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Past and future evolution in the Thames Estuary

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PAST AND FUTURE EVOLUTION IN THE THAMES ESTUARY

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Thames Estuary, morphological modelling, sediment budget, sea level rise

Abstract
In order to manage estuaries effectively it is important to be able to predict how they are likely to change in the future, both to natural and anthropogenic forcing. This paper looks at historical morphological development of the Thames Estuary, taking into account the effect of human intervention and uses the ASMITA morphological model to predict the long term evolution of estuary into the future, assuming either historic rates of sea-level rise, or accelerated sea-level rise.

The historical sediment budget for the Thames Estuary was examined and source and sink terms, including fluvial sediment supply and historical dredging rates were included in the ASMITA model. ASMITA predictions showed good overall agreement with the historical data highlighting the benefits of detailed historical review and the inclusion of anthropogenic effects in the model.

Future ASMITA predictions for the period 2000 to 2100 suggest that, under both historical and accelerated sea level rise scenarios, the estuary will experience accretion but, for the accelerated sea level rise scenario, accretion will be at a slower rate than sea level rise. With accelerated sea-level rise, intertidal profiles were predicted to be up to 0.5m lower with respect to High Water.

Introduction
The Thames Estuary in the UK is currently a focus for study because of the need to plan future protection against flooding in London and because of the need to protect the biodiversity associated with its wetland areas, in particular in the designated areas at Benfleet and Holehaven Creeks, Mucking Flats and North Kent Marshes. The Thames Estuary has a long history of anthropogenic intervention – reclamation, dredging and bridge building - and is home to many marine terminals and berths which require safe navigation. Balancing the demands of these different pressures requires effective estuary management. In addition to these existing management pressures, sea-level rise is predicted to accelerate over the next 100 years and may significantly influence the morphology of the Thames Estuary.

In order to manage estuaries effectively it is important to be able to predict how they are likely to change in the future, both to natural and anthropogenic forcing. However, whichever methodology is used there is a requirement to lend confidence to this prediction by being able to adequately reproduce the historical changes in the estuary. This paper looks at the historical morphological development of the Thames Estuary, taking into account the effect of human intervention and uses the ASMITA morphological model to reproduce this past behaviour and to predict the long term estuary evolution into the future. Two future scenarios are considered; one in which sea-level rise continues at its historical rate and a second which uses the DEFRA (2006) sea-level rise allowances for the Thames region (Table 1).

Table 1 DEFRA 2006 sea-level rise guidelines for the Thames region

Period	Rate of sea-level rise (mm/year)
1991-2025	4
2026-2055	8.5
2056-2085	12
2086-2115	15

Study site

The Thames Estuary is a funnel shaped estuary with an extensive river catchment located on the east coast of the United Kingdom (Dyer 2002) (**Error! Reference source not found.**). For this study, the estuary boundaries were defined as the tidal limit at Teddington and between Southend-on-Sea and the mouth of the Medway Estuary at the seaward end. The banks throughout much of the estuary are defended by sea walls or embankments and the Thames Barrier protects London from tidal/storm surges that could cause extensive flooding. Other barriers have been constructed across down stream tributaries.

The lower part of the Thames estuary, seaward of Gravesend has numerous nature protection designations, including Local Nature Reserves, Sites of Special Scientific Interest (SSSI) and internationally important intertidal areas, including mudflats, salt marsh and grazing marsh that are designated as Special Protected Areas under the EC Birds Directive.

The Thames Estuary is macro-tidal, with a spring tidal range of 5.3 m at Southend. The presence of a turbidity maxima in the Thames Estuary suggests that it is ebb-dominant in the upper part, but flood dominant further down stream. Wave heights within the estuary are relatively small due to sheltered provided by the sand banks present in the outer estuary. The mean annual wave height at Southend is around 1 m (van der Wal and Pye 2004) and reduces with landward distance into the estuary. As a result tidal processes dominate sediment transport. Sediment characteristics in the Thames differ along the estuary. The inner estuary (upstream of Lower Hope Point) has mainly fine, muddy sediment; seaward of this point the sediment is mainly sandy.

Historical sediment budget

Sediment enters the Thames Estuary from fluvial and marine sources, with additional inputs from sewage and industry. The contributions of each of these sources have been derived from a combination of sources including work on the Thames sediment budget by WPRL (1964), (which expands on Inglis and Allen's (1957) earlier seminal work "On the Regimen of the Thames Estuary"), Port of London Authority dredging records, bathymetric analysis of PLA charts (HR Wallingford 2006a), historical reviews of dredging and disposal of dredged sediment (HR Wallingford 2006b) and review of flow and suspended sediment measurements in the Lower Thames River (HR Wallingford 1988, 2006b). Best estimates of the Thames sediment budget derived from this re-analysis (Table 2) show how the sediment budget in the muddy part of the estuary (upstream of Lower Hope Point) changed over the course of the 20th Century.

Fluvial sediment supply between 1970 and 1990 was estimated to be between 118,000 and 234,000 dry tonnes/yr including sediment from the River Thames, tributaries and sewage treatment works, with a best estimate of 200,000 tonnes/yr (HR Wallingford 2006a). This amounts to approximately 0.5 Mm^3/yr of sediment (van der Wal and Pye 2004).

Historically, both capital and maintenance dredging has been carried out in the Thames Estuary. Details of capital dredging projects are uncertain, and information such as volumes removed, sediment types and disposal sites are not available and so capital dredging is not reported in this study. This uncertainty is most relevant to the earliest part of the 20th century (1908-1924) when substantial capital dredging occurred (HR Wallingford, 2006b). However, the dredged sediment is mostly thought to have been dredged from the Yantlet Channel (what is now the main channel between Southend and Lower Hope Point, see Figure 1) and placed north and south of this channel within the same reach. There is therefore less of an implication for the morphological modelling described later in this paper. Data on historic rates of maintenance dredging were obtained from Port of London Authority published and unpublished data, and other sources (as summarised in HR Wallingford, 2006a). These were converted from tonnes to m^3 assuming a dry density of 600 kg/m^3. The records indicate that maintenance dredging (which was disposed offshore) was of the order of 160,000 dry tonnes/yr in 1910 (Davis, 1949) rising to 900,000 tonnes/yr in 1952 and declining after that date to the present day. Much of the maintenance dredging at present in the Thames Estuary is undertaken using water injection dredging (which does not remove sediment from the estuary) and hence the rate of removal of sediment from the estuary through maintenance dredging is of the order of 100,000 m^3/yr. It was estimated that between 1910 and 1960, 80% of the dredging took place upstream of Broadness and the remainder between Broadness and Lower Hope Point; between 1960 and 1980, 50% of the dredging was upstream of Broadness and after 1980, 25% of dredging was upstream of Broadness.

Table 2 Estimated average net input and export of sediment for the Thames Estuary upstream of Lower Hope Point over the period 1920 to 1990s (dry tonnes/yr) (from HR Wallingford 2006a)

Sediment source/sink	**1920-1970**	**1970-1990**
Fluvial input (Thames + tributaries)	145,000	170,000
Sewage effluent	79,000	42,000
Storm sewage	13,000	13,000
Sewage sludge	28,000[a]	0
Industrial discharges	21,000	3,000
Morphological change (erosion is +ve)	192,000	-120,000
Total inputs	478,000	108,000
Maintenance Dredging (net placed outside system)	436,000[b]	95,000
Decomposition of sewage	69,000	24,000
Total outputs	505,000	119,000
Net difference (attributed to marine sources)	**-27,000**	**-11,000**

a) *The placement of sewage sludge occurred mainly during WWII at a much higher rate. This is an average over the period 1920-1970.*
b) *The placement of maintenance dredging presented is adjusted to account for periods of disposal at Mucking Flats*

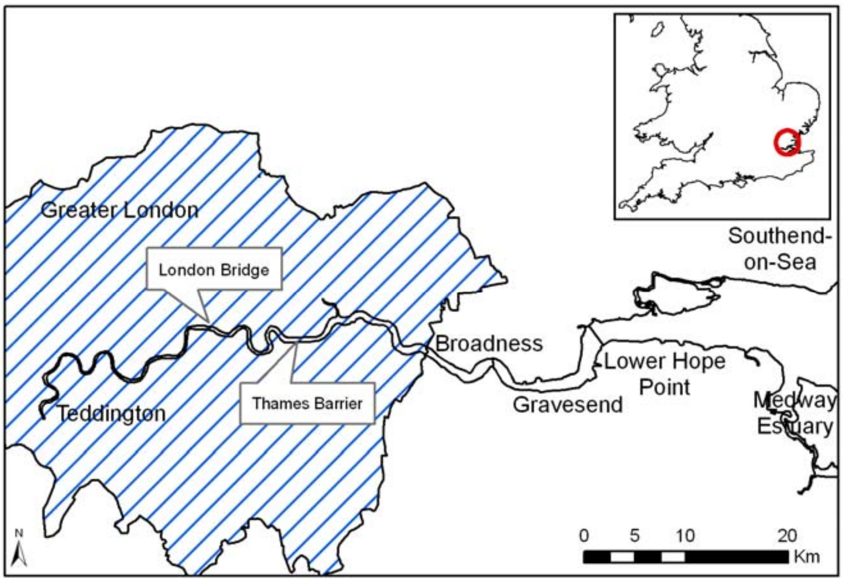

Figure 1 Thames Estuary location map

The contribution from marine sources is not possible to calculate independently from measured data because it represents the small difference between the large flood tide and ebb tide sediment fluxes. WPRL (1964) makes the point that if the concentration on the ebb tide was reduced by just 1.5 mg/l compared to that of the flood tide (on every tide) the resulting landward flux into the estuary would be of the order of 280,000 tonnes/yr. For this reason the sediment budget below evaluates the marine contribution on the basis of the balance of the other sediment contributions.

It is known that there are sources of sediment which could supply fine material to the estuary. Nicholls et al. (2000) estimated that erosion of cliffs on the Isle of Sheppey supplies approximately 450,000 tonnes/yr of fine sediment to the outer Thames estuary and southern North Sea, suggesting that there is a potential marine sediment supply that could be double the fluvial sediment supply, although there is considerable uncertainty regarding the net contribution of marine sources. Marine sediment supply is believed to have been greater in the past (Nicholls et al. 2000).

Table 2 represents a best attempt at a sediment budget for the Thames based on thorough analysis of the variation in sediment inputs and outputs to the estuary over time. However, each of the sediment contributions has uncertainty associated with it and the predicted difference between sediment inputs and outputs could easily have an associated uncertainty of +/- 50,000 tonnes/yr.

Methodology

ASMITA concept

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

The morphological elements in ASMITA, interact through sediment exchange and this interaction plays an important role in the morphological evolution of the whole system, as well as that of the individual elements (van Goor *et al.*, 2003). In cases where morphological elements are not present (e.g., ebb tidal delta), reduced element models can be applied. More complex estuaries can be divided into more elements if necessary (see Kragtwijk et al, 2004 for generalised model equations).

Model description

ASMITA characterises each model element by a single variable: its volume (Kragtwijk et al. 2004). It is assumed that each model element tends towards an equilibrium volume which can be defined using empirical equations. Single, two and three element versions of the ASMITA model are described by van Goor et al. (2003). The current study used a generalised version of the model equations to allowed any combination of model elements to be used. The equilibrium definitions for the two elements types found in the Thames Estuary were the same as those used by van Goor et al. (2003):

$$V_{fe} = \alpha_f A_b \cdot H \qquad (1)$$

$$V_{ce} = \alpha_c P^{bc} \qquad (2)$$

Where V_{fe} is the flat equilibrium sediment volume, V_{ce} is the channel equilibrium water volume, H is tidal range, A_b is basin area (*Flat Area* + *Channel Area*), a and b are empirically derived coefficients; the subscripts f and c refer to the flats and channel respectively and P is the tidal prism, calculated as:

$$P = A_b H - V_f \qquad (3)$$

When all model elements are in equilibrium, the sediment concentration throughout the whole system is equal to the sediment concentration in the surrounding sea, called the global equilibrium concentration (C_E). The sediment concentration in the sea is assumed to be unaffected by the evolution of the inlet and so the global equilibrium concentration is assumed to be constant (that is the long term average sediment concentration in the sea is assumed constant). Note, however, that while the concentration of the sea is assumed constant, this does not mean that there is a constant supply of sediment between the estuary and sea. The exchange between the estuary and the sea is governed by the differences in sediment concentration which will change over time with evolution of the estuary and/or with changes in sediment supply to the nearshore zone. Although the estuary morphology is sensitive to changes in offshore concentration such changes are not considered in this paper.

Each element also has a local equilibrium concentration (c_{ie}), which refers to equilibrium from a perspective of local demand (van Goor et al. 2003). Each element's local equilibrium concentration is equal to the global equilibrium concentration when the element is in equilibrium. The local equilibrium concentration indicates the extent to which the elements actual volume (V_i) deviates from its equilibrium volume (V_{ie}) and is given by equation 4.

$$c_{ie} = C_E \left(\frac{V_i}{V_{ie}} \right)^{\sigma_i n_i} \qquad (4)$$

Where C_E is the global equilibrium concentration and the subscripts i refers to the current element. n_i is greater than 1 and is usually taken as between 2 and 5 in compliance with a third power relationship for sediment transport and a non-linear function of flow velocity and σ_i is +1 or -1 depending on whether the element is described by a wet (water) or dry (sediment) volume (van Goor 2001; Wang 2007).

The difference between local equilibrium concentration (c_{ie}) and global equilibrium concentration (C_E) represents the sediment demand of the element (van Goor 2001). When c_{ie} is larger than C_E the element has a negative sediment demand and a tendency for erosion. When c_{ie} is smaller than C_E the element has a positive sediment demand and a tendency towards accretion. The extent to which the sediment demand of an element is satisfied depends on sediment availability in the adjacent elements. Sediment availability is represented in ASMITA as the difference between an element's actual concentration (c_i) and its local equilibrium concentration (c_{ie}). This difference drives volume changes within the elements (equation 5).

$$\frac{dV_i}{dt} = A_i\sigma_i\left(w_{si}(c_{ie} - c_i) + \frac{d\zeta}{dt}\right) + \sigma_i b_i \qquad 5$$

Where A_i is the element's area, σ_i is the sign of n in equation 4, w_{si} is the vertical exchange coefficient for the element, c_i is the element's actual concentration, c_{ie} is the local equilibrium concentration, $d\zeta/dt$ is the rate of relative sea-level rise and b_i is any change in volume due to dredging or dumping of sediment in the element.

When the element's local concentration (c_i) is smaller than the local equilibrium concentration (c_{ie}), erosion will occur within the element; when the local concentration is larger than the local equilibrium concentration, sediment will accrete. Erosion and accretion within an element must be balanced by transfers of sediment across the element's boundaries, with adjacent elements or the outside world (equation 6).

$$\sum \delta_{i,j}(c_i - c_j) = A_i w_{si}(c_{ie} - c_i) \qquad 6$$

Where $\delta_{i,j}$ is the horizontal exchange coefficient between the element and an adjacent element or the sea and c_j is the concentration of the adjacent element. When describing exchanges with the outside world, the concentration in the adjacent element (c_j) is replaced with the global equilibrium concentration (C_E).

Sea-level rise creates additional sediment accommodation space by increasing the difference between an element's actual volume and its equilibrium volume. Dredging, land reclamation and realignment also increase the difference between an elements actual and equilibrium volumes, either by altering the actual volume, or if tidal prism is changed, by changing its equilibrium volume.

Model Application

To apply ASMITA to the Thames estuary a six-element model was used (Figure 2) dividing the estuary into three sections each containing channel and flat elements. Channels are defined as the water volume below chart datum and flats as the sediment volume above chart datum. Although flats lie on both sides of the channel, they were represented in ASMITA as a single element.

The schematisation was chosen to capture the variation between the different areas of the estuary. Teddington to Broadness receives the majority of the river input and has historically had the most dredging. This section (referred to henceforth as the Inner Estuary) is relatively narrow with limited intertidal areas at the margins. The bed of this section consists mainly of gravel, stones, clay and chalk, with the exception of Gravesend Reach and the Mud Reaches. The next section, between Broadness and Lower Hope Point (Mid Estuary) is wider, with some large intertidal areas. Mucking Flats, which have shown rapid accretion in the past are located in this section. The section between Lower Hope Point and Southend (Outer Estuary) is wider and sandier than the landward sections and has large areas of intertidal sand flats as well as some muddier creek systems along the northern shore where saltmarsh grows. In the outer section of the estuary almost all the intertidal areas of the main estuary are backed by sea defences and the intertidal areas are at levels of mean tide level or lower.

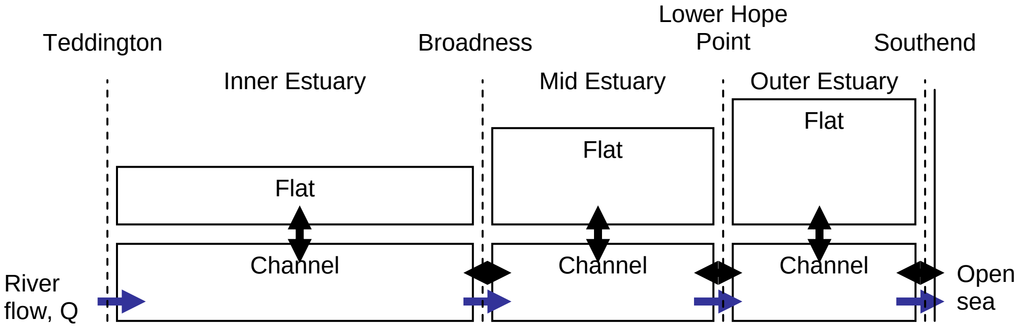

Figure 2 Thames Estuary schematisation

The sediment budget terms for fluvial sediment supply and dredging losses discussed above were introduced into the ASMITA model as sink/source terms. Each of the terms was allowed to vary over the course of the period modelled. Dredging for future periods was assumed to continue at the same rate as in 2000.

Historical areas and volumes for the elements were derived from data reported in HR Wallingford (2006b). The initial volumes and areas used for the ASMITA simulation were the 1910 values (Table 3). Sediment exchange parameters (Table 4) were estimated from bathymetry data (areas, lengths and depths), previous numerical modeling results (velocity) and knowledge of sediment characteristics, using the methodology described in Wang et al. (2007).

ASMITA simulations were carried out for the period 1910 to 1990 with a sea-level rise of 2mm/year (which is consistent with estimates of sea level rise based on tidal records). To validate the model, these predictions were compared with historical element volumes for the same period. Brier’s skill scores for the validation indicate that the ASMITA predictions were better than the baseline assumption (no change from 1910 volumes) for five out of 6 elements.

Following this validation, two future scenarios were simulated. In the first, the rate of sea-level rise was assumed to remain constant at the historical rate of 2 mm/year. In the second scenario, the response of the Thames to accelerated sea-level rise as described by DEFRA (2006) (Table 1) was simulated.

Table 3 Initial volume and area conditions used in ASMITA

Section	Channel Area (x 10^6 m^3)	Flat Area (x 10^6 m^3)	Channel Volume (x 10^6 m^3)	Flat Volume (x 10^6 m^3)
Inner Estuary	17.84	6.09	102.75	13.66
Mid Estuary	19.79	6.21	153.55	14.59
Outer Estuary	35.79	31.30	276.87	61.59

Table 4 Sediment exchange coefficients used in the Thames Estuary ASMITA model. *A* = Area of exchange, *L*= length scale of exchange, *u* = peak current speed, *H* = average depth, w_s = the vertical exchange coefficient, *D* = diffusion coefficient ($D=u^2H/w_s$) and *δ* = horizontal exchange coefficient ($\delta= (DA)/L$).

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

Results

Comparison with past evolution

Assuming a constant rate of sea level rise of 2 mm/year, ASMITA predictions showed good overall agreement with the historical data highlighting the benefits of detailed historical review and the inclusion of anthropogenic effects in the model (figure 3 and 4). Error bars for the volume of the different elements are shown in these figures which reflect the error resulting from random measurement error, errors caused by limited survey data, interpolation, and rounding error. Allowance has also been made for systematic errors which can occur in survey measurements, such as errors in relating measurements to the known water level at the time of the survey.

The model predictions were started in 1910 using the 1910 survey bathymetry as the initial bathymetry. Figures 3 and 4 show changes in volume immediately after 1910 indicating that the 1910 bathymetry was not close to equilibrium. The rapidity of the change suggests that the measured 1910 bathymetry may be significantly different to the true value. The magnitude of the error bars associated with the 1910 measurements supports this conclusion.

Brier Skill Scores were positive for five of the six elements, indicating that the ASMITA predictions were better than the baseline assumption (no change from initial volumes) in the majority of elements (Table 5). In particular, ASMITA predictions for the channels were better than the baseline assumption, with a minimum Brier's Skill Score of 0.59. The inner flat volume was also well predicted, but the mid and outer flats less so. Observed volumes for the mid flat did not change significantly over the study period, making it difficult for ASMITA to improve on the baseline assumption of no change. Conversely, the outer flat volume was variable, but showed no overall trend.

The ASMITA model shows that the signature of maintenance dredging, which increased during the 1930's, hitting a peak around 1952 and declining after that time, can be seen in the evolution of the estuary, particularly in the inner estuary (upstream of Broadness) (figure 5). The inner channel volume was predicted to increase between 1910 and 1980 when the volume of sediment removed by dredging exceeds the fluvial sediment supply. After 1980, the channel volume decreased slightly, showing a tendency to infill when dredging was reduced. The volume of tidal flats is relatively constant over time, suggesting that they are close to equilibrium over the time scale of interest.

Table 5 Mean square error for model and baseline predictions and Brier's Skill Score

	Inner Channel	Inner Flat	Mid Channel	Mid Flat	Outer Channel	Outer Flat
MSE (ASMITA)	6.21	0.17	0.76	2.00	12.27	21.20
MSE (Baseline)	53.80	1.39	1.86	2.05	142.16	12.89
BSS	0.88	0.88	0.59	0.03	0.91	-0.64

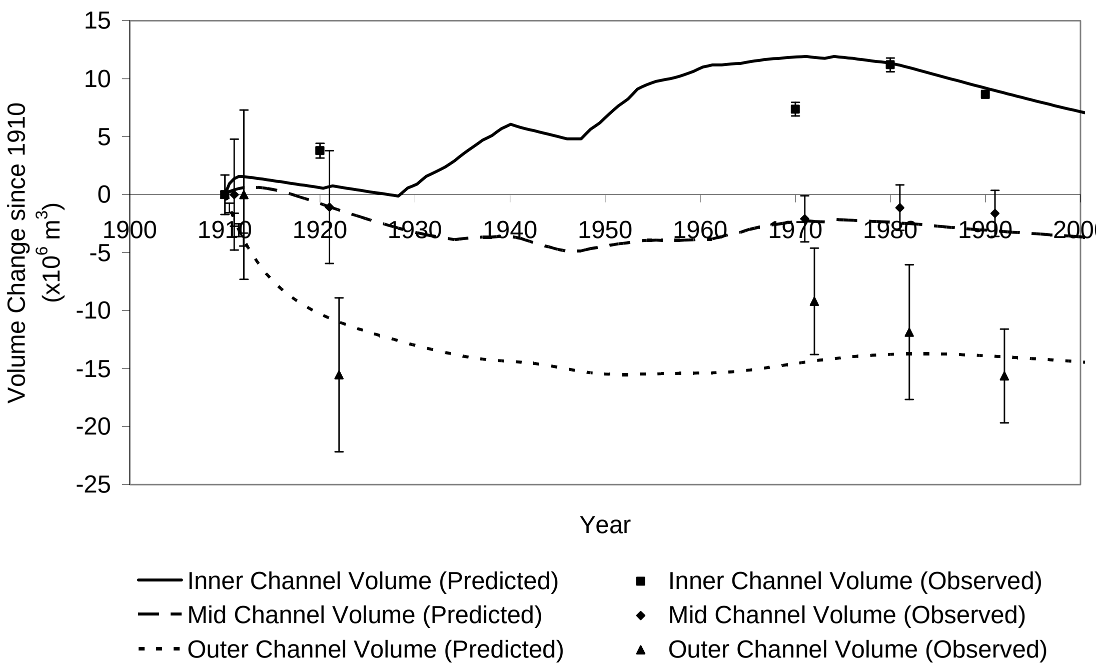

Figure 3 Predicted and observed changes in channel volumes for the period 1910 to 1990

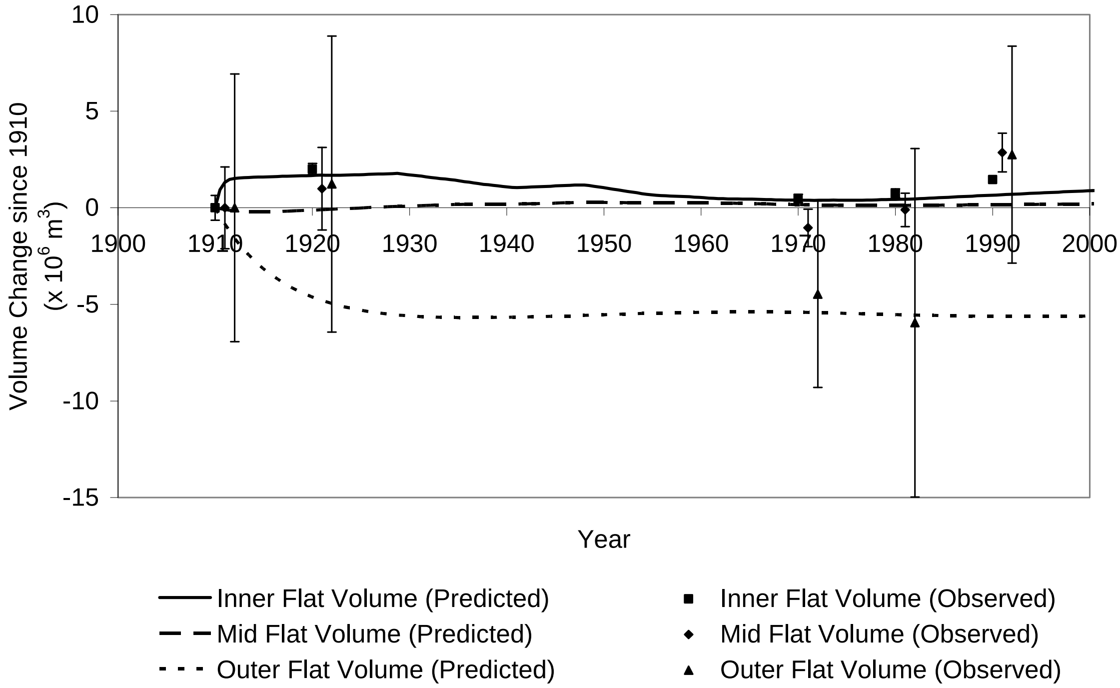

Figure 4 Predicted and observed changes in flat volumes for the period 1910 to 1990

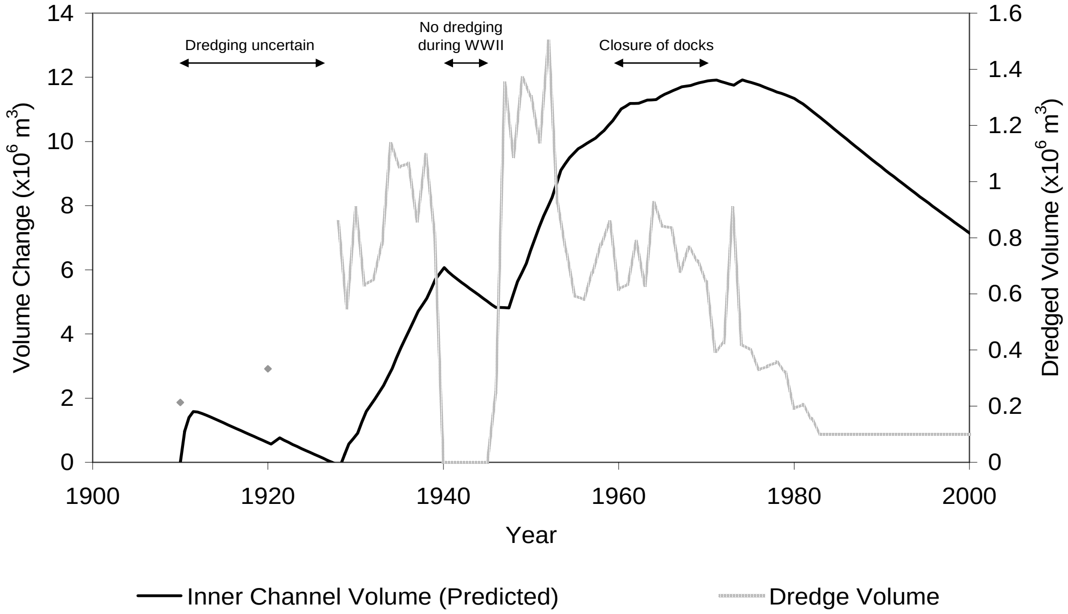

Figure 5 Estimated dredging volumes and changes in the inner channel volume

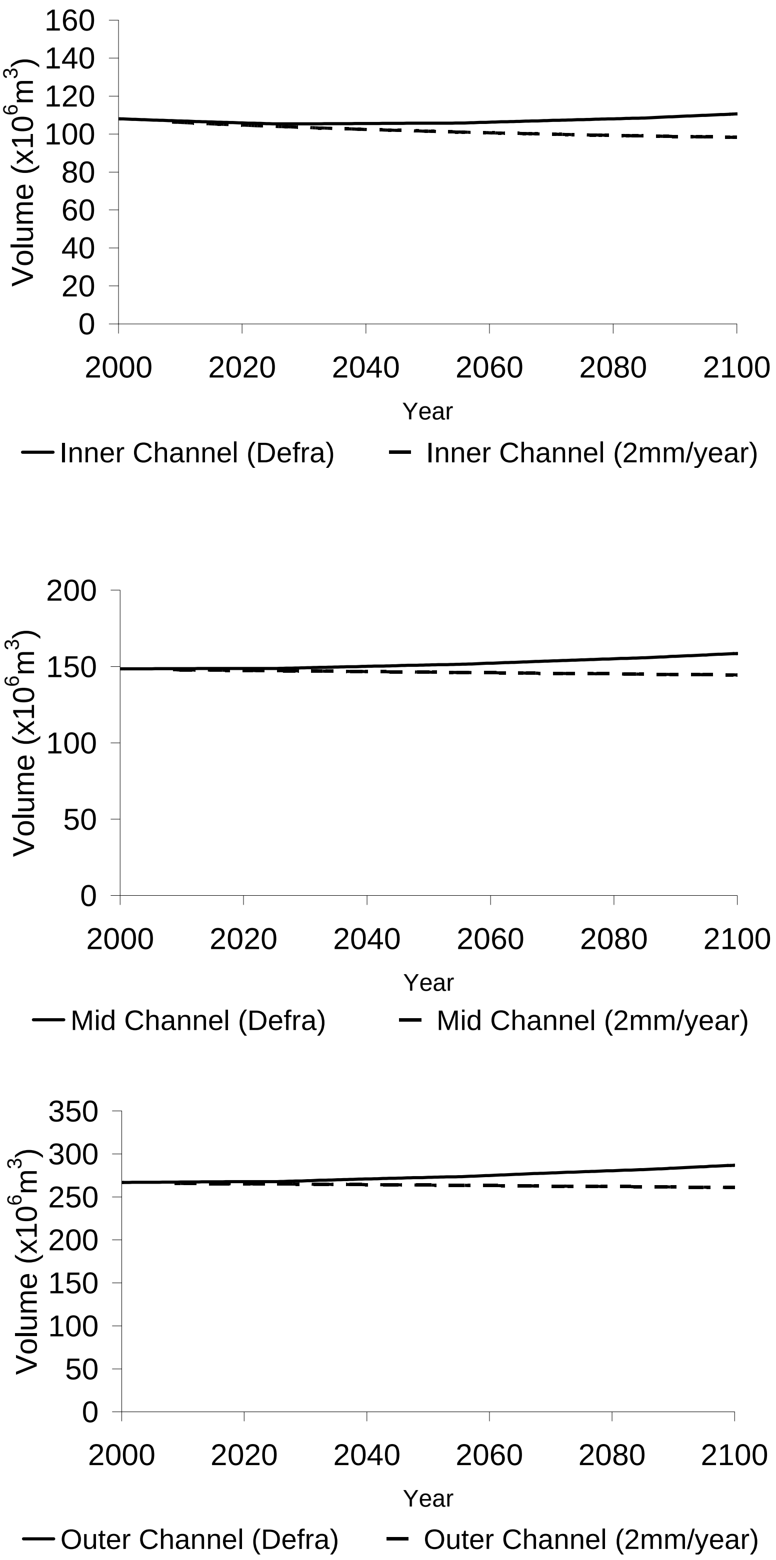

Figure 6 Predicted channel volumes with historical rates of sea-level rise (2mm/year) and DEFRA 2006 sea-level rise allowances for the inner (a), mid (b) and outer (c) estuary

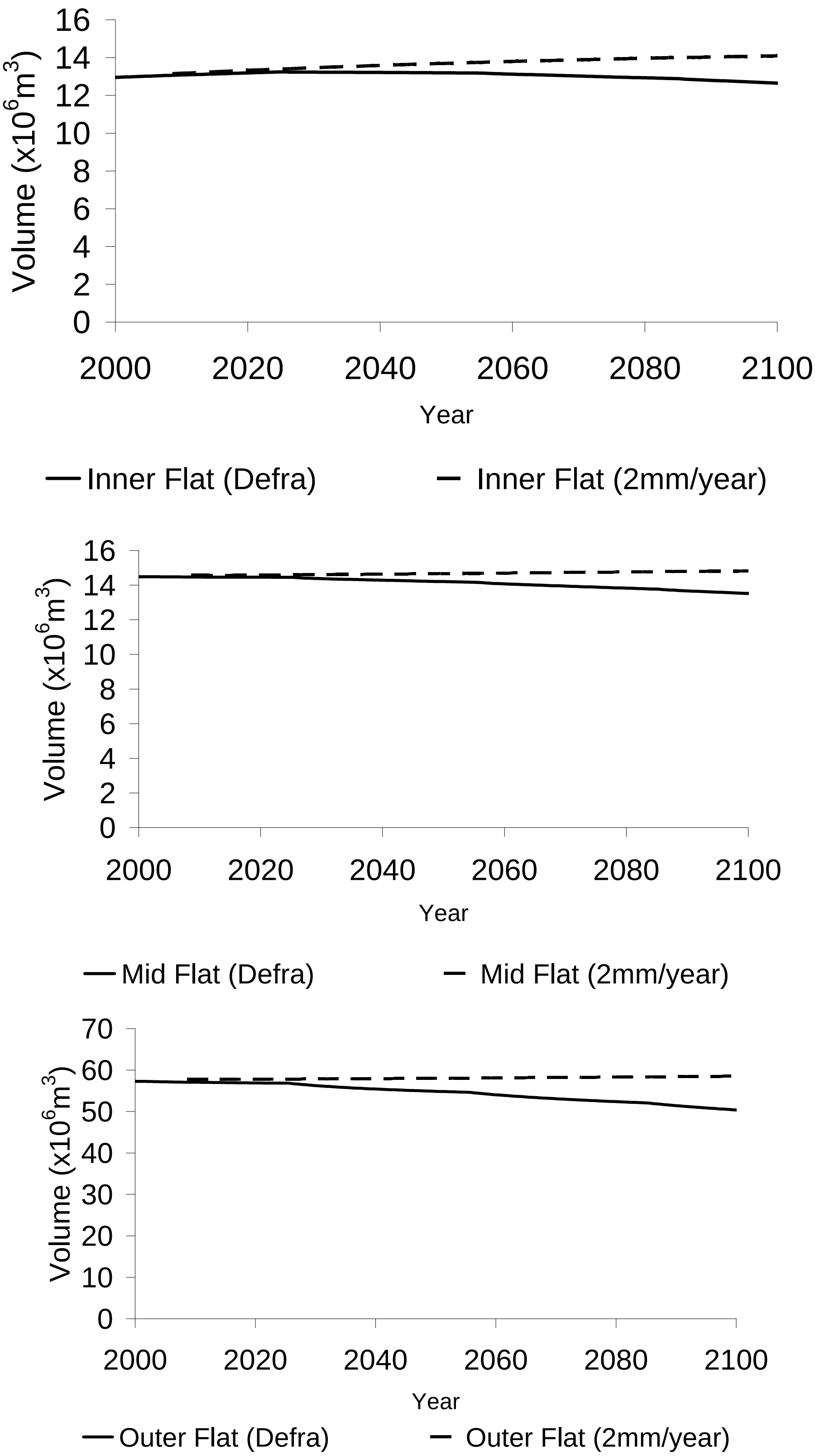

Figure 7 Predicted flat volumes with historical rates of sea-level rise (2mm/year) and DEFRA 2006 sea-level rise allowances for the inner (a), mid (b) and outer (c) estuary

Predicted future evolution

ASMITA predictions for the period 2000 to 2115 suggest that, under both sea level rise scenarios, the estuary will experience significant accretion but, for the accelerated sea level rise scenario, will not keep pace with sea level rise.

With sea-level rise kept constant at 2 mm/year the model predicts that channel volumes will show a slight tendency to decrease (Figure 6) and flat volumes to increase slightly (Figure 7) as the estuary continues to adapt to the reduction in the disposal of dredged sediment outside of the estuary. This implies that the rate of accretion exceeds rate of sea level rise. At the start of the simulation period, the Thames Estuary is out of equilibrium due to human disturbances in the preceding century. Channel volumes are greater than equilibrium because of high levels of dredging. As dredging decreased towards the end of the 20th Century, and was assumed to continue at lowered rates throughout the future simulations, ASMITA predictions show that the channels will gradually reduce in volume (infill) in response to these changes in forcing.

Under the accelerated sea-level rise conditions, ASMITA predictions suggest that channel volumes will tend to increase and flat volumes to decrease. These changes indicate that, whilst the estuary continues to accrete, the rate of accretion predicted by the model is less that the rate of sea-level rise. Overall this means that channels will increase in size and intertidal volume (and by implication area) will be lost.

Table 6 shows the percentage increase in channel volume and decrease in flat volume under the DEFRA sea-level rise allowances, compared to under a constant rate of 2 mm/year. Predicted differences were initially small, less than 2% by 2025, but increased as the modeled rate of sea-level rise accelerated. The point where the effect of sea level rise stops (and subsequently reverses) the slight trend for accretion on intertidal areas that is experienced at present within the estuary is around 2020. The largest relative change is predicted to be in the outer flat element, with a 15% volume reduction by 2105, compared to the constant rate of sea-level rise. This corresponds to a loss of 8.6 x10^6m^3 of intertidal sediment volume from the outer estuary, or a loss of approximately 0.5 m to the average intertidal height (relative to high water), compared to under a constant rate of sea-level rise. The loss of intertidal sediment does not imply erosion; rather the material is still present but is no longer intertidal due to the rising tidal frame. Any reduction in intertidal volume will contribute to intertidal area loss, with implications for the estuaries intertidal habitats.

Table 6 Difference in element volumes for DEFRA 2006 sea-level rise allowances compared to element volumes with 2 mm/year sea-level rise (x10^6m^3). Numbers in brackets are the percentage difference from 2 mm/year predictions.

Year	Inner Channel	Inner Flat	Mid Channel	Mid Flat	Outer Channel	Outer Flat
2000	0.41 (0%)	-0.05 (0%)	0.42 (0%)	-0.05 (0%)	0.86 (0%)	-0.44 (-1%)
2025	1.32 (1%)	-0.15 (-1%)	1.47 (1%)	-0.14 (-1%)	2.79 (1%)	-0.97 (-2%)
2055	4.75 (5%)	-0.57 (-4%)	5.35 (4%)	-0.52 (-4%)	10.07 (4%)	-3.40 (-6%)
2085	9.46 (10%)	-1.12 (-8%)	10.77 (7%)	-1.01 (-7%)	19.91 (8%)	-6.28 (-11%)
2105	13.22 (13%)	-1.54 (-11%)	15.03 (10%)	-1.38 (-9%)	27.62 (11%)	-8.58 (-15%)

Discussion

Using information on fluvial flows and historical dredging rates, ASMITA was able to successfully reproduce the observed evolution of the Thames Estuary between 1910 and 1990. This highlights the importance of having detailed knowledge of the anthropogenic influences on an estuary – had dredging not been included in the model, the fit of the predictions to the observed data would not have been as strong. In addition, this result suggests that the evolution of the Thames Estuary in the 20th Century was dominated by human activities, rather than by sea-level rise.

ASMITA was also applied to model the future evolution of the Thames Estuary under two sea-level rise scenarios: 1) assuming sea-level rise remained constant at the historical rate of approximately 2mm/year and 2) assuming the rate of sea-level rise accelerates as suggested in the DEFRA (2006) allowances (Table 1). Under the scenario of a constant rate of sea-level rise, the rate of accretion exceeded sea-level rise in all six elements. This is due to the estuary adjusting to decreases in dredging compared to the previous century.

With accelerated sea-level rise, the estuary was still predicted to accrete, but the rate of accretion was now less than the rate of sea-level rise, meaning that channel volumes increased and flat volumes decreased. The largest predicted lost of intertidal volume was in the outer estuary and could have significant implications for intertidal habitat. The effects attributed to accelerated sea-level rise were significant and are likely to become more important than anthropogenic activities as the next century progresses.

The version of ASMITA applied in this study assumed that the element areas were constant and that all changes in element volumes must therefore result from changes in depths. In the future it would be useful to apply newly developed versions of the model, which allow element areas to evolve as a function of tidal prism, to predict intertidal area losses directly from the model.

With accelerated sea-level rise based on the DEFRA (2006) allowances for the Thames, up to 15% of the intertidal volume is lost from the Thames. However, it should be noted that the DEFRA sea-level rise allowances are for flood defence purposes and as such give a pessimistic outlook for future sea-levels. Actual sea-level rises are likely to be smaller so the ASMITA predictions reported here for the Thames Estuary may represent a worse case.

Areas for further development of the ASMITA model

The ASMITA model enables an assessment of estuary evolution under the action of sea level rise, dredging and anthropogenic changes in sediment supply. The model represents processed-based long-term transport between macro-scale geomorphological elements of an estuary. At present the area of each element is fixed and the changes in flats and channels occurs in the depth only. This simplification is convenient for the modeller but not necessarily so convenient for the regulator who has a considerable interest in potential changes to the extent of intertidal area. Further work is required to extend the model to allow the area growth of flats. In doing so the nature of the equilibrium relationships governing tidal flat evolution will need to become more sophisticated than at present.

The ASMITA model assumes that the offshore area adjacent to the estuary provides a resource of sediment which is constant (although exchanges of sediment between the sea and the estuary vary depending on the relative differences in sediment concentration). It is quite possible that sea level rise will cause changes in littoral drift and hence changes to the sediment resource in the near shore zone, in turn changing the sediment supply to the estuary. This matter is an area of current research. The linkage of cliff erosion models to ASMITA to provide a better representation of sediment supply has been demonstrated by Walkden and Rossington (2009).

Conclusions

The evolution in the Thames Estuary over the last 100 years appears to have been more sensitive to human interventions than sea level rise, with dredging dominating morphological changes between 1910 and 1990. In the future, the effect of accelerated sea level rise is predicted to be more significant than any other change over the last century. Intertidal losses are to be expected under this scenario.

These results represent an initial appraisal of past and future evolution in the Thames Estuary. Further work is being undertaken within the Thames 2100 Project to improve these predictions and to test the impacts of potential flood risk management responses and habitat creation options on morphology.

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