets. If data resolution over the intertidal is poor, then any interpolation to create the digital ground model may not resolve the step or cliffing that occurs at the boundary between mudflat and saltmarsh. In this situation an overestimate of sediment volume is likely and consequently when comparing volumes with later data sets (based on more accurate representation of the intertidal) large amounts of erosion may be indicated.

Improving the representation of these areas in the raw data may reduce the error associated with these two issues. To achieve this may involve making a number of assumptions and generalising data between datasets. It is likely that the features can be resolved only with the use of cross-sections and/or LiDAR. It may then be necessary to apply this data to each dataset to allow more realistic comparisons. This procedure assumes features are static over time and also assumes that the error caused by the introduction of the data into the sparse data set is less than the reduction in error achieved by better defining the saltmarsh cliff or seawall. However, this method may provide the best available basis for comparison.

For quantitative comparisons of historical chart data, it is necessary to convert the individual data points from each survey onto a regular grid, providing a continuous surface or digital ground model with which to undertake analysis of horizontal and vertical changes on each sequential dataset. Interpolation is required to transform the discrete data onto the grid. This can be achieved through mathematical algorithms available within various software packages. Each algorithm operates in a slightly different manner and hence produces differing results. The choice of algorithm has potential implications in terms of the error introduced into the digital ground model and therefore any subsequent quantification of changes over time (ABP Research, 2001). Comparison of sediment volume data using different algorithms on Southampton Water showed errors in calculated sediment volumes. The differences were assessed to provide an error estimate. In this specific case, the errors in the intertidal volumes produced by the different routines ranged from 2% to 3%.

Sparse data can result in odd results when the more complex routines such as kriging are applied, particularly around low water where the steep side slope of the low water channel meets the shallower slope of the intertidal. For this reason, except where the user has some expertise in the theory of geostatistics and use of more complicated approaches, it is advised that linear interpolation be used at all times. On occasion linear interpolation will result in strikingly linear, rather than smooth, bathymetric contours and in this case more complicated routines can be used for aesthetic purposes (such as figure production) as long as they do not show significant departure from the linear-generated figure.

Chart production techniques
Several issues arise with chart production techniques. Four main issues can be identified:

- *Chart-biasing for navigation:* Most Admiralty and Port Authority charts are produced specifically for navigation and consequently there tends to be a focus of coverage within the main estuary channels, and a paucity across intertidal areas. This bias may influence data interpolation techniques used within a GIS or digital ground modelling package.
- *Rounding Errors:* bathymetric surveys are usually undertaken for navigational safety, so depths are usually rounded down, with the least depth illustrated on a chart (ABPmer, 2002; van der Wal and Pye, 2003).
- *Metrification:* metrification meant that depth recordings changed from feet to metres, introducing errors in conversions. Work on the Humber showed the conversion caused an average increase in depths of 0.1m (ABPmer, 2002).

- *Chart/Survey Dates:* Early bathymetric charts are often based on a single survey of a known, quoted, date. However, modern charts are often composites of several surveys over different years. Again, areas of less concern to navigation may be re-surveyed less frequently (e.g. intertidal or deep water areas) relative to more dynamic areas that pose a greater risk to navigation (van der Wal and Pye, 2003).

Investigation of the details of the survey and the resulting chart may allow the above data issues to be accounted for or noted during the interpretation of changes.

Data processing errors
Data processing can also create errors, such as digitisation, datum or projections corrections and grid interpolation in digital ground models. These issues are discussed below.

Digitisation
To facilitate detailed quantitative comparisons between paper historical charts or aerial photographs, the survey data contained in these records requires digitisation. However, inconsistency may occur in digitisation methods and/or levels of accuracy and detail, thus introducing errors to the historical datasets through the digitisation process. Techniques should be precise and well documented so that future studies can update the results using consistent methodologies as more information becomes available.

Datum or projection corrections
Chart depths ('z-values') can be referenced to several different datums, for example Ordnance Datum Newlyn (ODN), Chart Datum (CD) or a local datum. A simple correction is required to ensure each successive dataset datum is consistent, commonly ODN. The referenced datum level is often related to tide levels (e.g. chart datum is approximately the level of lowest astronomical tide at a particular location). These tide levels will obviously vary over time, according to a number of timescales, such as long term relative sea level rise and the nodal tidal cycle. Relative sea level rise will mean that any volumes calculated within historical analysis may indicate a trend of erosion; although this will depend on how often the reference datum is corrected.

Importantly, principal chart datums have changed: prior to 1921 the 'standard' datum was derived from measurements taken at Liverpool between 1840 and 1860. In subsequent years, large errors were found in the levelling for different parts of the country. At Harwich the error was as much as 0.55m (Doodson and Warburg, 1941). Data may also need to be projected to a common geographical projection ('x- and y-values') prior to analysis.

The need for supporting historical information and linkage with other analytical tools within an EGA
It is important when applying HTA to associate observed historical changes with specific anthropogenic activities or changes in forcing factors. Metadata should also be used during data interpretation; changes identified between an historical map and a contemporary survey may simply be due to different survey accuracies or different densities of survey points on each survey. Similarly, mapping of saltmarsh change from aerial photographs may reveal misleading results if one set of photographs was captured in summer and the other in winter, as vegetation coverage will be different.

Further, estuarine systems (and different internal components of estuarine systems) respond to different pressures over different timescales. For example, some changes observed through HTA might be cyclical, whilst others will be occurring only once; some might be short-term and others long-term. Additionally, estuarine systems can have long relaxation times: that is they may take decades or centuries to fully readjust morphologically to large-scale anthropogenic intervention (i.e. cause and effect is not necessarily synchronous).

Examples of previous applications of the approach

Various examples of previous application of HTA have been referred to throughout the previous section. Specific example applications are presented below and a further example relating to saltmarsh area changes, can be found in the Saltmarsh Analysis section.

Estuary bathymetry changes

Pye and van der Wal (2000) report on the application of HTA to four estuaries, the Ribble, Mersey, Southampton Water and Humber, as part of the ERP1 R&D programme. In all cases, sequential analysis of hydrographic surveys was undertaken, with these data supplemented by ground survey data and CASI or LiDAR data where available. The available Admiralty and Port Authority charts were digitised and converted to x,y,z (National Grid) and reduced in level to ODN to enable subsequent comparison of consistent datasets. The resulting data were interpolated to a grid and subject to both qualitative visual comparison and quantitative analysis using digital ground modelling software to assess:

- Sediment volumes and areas of erosion or deposition;
- Estuary tidal prism;
- Planimetric areas;
- Coastline positions;
- Foreshore gradients; and
- Estuary thalweg.

Application of HTA to the Mersey and Southampton Water were less successful owing to lack of temporal resolution (for the Mersey resulting from selection of too few data sets) and poor inter-tidal survey coverage (Southampton Water) application of the method to the Humber and the Ribble were more successful. In the Ribble, HTA using bathymetric data from 1847, 1904, 1951 and 1994 enabled historical patterns of channel bifurcation, opening, closure, infilling and migration to be documented, the effect of the training walls on this pattern to be identified, and the effect of both sediment infilling and historical reclamation on the estuary tidal prism to be calculated.

In the Humber Estuary, data from 1851, 1900, 1956 and 1998 were used to characterise historical changes in the channels and shoals, and identify areas where saltmarsh has developed. The HTA identified large spatial and temporal differences in the rate of sediment infilling within the estuary and revealed that whilst there had been recent historical net loss of inter-tidal area in the outer estuary, there had also been an increase in inter-tidal area in the inner estuary.

Long-term morphological behaviour in the Humber Estuary has also been investigated using advanced statistical methods as part of the Environment Agency-led Humber Estuary Geomorphological Studies. Reeve and Horrillo-Caballo (2003) applied Empirical Orthogonal Function (EOF) analysis to a series of 14 historical bathymetric surveys of the Humber to investigate temporal and spatial patterns of variability. EOF provides a means of representing the estuary bed morphology as a function of horizontal position and time and determines eigenfunctions of variations in bed level over time. The spectrum of the temporal eigenfunctions was calculated to gauge the strength of any cyclic behaviour in morphology. The eigenfunctions were then extrapolated to predict a future morphological state of the estuary, revealing the existence of oscillatory morphological behaviours over time periods ranging from 20 to 50 years.

The application of HTA to investigate the causes of change in the Mersey Estuary has been undertaken over the last 50 years (Cashin, 1949; Price and Kendrick, 1963; HR Wallingford 1983; Thomas, 2000; 2002). Regular surveys at five yearly intervals at the same cross-sections (160 in total) over the last 130 years has allowed variation in volume capacity to be calculated (i.e. the whole estuary volume to a nominal high water level) exists for the whole of the 130-year period.

Recently the availability of GIS methods has allowed a more in-depth analysis of historical bathymetric changes in the Mersey (Thomas 2000; 2002) allowing hindcasting of flow, waves and sediment transport and a re-evaluation of earlier work by Price and Kendrick (1963). The conclusions of this detailed re-evaluation essentially confirmed the previous study that changes in flow patterns in Liverpool Bay caused by the construction of training works resulted in a supply of sediment to the Mersey entrance that could be transported landwards by tidal pumping. This sediment transport resulted in deposition in the inner estuary until the changes in morphology enhanced ebb tide currents sufficiently as to reduce the landward transport.

Conclusions

Historical Trend Analysis (HTA) is an extremely useful tool to incorporate in any study of estuary morphology or processes. In the context of the present study, focus has been on medium- to long-term changes in estuarine morphology and in this context HTA, can yield valuable information regarding the following properties:

- The presence and persistence of morphological features;
- The opening, closing, switching, migration, infilling or deepening of sub-tidal channels;
- The evolution of spits at an estuary mouth;
- Changes in saltmarsh area;
- Changes in planimetric properties;
- Variation in volumetric properties and channel cross-sections;
- Movement in shoreline position (e.g. Mean High Water) and foreshore gradient, and
- Areas of sea bed erosion or deposition.

HTA can be used both qualitatively and quantitatively. In recent approaches, modern GIS and digital ground modelling software can output very precise calculations of sediment or water volume, planimetric area or bed level changes. However, the precision of these outputs, particularly if applied to older historical data, can potentially lead the user into a false sense of reliability and the data input and processing limitations should always be borne in mind. It is recommended that any issues that may affect the data quality, such as data coverage, survey technique, data quality, data processing, etc, be fully documented in any HTA study ensuring limitations are explicitly incorporated in any interpretation of the results. In addition, where uncertainty is known to exist due to data issues, sensitivity tests can be adopted to determine the significance of certain assumptions or estimated data errors.

Historical trends should not necessarily always be extrapolated in a linear fashion to yield future anticipated morphological behaviour. This is because of two key reasons. Firstly, many morphological changes, such as channel switching, exhibit a cyclic behaviour pattern and often the available historical data is not of sufficient temporal resolution to fully establish the precise timescales of, or controls on, such behaviour. Secondly, estuaries can have long response times to changes in forcing or controls. This means it is not always possible to correlate changes with specific causes and hence it is difficult to predict future behaviour when the causes of past or ongoing behaviour remain speculative. Instead, HTA should be used as one of a number of available tools to provide information that will be of some use in developing an understanding of estuary behaviour within an EGA.

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