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Risk Management R&D Programme

Development of estuary morphological models

Annex C2: Application of ASMITA to the Thames Estuary

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Development of Estuary Morphological Models

Application of ASMITA to the Thames Estuary

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Summary

Development of Estuary Morphological Models

Application of ASMITA to the Thames Estuary

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1. Introduction

1.1 BACKGROUND

This report describes work undertaken by Southampton University for Defra project, FD2107, "Development of hybrid estuary morphological models". This project is part of Phase 2 the Estuaries Research Programme and has the overall aim of developing new modelling tools capable of delivering 50-year forecasts of morphology enabling estimates of the associated flood risks in order to help Defra in its responsibilities relating to proposed estuarine management to accommodate climate change. This report has been written for Work Package 2.3, Task 1, "Development and application of ASMITA".

1.2 OBJECTIVES

This work was carried out to consider the consequences of sea-level rise in the Thames estuary. Historical morphological changes between 1910 and 1990 are used to calibrate a simple model, ASMITA, which is applied to predict how the Thames estuary will respond to accelerated rates of sea-level rise.

1.3 REPORT STRUCTURE

This report includes:

- A brief description of the Thames estuary, with details of processes relevant to the current study
- A description of ASMITA, the model used
- Model simulations examining the effect of sea-level rise
- A discussion of the predicted response to sea-level rise, sediment transport mechanisms and the uncertainty in the results.

2. The Thames Estuary

2.1 ESTUARY DESCRIPTION

For the purposes of this study the Thames estuary is defined as the tidal Thames between the tidal limit at Teddington Weir and the seaward boundary at Southend on Sea (Figure 1). The Thames estuary is a funnel shaped estuary with an extensive river catchment (FutureCoast, 2002). The banks are extensively defended by sea walls 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 (LNR), Sites of Special Scientific Interest (SSSI) and internationally important designations. Intertidal areas, including mudflats, salt marsh and grazing marsh are important habitats under these designations and these habitats are likely to change in response to sea-level rise, particularly where sea defences prevent them migrating landward.

2.2 SEDIMENT BUDGET

2.2.1 Introduction

The Thames Estuary is affected by sediment from fluvial sources, exchange with the sea, dredging and sewage. Much of the sediment budget data used in the current study comes from work on the Thames sediment budget by HR Wallingford (2006a) which was based on WPRL (1964) and Port of London Authority dredging records and charts.

Sediment characteristics in the Thames differ along the estuary. The inner estuary has mainly fine, muddy sediment and Sea Reach is sandy. For the purposes of this study, sand and mud fractions have been lumped together in terms of their contribution to the sediment budget.

2.2.2 Fluvial Sediment Supply

Fluvial sediment supply is estimated to be between 118,000 and 234,000 dry tonnes/year (HR Wallingford, 2006a) including sediment from the River Thames, tributaries and sewage treatment works. A best estimate value of 200,000 dry tonnes/year is used in this study.

2.2.3 Marine sediment supply

The extent of supply of sediment from marine sources into the Thames Estuary is uncertain although it can be concluded that the estuary has in broad terms kept pace with sea level rise since the Holocene period. There are potentially significant sources of sediment to the Estuary, for instance, Nicholls *et al* (2000) estimate that erosion of cliffs on the Isle of Sheppey supplies approximately 450,000 tonnes/year of fine sediment to the Outer Thames estuary and Southern North Sea which, potentially at least, represents a source at least double the fluvial sediment supply. Other sediment sources are sea bed sediments in the Southern North Sea and erosion of Anglian coast. The pathways and sinks for this sediment are uncertain (HR Wallingford, 2006a).

A sediment budget analysis was undertaken for the Thames by Inglis and Allen (1957) who noted that there was a shortfall in the sediment input required to balance the sediment budget of around 276,000 tonnes/yr. Inglis and Allen interpreted this shortfall as evidence that there was an input of sediment from marine sources. The Water Pollution Research Laboratory (1964) in a following report noted that the shortfall identified by Inglis and Allen could be due to morphological change which was not included in their analysis. A repeat of the sediment budget analysis (HR Wallingford, 2006a), but this time including detailed data regarding historic bathymetric change showed that morphological change could account for the discrepancy between sediment inputs and outputs in the Thames Estuary but that there was still considerable uncertainty about the net exchange. The Water Pollution Research Laboratory report (1964) makes the point that the import of material identified by Inglis and Allen as coming from marine sources (276,000 tonnes/yr) would only require a difference in suspended sediment concentration of 1-2mg/l between the flood and ebb tides at Southend.

It should be noted that in general, unless a strong residual current exists in the opposite direction, suspended sediment will diffuse from a location of higher suspended sediment to a location of lower suspended sediment. In the case of the lower Thames Estuary the suspended sediment concentrations reduce with distance seawards and it would be expected that there would be a residual flux of sediment seaward if there is no landward near bed velocity residual. The presence of a turbidity maxima and tracer experiments (Inglis and Allen, 1957) suggests that there is landward residual transport in Gravesend Reach. Further seaward, in the Outer Thames, there is still a reduction in suspended sediment concentration with distance seawards but there is no evidence of an accompanying strong residual. Radio-nuclide tracer tests and ecological monitoring of placement of sewage sludge in Barrow Deep (Whitelaw et al, 1988) showed that sludge mainly dispersed to north and seaward of the placement site but not landward towards Southend.

2.2.4 Dredging

Historically both capital and maintenance dredging has been carried out in the Thames estuary. Data on historic rates of dredging were obtained from HR Wallingford (2006a) which draws on sources from the Port of London Authority and the Water Pollution Research Laboratory. These were converted from tonnes to m^3 assuming a dry density of 600 kg/m^3. 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. A summary of the assumed annual dredging volumes used in ASMITA are given in Appendix A. For future simulations, it is assumed that dredging remains constant at current rates of approximately 100,000 m^3/year.

2.2.5 Sediment demand

Within each section of the estuary, sediment demand is created by sea-level rise and by human activities such as dredging. Sediment demand is defined as the volume of sediment needed to for the morphological evolution of the estuary to maintain equilibrium with sea-level rise. Sediment demands under different potential rates of sea-level rise are given in Table 1.

Table 1 Sediment demand in the Thames estuary due to sea-level rise at different rates (m^3 sediment/year)

Section	2 mm/year	6 mm/year	20 mm/year
Teddington to Broadness	48,000	144,000	479,000
Broadness to Lower Hope Point	52,000	156,000	520,000
Lower Hope Point to Southend	134,000	403,000	1,340,000
Total	**234,000**	**703,000**	**2,340,000**

2.3 SEA-LEVEL RISE

The historical rate of relative sea-level rise in the Thames estuary is approximately 2 mm/year (HR Wallingford, 2006b). The rate of sea-level rise is expected to accelerate over the next century, with predictions suggesting rates up to 15 mm/year (Defra, 2006). The predicted rates of sea-level rise for the Thames area are given for 30 year periods from 1990 to 2115 in Table 2.

Table 2 Rates of sea-level rise predicted by DEFRA (2006) for the Thames area. (*1910 - 1990 value is the approximate average rate for this period)

Period	Rate of Sea-level Rise
1910 – 1990	2 mm/year*
1990 – 2025	4 mm/year
2025 – 2055	8.5 mm/year
2055 – 2085	12 mm/year
2085 – 2115	15 mm/year

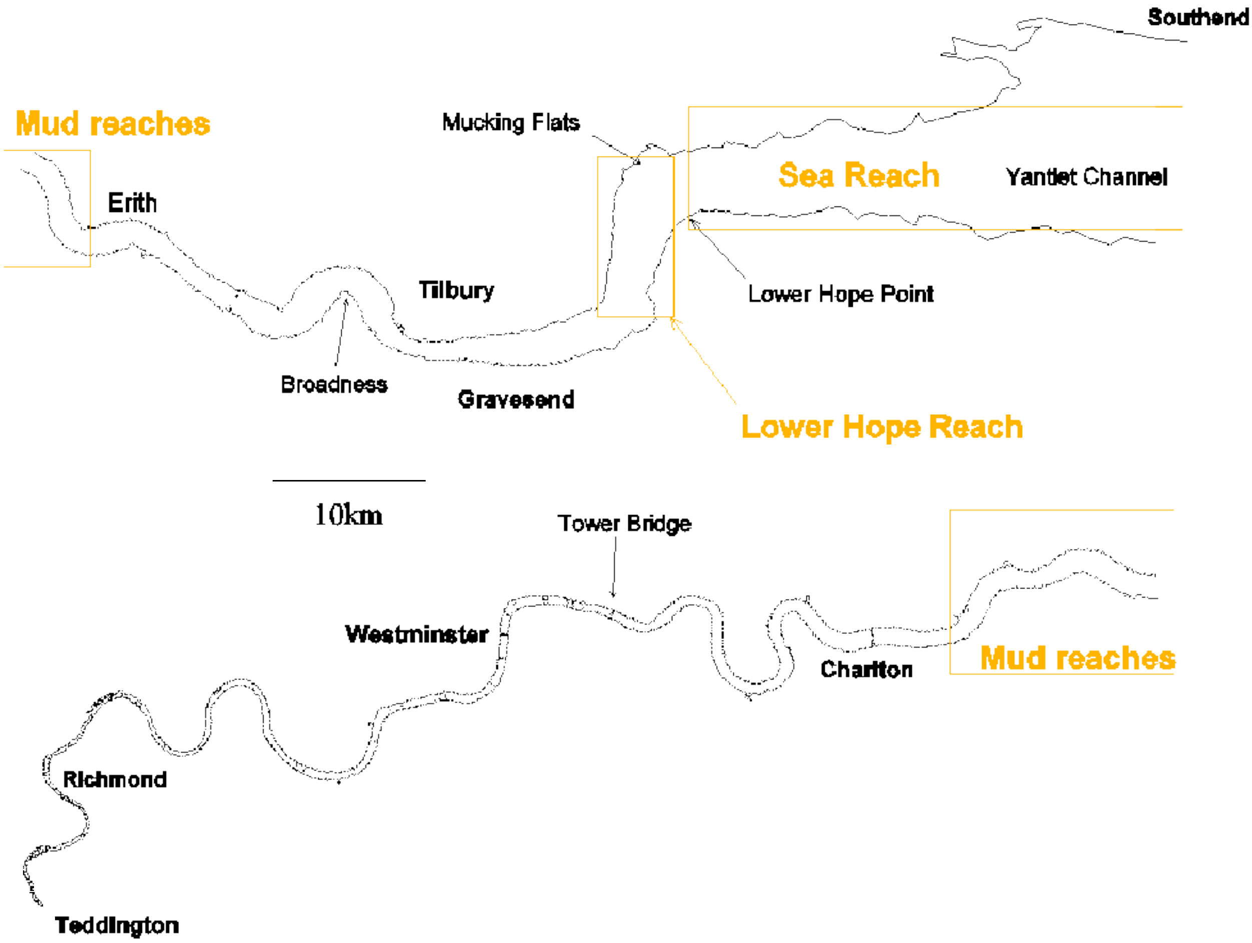
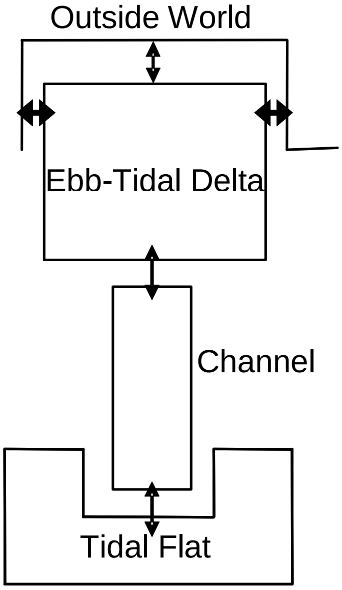


Figure 1 Outline map of Thames Estuary

3. ASMITA

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 (Figure 2). 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).

Sea-level rise creates accommodation space within the estuary and causes the estuary to become a sink for available sediment. In AMSITA this is represented by an increase in the difference between the elements actual volume and equilibrium volume and sediment diffuses into the estuary.



Element definitions:

Ebb-tidal Delta: Excess sediment volume above a hypothetical non-inlet shoreface

Channel: Water volume below mean low water

Tidal flat: Sediment volume above mean low water

Figure 2 ASMITA schematisation and element definitions (from van Goor *et al.*, 2003)

The morphological elements in ASMITA, intertidal area, channels and ebb-tidal delta, 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. Long-term, residual sediment exchange is assumed to occur between adjacent model elements and it is assumed that development of the tidal inlet does not affect the availability of sediment in the outside world, represented by the global equilibrium concentration (van Goor *et al*., 2003). Volume changes within elements are described by equations 1, 2 and 3. Sediment is transferred between elements to satisfy mass balance equations (4-6).

$$dV_f / dt = Ws_f * FlatArea * (c_f - c_{fe}) - FlatArea * (d\xi / dt) \tag{1}$$

$$dV_c / dt = Ws_c * ChannelArea * (c_c - c_{ce}) + ChannelArea * (d\xi / dt) \tag{2}$$

$$dV_d / dt = Ws_d * DeltaArea * (c_d - c_{de}) - DeltaArea * (d\xi / dt) \tag{3}$$

Where A_n is the area of element n; Ws_n is the vertical exchange coefficient for element n; c_n is the actual concentration; ξ is sea-level and c_{ne} is the element's local equilibrium concentration, defined in equations 7, 8 and 9. Subscripts, *f*, *c* and *d*, refer to the tidal flat, channel and ebb-tidal delta elements, respectively.

$$\delta_{fc} * (c_f - c_c) = Ws_f * FlatArea * (c_{fe} - c_f) \qquad 4$$

$$\delta_{fc} * (c_c - c_f) + \delta_{cd} * (c_c - c_d) = Ws_c * ChannelArea * (c_{ce} - c_c) \qquad 5$$

$$\delta_{do} * (c_d - C_E) + \delta_{cd} * (c_d - c_c) = Ws_d * DeltaArea * (c_{de} - c_d) \qquad 6$$

Where δ_{fc}, δ_{cd} and δ_{do} are coefficients for horizontal exchange between the flat and channel, the channel and delta, and the delta and outside world;

$$c_{fe} = C_E * (V_f / V_{fe})^n \qquad 7$$

$$c_{ce} = C_E * (V_{ce} / V_c)^n \qquad 8$$

$$c_{de} = C_E * (V_d / V_{de})^n \qquad 9$$

Where V_n is elements *n*’s current volume; V_{ne} is elements *n*’s equilibrium volume; C_E is the global equilibrium concentration and *r* is greater than 1 and is usually taken as 2 in compliance with a third power of sediment transport and a non-linear function of flow velocity (van Goor, 2001).

3.1 SIX ELEMENT VERSION

To apply ASMITA to the Thames estuary a six-element model was used (Figure 3). This schematisation was used 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 (Figure 1). The next section, between Broad Ness and Lower Hope Point (middle 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 (Sea Reach) 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 lower 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 MWL or lower.

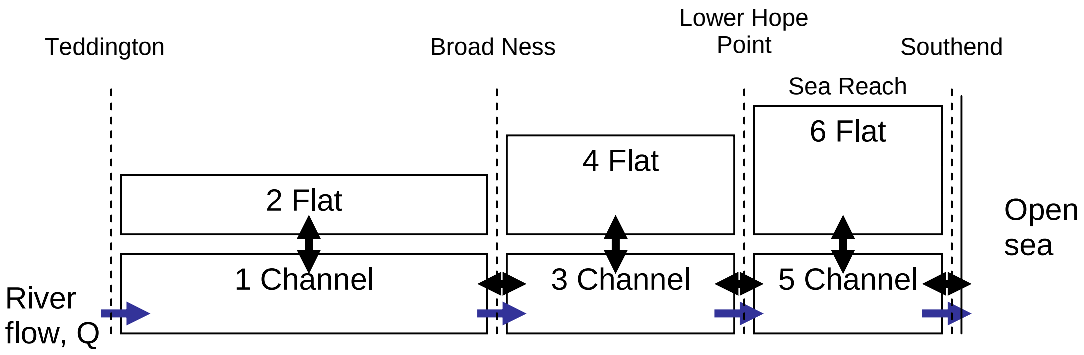


Figure 3 **Schematisation used for six element ASMITA in the Thames**

3.2 MODEL APPLICATION

ASMITA was applied to the Thames estuary to investigate the potential response of the estuary to sea-level rise and to investigate the sensitivity of this response to fluvial and marine sediment supply and possible mechanisms for trapping sediment within the estuary. The initial volume and area conditions are given in Table 3.

Table 3 **Initial volume and area conditions used in ASMITA (From HR Wallingford, 2006c)**

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)
Teddington to Broadness	17.8	6.1	102.8	13.7
Broadness to Lower Hope Point	19.8	6.2	153.6	14.6
Sea Reach	35.8	31.3	276.9	61.6

Equilibrium relationships for the channel equilibrium volume (V_{ce}) and the flat equilibrium volume (V_{fe}) were estimated from historic volume and area data (Eq. 10 & 11). Equilibrium coefficients were selected to give the best representation of the estuary geomorphology during the period of data availability (Table 4). They describe equilibrium on timescales of 10s to 100s of years, but may not be valid for predictions over longer periods.

$$V_{ce} = a_c * P \qquad 10$$

$$V_{fe} = H * a_f * (A_{Basin}) \qquad 11$$

Where H is the mean spring tidal range, A_{Basin} is the basin area, P is the tidal prism, a is an empirically derived coefficient and the subscripts f and c refer to the flats and the channels respectively.

$$P = (1 - a_f) * (A_{Basin}) * H \qquad 12$$

$$a_f = (A_f / A_{Basin}) * (h_f / H) \qquad 13$$

Where a_f is the flat equilibrium coefficients, A_f is the flat area, h_f is the equilibrium flat height and H is the tidal range.

Table 4 Equilibrium parameters used in ASMITA

Section	a_f	a_c
Teddington to Broadness	0.11	0.88
Broadness to Lower Hope Point	0.11	0.60
Sea Reach	0.17	0.48

Sediment transport coefficients (ws_n, δ_{nm}, C_E) were estimated based on the following rules (Wang, 2005):

- Vertical exchange coefficient (ws_n): same order of magnitude as, and proportional to the average fall velocity (in m/s). For the muddy inner and middle estuary sections a *ws* of 0.0006 was used. For the sandier Sea Reach, *ws* was 0.003.
- Coefficient *r*: equal to the power law in the sediment transport formula and typically 3 for mud and 5 for sand.
- Horizontal exchange coefficient (δ_{nm}): estimated based on the area available for sediment exchange (*A*), the length scale of exchange (*L*) and the diffusion coefficient (*D*) (Eq. 9).

$$\delta = (D \cdot A) / L \qquad \mathbf{14}$$

Where D is the diffusion coefficient, A is the area available for exchange and L is the length scale of exchange.

$$D = u^2 * H / ws \qquad 15$$

u is the peak velocity and H is the average water depth.

- Global equilibrium concentration (C_E): Once the other parameters have been estimated, C_E is used to fit the model to the observed morphological time scale.

Van Goor *et al* (2003) suggest that the uncertainty associated with these parameters is approximately +/- 50 %. Model calibration was carried out based on the estimated parameter values and this estimate of uncertainty. The “goodness of fit” was measured using a Brier’s skill score (BSS) (Sutherland and Soulsby, 2003).

$$BSS = 1 - (MSE(P,O) / MSE(B,O)) \qquad \mathbf{16}$$

Where MSE(P,O) is the mean square error between the predicted and observed and MSE(B,O) is the mean square error between a baseline condition and the observed data. In this case the baseline is assumed to equal the initial volume for each element. The Briers skill score compares the goodness of fit of the model prediction against that of a null hypothesis, here represented by the assumption that the estuary bathymetry continues to be the same as the baseline condition.

The parameter values selected for each element are given in Table 5. Values of D are higher in the inner estuary because of the smaller values of ws_n. The global equilibrium concentration (C_E), imposed at the outside world boundary is 0.000085. This non-dimensionalised concentration corresponds to the measured concentrations at Southend, which are of the order of 50mg/l on average, divided by the typical bed density for the Thames, here assumed to be 600kg/m^3. The river concentration (C_R) available to the upper estuary section is 0.00014. Average river flow (Q) (from all tributaries) is approximately 200,000 dry tonnes/year. Assuming a sediment dry density of 440 kg/m3 this gives a total river sediment supply of 100 m^3/s. This is the lower limit of the likely sediment densities quoted in HR Wallingford (2006a) and was selected during model calibration.

Table 5 Sediment exchange coefficients used in ASMITA. ws_n is the coefficient for vertical sediment exchange, δ_{nm} is the coefficient for horizontal sediment exchange between elements n and m (where the subscripts f, c and o refer to the flats, channel and outside world)

Section	w_{sn}	D	δ_{fc}	D	δ_{cc} or δ_{co}
Teddington to Broadness	0.0006	125	15000	1200	260
Broadness to Lower Hope Point	0.0006	125	1350	4400	5000
Lower Hope Point to Southend	0.003	50	825	700	1270

4. Results

4.1 EVOLUTION WITH HISTORIC RATES

Under conditions of 2 mm/year sea-level rise, ASMITA was able to reproduce the evolution of the estuary reasonably successfully (Figure 4). Brier Skill Scores indicate that ASMITA predictions were better than assuming the volumes continued at their initial values in the five of the six elements (Table 6). The exception was the channel between Broadness and Lower Hope Point where the BBS was close to zero, indicating that ASMITA was no better than assuming the channel volume remained constant at its initial volume for this element; this is likely to be because the volume changes in this section were very low.

Table 6 Mean square error and Brier Skill Score between ASMITA predictions and observed data under 2 mm/year sea-level rise

	Teddington to Broadness		Broadness to Lower Hope Point		Sea Reach	
	Channel	Flat	Channel	Flat	Channel	Flat
MSE(P,O)	7.27	2.95	8.47	2.27	22.30	14.19
MSE(I,O)	276.67	7.71	8.33	11.05	641.47	60.68
BSS	0.97	0.62	-0.02	0.79	0.97	0.77

The ASMITA model predicts that in the inner estuary the channel volume increases between 1910 and 1980. During this period the volume of sediment removed by dredging exceeds the fluvial sediment supply. After 1980, the channel volume decreases slightly, showing a tendency to infill towards equilibrium. The flat volume is relatively constant over time, suggesting that it is in quasi-equilibrium over the time scale of interest.

The channel and flat volumes between Broadness and Lower Hope Point are also relatively constant over the study period. ASMITA suggests the channel infills slightly, but predictions remain close to the baseline (initial) volume (less than 2% change). ASMITA also predicts that the Sea Reach channel will infill slightly (6% change) and that the flat volume will decrease slightly (5%).

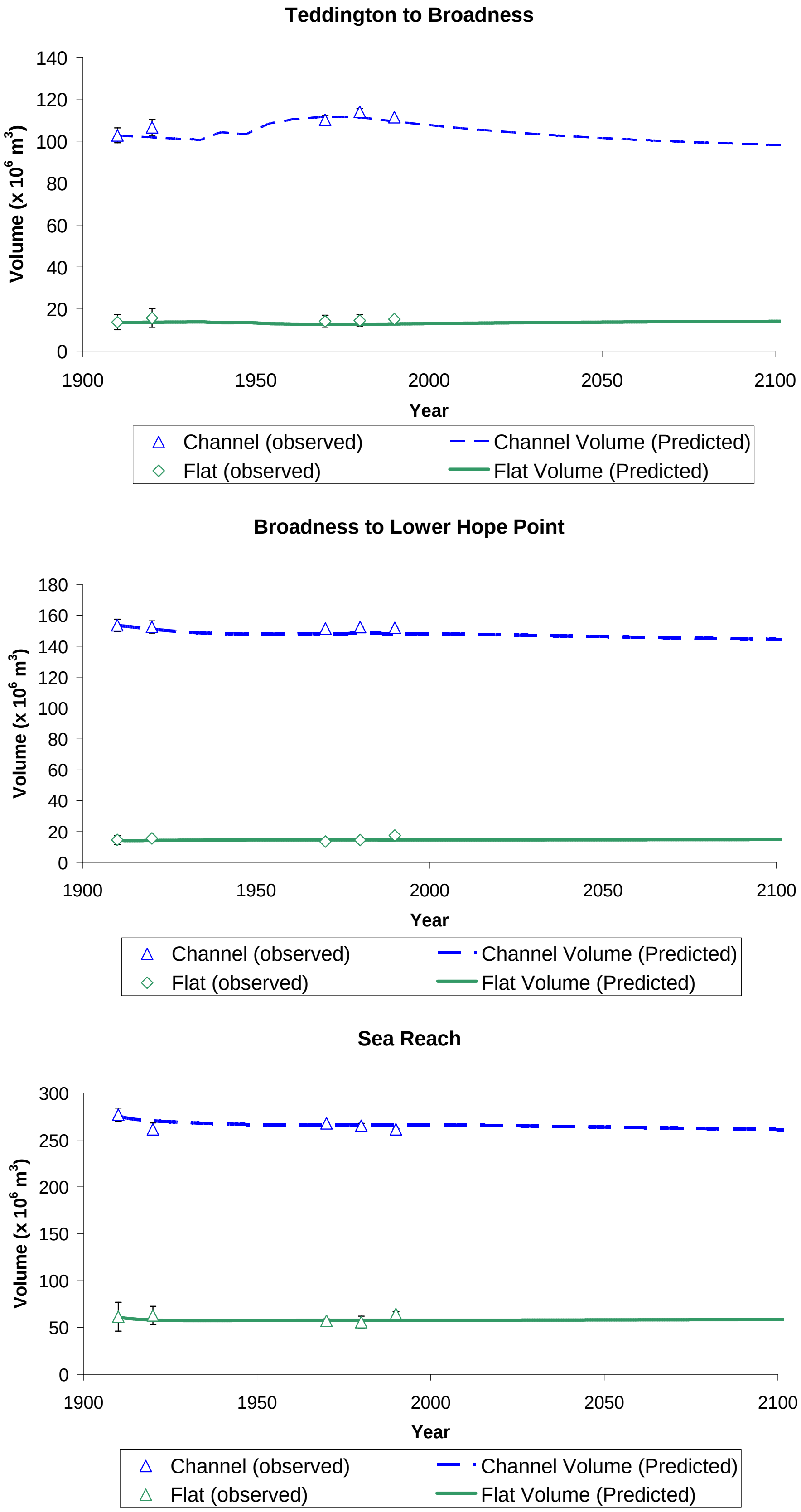


Figure 4 Evolution of the Thames estuary assuming external forcing remains the same as at present

4.2 EVOLUTION WITH DEFRA PREDICTIONS

The DEFRA (2006) (Table 7) predictions were used as sea-level rise forcing in ASMITA to predict the response of the Thames Estuary to accelerated sea-level rise (Figure 5). Channel volumes tend to increase and flat volumes decrease. Elements appear to evolve towards a new steady state where deposition in the element can keep pace with sea-level rise only when the rate of sea-level rise becomes constant (after 2115). Table 7 shows the percentage difference between the elements current volume and its equilibrium volume.

Table 7 Percentage differences between element volume and equilibrium volume under the DEFRA (2006) predicteed rates of sea-level rise

	Teddington to Broadness		Broadness to Lower Hope Point		Sea Reach	
	Channel	Flat	Channel	Flat	Channel	Flat
2025	5.41	-5.06	4.62	-4.66	4.19	-5.96
2055	5.80	-5.52	6.40	-6.56	5.93	-9.60
2085	8.17	-7.65	9.08	-9.14	8.42	-13.83
2115	11.93	-10.83	12.47	-12.20	11.48	-18.62
2400	30.17	-23.31	24.75	-21.21	21.77	-29.86
2800	37.21	-27.22	27.75	-23.15	24.12	-32.23

By 2025 (sea-level rise rates of 4 mm/year) channel volumes are between 4.2% and 5.4% larger than their equilibrium volumes (based on historical morphology). Flat volumes have decreased by between 4.7% and 6%. In 2115, with predicted sea-level rise rates accelerating to 15 mm/year, channel volumes are between 11.5% and 12.5% larger than equilibrium. Flat volumes have decreased by between 10.8% and 18.6%, representing a significant loss in intertidal volume.

Longer term predictions are subject to numerous uncertainties. Equilibrium volumes in ASMITA are defined based on data covering 10s to 100s of years. The validity of extending this equilibrium definition to model periods closer to geological time scale is questionable. On geological timescales, many estuaries tend to infill, and this is unlikely to be captured by equilibrium equations based on shorter timescales. In addition, factors such as river flow, land use and sediment supply, tidal range, wave activity, storminess, and in particular, management policies, are likely to change over such long periods, decreasing the value of ASMITA predictions made using forcing influences based on the current estuary conditions and management strategy.

Despite the uncertainties, ASMITA was used to predict the evolutions of the estuaries up to 2800. Assuming sea-level rise remained constant at a rate of 15 mm/year after 2115, channel volumes could be between 20% and 30% larger by 2400, and between 25% and 37% larger by 2800. Under this scenario, flat volumes could decrease by 21% to 31% by 2400 and by between 23% and 32% by 2800. These values should be taken as an indication of the likely trend only

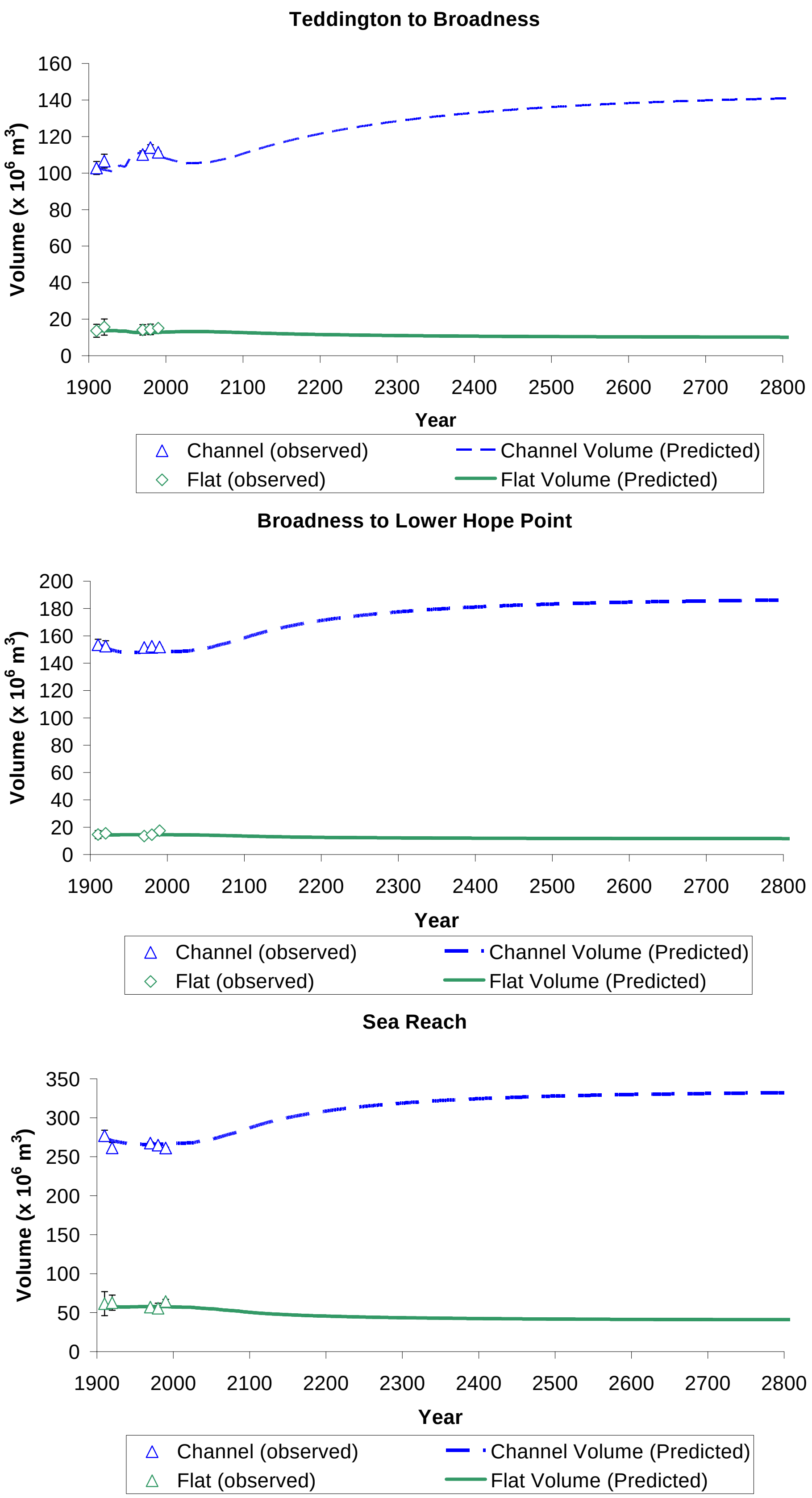


Figure 5 Predicted evolution of the Thames estuary using increasing rates of sea-level rise predicted by DEFRA (2006) (Table 2) and assuming a constant rate of 15 mm/year after 2115

4.3 EVOLUTION WITH EXTREME RATES OF SEA-LEVEL RISE

To examine the effect of an extreme increase in the rate of sea-level rise, ASMITA was applied to simulate the evolution of the Thames Estuary with sea-level rise rates of 20 mm/year after 2000. The volume evolution predicted by ASMITA with 20 mm/year sea-level rise is shown in Figure 6. Channel volumes increase and flat volumes decrease. In the time scale of the simulation (800 years) new steady state volumes are not achieved. Table 8 gives the percentage difference between the elements current volume and its equilibrium volume.

Table 8 Percentage differences between element volume and equilibrium volume under 20 mm/year sea-level rise after 2000

	Teddington to Broadness		Broadness to Lower Hope Point		Sea Reach	
	Channel	Flat	Channel	Flat	Channel	Flat
2025	9.25	-8.69	7.58	-8.08	7.77	-13.49
2055	15.74	-13.42	14.39	-13.44	14.45	-21.90
2085	21.29	-17.24	19.50	-17.22	18.98	-27.15
2115	26.23	-20.48	23.49	-20.07	22.27	-31.15
2400	58.17	-36.28	41.93	-30.94	37.47	-47.97
2800	83.24	-44.69	50.23	-34.82	44.05	-55.32

In 2025, channel volumes were between 7.8% and 9.3% larger than equilibrium volume. Flat volumes were reduced by between 8.1% and 13.5%. By 2055, predicted sediment losses had increased – channel volumes were predicted to be between 14.4% and 15.7% larger, while flat volumes were up to 22% smaller. 2400 and 2800 saw greater increases in channel volume and decreases in intertidal volume. In 2800, element volumes are still changing and do not appear to have reached a new equilibrium.

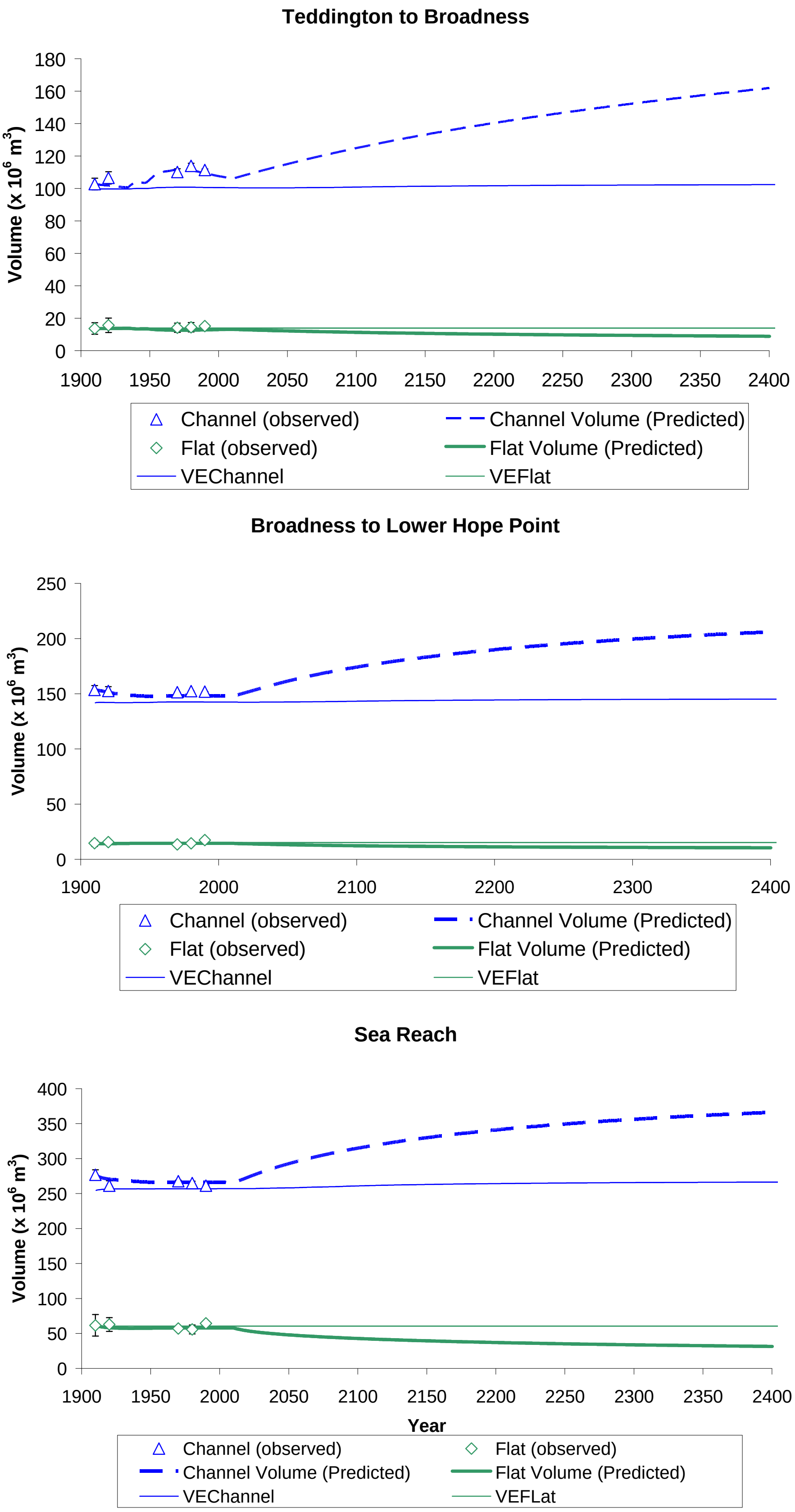


Figure 6 Predicted evolution of the Thames estuary assuming sea-level rise increases to 20 mm/year after 2000

4.4 TOTAL CHANGE

The predicted volumes of channels and flats of the Thames estuary under the DEFRA sea-level rise scenario and the extreme (20 mm/year) scenario between 2000 and 2050 are given in Table 9. Again, this shows that channel volumes increase and flat volumes decrease under conditions of accelerated sea-level rise.

Total volume change between 2000 and 2050 under the DEFRA scenario represents a loss of 8.66 x10^6 m^3 of sediment relative to chart datum, with around 2.46 x10^6 m^3 being lost from the intertidal and the remainder by deepening of the channels. Under the extreme scenario the losses are much greater, with a total of 50.7 x10^6 m^3 of sediment being lost by 2050.

Table 9 Predicted total flat and channel volumes for the Thames Estuary until 2050

	DEFRA (2006)		20 mm/year	
	Flat	Channel	Flat	Channel
	Total volume (x10^6 m^3)		Total volume (x10^6 m^3)	
2000	84.7	523	85.3	522
2030	83.8	523	77.6	546
2050	82.3	529	73.4	569

1.1. CRITICAL RATES OF SEA-LEVEL RISE

For a constant rate of sea-level rise, ASMITA predicts that estuary elements will evolve to a steady state volume that is greater than equilibrium volume for channels and smaller than equilibrium volume for flats. The steady state volume changes with rate of sea-level rise. The critical rate of sea-level rise is defined as the rate at which the flat element has no steady state volume (0 m^3) and thus is a measure of when the sediment supply to the estuary can no longer prevent the volume of the estuary from increasing steadily as a result of the rise in water level. ASMITA can be used to assess when this critical point might occur but of course ASMITA assumes that the sediment supply to the estuary (in terms of tidal exchange and sediment concentration) remains the same as the present day scenario. In practice there is much uncertainty regarding this and it can be argued that sea level rise in combination with increased storminess could result in increased erosion of cliffs and near shore areas leading to greater sediment supply. Nevertheless the analysis presented below gives a precautionary idea of the estuary sensitivity to high rates of sea level rise.

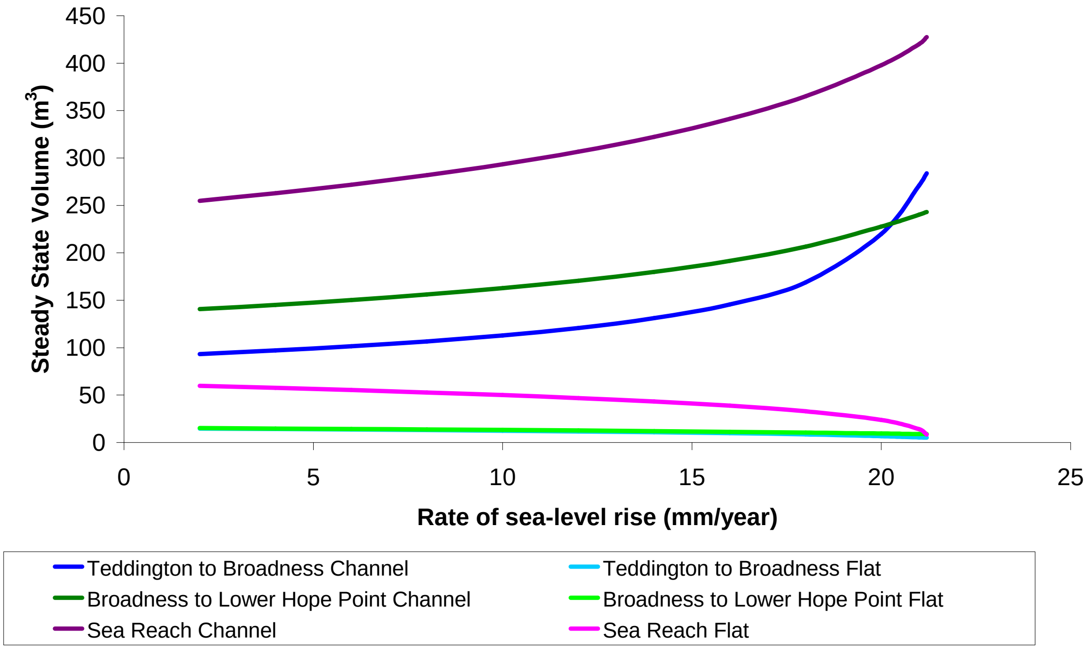


Figure 7 Predicted steady state volumes with increasing rates of sea-level rise for the Thames Estuary

Figure 7 shows the steady state volumes over the very long term predicted for the Thames Estuary with rates of sea-level rise up to the critical rate of sea-level rise for the flats in the Sea Reach section of the Thames estuary (21.2 mm/year). Note that before this critical point is reached channel volumes are predicted to increase dramatically, particularly between Teddington and Broadness where the channel volume is predicted to double with sea-level rise rates of 19 mm/year. Flat volumes are predicted to reduc with increasing rates of sea-level rise. This is most noticeable in the Sea Reach flats, where the initial volume is large.

5. Discussion

5.1 EFFECT OF SEA-LEVEL RISE

ASMITA was calibrated to reproduce the observed behaviour of the Thames between 1910 and 1990. In general the ASMITA predictions were much better than assuming that element volumes remained constant at their initial values. The exception was the channel element between Broadness and Lower Hope Point, where volume changes were limited and the element remained close to its initial volume.

Under conditions of accelerated relative sea-level rise, ASMITA predicts channel volumes will increase and flat volume will decrease. Using the DEFRA (2006) predictions for rates of sea-level rise, element volumes progressively deviated from their equilibrium volumes. In 2025, channel volumes were approximately 5% larger and flat volumes 5% smaller than equilibrium volumes based on historic volume analysis. By 2055, differences had increase to between 5.5% and 10%.

By 2115, the limit of the DEFRA (2006) predictions, channel volumes were around 12% bigger than historic equilibrium values and flat volumes were 11% to 19% smaller.

These values refer to volumes only. In reality, the area of intertidal loss associated with these volumetric changes could be greater, as sediment may be eroded from the edges of intertidal areas to maintain the average height within the tidal frame.

The effect of 20 mm/year sea-level rise is included as an extreme scenario. Whilst it is unlikely that sea-level rise would jump from 2 mm/year to 20mm/year as in the simulation, it is instructive to investigate how the Thames might respond to extreme rates of sea-level rise. Under this scenario, channel volumes are 8-9% larger by 2025, and flat volumes are 8 to 13.5% smaller. By 2115, channel volumes have increase up to 26%, and flat volumes are decreased by up to 31%. If sea-level rise of 20 mm/year is simulated to continue, channel volumes could be up to 60% larger by 2400 and up to 83% larger by 2800, Flat volumes could have decreased by up to 50% in 2400 and 55% in 2800.

Under 20 mm/year sea-level rise, the Thames Estuary was not predicted to reach a new equilibrium within the next 800 years. Predications of steady state volume with increasing sea-level rise indicate that this extreme sea-level rise scenario is very close to the critical rate of sea-level rise for the Sea Reach section of the estuary. For sea-level rise rates of greater than 21.2 mm/year the critical rate is exceeded and the estuary becomes unable to keep pace with sea level rise.

Care should be taken when extending ASMITA predictions far into the future. Simulations covering time periods much longer than the period of calibration may be subject to additional uncertainties. Equilibrium volumes in ASMITA are defined based on data covering the period 1910 to 1990. The validity of extending this equilibrium definition to model periods closer to geological time scale is questionable. On geological timescales, many estuaries tend to infill, and this is unlikely to be captured by equilibrium equations based on shorter timescales. In addition, factors such as river flow, land use and sediment supply, tidal range, wave activity, storminess and management policies are likely to change over such long periods, decreasing the value of ASMITA predictions, which have been calibrated over the past 100 years or so.

The parameter values selected for use in ASMITA are subject to some uncertainty. van Goor *et al* (2003) estimated that each parameter could only be estimated to within 50% of its true value. This estimate of uncertainty was used to give a range of possibly values, and ASMITA was calibrated to fit the data within this range. The modelling results are also likely to be subject to some uncertainty, although this is less than the 50% suggested for individual parameters. For the critical rate of sea-level rise (rate at which all intertidal area is lost) the uncertainty is estimated to be a maximum of 30%.

6. Conclusions

ASMITA was used to successfully reproduce the evolution of the Thames estuary between 1910 and 1990. Under conditions of accelerated sea-level rise, ASMITA predicts that channel volumes will increase and flat volumes will decrease. The volume lost depends on the rate of sea-level rise.

It is predicted that under the DEFRA (2006) sea-level rise predictions, 12.5 X106 m3 of intertidal sediment will have been lost by 2115, representing a significant intertidal loss. Most of this (10 X106 m3) will be from the Sea Reach section of the estuary, with the remainder divided between the inner and mid estuary.

7. References

DEFRA, 2006. Flood and Coastal Defence Appraisal Guidance, FCDPAG3 Economic Appraisal. Supplementary Note to Operating Authorities – Climate Change Impacts.

FutureCoast, 2002. FutureCoast Estuary Assessment. FutureCoast, Halcrow, Swindon.

HR Wallingford, 2006a. Thames Estuary 2100: Morphological changes in the Thames Estuary. Technical note EP6.8, The Development of a historical sediment budget.

HR Wallingford, 2006b. Thames Estuary 2100: Estuary Processes Studies Consolidation Report. HR Wallingford Report EX5337.

HR Wallingford, 2006c. Thames Estuary 2100: Morphological changes in the Thames Estuary. Technical note EP 6.4, Historical Trend Analysis.

Inglis, C.C. and Allen, F.H. 1957. The Regimen of the Thames estuary as affected by currents, salinities and river flow. *Proceedings of the Institute of Civil Engineers*, **7**, 827-878.

Nicholls, R. J., Dredge, A. and Wilson. T., 2000. Shoreline change and fine-grained sediment input: Isle of Sheppey Coast, Thames Estuary, UK. In Pye and Allen (eds). Coastal and Estuarine Environments: Sedimentology, geomorphology and geoarchaeology. Geological Society, London, Special Publications, 175, 305-315.

Stive, M. J. F., Wang, Z. B., Capobianco, M., Ruol, P., and Buijsman, M. C. Morphodynamics of a tidal lagoon and the adjacent coast. *Physics of Estuaries and Coastal Seas*, Rotterdam, 397-407.

Sutherland, J. and Soulsby, R.L., 2003. Use of model performance statistics in modelling coastal morphodynamics. Proceedings of the International Conference on Coastal Sediments 2003, Texas, USA.

van Goor, M. A., Zitman, T. J., Wang, Z. B., and Stive, M. J. F. 2003. Impact of sea-level rise on the morpholigical equilibrium state of tidal inlets. *Marine Geology*, **202**, 211-227.

Wang, Z. B. 2005. Application of semi-empirical long-term morphological models ESTMORPH and ASMITA. *Z2839*, Delft Hydraulics, Delft.

Whitelaw, K. and Andrews, M. J. 1988. Sludge Disposal to Sea: the Barrow Deep in the Thames Estuary as a case study, Journal of the Institution of Water and Environmental Management, Volume 2, April 1988, pp159-170.

Water Pollution Research Laboratory. 1964) Effects of polluting discharges on the Thames Estuary, The Reports of the Thames Survey Committee and of the Water Pollution Research Laboratory, Water Pollution Research Technical Paper Number 11, Water Pollution Research Laboratory, HMSO.

Appendix

Appendix A Dredging Volumes

Positive volumes indicate dredging in channels and dumping on flats (although Negative values are dumping in channels, sediment removal from flats.

	Disturbance volume					
	Teddington to Putney		Mucking		Sea Reach	
Year	Channel	Flat	Channel	Flat	Channel	Flat
1910	0	0	0	0	0	0
1911	0	0	0	0	0	0
1912	0	0	0	0	0	0
1913	0	0	0	0	0	0
1914	0	0	0	0	0	0
1915	0	0	0	0	0	0
1916	0	0	0	0	0	0
1917	0	0	0	0	0	0
1918	0	0	0	0	0	0
1919	0	0	0	0	0	0
1920	0	0	0	0	0	0
1921	0	0	0	0	0	0
1922	0	0	0	0	0	0
1923	0	0	0	0	0	0
1924	0	0	0	0	0	0
1925	0	0	0	0	0	0
1926	0	0	0	0	0	0
1927	0	0	0	0	0	0
1928	0	0	0	0	0	0
1929	0	0	0	0	0	0
1930	0	0	0	0	0	0
1931	0	0	0	0	0	0
1932	0	0	0	0	0	0
1933	0	0	0	0	0	0
1934	908000	0	227000	0	0	0
1935	841333.3	0	210333.3	0	0	0
1936	852000	0	213000	0	0	0
1937	686666.7	0	171666.7	0	0	0
1938	877333.3	0	219333.3	0	0	0
1939	654666.7	0	163666.7	0	0	0
1940	0	0	-105000	0	0	0
1941	0	0	-105000	0	0	0
1942	0	0	-105000	0	0	0
1943	0	0	-105000	0	0	0
1944	0	0	-105000	0	0	0
1945	0	0	-105000	0	0	0
1946	198666.7	0	49666.67	0	0	0
1947	1081333	0	270333.3	0	0	0
1948	870666.7	0	217666.7	0	0	0
1949	1096000	0	274000	0	0	0
1950	1042667	0	260666.7	0	0	0
1951	912000	0	228000	0	0	0
1952	1200000	0	300000	0	0	0

Year	Disturbance volume					
	Teddington to Putney		Mucking		Sea Reach	
	Channel	Flat	Channel	Flat	Channel	Flat
1953	740000	0	185000	0	0	0
1954	601333.3	0	150333.3	0	0	0
1955	474666.7	0	118666.7	0	0	0
1956	464000	0	116000	0	0	0
1957	541333.3	0	135333.3	0	0	0
1958	621333.3	0	155333.3	0	0	0
1959	685333.3	0	171333.3	0	0	0
1960	492000	0	307500	0	0	0
1961	317500	0	317500	0	0	0
1962	393333.3	0	393333.3	0	0	0
1963	315000	0	315000	0	0	0
1964	462500	0	462500	0	0	0
1965	420833.3	0	420833.3	0	0	0
1966	417500	0	417500	0	0	0
1967	340000	0	340000	0	0	0
1968	382500	0	382500	0	0	0
1969	358333.3	0	358333.3	0	0	0
1970	321666.7	0	321666.7	0	0	0
1971	197500	0	197500	0	0	0
1972	212500	0	212500	0	0	0
1973	453333.3	0	453333.3	0	0	0
1974	210833.3	0	210833.3	0	0	0
1975	200000	0	200000	0	0	0
1976	165000	0	165000	0	0	0
1977	170833.3	0	170833.3	0	0	0
1978	178333.3	0	178333.3	0	0	0
1979	160833.3	0	160833.3	0	0	0
1980	95833.33	0	95833.33	0	0	0
1981	51250	0	153750	0	0	0
1982	38750	0	116250	0	0	0
1983	25000	0	75000	0	0	0
1984	25000	0	75000	0	0	0
1985	25000	0	75000	0	0	0
1986	25000	0	75000	0	0	0
1987	25000	0	75000	0	0	0
1988	25000	0	75000	0	0	0
1989	25000	0	75000	0	0	0
1990	25000	0	75000	0	0	0
1991	25000	0	75000	0	0	0
1992	25000	0	75000	0	0	0
1993	25000	0	75000	0	0	0
1994	25000	0	75000	0	0	0
1995	25000	0	75000	0	0	0
1996	25000	0	75000	0	0	0
1997	25000	0	75000	0	0	0
1998	25000	0	75000	0	0	0
1999	25000	0	75000	0	0	0
2000	25000	0	75000	0	0	0

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