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One hundred years of morphological change in the Thames Estuary

Impacts on tide levels and implications for flood risk management to 2100

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ONE HUNDRED YEARS OF MORPHOLOGICAL CHANGE IN THE THAMES ESTUARY. IMPACTS ON TIDE LEVELS AND IMPLICATIONS FOR FLOOD RISK MANAGEMENT TO 2100

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Abstract

An analysis of one hundred years of morphological changes has been undertaken in the Thames Estuary. The cumulative effect of these changes is seen to have led to an increase in the tide range from Tower Pier upstream to Richmond, with mean spring tide range under low fluvial flow conditions predicted to have increased by up to 1.1m (25%) at Richmond.

High water levels in the Thames Estuary have been relatively insensitive to changes in morphology of the Outer Estuary.

The effect of morphology changes on the propagation of extreme tide/surge events has been tested and found to be similar in location (increased high water levels in the Upper Estuary) but smaller in magnitude than for a mean spring tide. Finally, the implications of these findings for flood risk management in the future are considered.

Key Words: (Thames Estuary, Morphology, Tides)

Background

Thames Estuary 2100 (TE2100) is an Environment Agency led project to deliver a flood risk management plan for London to the year 2100. Key to the development of a plan that is preferred from an engineering, social, and environmental perspective, is an understanding of the Estuary itself.

HR Wallingford was commissioned to undertake the Estuary Process Studies in December 2004, with the objective of providing a baseline understanding of the physical characteristics of the Thames Estuary, against which the performance and impacts of future flood risk management options may be measured.

This objective was realised through:

- Understanding of the physical characteristics of the Estuary today and how these have historically changed (particularly changes over the last 100 years).
- Development of conceptual and state-of-the-art numerical tools (models) to represent these physical characteristics and trends.
- Provision of a toolkit for testing the performance of options for managing flood risk to 2100, and providing inputs to the impact assessment.

Thames Estuary morphology

This paper details morphological analysis and TELEMAC-2D modelling to investigate:

- Changes to the morphology of the Thames Estuary over the last 100 years
- Changes to water levels in the Thames Estuary over the last 100 years
- Implications of the findings for flood risk management in the future.

Changes to Thames Estuary morphology over the last 100 years

Data Sources

An extensive exercise was undertaken to selectively digitise some sets of Port of London Authority (PLA) Charts from the last 100 years, and assemble an atlas of morphological change. The following groups of charts were digitised, and levels converted from local Chart Datum to Ordnance Datum for the atlas of morphological change (a location plan is shown in Figure 1 below):

1910-15	Complete Estuary from Barking to Southend, partial coverage between London Bridge and Barking and no coverage upstream of London Bridge.
1920-25	Complete Estuary except between Putney and Barking where coverage is partial.
1970-75	Complete Estuary
1980-85	Complete Estuary
1990-95	Complete Estuary

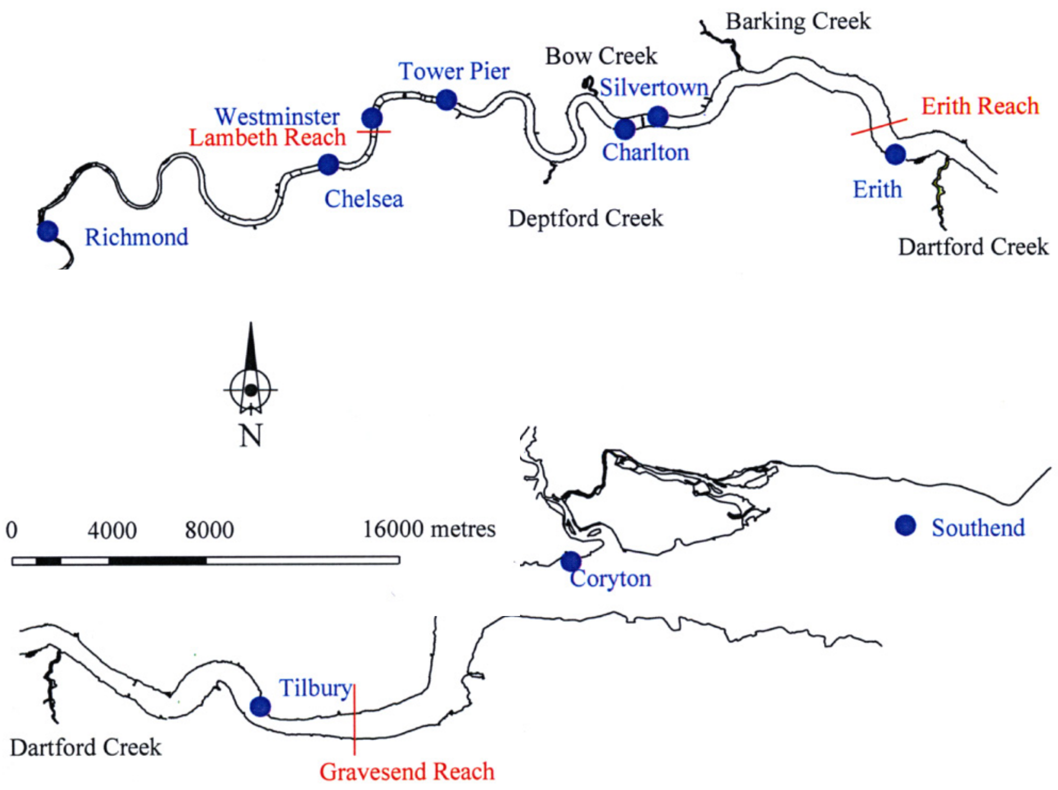

Figure 1 Location Plan

The 1970's, 1980's and 1990's data sets were composed of 42 charts covering different reaches of the Thames Estuary. The 1910's and 1920's datasets were organised on a different basis but to maintain consistency were separated in this study into the same 42 reaches. The density of data points varies from chart to chart and within the areas depicted in each chart. On average, however, the resolution of data points varied from around every 10m in the Upper Estuary upstream of London Bridge to around 20-50m (subtidal areas) and around 100m (intertidal areas) at the seaward end of the Estuary.

Other surveys existed prior to 1910 but it was considered that these surveys are partial or would be insufficiently accurate to provide a reasonable comparison. For this reason the focus of this study was constrained to the surveys identified above.

An Atlas of Morphological Change in the Thames Estuary

The changes in bathymetries between the selected time periods were quantified by using the STBTEL interpolation software from the TELEMAC suite developed by LNH-EDF, France. This software was used to build a Digital Terrain Model (DTM) for each of the 42 separate chart data sets, and then to make a direct comparison between the different historical bathymetries for each chart.

Difference plots were generated, for each of the 42 chart areas, for the following combinations: 1910/1920, 1920/1970, 1970/1980, 1980/1990 and 1910/1990. For the purpose of this study, which aims to identify the main trends within the Estuary rather than the detail of changes in individual reaches, the volumes of water below 0mCD and the volumes of intertidal above 0mCD were then calculated for the individual reaches and amalgamated to give summary changes for the following sections of the Estuary:

- Teddington to Putney Bridge – the section dominated by fluvial flow
- Putney Bridge to London Bridge
- London Bridge to Barking
- Barking to Broadness – the section representing the "mud reaches"
- Broadness to Coryton - the section representing a transition between the mud reaches and the sandier Lower Estuary
- Coryton to Southend – the section where the Estuary is considerably wider, open to more wave action and predominantly sandy

It is important to note that the definition of subtidal and intertidal in this paper refers to volumes or areas above or below a plane, fixed through time, relevant to each chart (namely the height of present-day chart datum in m OD). Therefore changes to intertidal and subtidal quoted are not reflective of any historical changes in low water and subsequent changing of chart datum relative to ordnance datum (as was historically undertaken). The changes are simply a measure of morphological change.

Historical Trend Assessment

The historical changes in subtidal and intertidal volume, area and depth are presented in Table 1 for each reach. Where data is incomplete for the whole of one of six sections listed above it is not presented. Presented in Table 2 is a summary of the main activities occurring over the study period.

The calculated volumes and depths are presented together with an estimate of the corresponding error. The error was calculated by considering the following sources: error in the measurement of depths; error arising from coarseness of the data (a limited number of spot measurements); and error arising from interpolating the measured data onto a grid to enable comparison. The error in the estimate of area is small by comparison and so has not been presented. The results of the historical trend assessment show the following main points:

- Overall loss of intertidal volume (40%-50%) in the Upper Estuary above

London Bridge accompanied by a reduction in intertidal area (15%-25%).
- Overall gain in subtidal volume (15%-25%) in the Upper Estuary above London Bridge accompanied by an increase in subtidal area (6-12%).
- Overall gain in intertidal volume (10%) in the Lower Estuary below Barking accompanied by an increase in intertidal area (12%)
- Overall loss of subtidal volume (2%) in the Lower Estuary below Barking accompanied by an overall loss of subtidal area (6%).

As shown in Table 1, over the study period the changes in volume and area result in an increase in subtidal depth between Barking and Broadness (1m) and Broadness and Coryton (0.35m) and to a lesser extent upstream of Putney (0.1m). Figure 2 highlights areas in the Thames Estuary where bed levels have decreased or increased by at least 0.5m over the period between the 1910's and 1990's.

Over this period, the Thames Estuary appears to have displayed different behaviour in the Upper Estuary landward of London Bridge and in the Lower Estuary seaward of Barking. Generally, in the Upper Estuary the subtidal channel has deepened and widened and accompanied a loss of intertidal area. In the Lower Estuary the subtidal channel has deepened and narrowed and accompanied a gain in intertidal area. In different locations of the Estuary the largest part of this change takes place at different times.

The largest changes in volume occurring in the Estuary over the period 1910 to 1990 are the loss of subtidal volume between Coryton and Southend between 1910-15 and 1920-25 (around $13Mm^3$) and the increase in intertidal volume between Coryton and Southend between 1970-75 and 1990-95 (around $6.6Mm^3$). The former appears to principally result from a loss of subtidal area while the latter principally results from an increase in intertidal area, particularly along the foreshore of Blyth Sands.

These changes have been influenced by the scale of anthropogenic activity described in Table 2.

Table 1 Historical changes in intertidal and subtidal area, volume and depth

Time period	1910-1915		1920-1925		1970-75		1980-85		1990-95	
	Subtidal	Intertidal	Subtidal	Intertidal	Subtidal	Intertidal	Subtidal	Intertidal	Subtidal	Intertidal
Area (sq.km)										
Teddington to Putney			1.29	1.13	1.43	0.92			1.45	0.87
Putney to London Br.					1.95	0.85	1.95	0.83	1.96	0.82
London Br. To Barking					5.59	1.84	5.58	1.80	5.56	1.85
Barking to Broadness	11.5	3.16	11.5	3.52	11.16	3.58	11.02	3.55	10.84	3.61
Broadness to Coryton	26.02	11.73	25.9	11.79	24.62	13.4	24.32	13.57	24.5	14.09
Coryton to Southend	29.57	25.77	28.11	27.15	29.09	26.55	29.39	26.23	27.82	28.03
Volume (Mm^3)										
Teddington to Putney			1.45+/-0.16	1.72+/-0.13	1.83+/-0.05	1.28+/-0.05	1.82	1.16	1.80+/-0.02	1.03+/-0.02
Putney to London Br.					3.54+/-0.2	1.24+/-0.2	3.65+/-0.02	1.20+/-0.03	3.53+/-0.02	1.03+/-0.02
London Br. To Barking					27.36+/-0.08	3.63+/-0.08	27.73+/-0.02	3.30+/-0.03	27.06+/-0.03	3.56+/-0.03
Barking to Broadness	70.4 +/-1.6	7.1 +/-0.4	74.2+/-1.3	9.1+/-0.5	77.4+/-0.08	8.0+/-0.1	80.8+/-0.03	8.8+/-0.04	79.0+/-0.04	9.5+/-0.04
Broadness to Coryton	209.6 +/-2.8	25.5 +/-1.5	207.6+/-2.9	26.0+/-1.5	208.2+/-0.1	22.8+/-0.2	208.7+/-0.1	23.5+/-0.1	205.7+/-0.1	27.4+/-0.2
Coryton to Southend	220.8 +/-3.7	50.3 +/-3.8	206.2+/-3.2	52.5+/-4.4	211+/-1.1	47.8+/-1.6	208.8+/-2.3	46.6+/-5.8	207.5+/-0.7	54.4+/-2.2
Average depth (m)										
Teddington to Putney			1.12 +/-0.03	1.53 +/-0.02	1.28 +/-0.03	1.39 +/-0.06			1.24 +/-0.02	1.18 +/-0.02
Putney to London Br.					1.82 +/-0.1	1.46 +/-0.2	1.88 +/-0.01	1.45 +/-0.03	1.80 +/-0.02	1.25 +/-0.03
London Br. To Barking					4.89 +/-0.01	1.97 +/-0.04	4.97 +/- 0.00	1.83 +/-0.01	4.87 +/-0.00	1.92 +/-0.02
Barking to Broadness	6.12 +/-0.2	2.24 +/-0.2	6.46 +/-0.2	2.58 +/-0.2	6.93 +/-0.01	2.23 +/-0.03	7.33 +/-0.00	2.46 +/-0.01	7.29 +/-0.00	2.63 +/-0.01
Broadness to Coryton	8.05 +/-0.2	2.17 +/-0.2	8.02 +/-0.2	2.20 +/-0.2	8.45 +/-0.00	1.70 +/-0.01	8.58 +/-0.00	1.73 +/-0.01	8.40 +/-0.00	1.94 +/-0.01
Coryton to Southend	7.47+/-0.2	1.95 +/-0.25	7.33 +/-0.2	1.93 +/-0.3	7.25 +/-0.04	1.80 +/-0.06	7.10 +/-0.08	1.78 +/-0.2	7.46 +/-0.03	1.94 +/-0.08

1 Subtidal volume refers to the volume of water below 1990's Chart Datum
2 Intertidal volume refers to the volume of bed material above 1990's Chart Datum
3 Average channel depth for subtidal is the average channel depth below 1990's Chart Datum
4 Average depth for intertidal is the average elevation of bed material above 1990's Chart Datum

Table 2 Historical anthropogenic activities in the Thames Estuary

Activities General:	1910's to 1920's	1920's to 1970's	1970's to 1980's	1980's to 1990's
• Gradual increased abstraction • 1-2mm SLR • Reduction in sewage discharge • Changes in commercial practice – reduction in loose waste and industrial discharges • Large scale capital dredge campaigns and major maintenance dredging of docks and river between 1920's and 1960's	• 1910 to 1928 37M yd^3 of dredging between Nore and London Bridge (see right) • Widening of channel in Lower Hope Reach (completed in 1912) – ballast dredging • Extension of ballast dredging to Horseshoe Bay (till 1919)	• 1910 to 1928 37M yd^3 of dredging between Nore and London Bridge including: • dredging of Yantlet channel and disposal in Leigh Channel • dredging between Tilbury and Gallions Reach to -30ftCD • dredging between Gallions Reach and Upper Pool to approx. -20ftCD • Limited dredging upstream of London Bridge • WW2: dumping of maintenance, sludge and "other material" in Lower Hope Reach • 1953 cessation of disposal of maintenance material at Black Deep • 1960's cessation of maintenance dredging in mud reaches • 1963/4 dredging to move navigation channel in Lower Gravesend Reach to south bank • 1965 further deepening of Yantlet channel • Reclamations including works adjacent to: Blackfriars and Vauxhall Bridges, Thamesmead and Tilbury (started) • Increase in loose waste from dock handling till around the 1950's-60's when a reduction set in caused by with changes in dock handling and reduction in trade • Deepening of Yantlet Channel • Wandsworth, Westminster, Waterloo and London Bridges rebuilt • Closure of most of Up-Estuary docks and wharves	• Dredging within Sea Reach and Yantlet Channel • Placement of maintenance material in Lower Hope Reach and along the south side of Sea Reach and West Leigh • Legislation and improvement to polluted discharges	• Limited Dredging within Sea Reach and Yantlet Channel • Placement of maintenance material in Lower Hope Reach

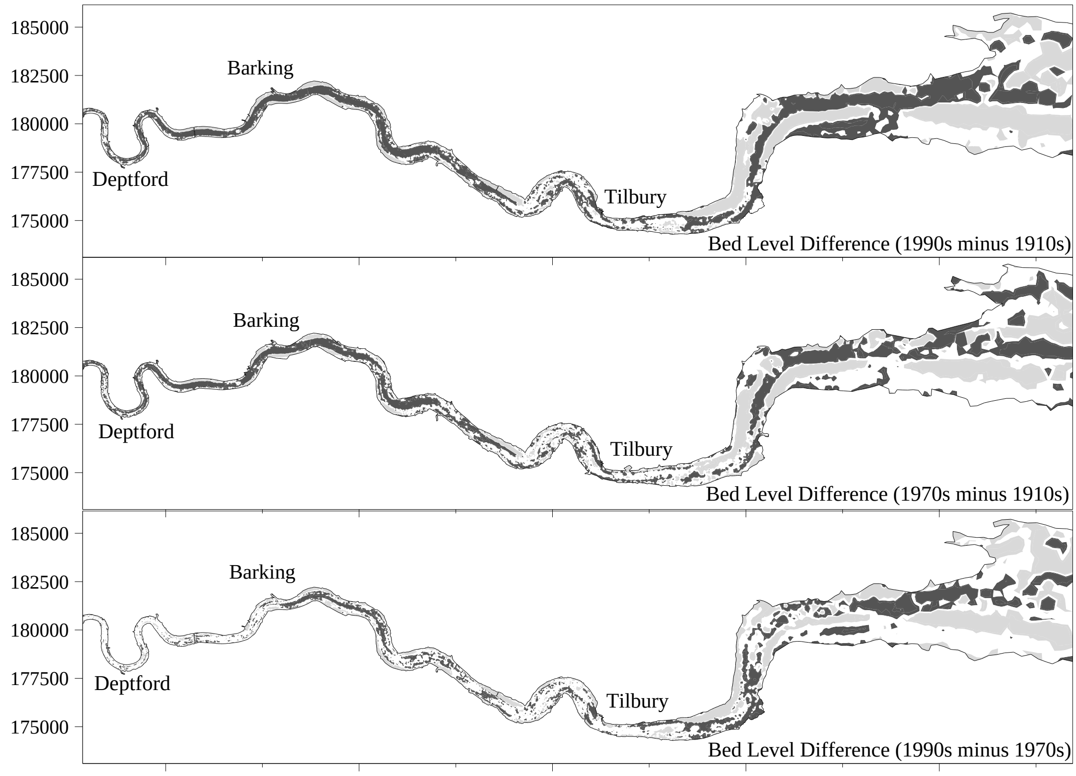

Figure 2 Summary of changes to Thames Estuary morphology between the 1910's and 1990's

(Light grey indicates depth has reduced, dark grey indicates depth has increased. Changes of less than 0.5 metre are not shown)

Modelling the effect of morphology changes on tidal propagation in the Thames Estuary

Data Sources and Methodology

The Thames Estuary TELEMAC-2D flow model was used together with the historical bathymetric data sets described above to simulate the flow conditions present in the 1910's, 1920's, and 1970's and these were compared with results for the present day scenario. The model was used to reproduce mean spring tide conditions for all of the historical scenarios during summer flow conditions. This was done by selecting the boundary conditions from real tide data at Southend for a period approximating a mean spring tide (with no surge) and for which the existing 2D model had been extensively validated. Initially, no allowance for historical climate change was included in the boundary conditions to isolate changes in the tidal propagation arising due only to changes in morphology (including bridges). Subsequently, the effect of historical climate change was considered.

Modelled Historical Changes in Water Levels

The historical changes in water levels are summarised in Table 3 and Figures 3 and 4 which present the maximum water level (HW), minimum water level (LW) and tidal range predicted in the simulations at locations along the river from Southend to Richmond.

The model results show that upstream of Coryton the tide range has progressively increased throughout the 20th century. The predicted increase is small up to Charlton (a maximum of 0.15m, or 1.5%), but then rises to an increase of 0.6m at Tower (9%), to 0.75m at Westminster (13%), and 1.1m at Richmond for low river flows (27%).

Table 3 Modelled changes in spring tide water levels arising as a result of morphological changes over the last century

Year		Richmond	Westminster	Tower Bridge	Charlton	Erith	Tilbury	Coryton
1910–1915	High Water (m OD)	4.01	3.70	4.01	4.08	3.88	3.65	3.43
	Low Water (m OD)	-0.15	-2.23	-2.55	-3.00	-2.99	-2.92	-2.80
	Range (m)	4.16	5.93	6.56	7.08	6.87	6.57	6.23
1920–1925	High Water (m OD)	4.01	3.71	3.98	4.03	3.85	3.63	3.41
	Low Water (m OD)	-0.15	-2.26	-2.84	-3.06	-3.01	-2.92	-2.80
	Range (m)	4.16	5.97	6.82	7.09	6.86	6.55	6.21
1970–1975	High Water (m OD)	4.33	3.90	4.04	4.10	3.88	3.67	3.41
	Low Water (m OD)	-0.78	-2.73	-3.07	-3.13	-3.04*	-2.95	-2.79
	Range (m)	5.11	6.63	7.11	7.23	6.92	6.62	6.20
2000	High Water (m OD)	4.46	3.94	4.06	4.06	3.88	3.66	3.40
	Low Water (m OD)	-0.82	-2.78	-3.07	-3.11	-3.05*	-2.94	-2.80
	Range (m)	5.28	6.72	7.13	7.17	6.93	6.60	6.20

* *Tide gauge dries out at LW (these levels were extracted from a nearby wet location in the model)*

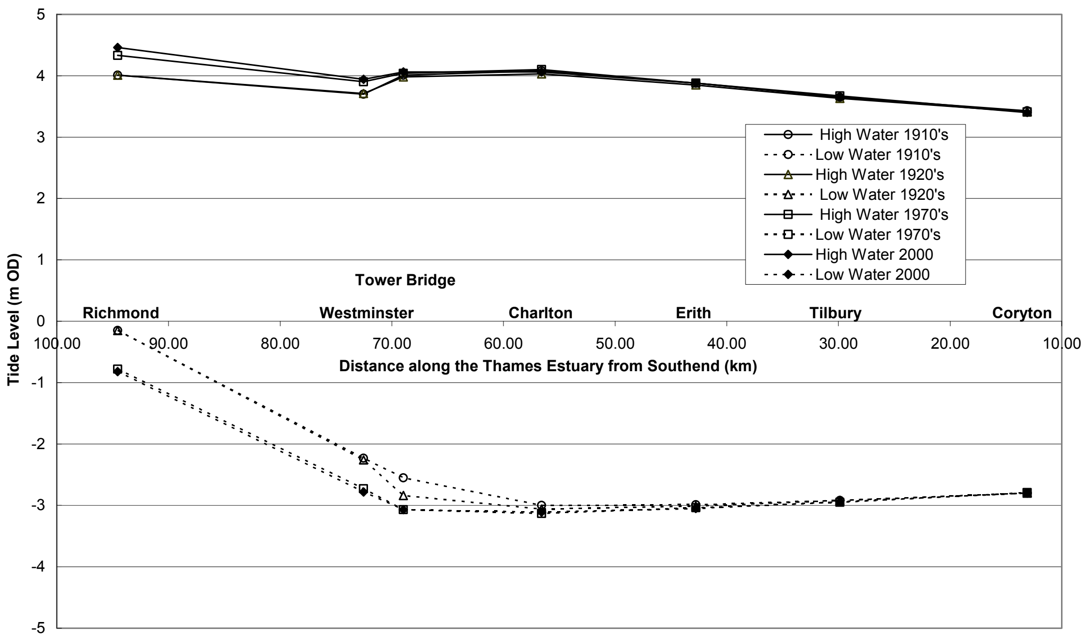

Figure 3 Modelled changes to spring tide levels in response to changes in morphology

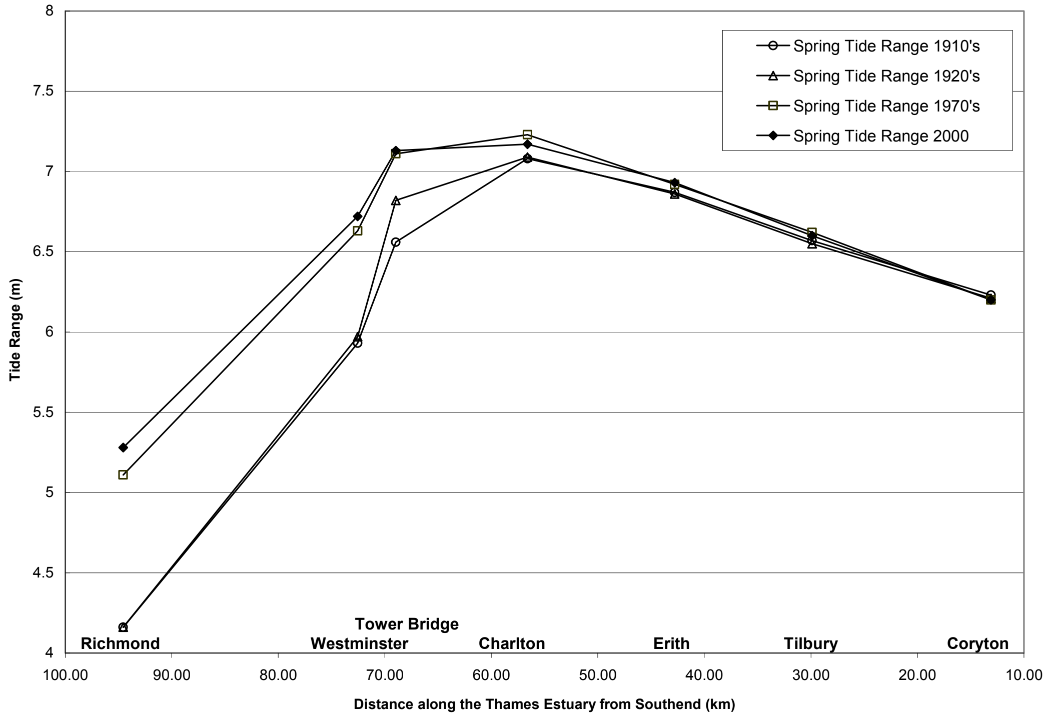

Figure 4 Modelled changes to spring tide range in response to changes in morphology

Modelled Historical Changes in Tidal Currents

The changes in water levels presented in Table 3 correspond to significant changes in tidal currents within the Thames Estuary over the period in question. The changes in modelled (mean spring tide) peak current speeds within the Estuary between the 1910's and the present day, arising due solely to changes in morphology, are summarised below:

A fairly mixed and localised response in the Lower Estuary (downstream of Crossness) - the reduction in current speed arising from dredging in Sea Reach can be discerned as can the effect of groynes at Diver Shoal (Coalhouse Point) and of the Dartford Bridge Crossing; A reduction in peak current speeds (around 0.1m/s) between Crayford Ness and Greenwich; An increase in speeds upstream of Westminster – around 0.1m/s in general with larger increases around Chelsea and Chiswick.

Further analysis of changes in current speed over this period indicates that the changes in the Lower Estuary have mainly occurred since the 1970's, while other changes in the Upper and Middle Estuary areas predominantly occurred over the 1920's – 1970's period.

Climate Change

All the changes to water levels quoted thus far are in response to changes in morphology only. An additional model test of lowering the mean water level for the 1910 mean spring tide boundary condition at Southend by an amount similar to observed sea level rise at Southend (approximately 16cm relative to land), has an effect of increasing the predicted differences in MHWS by 18cm at Richmond and 17cm at Westminster, with changes in current speeds generally less than 5cm/s, when compared with the 1910 mean spring tide run without sea level rise.

In conclusion, MHWS at Richmond during periods of low fluvial flow, is predicted to have increased by 0.45m due to changes in morphology and a further 0.18m due to historical sea level rise. MHWS at Westminster is predicted to have increased by 0.24m due to changes in morphology and 0.17m due to historical sea level rise. These combinations may also be expressed as rates of increase in mean high water of 7-8 mm/year at Richmond, and approximately 5mm/year at Westminster.

Observations

Inglis and Allen (1957) reported that as a result of the capital dredging carried out between 1909 and 1928 the low water level was lowered by 6 inches (150 mm) and the level of high water raised by 2 inches (50 mm) at London Bridge.

Inglis and Allen in the same paper also reported that, over the period of 1951 to 1952, the mean spring tidal range at Richmond was "about" 15.1 feet (or 4.6m). This figure falls comfortably in the middle of the model predictions for 1920 and 1970 (See Table 3 above). This result lends confidence to the model predictions but it should be remembered that the water level in this part of the Thames may be significantly affected by fluvial flow.

A limited investigation of tide levels as marked on PLA charts was undertaken to see if there was any evidence to support a view of increasing tidal range in the Upper Estuary. The quoted tide levels as written on the charts, although updated infrequently, suggested an increase in high water levels in the Upper Estuary of approximately 5-10mm/year. There is a high degree of uncertainty in this figure as the exact dates used for the tidal analysis were not always known for quoted chart figures. However, in all six instances of comparing historical charts, the high water levels in the Upper Estuary were seen to have risen by an amount comparable to those modelled.

Outer Estuary Changes

A similar and separate exercise was undertaken looking at changes to morphology of the banks and channels in the Outer Estuary and the effect of these changes on tidal propagation.

Viewed in terms of the whole Outer Thames Estuary, changes to the plan shape alignments of banks and channels show no major systematic pattern, with the exception of some extensions of the longer banks seawards and other significant changes in localised areas such as the Edinburgh Channels.

The effect of these historical changes (1909 to 2000) in Outer Estuary morphology on predicted mean spring tide levels from Richmond to Southend was modelled and found to be small (less than 1cm change in mean high water at all locations except Richmond an increase of 3-4cm was modelled).

Implications for flood risk management to 2100

Modelled effect of morphology changes on extreme tide/surge events

Most of London offers a standard of protection against tidal flood levels with an annual likelihood of exceedence of 0.1%. The effect of 100 years of morphological change on predicted extreme levels has been assessed through the use of two further model simulations. The boundary conditions for these simulations were defined by combining a mean spring tide with a surge profile similar to the 1953 surge, but scaled to achieve the target high water levels at Southend. The predicted changes to extreme levels are presented in Table 4 below. They both represent combined events with a 0.1% likelihood of exceedance in a given year. One represents an extreme high water (tide and surge) at Southend in combination with a low fluvial flow at Teddington, and the other event represents a (lower) extreme high water at Southend in combination with an extreme fluvial flow at Teddington. In both cases the results are shown in the absence of Thames Barrier operation.

Firstly, it is seen that the historical morphology changes represented in the tidal Thames have had little effect on peak water levels for a modelled combined fluvial / tidal event. Further, it is seen that the changes to morphology have very little effect on peak water levels up to Tower Pier (<5 cm change) for both the events tested. However, it is seen that the predicted high water from the same tide dominated event has risen by 0.18m at Westminster and 0.25m at Richmond due to changes in morphology only.

The effect of historical changes in the morphology of the Outer Estuary was also tested and found to be small (< 4cm) for all events, typical and extreme, modelled.

It should be recognised that the seaward boundary conditions for these extreme events were defined according to a set of assumptions on the interaction of tide and surge. In reality, the interaction of tide and surge may be different. High water levels in the estuary are known to be affected by the rate of rise of seawater, which is in turn affected by the timing of tide-surge interaction. Therefore these represent specific tests for comparison only.

Table 4 The modelled effect of historical changes in morphology on extreme levels in the Thames Estuary, assuming no operation of the Thames Barrier

	Difference in Water Level (m)								
	Southend High Water (m OD)	Kingston Flow (cumecs)	Richmond	Westminster	Tower Pier	Charlton	Erith	Tilbury	Coryton
Present minus 1970s	5.03	11	-0.01	0.01	0.01	-0.04	-0.02	-0.03	-0.03
Present minus 1970s	4.55	800	0	-0.01	0.01	-0.01	-0.02	-0.03	-0.02
			0	0	0	0	0	0	0
Present minus 1920s	5.03	11	0.24	0.15	0.04	-0.05	-0.04	-0.04	-0.03
Present minus 1920s	4.55	800	-0.02	-0.01	0.05	-0.02	-0.02	-0.03	-0.02
			0	0	0	0	0	0	0
Present minus 1910s	5.03	11	0.25	0.18	0.05	-0.05	-0.05	-0.02	-0.02
Present minus 1910s	4.55	800	-0.05	-0.03	0.02	-0.03	0	0	-0.02

Discussion

The results of the simulations undertaken here must be assessed in terms of their implications for the current flood management system of integrated tidal defences including the Thames Barrier. The Thames Barrier protects London from tidal flooding and is currently operated to a critical rule based upon observed high water at Southend and fluvial flow at Kingston.

The present-day frequency of barrier closure is therefore a function of extreme levels at Southend, extreme flows at Kingston, and the uncertainties in the forecasts supplied to the Thames Barrier team. The Duty Controller must take a precautionary attitude to protecting London from flooding in the face of uncertainty in forecast conditions and so it is inevitable that the barrier is closed more frequently than the critical rule is actually exceeded.

Consider, for demonstration purposes only, a threshold level for closure of 3.8m at Sheerness (similar to Southend). In reality the threshold level would be lower than this for high fluvial flows at Kingston. The Table below shows the changes to frequency of barrier closure that would be expected, were the trends over the past century to be linearly extrapolated to 2100. The frequency considered here is based upon an analysis of observed tide data from 1992 to 2000, and assumes that there is no uncertainty in the quality of forecast or observed levels (this is another issue entirely, not considered here). No account is taken either of the occasions where the barrier would also require closing in response to high fluvial flows in combination with (lower) high tide levels.

Table 5 Effects of historical relative sea-level and morphology-induced changes projected forwards in terms of barrier operations (based upon observed tide data 1992-2000)

High Water (m OD) Sheerness	Scenario	Average annual frequency of exceedance	Factor
3.80m OD	Threshold level (current)	0.3	1
3.64m OD	Current equivalent threshold level given historical relative sea level rise projected linearly through the next century	1.1	3
3.43m OD	Current equivalent threshold level given historical relative sea-level and morphology-induced changes at Westminster projected through the next century*	4.6	14
3.27m OD	Current equivalent threshold level given historical relative sea-level and morphology-induced changes at Richmond projected through the next century*	14.7	44

*Linearly interpolated between changes for Mean Spring and Extreme Tide

This table merely demonstrates the effect of linearly extrapolating the modelled increases in peak water levels in the Upper Estuary, arising due to changes in morphology and mean sea level over the last century, on the frequency of operation of the barrier for tide/surge events into the next century.

In reality, during this period the barrier was closed 39 times, exceeding the critical rule on 11 occasions and approaching the rule (on average 0.2m below the rule level at Southend) on the remaining occasions. The need for the Duty Controller to adopt a precautionary approach in the face of uncertainties in forecast information therefore means actual numbers of closures will always be much greater than shown in Table 5.

Two questions remain:

1) Are the morphology-induced trends in high water levels in the Upper Estuary going to continue at the same rate into the future, or are they going to reduce or even reverse through the implementation of policies such as the Environment Agency's Tidal Encroachment Policy or the Port of London's Maintenance Dredging Strategy.

2) Is the historical rate of sea level rise relative to land going to continue at the same rate into the future, or will it begin to accelerate and will there be an associated increase in storminess?

Both these questions are the subject of ongoing investigation within TE2100. Climate change, and its effect on mean sea levels as well as storm levels, is essential design input information to the development of a robust flood management plan. The effect of morphology has shown the need for such a plan to interact with the needs of planners, developers, and navigation.

Conclusions

An atlas of morphological changes over the last century has been developed for the Thames Estuary.

The effect of these changes on tidal levels in the Thames Estuary has been modelled and shown to have led to an increase in tide range in the Upper Estuary.

Although the effect of historical morphology change on flood levels has been demonstrated to have been smaller than for normal tides, the cumulative effect of climate change and morphology-induced change may have a potentially significant effect on the frequency of operation of the Thames Barrier.

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NOTES

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