Joint Defra/EA Flood and Coastal Erosion
Risk Management R&D Programme

# Development of estuary morphological models

## Annex G: Predictions of estuarine morphology

R&D Project Record FD22107/PR

Environment Agency

defra
Department for Environment
Food and Rural Affairs

# Predictions of estuarine morphology

## Executive Summary

Models of varied approach ("bottom-up", "top-down", "Hybrid" and inverse) have been run to predict eight UK estuaries' responses to possible scenarios 50 years hence. Changed river flow, tidal range, mean and surge levels and wave stresses were considered. The estuaries were the Thames, Blackwater, Humber, Mersey, Dee, Ribble, Southampton Water, Tamar.

Without morphological evolution, raised mean sea level results in increased low-water and high-water areas and volumes, tidal prism and fluxes of water at the mouth. Intertidal and saltmarsh areas increase or decrease with raised mean sea level as cross-sections are convex or concave. Increased tidal range increases high-water volume and area, intertidal area, the tidal prism, fluxes of water at the mouth and suspended sediment concentrations; low-water volume and area must decrease. Increased river flow increases low-water volumes and areas.

Allowing for morphological evolution, modelled low-water volumes and areas do in fact increase for raised mean sea level. In most estuaries, high-water volumes and areas also increase, but by less, especially where constrained by hard structures. Accordingly, intertidal area decreases in all estuaries where evolution with such constraints was modelled (Thames, Blackwater, Humber, Mersey, Southampton Water); the Blackwater decrease is large.

Results of a Hybrid Regime model suggest that infill does not keep pace with sea-level rise, except in the Mersey, where scope for infill is known historically and a "2.5-D" model and Emulator predict a relatively short infill time. This is despite sufficient sediment input to enable the morphology to keep pace in most cases. ASMITA results for the Thames do suggest that infill keeps pace with sea-level rise; however, for faster rates of sea level rise, this balance involves a loss of intertidal area.

Likely effects of realistic changes in tidal range (e.g. +2 per cent) are relatively modest. A 20 per cent increase in river flow gives only O(2 per cent) changes in low-water and high-water areas and volumes in the Hybrid Regime model, but the Mersey and Blackwater lose substantial intertidal area. [The Emulator predicts much greater increases in areas and volumes]. Estimated flushing times vary from O(1 day) to months according to definition; values based on saline intrusion length are between six days and three weeks.

Generation of an ensemble of possible outcomes is recommended, so that model results are tested against alternative techniques, to help validate predicted future morphologies.

The results show that not all estuaries can be expected to respond in the same manner.

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## 1. Introduction

Interest in estuaries and associated flood risks, sediment regimes and morphology is raised by their socio-economic importance. Estuaries support or are affected by dense populations, transport, renewable energies, cooling water abstraction, aggregate mining, fishing, habitats, agriculture, waste disposal and leisure activities. They face change. Over the next 50 years Global Climate Change (GCC) is expected significantly to affect mean sea levels, storminess, river flows and sediment supply which will inevitably impact on future flood risk. Modified flood probabilities can be readily calculated by incorporating GCC scenarios into numerical models. However, the response for any particular estuary will be further modified by concurrent morphological adjustments; arising naturally (post-Holocene adjustments), as a consequence of GCC and via past and present 'interventions'. Morphological change (depending on the sediment regime) is challenging to predict.

Models are needed to predict changes over many decades, manage estuaries and assess future flood risk. The Defra/EA project FD2107 has involved the development of Hybrid estuarine morphology models under the framework of the UK Estuaries Research Programme (ERP). The ultimate goal of this research project is to provide a suite of modelling tools and algorithms to assist with the assessment of flood risk, planning and management in our estuaries. Progress towards this goal has been achieved through the development of a range of models capable of predicting estuarine morphological change for timescales of up to 50 years. More emphasis on the models *per se*, their approaches, description and intercomparison on seven estuaries, is given in a companion report *Intercomparison of models predicting estuarine morphology*.

Here we build on this model development through an "ensemble" of model applications to UK estuaries (table 1), for a range of possible future climate scenarios. Different models are bottom-up, top-down and Hybrid. The estuaries are the Thames, Blackwater, Humber, Mersey, Dee, Ribble, Southampton Water, Tamar. Reliability of the model predictions of future morphology remains a key issue that is assessed as part of this ensemble approach. Through this approach we can potentially

- indicate the range of likely outcomes of morphologies and associated flood risks
- translate possibilities to probabilities with the help of subsequent assessment against observational data
- assess the relative sensitivity of the estuaries to climate change
- identify areas, in individual estuaries, that are likely to be most at risk from future flooding.

After describing the eight estuaries (Section 2), scenarios (applied variations in sea level, etc., Section 3) and models (briefly, Section 4), results are presented for each estuary in turn (Section 5). Behaviours common to estuaries and discrepant between estuaries are discussed (in Section 6), along with possible reasons for trends found, and factors in these behaviours or trends. Conclusions are given in Section 7.

*Table 1 Models, estuaries and their characteristics in the intercomparisons. Entries* Y *show the estuaries in which each model was run.*

| ***Model*** | *Type* | *Thames* | *Blackwater* | *Humber* | *Mersey* | *Dee* | *Ribble* | *S'ton Water* | *Tamar* |
|---|---|---|---|---|---|---|---|---|---|
| *Analytical Emulator* | Hybrid | Y | Y | Y | Y | Y | Y | Y | Y |
| *Hybrid Regime* | T-D | Y | Y | Y | Y |  |  | Y |  |
| *"2.5-D"* | B-U |  |  |  | Y | Y | Y |  |  |
| *ASMITA-type* | Hybrid | Y |  |  |  |  |  |  |  |
| *SandTrack* | Hybrid | [S]Y |  |  |  |  |  |  |  |
| *TE2100* | Trend | Y |  |  |  |  |  |  |  |
| *Realignment* | process |  | Tollesbury Creek |  |  |  |  |  |  |
| *Inverse* | Hybrid |  |  | Y |  |  |  |  |  |
|  |  |  |  |  |  |  |  |  |  |
| ***Estuary properties*** *(From Future-Coast database)* |  |  |  |  |  |  |  |  |  |
| *Spring tidal range (m)* |  | 5.3[T] | 4.6 | 6.0 | 8.9 | 7.6 | 7.9 | 4.0 | 4.7 |
| *Mean river flow ($m^3$/s)* |  | 66 | 3.8 | 234 | 67.1 | 31.2 | 33.3 | 18.1 | 27 |
| *Length (km)* |  | 100 | 21.2 | 144.7 | 45.6 | 37.0 | 28.4 | 20.2 | 34.1 |
| *HW Area ($km^2$ as in Analytical Emulator)* |  | 193 | 46.1 | 618 | 194 | 99 | 119 | 38.6 | 37.7 |
| *Intertidal Area ($km^2$)* |  | 52[I] | 27.8 | 455 | 118 | 43 | 107 | 13.8 | 18 |
| *Marsh Area ($km^2$)* |  | 2.1[M] | 11.0 | 14.2 | 8.5 | 21 | 22 | 3.6 | 3.6 |

[I] TE2100 area 42km$^2$ above 0mCD, plus ~10km$^2$ for Benfleet and Holehaven Creeks. ABPmer CHaMPs area above mean LW is 47km$^2$.

[M] ABPmer CHaMPs.

[S] The SandTrack model is primarily applicable (only) to the sandier parts of the Outer Thames. Hence the model results were not really comparable with the other model results focused on the estuary landward of Southend.

[T] Tidal range at the Thames mouth; 6.7 m range at Tower Bridge.

References for the models are:

- Analytical Emulator - Prandle (2006)
- Hybrid Regime - Wright and Townend (2006)
- "2.5-D" - Lane and Prandle (2006)
- ASMITA-type - Rossington and Spearman (2007)
- SandTrack - Soulsby *et al.* (2007)
- TE2100 - HRW (2006c)
- Realignment - Spearman (2007).

## 2. The estuaries

Altogether models were run for eight estuaries as shown in table 1: Thames, Blackwater, Humber, Mersey, Dee, Ribble, Southampton Water, Tamar. Table 1 shows some characteristics. The Humber is the largest estuary (in area); there is a middle group comprising the Thames, Mersey, Dee and Ribble; the Blackwater, Southampton Water and Tamar are "smaller" estuaries (but still tens of km$^2$ and so sizeable by UK standards; the Ribble would also be "smaller" if judged by area at low water). All have large tidal range by world standards; the range is greatest for the Mersey, Dee and Ribble. Interestingly, most have a similar ratio of river flow to area, but Blackwater river flow is relatively small and the Tamar's is relatively large (this is the only ria; the estuary area is constrained). The Thames and Tamar are relatively long for their area (and therefore narrow). A large proportion of the

Ribble area is intertidal; the proportion is least for Southampton Water and the Thames. The proportion of saltmarsh is large for the Dee, Blackwater and Ribble, and least in the Thames.

2.1 The *Thames* Estuary in south-east England has a length of 100 km and varies up to a width of 3 km at Southend; relatively long and narrow for its area. Freshwater runoff to the estuary is from a total catchment area 10,000km$^2$ via the Thames (mean flow 66 m$^3$/s) and a number of much smaller rivers and channels. At the seaward end there is a large tidal range (mean spring tidal range is 5.3 m); the tide is amplified further as it propagates up the estuary. The estuary has large intertidal areas in its lower reaches and a heavily modified channel in its upper reaches from historic development. Along most of the estuary, the level at mean high water springs (MHWS) intercepts tidal defences.

Much research has recently been undertaken as part of the Thames Estuary 2100 (TE2100) study, including morphological predictions. From a detailed atlas of morphological change over the last century, two 2030 morphologies were developed by extrapolating recent historical changes. Being based on data, this method of prediction represents a baseline for predicted 2030 morphology. Century trends shown include:

- loss of intertidal volume (40-50 per cent) and intertidal area (15-25 per cent) above London Bridge
- gain in subtidal volume (15-25 per cent) and subtidal area (6-12 per cent) above London Bridge
- gain in intertidal volume (10 per cent) and intertidal area (12 per cent) below Barking (to Southend)
- loss of subtidal volume (2 per cent) and subtidal area (6 per cent) below Barking (to Southend).

Thus trends in the upper and lower portions of the estuary differed. The upper-estuary subtidal channel has deepened and widened with a loss of intertidal area. In the lower estuary the subtidal channel has deepened and narrowed with a gain in intertidal area. In different parts of the estuary the greatest changes have taken place at different times.

2.2 The *Blackwater* Estuary is relatively small (length 21 km). River inflow (Blackwater and Chelmer) is particularly low, from a catchment area ~ 800 km$^2$. However, marsh occupies a large proportion of the total estuary area. Tidal range is 4.6 m at the mouth. Whilst this estuary has not been the focus for major studies in recent times, some managed realignment projects have been undertaken, notably the Tollesbury managed realignment about which there is considerable information. This realignment site is at the end of a 1 km creek, part of Tollesbury Fleet in the Blackwater Estuary. Mean-spring tidal range in the creek is about 4 m; most of the creek dries out at low water.

2.3 The *Humber* Estuary in north-east England is the largest of the eight estuaries studied here, with a length of 81 km (plus additional channel length in the Don and Trent, to a total 145 km) and mean width 3 km. Freshwater runoff to the estuary is from a total catchment area 23,690 km$^2$ via the Ouse, Don and Trent (mean flows exceeding 120, 16, 95 m$^3$/s respectively). At the seaward end there is a large tidal range (up to 6.6 m); the tide is amplified further as it propagates up the estuary. The Humber has areas of saltmarsh, and a complex (almost braided) channel system in its lower reaches. The hinterland has a mixture of heavy industry, conurbations, agricultural land and sites of environmental importance. There has been a wealth of research on the estuary and a detailed description is not attempted here. Background information is in the Humber Estuary Shoreline Management Plan (EA,

2000) and the Humber Estuary Geomorphological Studies Reports (Murray and Pethick, 1999).

2.4 The *Mersey, Dee* and *Ribble* have the largest tidal ranges of the estuaries considered; the Ribble has the largest proportion of intertidal area and the Dee and Ribble have relatively large areas of saltmarsh. Bathymetry for the Mersey, Dee and Ribble was gridded from Environment Agency Lidar/echo sounder surveys in 2002, 2003, 2004 respectively. "2.5-D" model boundaries were generally located in water depths of about 20 m: Mersey – E-W line at mouth between New Brighton and Gladstone Lock; Dee – north from Hoylake and north from Rhyl with northern boundary through Hilbre Swash; Ribble – west from Lytham and west from Formby Point to N-S line approximately 3 km offshore. Tidal amplitudes ($M_2$, $S_2$ in m) were taken as: Mersey – 3.04, 0.98; Dee – 2.92, 0.95; Ribble – 2.95, 0.88. A 50-year extreme surge for Liverpool, +1.732 m (Flather *et al*., 2001), is derived from observations and a 40-year storm surge model run. River flows used were: Mersey and Dee 150 $m^3 s^{-1}$, Ribble 100 $m^3 s^{-1}$. Fine sediment (settling velocity $w_s = 0.0005$ m $s^{-1}$) was assumed in the "2.5-D" model. Wind speed (if applied, with the effect of wave-enhanced bed stress) was 10 m $s^{-1}$ from the west, other scenarios being 5, 9, 11 and 20 m $s^{-1}$.

2.5 *Southampton Water* is 19 km long with Itchen and Hamble sub-estuaries (length 7, 8.6 km respectively). Mean river inputs to the three (sub-) estuaries are 12.3, 5.6, 0.4 $m^3$/s respectively. Southampton Water is about 2 km wide seaward of the Itchen. Tidal range at the mouth, 3.75 m, is moderate by UK standards (large by world standards). A "double high water" results as arrivals via the two sides of the Isle of Wight are kept distinct by non-linear steepening.

2.6 The *Tamar* Estuary is distinctive as a ria rather than coastal plain estuary. It is small in area but relatively long and narrow, with large river flow. Future-Coast data are relied on for its characteristics as modelled (only by the Analytical Emulator).

## 3. Scenarios

Intercomparisons of model predictions were generally for 2050. Various scenarios are intended to represent possible effects of climate change 50 years hence [as used in TE2100, CDV2075; referring to UKCIP02, IPCC(2001), Defra (2003); the scenarios were defined prior to issue of the latest government guidelines (Defra, 2006)]:
*Mean sea level*: baseline as at present; rises of 0.3 m (realistic over 50 years), 1 m (extreme)
*50-year extreme level*: in practice applied as a constant addition to sea level
*Tidal range*: baseline as at present; an increase of 2 per cent (Flather *et al*., 2001)
*River flow*: baseline as at present; an increase of 20 per cent
*Waves*: (a) as enhanced bed stress associated with wind (nominal value and ± 10 per cent)
(b) as forced by eight wind scenarios representing the distribution of conditions in Liverpool Bay (for the Mersey, Dee and Ribble; see Annex A1 *SWAN modelling of Liverpool Bay including Mersey, Dee and Ribble*).

See also Section 4.6 for scenarios specific to Historical Trend Analysis in the Thames.

## 4. The models

The different models and types are listed in table 1 (along with the estuaries to which they were applied). More details about the models are in the companion report *Intercomparison of models predicting estuarine morphology*. Here we give a brief outline for each.

4.1 The *Analytical Emulator* (Prandle, 2006) is largely based on one-dimensional equations of axial momentum and continuity. It assumes that tidal amplitudes are uniform along the estuary, and provides an expression for estuarine depth in terms of time-averaged river flow and channel side slope. Baseline conditions are derived from the newly enhanced Future-Coast database of UK estuaries (Manning, 2007). Estuary length and side slope are assumed constant. The assumed uniform side slope involves a compromise between correct volumes or areas at HW, LW or intertidal. Then morphology (depth and width) respond only to changes of river flow among the scenario changes. However, imposed sea level rise gives new values for estuary volume and area. A minimum infilling time (of the increased volume) is estimated from flushing time and mean SPM concentration (Prandle, 2004); mean SPM concentrations were assumed constant for the various sea level rise scenarios but increase with tidal range.

4.2 The *Hybrid Regime* model (ABP; Wright & Townend, 2006) allows the application of a “regime theory” relationship with a 1-D hydrodynamic model (ISIS or Mike11). The regime relationship is empirical, generated from baseline flow model results; it characterises the estuary morphology as a power-law relation, between cross-sectional area and maximum discharge during the tidal cycle. This characteristic relationship is assumed to describe the equilibrium state of the estuary. Then some condition is altered, e.g. changed water levels, engineering works. The hydrodynamic model runs the altered simulation and regime relationships are reapplied to update the cross-section (taking account of constraints of the Holocene surface, solid geology or structures). In the runs reported here, sea-level rise was applied in 5-year increments. (This methodology does not model the evolution of the estuary in real time in parallel with sea level rise). Physical constraints tend to prevent some sections from widening; such sections then tend to deepen to maintain regime cross-sectional area, and intertidal area is lost.

4.3 The *“2.5-D”* B-U model (POL) integrates the 2-D shallow-water equations, stepping forward in time, on a finite-difference grid. Vertical structure is then derived from the 2-D model pressure gradient and assumed viscosity. Sediment movement is tracked concurrently as particles moving with the flow (plus random vertical steps and settling velocity); erosion at the bed is proportional to stress from the flow; suspended sediment is supplied at the estuary mouth according to the flow there. Bathymetry is fixed through the model run.

4.4 *ASMITA* is a behaviour-based model describing morphological interaction between a tidal basin and its adjacent coastal environment (Stive *et al.*, 1998). It schematises a tidal inlet as aggregated morphological elements: intertidal area, channels and ebb-tidal delta. ASMITA assumes that, under constant hydrodynamic forcing, each element tends towards a morphological equilibrium, definable as a function of hydrodynamic forcing and basin properties. The morphological elements interact through sediment exchange, which evolves the whole system morphology as well as the individual elements. Sea-level rise creates accommodation space in the estuary which can then be a sink for available sediment. In its basic form ASMITA predicts changes in the volume of channel and intertidal-flat elements; it does not directly predict changes in intertidal area. In application here, changes to (Thames) intertidal area are calculated by assuming that changes in surface area vary linearly with changes in intertidal volume.

4.5 The *SandTrack* model (HRW) has Lagrangian particle-tracking of sand-grains including bedload, suspended load, incipient motion and burial processes. “Tagged” grains of sand are tracked, each representing many billions of similar grains. Runs typically cover a period of a few weeks to a few decades, predicting where the tagged grains go to. In FD2107 SandTrack has been extended (to *Morpho-SandTrack*); a volume of sediment is associated with each tagged grain, and deposited on the bed diffusively as a sediment "lens" with a defined maximum thickness and extent; the lenses sum to give the morphodynamic development of the estuary. This process is iterated with re-calculated hydrodynamics. Wave-effects are not presently included (but could be). An advantage over other Hybrid models is that it gives the *source* of deposited sediment (on tidal flats, saltmarshes) as well as its thickness. The model was applied to the Thames Estuary, using one-year update intervals for the bed and the flow.

4.6 *TE2100 Historical Trend Analysis* (HRW) derived 2030 bathymetry for the Thames by calculating the change between the 1970 and 2000 bathymetries and adding the change in bed level between 1970 and 2000 to the 2000 bathymetry. However, this approach does not properly represent changes in channel position, the outcome of dredging, managed navigation channels or works. Hence the extrapolated bathymetry was further modified by rules to make the extrapolated estuary bathymetry more realistic: no subtidal erosion of more than 2 m was allowed; subtidal accretion was not allowed above 0 mOD. In addition, alternatives allowed for the range of possible navigation management strategies:

- "Geometry 1" case with HTA applied
- "Geometry 2" as Geometry 1 except for no change in bathymetry below -5mOD seaward of Charlton (i.e. depths in the navigable river are exactly maintained to keep the *status quo*).

4.7 The *Realignment* model (HRW) predicts local changes in morphodynamics resulting from managed realignment. It builds on the approach to habitat development of di Silvio (1989), di Silvio and Gambolati (1990) for lagoons. It combines B-U and T-D aspects and can incorporate the effects of waves and vegetation. A shell script controls application of a flow model, wave model, derived equilibrium concentrations and time-averaged dispersion characteristics, and time-averaged sediment transport. Sediment transport is modelled using the approximation by Galappatti and Vreugdenhil (1985), sediment erosion $E = w(C_E - C)$ where $w$ is settling velocity, $C_E$ an equilibrium concentration and $C$ the actual concentration. The model sequence is:

(a) Set up initial bathymetry
(b) Work out time-averaged wave heights and periods everywhere
(c) Use TELEMAC-2D flow model for flow conditions in set back field
(d) Derive time-averaged fields of diffusion coefficients and equilibrium concentrations $C_E$
(e) Run a time-averaged sediment transport model using "d" and updating bathymetry
(f) Extrapolate predicted change in bathymetry over a longer time step
(g) Go to "b".

As there is no model residual transport in the setback fields, the time-averaged transport "e" is modelled as a diffusive process with a diffusion coefficient from "d" proportional to the square of the time-averaged current speed (and a coefficient to be calibrated). $C_E$ is chosen on the basis that, in equilibrium, deposition occurring during slack water equals erosion during the rest of the tide.

The Realignment model was applied to evolution of a managed realignment at Tollesbury Creek within the Blackwater Estuary, as described in detail in Spearman (2007).

4.8 The *Inverse model* (UoP) uses a 2-D diffusion-type morphological equation with source:

$$\partial h/\partial t = K(\partial^2 h/\partial x^2 + \partial^2 h/\partial y^2) + \text{source} \qquad (4.8).$$

Bathymetry at two times allows “inversion” for the time-averaged source during the interim. For bathymetry data at frequent intervals (relative to changes in the estuary and intervention regime), Principal Component or Empirical Orthogonal Function (EOF) analysis of the source identifies trends in bathymetric change (Horrilo-Caraballo and Reeve 2002, Reeve and Horrilo-Caraballo 2003). The Inverse model was applied to the Humber. Here, the first EOF eigenfunction contains almost 92 per cent of the source function, and indicates its near-constant strength through time. Prediction uses equation (4.8) with this time-average first EOF eigenfunction to represent the future source.

## 5. Results

Some Analytical Emulator results for all the estuaries are given in table 5a. Table 5b gives further results for the five estuaries where the Hybrid Regime model was also applied. We initially consider each estuary in turn, including the other model applications in each case.

**Table 5a Emulator characteristics and results for the estuaries**

| ***Estuary*** ***Scenario / Characteristic*** | *Thames* | *Black-water* | *Humber* | *Mersey* | *Dee* | *Ribble* | *S’ton Water* | *Tamar* |
|---|---|---|---|---|---|---|---|---|
| *Length, km* | 82.5 | 21.2 | 144.7 | 45.6 | 37.0 | 28.4 | 20.2 | 34.1 |
| $\langle D_{AE} \rangle$, m | 6.4 | 6.8 | 5.5 | 7.5 | 23.1 | 4.3 | 11.5 | 8.8 |
| *Mean width, km* | 1.6 | 1.6 | 2.9 | 2.8 | 2.3 | 2.3 | 1.6 | 0.90 |
| *LW volume,* km$^3$ | 0.124 | 0.051 | 0.3 | 0.106 | 0.73 | 0.0049 | 0.130 | 0.079 |
| *HW volume,* km$^3$ | 0.898 | 0.209 | 2.5 | 1.11 | 1.31 | 0.464 | 0.261 | 0.204 |
| *LW area,* km$^2$ | 72 | 22.7 | 223 | 60 | 74 | 12 | 27.2 | 23.5 |
| *HW area,* km$^2$ | 193 | 46.1 | 618 | 194 | 99 | 119 | 38.6 | 37.7 |
| *Hence intertidal area,* km$^2$ | 121 | 23.4 | 395 | 134 | 25 | 107 | 11.4 | 14.2 |
| | | | | | | | | |
| *MSL +0.3m, +1m* | | | | | | | | |
| *LW volume change* | 18.1%,<br>66.4% | 15%,<br>49% | 21.5%,<br>80% | 17.7%,<br>64.6% | 3%,<br>10.3% | 90%,<br>409% | 6.4%,<br>22% | 9.1%,<br>31.8% |
| *Tidal prism change* | 6.5%,<br>22.7% | 4.4%,<br>14.6% | 5.4%,<br>17.1% | 4.0%,<br>13.4% | 2.3%,<br>7.7% | 7.0%,<br>23.3% | 2.6%,<br>8.7% | 3.4%,<br>11.4% |
| | | | | | | | | |
| *Baseline flushing*[F] *time, days* | 7 | 9 | 6.3 | 7.5 | 21.3 | 4.7 | 14.9 | 11.5 |
| [E]*Extreme flushing*[F] *time, days* | 11 | 14.5 | 10.2 | 11 | 25.5 | 8.3 | 19.2 | 14.1 |
| | | | | | | | | |
| *Baseline mean SPM, mg/l* | 127 | 69 | 112 | 164 | 214 | 125 | 77 | 74 |
| *Baseline infill time, years* | 218 | 516 | 223 | 182 | 395 | 149 | 765 | 619 |
| [E]*Extreme infill time, years (+%)* | 344<br>(+58%) | 822<br>(+59%) | 354<br>(+60%) | 263<br>(+44.6%) | 467<br>(+18%) | 259<br>(+74%) | 976<br>(+27.6%) | 751<br>(+30%) |

[E] Extreme scenario for flushing time and infill time means MSL + 1m, + 50-year surge, + extra 2 per cent tide range + extra 20 per cent river flow.

[F] Different definitions of flushing and related time-scales are possible. The Emulator estimate is the time to replace by freshwater, half of the salinity content over the saline intrusion length. For the eight estuaries considered, this estimate is longer than estimates based on flushing by the tidal prism O(1 day) and less than estimates (months) based on river inflow and the whole estuary volume.

**Table 5b Emulator and Hybrid Regime model results**

| ***Estuary*** | *Thames* | *Blackwater* | *Humber* | *Mersey* | *S'ton Water* |
|---|---|---|---|---|---|
| ***Scenario / characteristic*** | | | | | |
| | | | | | |
| *MSL Baseline (2050) + $^E$0.3m/$^E$1.0m* | | | | | |
| *Regime* | 634 | 110 | 1240 | 169 | 160 |
| *LW volume, $10^6m^3$* | 663/729 | 133/155 | 1290/1430 | 184/183 | 164/173 |
| *Emulator* | 124 | 51 | 330 | 106 | 130 |
| | 146/206 | 58/76 | 400/590 | 125/174 | 138/158 |
| *Regime* | 1340 | 330 | 3170 | 639 | 263 |
| *HW volume, $10^6m^3$* | 1390/1490 | 357/386 | 3270/3500 | 682/625?? | 268/281 |
| *Emulator* | 898 | 209 | 2510 | 1110 | 261 |
| | 957/1102 | 223/257 | 2700/3170 | 1170/1310 | 273/301 |
| *Regime* | 82 | 31.5 | 198 | 31.5 | 26.7 |
| *LW area, $km^2$* | 85/93 | 35.5/38.3 | 202/212 | 34.9/36.3 | 27.5/29.5 |
| *Emulator* | 72 | 22.7 | 223 | 60 | 27.2 |
| | 78/92 | 24.2/27.8 | 246/299 | 65/77 | 28.0/30.0 |
| *Regime* | 142 | 44.1 | 323 | 82.8 | 35.5 |
| *HW area, $km^2$* | 143/144 | 44.1/44.5 | 323/324 | 85.6/83.7 | 36.3/37.4 |
| *Emulator* | 193 | 46.1 | 618 | 194 | 38.6 |
| | 199/214 | 47.6/51.2 | 641/694 | 199/211 | 39.4/41.4 |
| *% change for 2% bigger tide* | | | | | |
| *Regime* | 1.6/1.5; | 4.5/3.0; | 0/0; | 0.5/3.4; | -1.9/-0.4; |
| *LW/HW volume; area* | 1.7/-0.7 | 3.8/0.0 | 0/1.3 | 3.5/1.7 | -1.5/0.8 |
| *Emulator* | -3.4/1.2; | -2.0/1.0; | -3.5/1.3; | -4.4/1.4; | -0.8/0.6; |
| | -1.7/0.6 | -0.9/0.6 | -1.8/0.6 | -2.2/0.7 | -0.4/0.3 |
| *% change for 20% more river flow* | | | | | |
| *Regime* | 0.2/0; | 1.8/0.9; | 0/0; | 0/-0.1; | -1.2/-1.5; |
| *LW/HW volume; area* | 0.2/0 | 2.2/0.0 | 0/0 | 1.6/-0.1 | -1.5/0.3 |
| *Emulator* | 30/10.6; | 24/11.5; | 30.6/10.6; | 34.6/10.1; | 19.1/13.3; |
| | 14/5.2 | 11.5/5.6 | 14.3/5.1 | 16.0/5.0 | 9.1/6.4 |
| *% change for $^F$Full scenario* | | | | | |
| *Regime* | 44/32; | 44/18; | 15/10; | 11.8/0.1; | 15/13; |
| *LW/HW volume; area* | 32/3.5 | 20/1.1 | 7, 0.3 | 11.8/-7.1 | 15/7 |
| *Emulator* | 112/40; | 92/48; | 137/46; | 120/35.2; | 51/36; |
| | 46/18 | 38/22 | 54/21 | 48.2/16.3 | 23/17 |

$^E$Approached at 6 mm/y, 20 mm/y respectively in Hybrid Regime model.

$^F$Full scenario means MSL + 1m, + extra 2 per cent tide range + extra 20 per cent river flow.

### 5.1 Thames

The two 2030 geometries and differences predicted by Historical Trend Analysis (HTA) are shown in figures 5.1a to 5.1d. Further upstream the two geometries are the same (not shown). The predicted differences in bathymetry result in the following features:

- Continued accretion in the Leigh Channel, along the foreshore of Blyth Sands, in the entrance to Holehaven Creek, on Mucking Flats, along the northern foreshore at Coalhouse Point, intertidally between Broadness and Woolwich, locally in the deepest part of the Low Water channel between Putney and Richmond
- Continued deepening of some navigation channels: Sea Reach and Lower Hope Reach; between Broadness and Woolwich
- Varied and localised subtidal and intertidal changes between Woolwich and Putney

- Continued overall erosion of the subtidal foreshore between Putney and Richmond.

Figures 5.1e,f show Hybrid-Regime-predicted future Thames Estuary morphologies; figures 5.1g,h present Thames Estuary predictions from SandTrack.

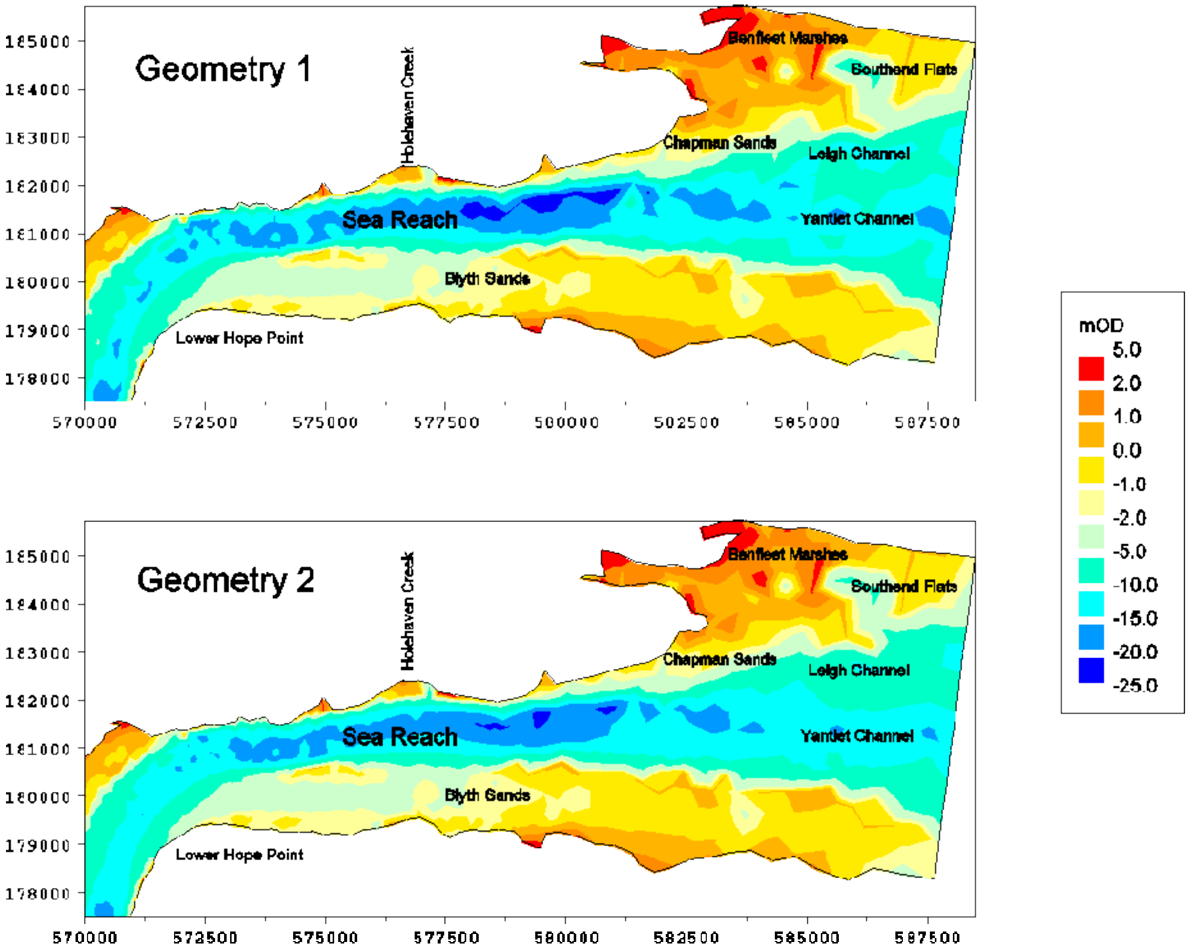

**Figure 5.1a Predicted 2030 bathymetry between Lower Hope Point and Southend, using Historical Trend Analysis**

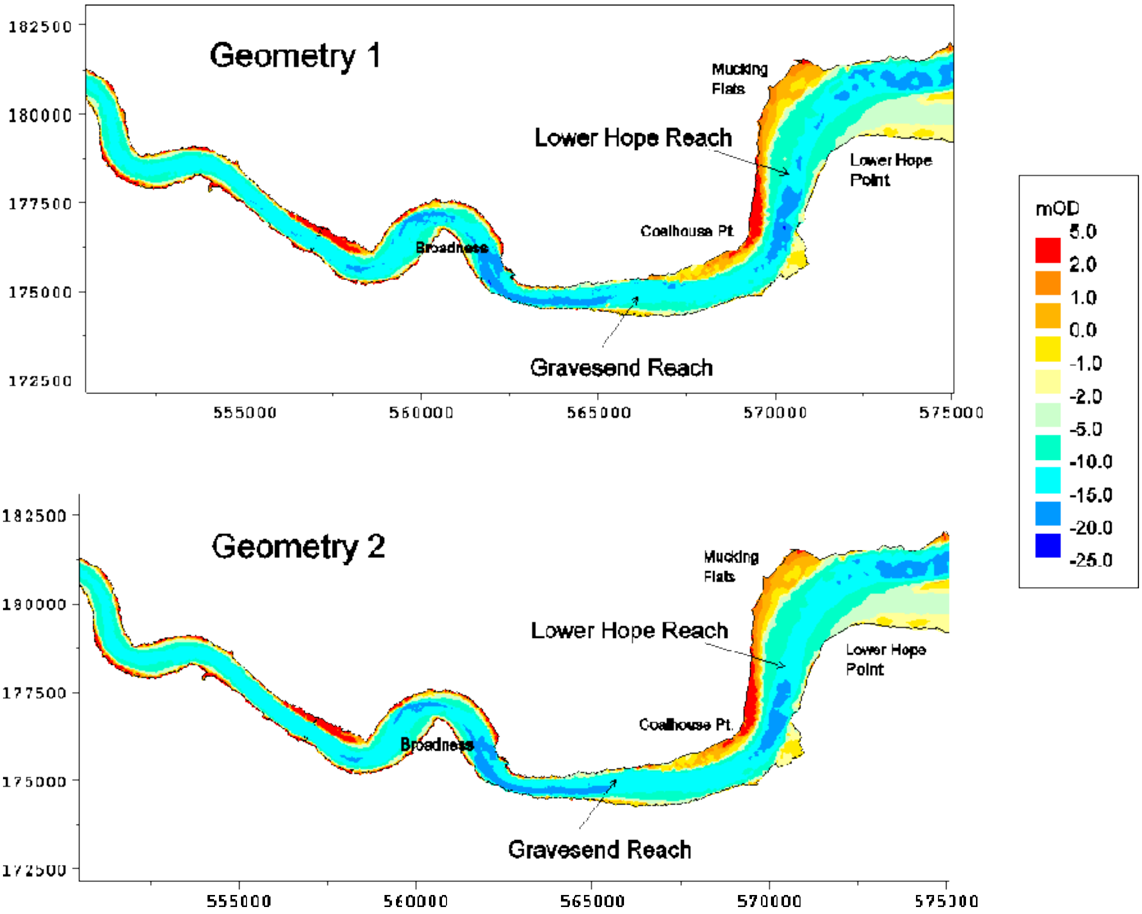

**Figure 5.1b Predicted 2030 bathymetry between Lower Hope Point and Erith using Historical Trend Analysis**

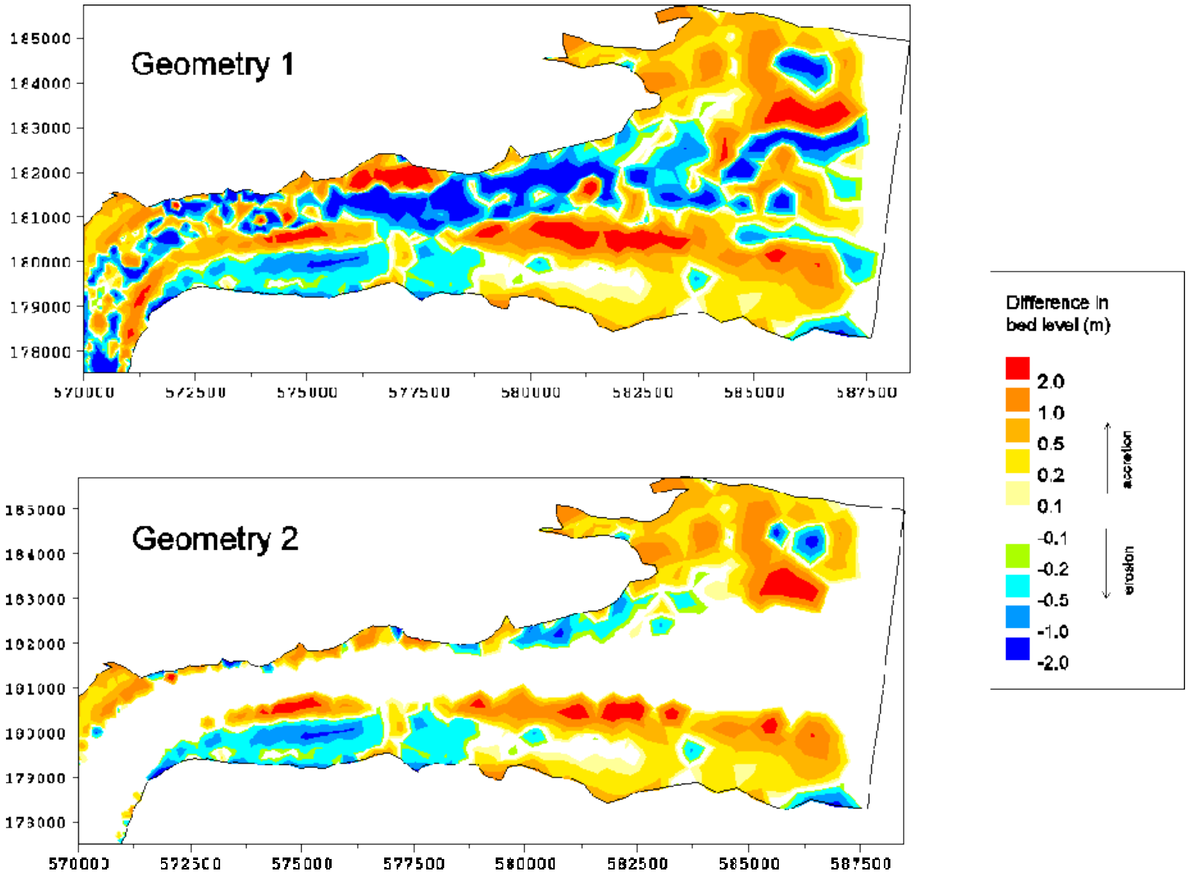

**Figure 5.1c Predicted changes in bathymetry, 2000 to 2030, Lower Hope Point to Southend using Historical Trend Analysis**

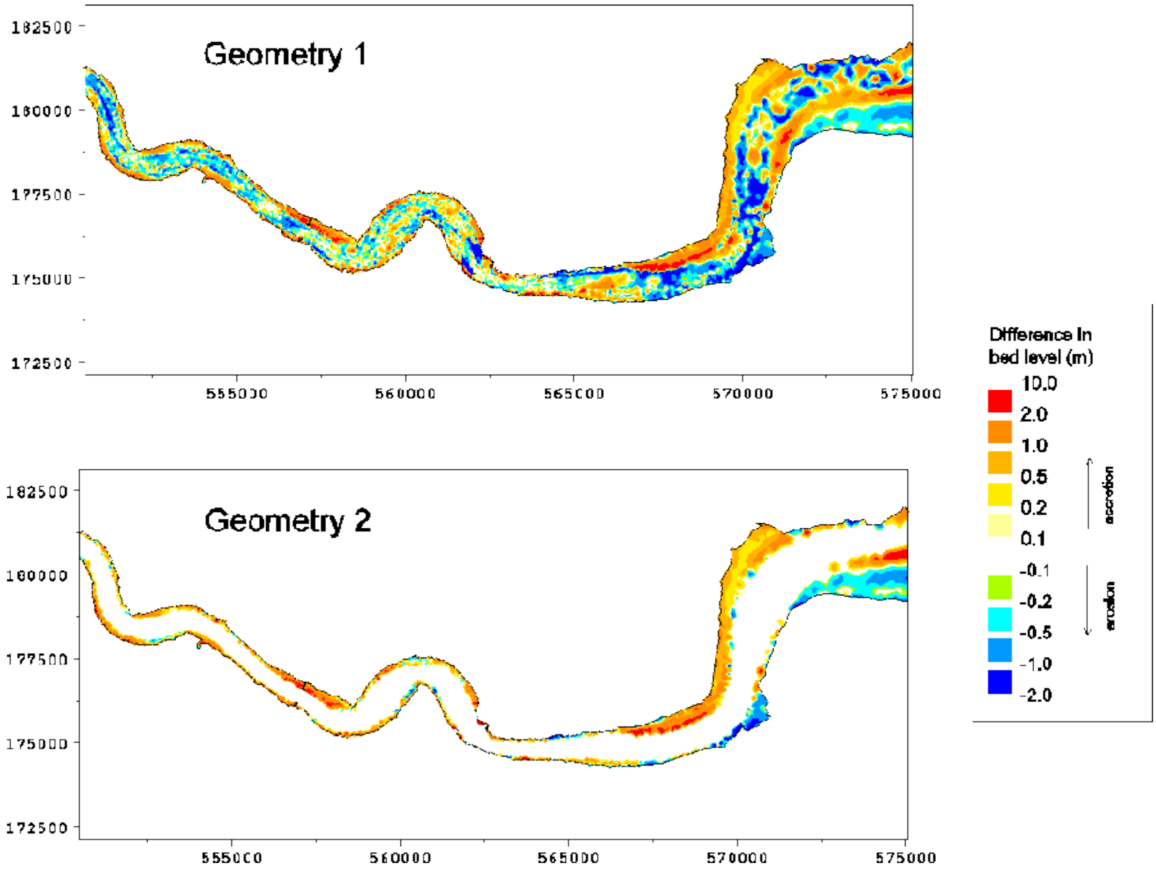

**Figure 5.1d  Predicted changes in bathymetry, 2000 to 2030, Erith to Lower Hope Point** using Historical Trend Analysis

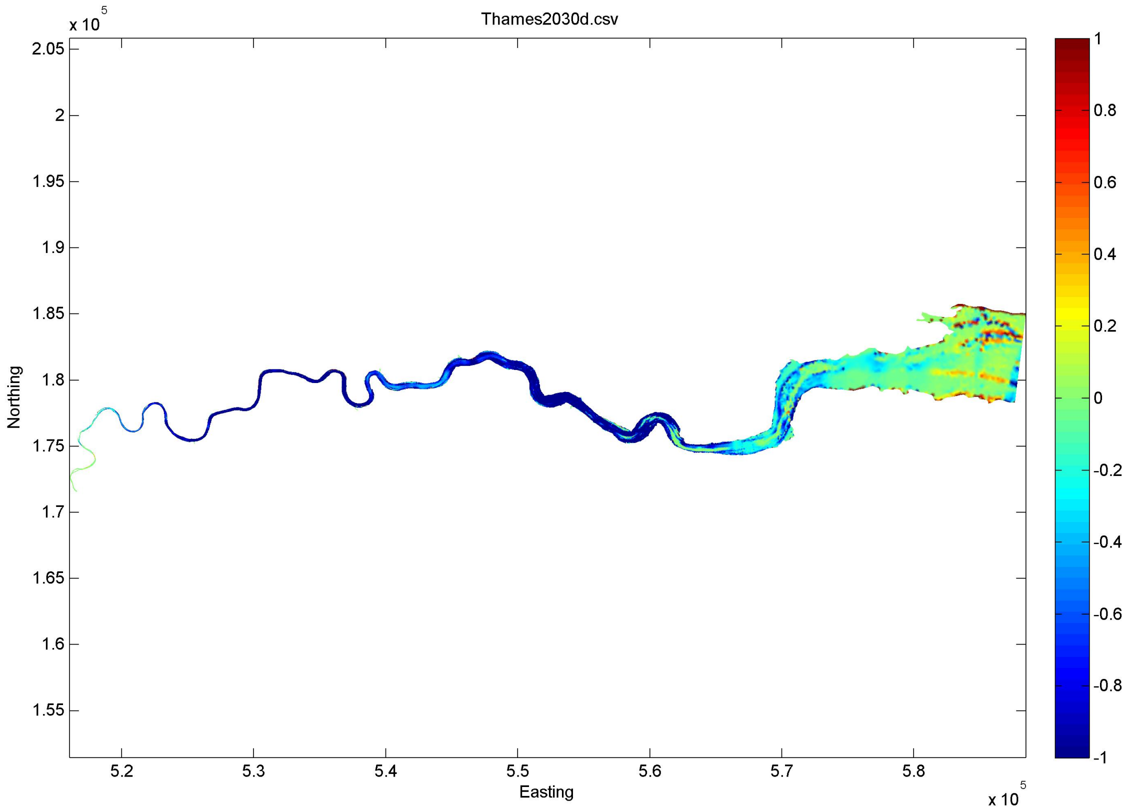

**Figure 5.1e Hybrid-Regime baseline and 2030 predictions (6mm/yr mean sea level rise)**

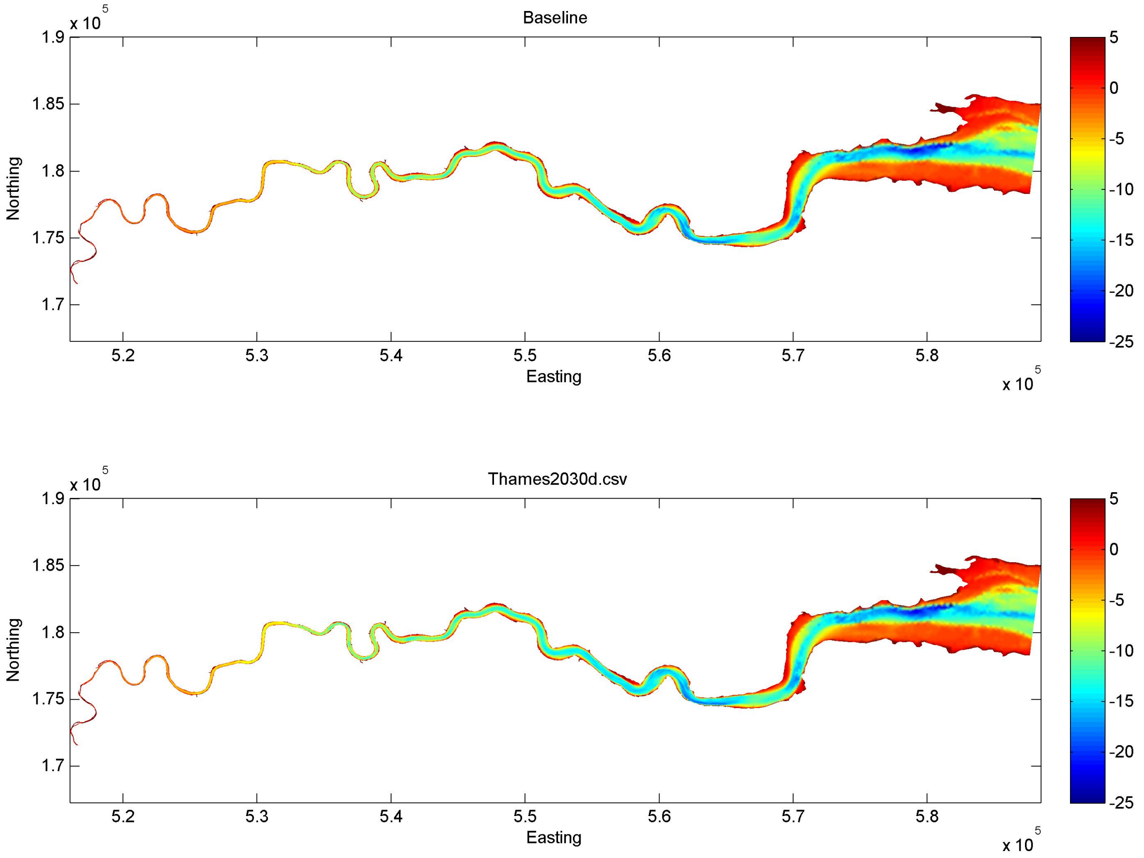

Figure 5.1f Hybrid-Regime predicted bathymetry changes to 2030 (6mm/yr mean sea level rise)

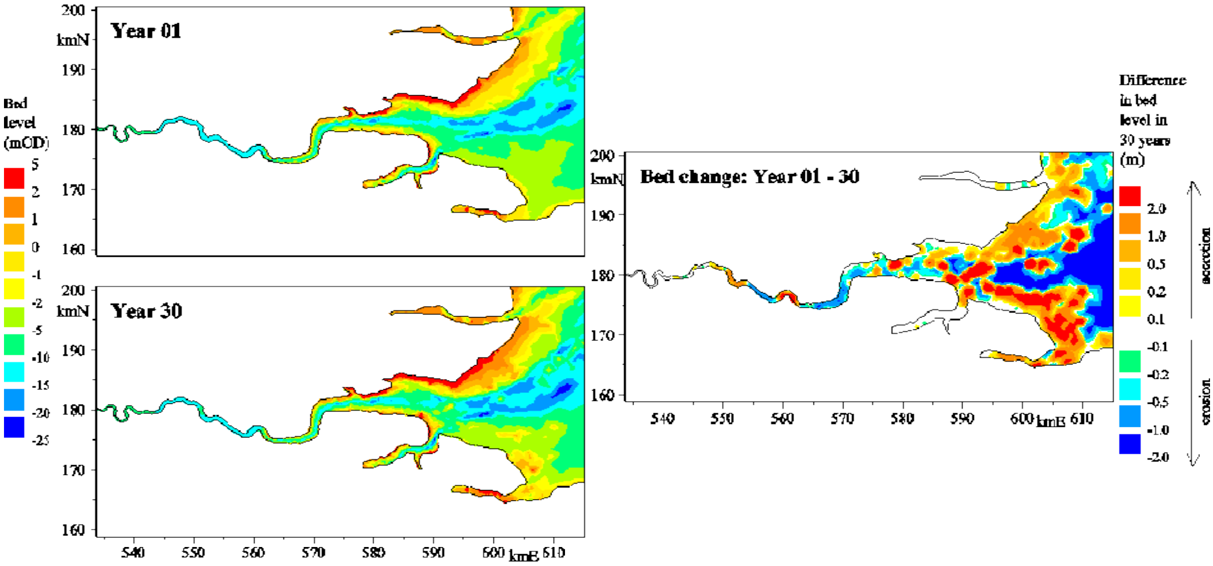

Figure 5.1g SandTrack model evolution of the Thames over year 1 to year 30 of a 50-year morphodynamic simulation, using yearly bed updates

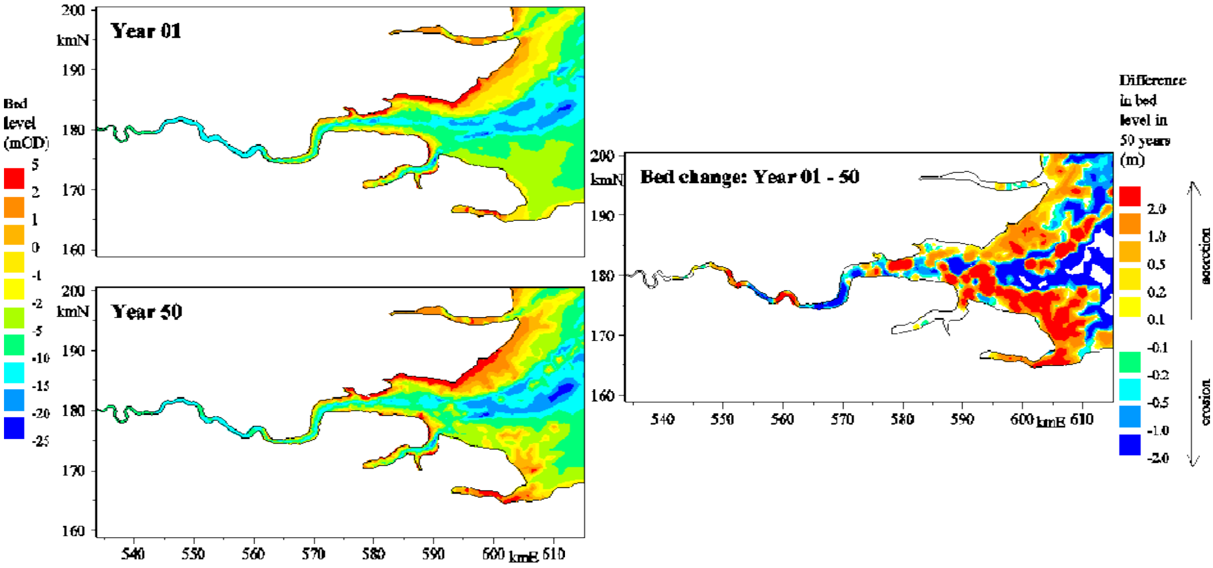

**Figure 5.1h SandTrack model evolution of the Thames over year 1 to year 50 of a 50-year morphodynamic simulation, using yearly bed updates**

Table 5.1a shows some Estuary-wide volumetric comparisons of HTA predictions with the 1920, 1970 and 2000 geometries. Table 5.1b presents various models' predicted changes for sea level rise of 6mm/yr or 0.18m by 2030 (0.3m by 2050). The volumes and areas in table 5.1a are for sea level rise only (no morphological change), for change in morphology only (no sea level rise) and for change in morphology and sea level rise combined.

**Table 5.1a Volume and surface area of historical and future bathymetries in the Thames Estuary** (HRW, 2006b)

| *Bathymetry* | *Surface area ($km^2$)* | | *Intertidal Area ($km^2$)* | *Volume ($km^3$)* | | *Tidal prism ($km^3$)* |
|---|---|---|---|---|---|---|
| | *LW* | *HW* | | *LW* | *HW* | |
| 1920 | 82.4 | 125.8 | 43.4 | 0.5639 | 1.2608 | 0.6969 |
| 1970 | 77.2 | 117.5 | 40.3 | 0.5212 | 1.1779 | 0.6567 |
| 2000 | 73.8 | 117.7 | 43.9 | 0.5203 | 1.1575 | 0.6372 |
| 2030 (just effect of sea-level rise) | 74.7 | 117.7 | 43.0 | 0.5302 | 1.1725 | 0.6423 |
| 2030 Geometry 1* (just effect of morphology) | 72.6 | 117.6 | 45.0 | 0.5398 | 1.1462 | 0.6064 |
| 2030 Geometry 2* (just effect of morphology) | 72.5 | 117.6 | 45.1 | 0.5245 | 1.1339 | 0.6094 |
| 2030 Geometry 1* (sea-level rise + morphology) | 72.9 | 117.6 | 44.7 | 0.5518 | 1.1675 | 0.6157 |
| 2030 Geometry 2* (sea-level rise + morphology) | 72.9 | 117.6 | 44.7 | 0.5364 | 1.1552 | 0.6188 |

* Geometry 1 extrapolates the subtidal bathymetry assuming there is no overall effect of dredging on the morphological trend.

Geometry 2 assumes that because of dredging the channel-bed part of the subtidal area will remain constant in depth over time.

HW (LW) volumes were calculated from maximum (minimum) depths over the tide, summed over the whole estuary. HW (LW) areas were calculated by summing up the areas over which the maximum (minimum) depths are non zero.

**Table 5.1b Emulator, Hybrid Regime, ASMITA and SandTrack results for Thames: baseline; 2030 after 6 mm/yr; 2050 after 6 mm/yr**

| *Model* | *LW area (km$^2$)* | *HW area (km$^2$)* | *LW volume (km$^3$)* | *HW volume (km$^3$)* | *Sediment Fluxes (10$^3$ tonnes / tide)* |
|---|---|---|---|---|---|
| Emulator | 71.66;<br>--; 77.89 | 193.25;<br>--; 199.48 | 0.1235;<br>--; 0.1459 | 0.90;<br>--; 0.96 | 98.4;<br>--; 103.04 |
| Hybrid Regime | 85;<br>90.4; 93 | 140;<br>142; 142 | 0.663;<br>0.722; 0.752 | 1.31;<br>1.40;<br>1.44 | N/A |
| ASMITA | 73.8;<br>74.4 ; 74.7 | 117.7 | -- | -- | -- |
| SandTrack | 75.7 to 83.9;<br>74.44 or 76.9; -- | 117.75;<br>117.75; -- | 0.5727;<br>0.5934; -- | -- | 29 to 68;<br>N/A; -- |

In the raised sea-level scenarios, LW, HW and tidal prism volumes naturally increase for the Emulator and Hybrid Regime simulations (Table 5b). The Emulator increases (as percentages) are generally the larger; nevertheless the Hybrid Regime model predicts increases ~ 15 per cent (LW volume), 10 per cent (HW volume), 8 per cent (tidal prism) per metre MSL rise. Along most of the Thames Estuary, MHWS intercepts tidal defences. Hence under raised MSL, MHWS area would hardly increase (less than 1 per cent; a constraint applicable in the Hybrid Regime model but not the Emulator). In fact predicted increases for HW area are 6.2 km$^2$ (Emulator; excessive), 2 km$^2$ (Hybrid Regime), and 5-6 km$^2$ (5-10 per cent) for LW area. By contrast, HTA (table 5.1a) shows a steady reduction in LW channel area and tidal prism since 1920; its predictions for 2030 show this trend continuing (along with minimal change in HW area).

Intertidal area is predicted to decrease (by 4.8 km$^2$ after 0.18m of sea level rise, or ~ 15 per cent per metre MSL rise) by the Hybrid Regime model, because HW area is constrained and LW area increases. As well as deepening due to sea level rise, the model predicts erosion of the sea bed along most of the estuary length. By contrast, table 5.1a indicates a steady historical increase of intertidal area, and HTA-predictions of only +/- 1 km$^2$ change[1]. The HTA-predicted intertidal area without morphological response can be regarded as providing an upper limit on losses; morphological response would act to decrease losses. The prediction for only morphological change gives the other end of the range of outcomes.

The ASMITA model predicts an intertidal area loss of 0.6 km$^2$ for 6 mm/yr sea level rise to 2030, but a 0.3km$^2$ gain in intertidal area with the present trend in sea level rise, ~ 2mm/yr

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[1] The Hybrid Regime model's average LW (HW) depth increases by 0.22m (0.5m) by 2030, i.e model erosion of intertidal areas is many times the rate of sea level rise. The Emulator cannot change intertidal area under MSL rise, because of the constant side-slope. Hybrid Regime intertidal and channel areas are just slightly greater than TE2100 values, probably as a result of a slight difference in the extent of the modelled estuary used to compare areas and volumes. The TE2100 study area included 42 km$^2$ of intertidal areas in the Thames Estuary but the Hybrid Regime included 57 km$^2$ of intertidal areas. The Outer Thames Estuary between the TE2100 Estuary area boundary and a line from Margate to Clacton-on-Sea contains another 230 km$^2$ of intertidal area.

(Rossington and Spearman, 2007). This compares with the TE2100 HTA extrapolations which are for the 2mm/yr scenario: a loss of 0.9 $km^2$ with no morphological response; a gain of 0.8$km^2$ when both sea level rise and morphological change are taken into account.

Observed changes to features landwards of Southend include growth of intertidal areas at Blyth Sands and deepening of the channel (HRW, 2006a). Further upstream, a similar pattern has been observed, with a deepening and narrowing of the subtidal channel and an increase in intertidal areas. SandTrack's relatively coarse resolution limited its potential to predict changes to Blyth Sands. Rapid accretion along Grain Spit is predicted (extending further eastwards) but seems too extreme and may also be an effect of coarse resolution.

In the Outer Thames Estuary, Morpho-SandTrack seems to predict a relatively stable future system of channels and banks, except for the region (about 625 km E, 180 km N) around the Edinburgh Channels crossing Long Sand. This accords with the TE2100 studies of changes over the last century (HRW, 2005) which concluded that the system of channels and banks appeared relatively stable (with extension of some of the banks seawards by up to a few km) except for the region around the Edinburgh Channels which appeared quite dynamic.

Models vary in whether Thames Estuary morphology will respond in keeping with sea level rise. Only the Hybrid Regime model predicts erosion (at a greater rate than sea-level rise, and faster erosion for faster sea-level rise. Although the Emulator has deepening due to sea level rise simply according to unchanged morphology (and more deepening for greater river flow), it also estimates infilling times – 218 years for the baseline state, 228 years with MSL + 0.3m; these times are short enough to keep pace overall with volume changes following MSL rise. The ASMITA model predicts a time-scale of 300 years before the estuary reaches dynamic equilibrium with 6mm/yr MSL rise. TE2100 suggests that the estuary will probably keep pace with current rates of sea-level rise. ASMITA predicts that infill can keep pace with sea level rise up to 21mm/yr. Thus the consensus is that Thames infill should keep pace with sea level rise at rates somewhat faster than at present.

Modelled effects of tidal range for the Thames were small in comparison with the impact of sea level rise. The Hybrid Regime model shows little effect of (20 per cent) increase in river flow, to which the Emulator is more sensitive as the depth increases in response.

### 5.2 Blackwater

Table 5b gives the results of the model predictions for the baseline (2000) Blackwater Estuary and for the 2050 scenarios: 0.3m and 1.0m sea level rise; increase in tidal range (by 2 per cent); increase in freshwater flow (by 20 per cent). [The modelled area and downstream boundary are not exactly the same for the two models].

Hybrid-Regime and Emulator predictions of percentage increases in Blackwater volume for raised MSL are similar, despite LW volume discrepancies (the Emulator is constrained by its assumed triangular cross-section). LW (HW) volume increases are about 45 per cent (20 per cent) per metre MSL rise.

For intertidal area, the Hybrid Regime model predicts a substantial reduction ~ 15 per cent (for 0.3m MSL rise), ~ 35 per cent (for 1m MSL rise). [The Emulator is unable to predict any change]. The Hybrid Regime model predicts a LW depth increase by less than the sea level rise while the HW depth increases by more than the sea level rise, i.e. there is net erosion as well. ??In the case of 0.3m sea level rise, this predicted erosion is as large as the sea level rise. However, this behaviour may be an artefact of the Hybrid Regime model initialisation. ?? [Emulator HW and LW depths are necessarily increased by half the sea level rise].

For a 2 per cent increase in tidal range, the Emulator predicts only modest changes. Hybrid-Regime-predicted changes are somewhat greater: a 5 per cent increase in LW estuary volume, 7 per cent loss of intertidal area, HW depth increase by 3 per cent.

For a 20 per cent increase in river flow, the Emulator predicts a significant increase in estuary volumes: 24 (11.5) per cent for LW (HW) volume. However, the Hybrid Regime model predicts very little change (less than 2 per cent in any of the variables).

The Realignment model was applied to Tollesbury Creek specifically. Figure 5.2 shows a prediction of the evolution of this managed realignment, compared with the observed evolution. For the longer term, the model predicts only slow development of (saltmarsh) area above HW neaps; vegetation-enhanced retention of deposited sediment tends to concentrate rather than extend saltmarsh development. Rising sea level (6 mm/yr) increases accretion in the model, but not enough to keep pace, so that salt marsh area decreases and the equilibrium volume of water increases by ~ 17 per cent. ASMITA analysis predicts a comparable 16 per cent increase in water volume. This modelling is described in detail in Spearman (2007).

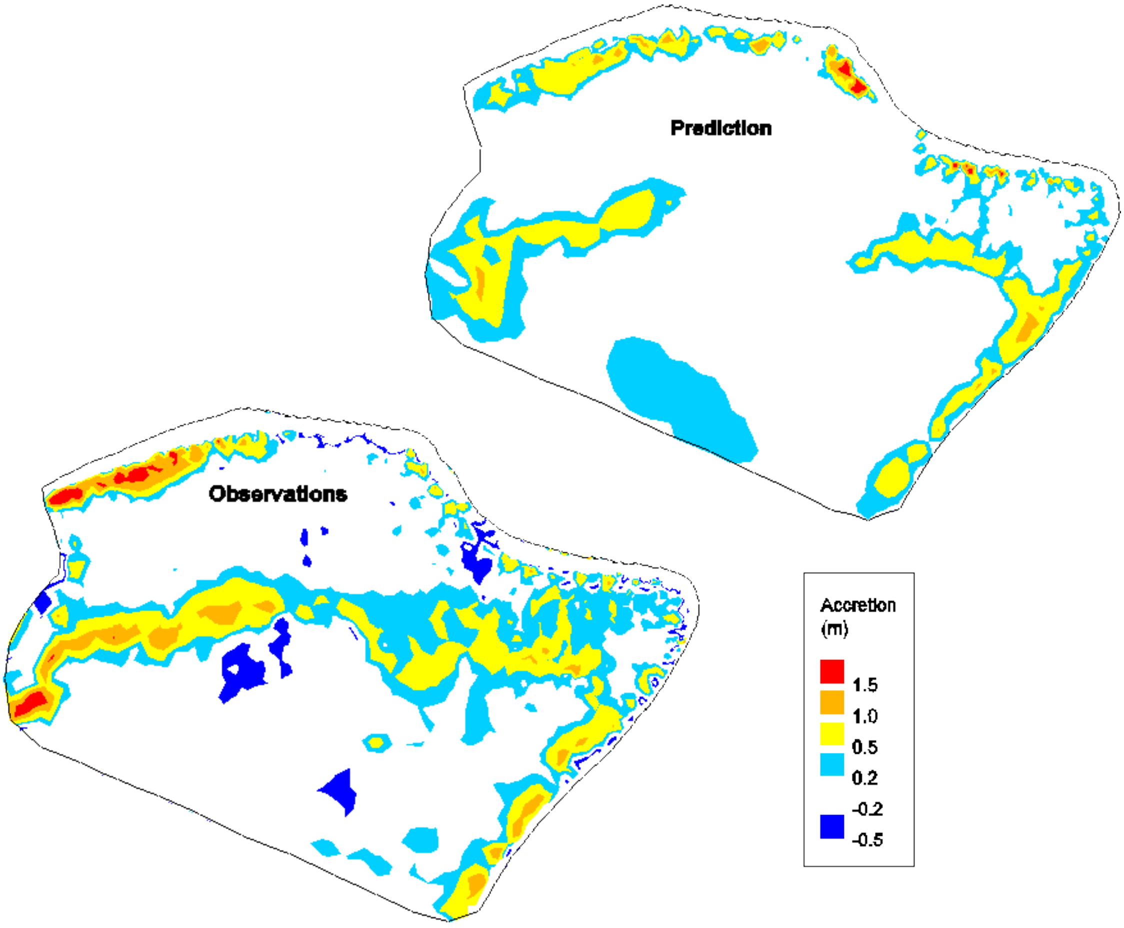


**Figure 5.2 Comparison of observed and predicted bed level change in Tollesbury Managed Realignment site 1995-2002**

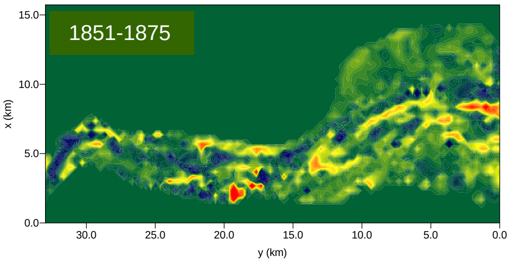
## 5.3 Humber

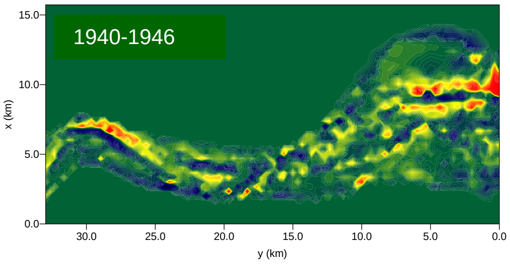
The Inverse model procedure was applied to the Humber. We show:

- bathymetry changes between successive charts – changes due to all external forcing;
- reconstructed source functions – the morphological response to non-diffusive processes;
- EOFs representing the source functions.

Figure 5.3a shows bathymetry changes between consecutive bathymetric surveys of the outer and middle estuary. Alternate erosion and accretion can be seen in the periphery. Prior to 1925 these areas are mostly accretive, but from 1925 to 1966 erosion and accretion have taken place in approximately 10-year cycles. For 1966 to 1985, these areas show alternate accretion and erosion. From 1986 to 1998, changes in these peripheral areas were almost negligible. A small amount of accretion has taken place from 1998 to 2000.

Accumulation in the main channels and erosion of shallow flats is eminent throughout, with a few exceptions that could well be due to dredging to maintain the navigation channel. However, morphological changes are comparatively small after 1986, except near the mouth of the estuary and at Hull. Apart from these changes, other localised changes in the estuary morphology show erosion/accretion behaviour with little apparent structure. The estuary was more morphologically active prior to 1960. Morphological changes show a more gradual and streamlined nature after 1960.


1851-1875
15.0
10.0
5.0
0.0
x (km)
30.0
25.0
20.0
15.0
10.0
5.0
0.0
y (km)


1940-1946
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10.0
5.0
0.0
x (km)
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15.0
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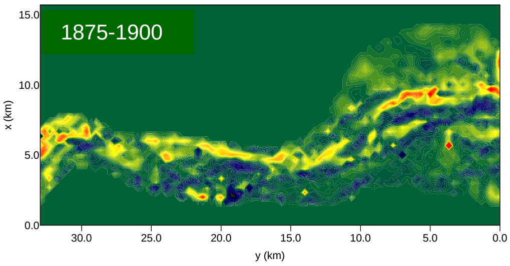
0.0
y (km)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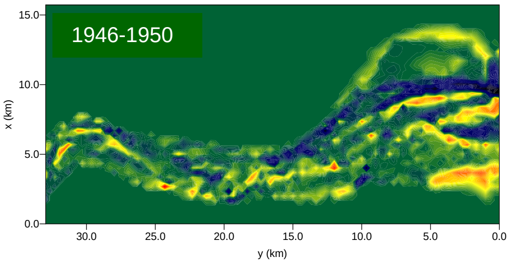
y (km)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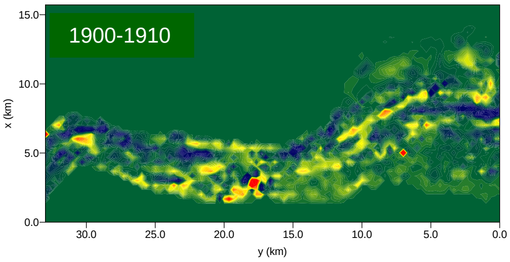
y (km)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x (km)
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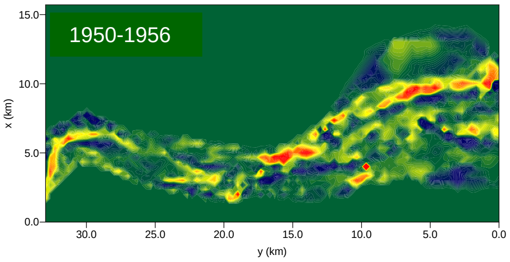
5.0
0.0
y (km)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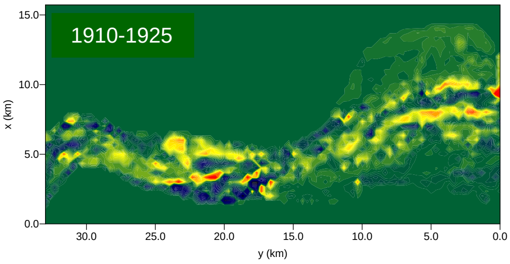
y (km)


1910-1925
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10.0
5.0
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x (km)
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25.0
20.0
15.0
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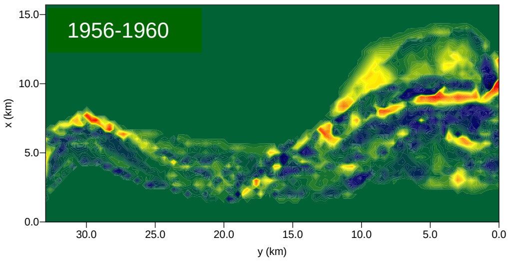
0.0
y (km)


1956-1960
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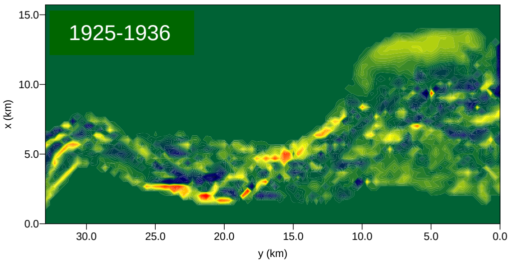
y (km)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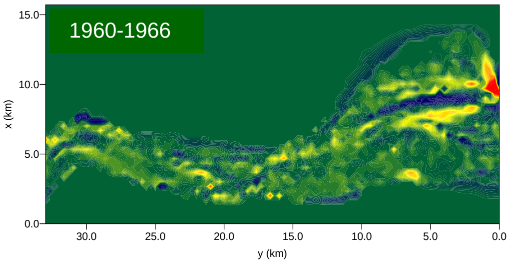
y (km)


1960-1966
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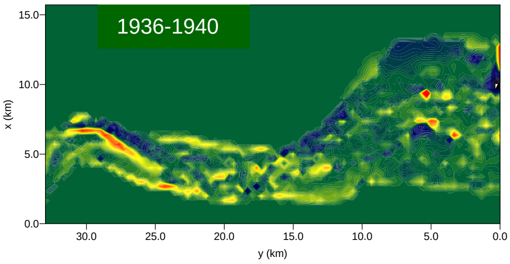
y (km)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5.0
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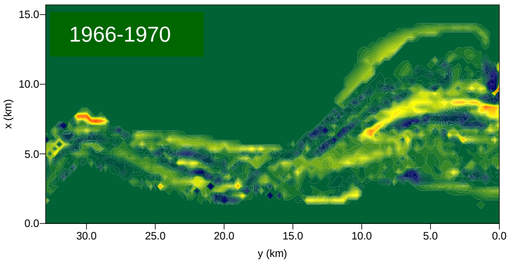
y (km)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y (km)

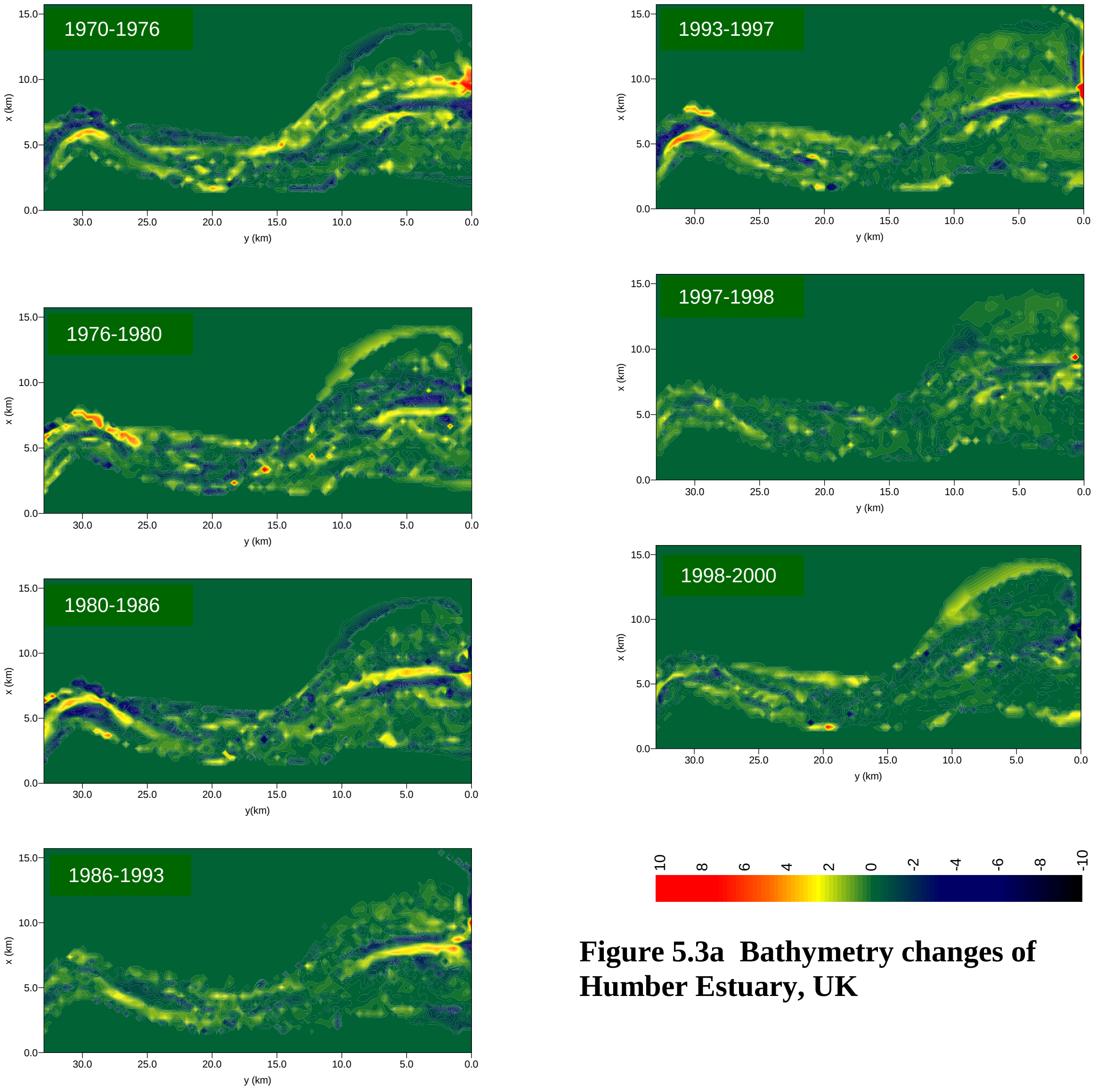
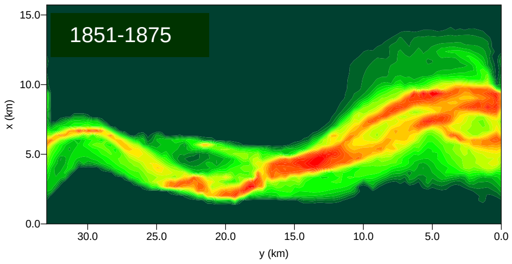


**Figure 5.3a Bathymetry changes of Humber Estuary, UK**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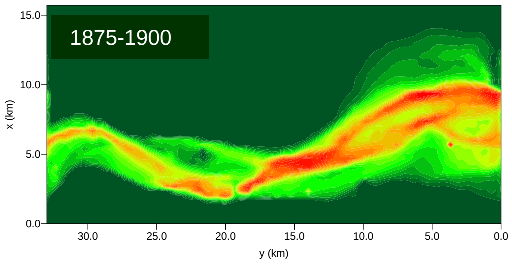
10.0
5.0
0.0
x (km)
30.0
25.0
20.0
15.0
10.0
5.0
0.0
y (km)


1875-1900
15.0
10.0
5.0
0.0
x (km)
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25.0
20.0
15.0
10.0
5.0
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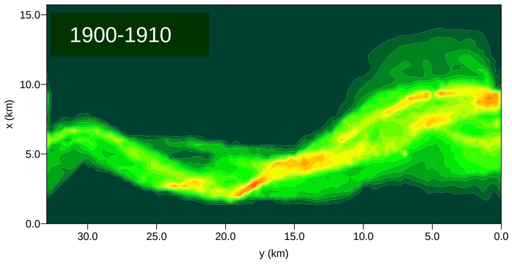
y (km)


1900-1910
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10.0
5.0
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x (km)
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25.0
20.0
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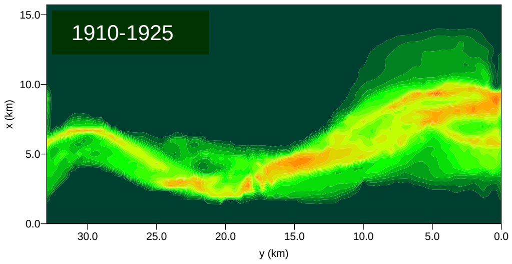
0.0
y (km)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x (km)
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25.0
20.0
15.0
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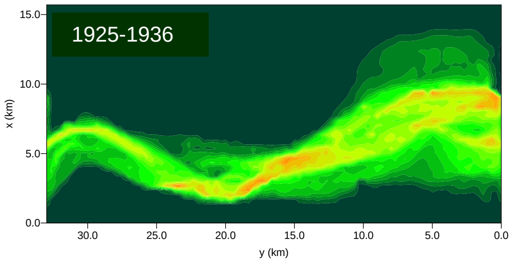
5.0
0.0
y (km)


1925-1936
15.0
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5.0
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x (km)
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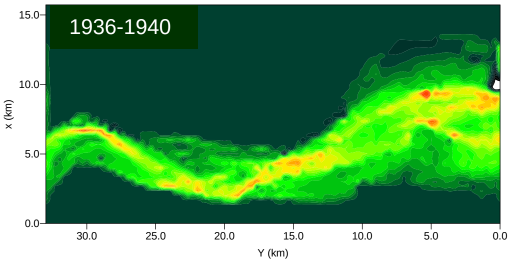
0.0
y (km)


1936-1940
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x (km)
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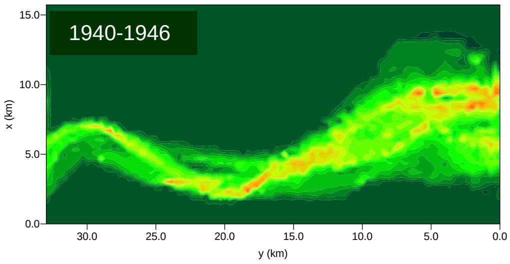
25.0
20.0
15.0
10.0
5.0
0.0
Y (km)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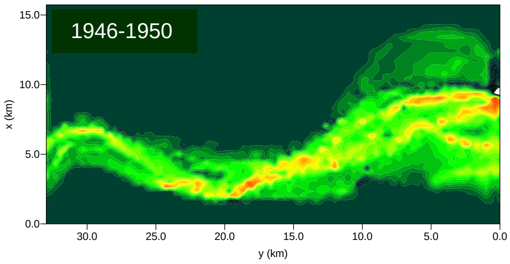
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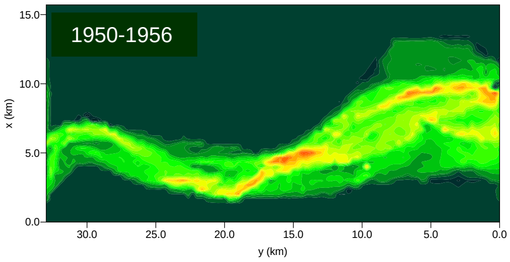
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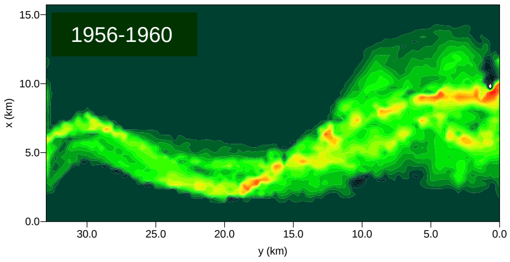
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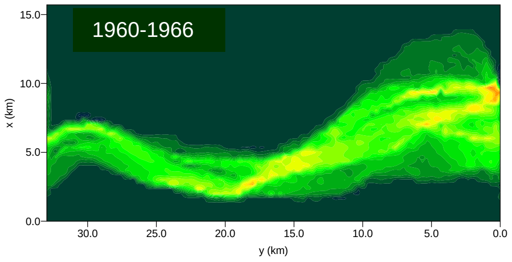
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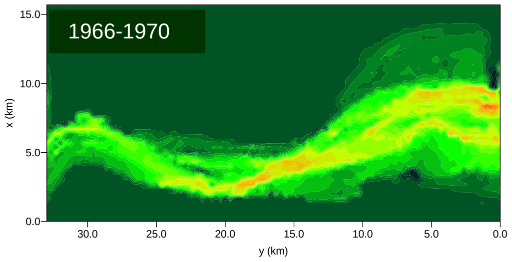
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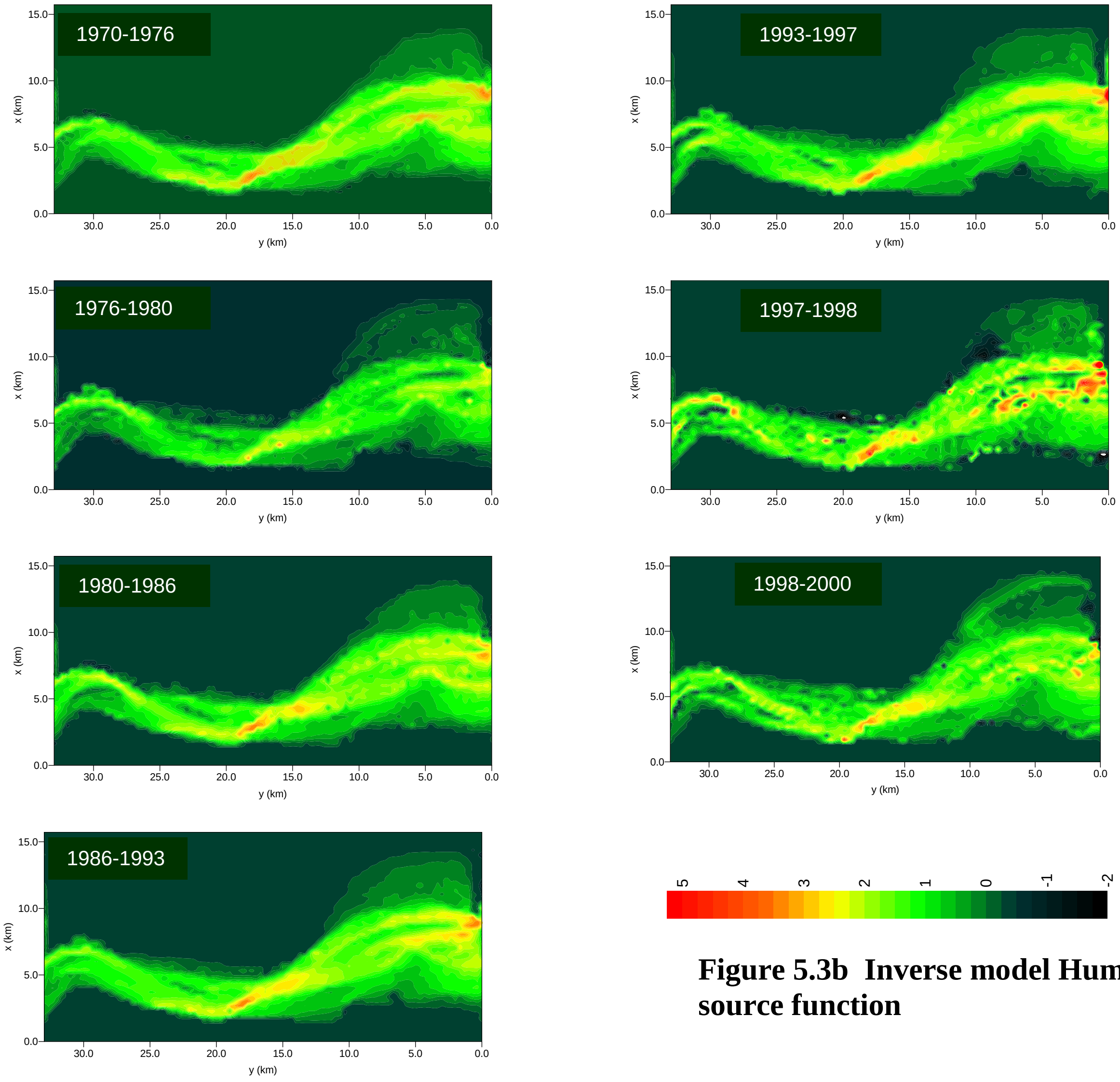
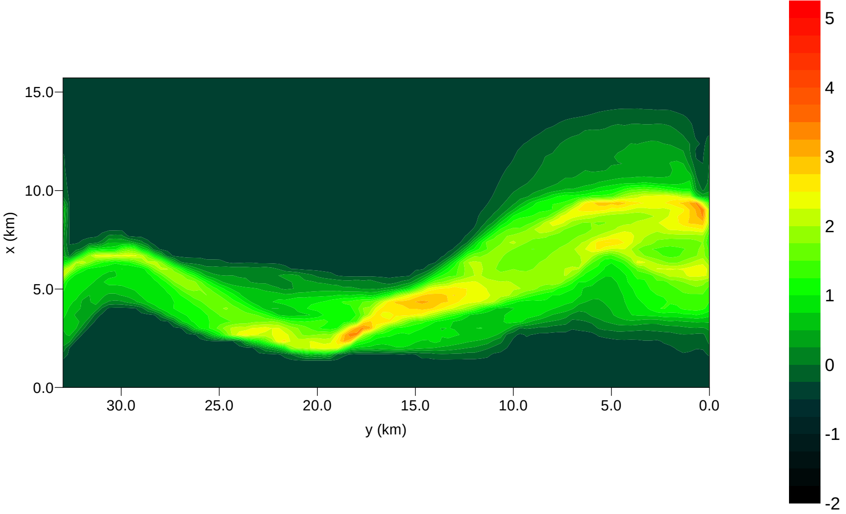


**Figure 5.3b Inverse model Humber source function**

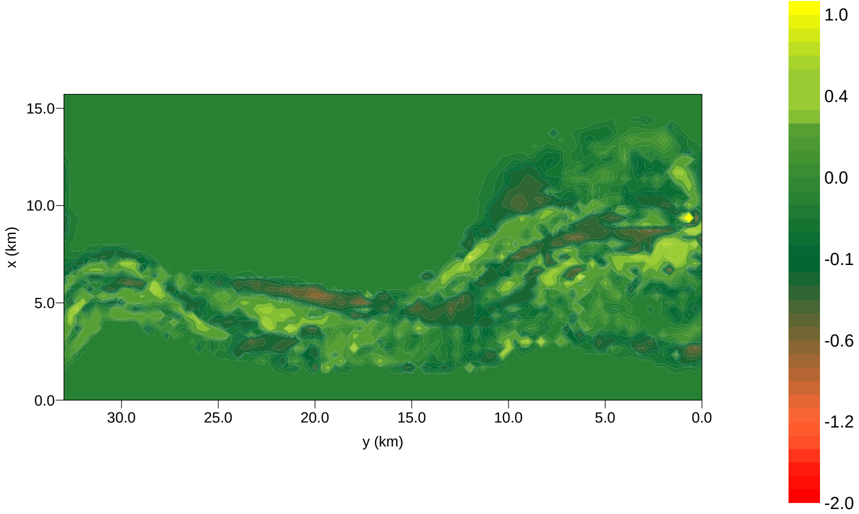
Figure 5.3b shows the (inverse-derived) source functions for the diffusion-type evolution equation. Overall, there is no rapid variation of source function from one interval to another. Large-scale features such as tidal channels, tidal flats and linear banks in the estuary are persistently visible. Smaller-scale structures are apparent than in bathymetric data *per se*. Other large-scale elongated features, possibly mud banks, are also visible in the middle estuary.

The large positive source functions in the tidal channels (during the entire period) indicate accretion, faster than predicted by large-scale diffusion. In other words, tidal channels in the outer and middle estuary draw sediment from surrounding mud flats and external sources and are subject to accretion. This is in line with ABPmer (2004) finding that infill was observed during the last 150 years. Localised negative source functions on the south and north banks indicate erosion or sediment removal from those areas, either by wave and tidal forcing or by dredging. Localised alternate erosion and accretion on certain mud flats, in the outer estuary between main channel and north bank, is indicated by negative and positive source functions respectively.

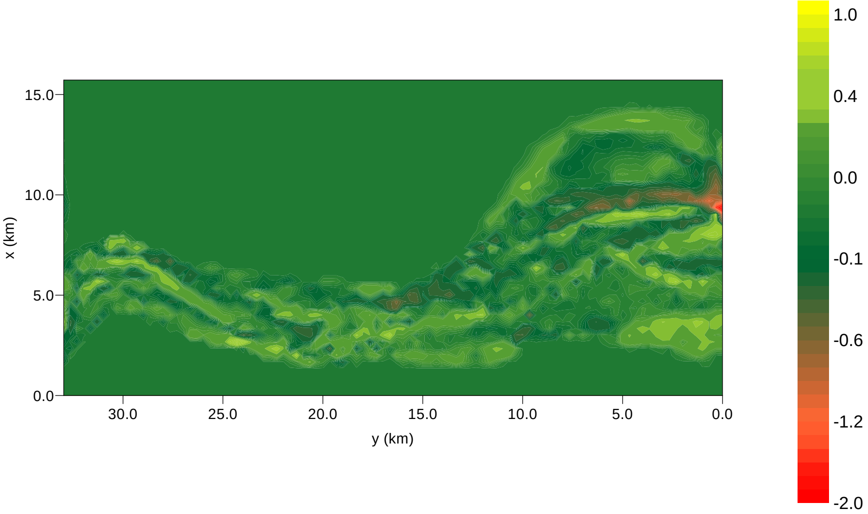
The source functions have significant differences from the corresponding bathymetry changes. These differences show that the large-scale sediment diffusive process is significant in the long term evolution of estuary morphology.



First spatial eigenfunction.



Second spatial eigenfunction.



Third spatial eigenfunction.

**Figure 5.3c Spatial Orthogonal eigenfunctions for Inverse model Humber source function**

Figure 5.3c shows plots of the first three EOF spatial eigenfunctions for the source; corresponding time series are shown in figure 5.3d. The first EOF, with 92 per cent of the mean square, corresponds to the mean source for the whole period; its corresponding time-series is almost constant. The second EOF shows the strongest variation in the source function, with areas of maxima and minima, mostly a few kilometres long and elongated along the estuary. Through time it shows an upward trend, but oscillates in 1960-1990. The oscillations may be attributed to bathymetry changes associated with large-scale dredging and development in the estuary at times between 1960 and 1994 (Townend and Whitehead, 2003). However, the survey frequency in general is not sufficient for a definite temporal signature of the second EOF. The third EOF shows smaller-scale patterns; subsequent eigenfunctions (not shown) are less coherent spatially.

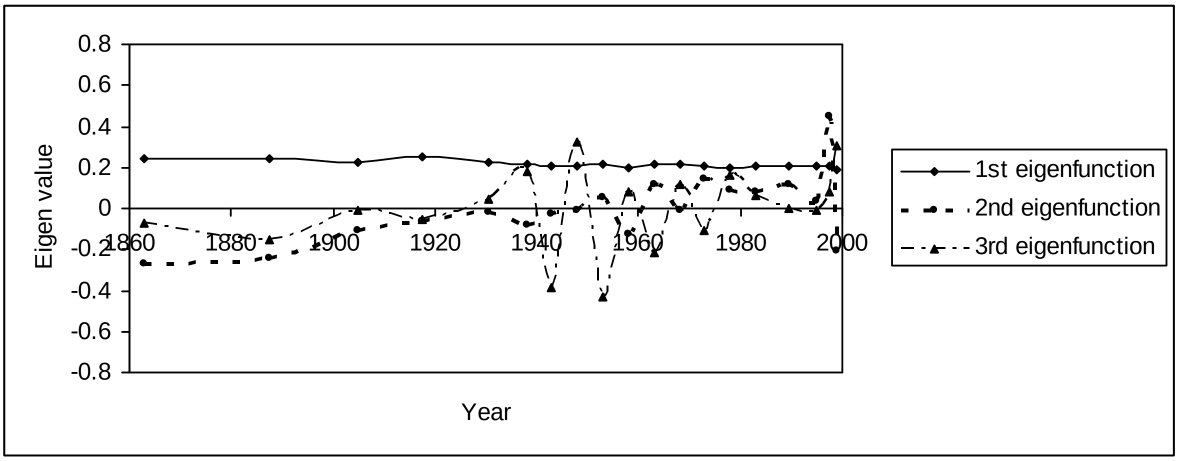


**Figure 5.3d Temporal eigenfunctions for Inverse model Humber source function**

Humber LW, HW and tidal prism volumes naturally increase for raised MSL, in the Emulator and Hybrid-Regime simulations (as for the Thames, Table 5b). Emulator increases (as percentages) exceed those predicted by the Hybrid Regime model and are probably excessive (the Emulator LW baseline appears to be too small and rigid constraints on HW area are not allowed for). The Hybrid Regime model predicts increases ~ 15 per cent (LW volume), 10 per cent (HW volume), 7 per cent (tidal prism) per metre MSL rise (very close to Thames values). It predicts a 13 km$^2$ (10 per cent) loss of intertidal area after 1m of sea level rise.

Effects of tidal range were small compared with the impact of sea level rise (again as for the Thames). An increase in river flow (20 per cent) has no effect in the Hybrid Regime model, but the Emulator is just as sensitive as for the Thames; the depth increases in response.

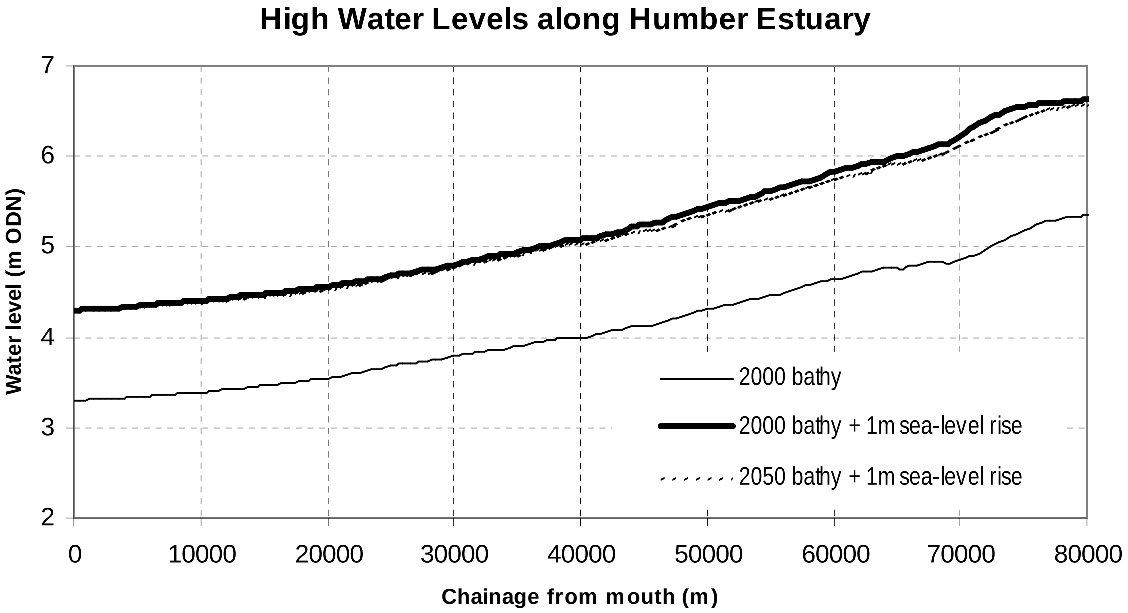


Figure 5.3e High water levels along the Humber Estuary

An example of the change in future flood risk is shown in figure 5.3e. Predicted water levels along the estuary for existing conditions are compared with 2050 assuming fixed estuary morphology; a further assessment accounts for predicted changes in estuary morphology over a 50 year period. Figure 5.3e shows that assuming a static bathymetry results in predicted peak water levels higher than in the case which includes the 2050 updated bed morphology. For the Humber at least, this suggests that flood studies undertaken with fixed bathymetries should provide a conservative assessment of future flood risk. A similar previous finding holds in the Severn Estuary (Wright & Townend, 2006).

## 5.4 Mersey

In the Mersey, the Emulator LW (HW) volume is sensitive to sea-level rise; area rather less so. Hybrid-Regime changes are much less (especially HW area is constrained) and trends are unclear. In common with the Emulator, the “2.5-D” model has no morphological change for raised MSL. Thus the changes (necessarily increases) in HW and LW volumes and areas depend only on the fixed geometry. Values for the “2.5-D” model LW (HW) volume increase (table 5.4) are ~ 17 per cent (15 per cent) per metre MSL rise; ~ 23 per cent (7 per cent) per metre MSL rise for LW (HW) area increase. Thus the “2.5-D” model predicts an intertidal area decrease for raised MSL, corresponding to a concave cross-section on average.

**Table 5.4 Emulator and “2.5-D” model results for the Mersey, Dee and Ribble**

| ***Scenario / characteristic*** | ***Estuary*** | *Mersey* | *Dee* | *Ribble* |
|---|---|---|---|---|
| *Baseline; 2050 MSL+0.3/ 1.0m* | | | | |
| *LW volume, $10^6m^3$* | *2.5-D* | 158; 166/185 | 81; 88/106 | 12; 14/21 |
| | *Emulator* | 106; 125/174 | 733; 756/809 | 5; 9/25 |
| *HW volume, $10^6m^3$* | *2.5-D* | 510; 534/586 | 395; 421/489 | 195; 212/255 |
| | *Emulator* | 1110; 1170/1310 | 1308; 1338/1409 | 464; 501/591 |
| *LW area, $km^2$* | *2.5-D* | 28.1; 30.9/34.6 | 22.0; 23.9/28.8 | 9.08; 10.80/14.84 |
| | *Emulator* | 60; 65/77 | 74.0; 75.1/77.7 | 12.2; 16.8/22.6 |

| | | | |
|---|---|---|---|
| *HW area, km$^2$ 2.5-D*<br>*Emulator* | 66.8; 69.1/71.7<br>194; 199/211 | 75.3; 78.8/85.0<br>99; 100/102 | 49.1; 51.5/56.5<br>120; 124/135 |
| *2% bigger tide: % changes*<br>*LW/HW volume; area 2.5-D*<br>*Emulator* | -1/1.2; -1.4/0.6<br>-4.4/1.4; -2.2/0.7 | -1.45/1.0; -0.87/0.86<br>-0.7/0.5; -0.3/0.3 | -1.95/1.5; -1.8/1.0<br>-16.8/1.8; -8.8/0.9 |
| *% change for river flow + 20%*<br>*LW/HW volume; area (Emulator)* | 34.6/10.1; 16.0/5.0 | 18.4/13.7; 8.8/6.6 | 98/8.5; 41/4.2 |
| *2.5-D saltmarsh*[S] *Baseline, km$^2$*<br>*% change: MSL +0.3/1.0m;*<br>*tide+2%* | 18.3<br>-12.4/-26.9;<br>-2.3 | 50.8<br>-6.9/-23.0;<br>-1.3 | 58.2<br>-4.1/-12.6;<br>-0.85 |
| *2.5-D convexity*[C]*: Baseline*<br>*MSL +0.3/1.0m;*<br>*tide+2%* | -0.107<br>-0.107/-0.134;<br>-0.107 | -0.075<br>-0.086/-0.113;<br>-0.071 | -0.130<br>-0.141/-0.173;<br>-0.125 |
| *2.5-D mean SPM "in",*<br>*Baseline tonnes/tide*<br>*% change: MSL+0.3/1.0m;*<br>*tide+2%, wind 10m/s* | 117000<br>0.7/6.1;<br>2.9, 0.7 | 24900<br>-8.4/-15;<br>8, 74 | 7120<br>14/55;<br>6.8, 102 |

[C] Cross-channel convexity is 0.5(MHW area+MLW area)/(Mean water level area) – 1 (identically zero for Analytical Emulator)

[S] Saltmarsh is defined here as the area covered at Highest Astronomical Tide less that covered at mean HW.

For a 2 per cent increase in tidal range, the Emulator necessarily predicts less LW area (-2.2 per cent) and volume (-4.4 per cent), and increased HW area (0.7 per cent) and volume (1.4 per cent). The "2.5-D" model gives comparable changes; LW volumes and areas necessarily decrease (percentage changes are less because the baseline values are larger – and probably more realistic). Hybrid Regime model predicted changes are all positive, indicating erosion below low water. Saltmarsh area (estimated in the "2.5-D" model as the area covered at Highest Astronomical Tide but uncovered at mean HW) notably decreases for raised MSL and increased tidal range. This is because the sides of the estuary are steeper above mean HW, consistent with the negative convexity (albeit this is evaluated between mean LW and mean HW)

For a (20 per cent) increase in river flow, the Emulator is as sensitive as in the Humber and Thames (the depth increases in response), whereas the Hybrid Regime model again shows little effect.

The mean (spring-neap) suspended sediment flux into the Mersey is estimated by the "2.5-D" model as 117,000 tonnes per tide. As expected, this increases with increased tidal range (and hence currents); it also increases with raised MSL but only because fluxes of water increase – concentrations actually decrease; it is remarkably insensitive to wind-(wave) enhanced bed stress. Sediment deposited (per tide) is ~10 per cent of "flux in", with little change over the different scenarios.

The "2.5-D" model predicts sediment transport and deposition (from which morphological change could be inferred until deposition patterns change significantly). These predictions enable inference of infill times to baseline HW level; 152years for the Mersey. This value is comparable with that of the Emulator (182 years). In practice deposition would change before infill is substantial, i.e. before the inferred infill time.

### 5.5 Dee and Ribble

These estuaries were modelled by the Emulator and the “2.5-D” model. [The “2.5-D” model geometry appears more realistic: the Emulator LW area and volume are too large in the Dee and so probably not sensitive enough to changed MSL etc.; the Emulator HW/LW volume ratio for the Ribble is extreme]. “2.5-D” model estimates for LW (HW) volume increase in the Dee are ~ 31 per cent (24 per cent) per metre MSL rise; ~ 31 per cent (13 per cent) per metre MSL rise for LW (HW) area increase. Corresponding values for the Ribble are ~ 75 per cent (30 per cent) for volumes, ~ 70 per cent (15 per cent) for areas. For both estuaries the “2.5-D” model predicts a small increase of intertidal area for raised MSL, unlike the Mersey (albeit all three are concave as here defined).

For a 2 per cent increase in tidal range, there are the expected small trends in LW and HW areas and volumes [except that Ribble LW area and volume are very small in the Emulator’s baseline representation, and hence very sensitive].

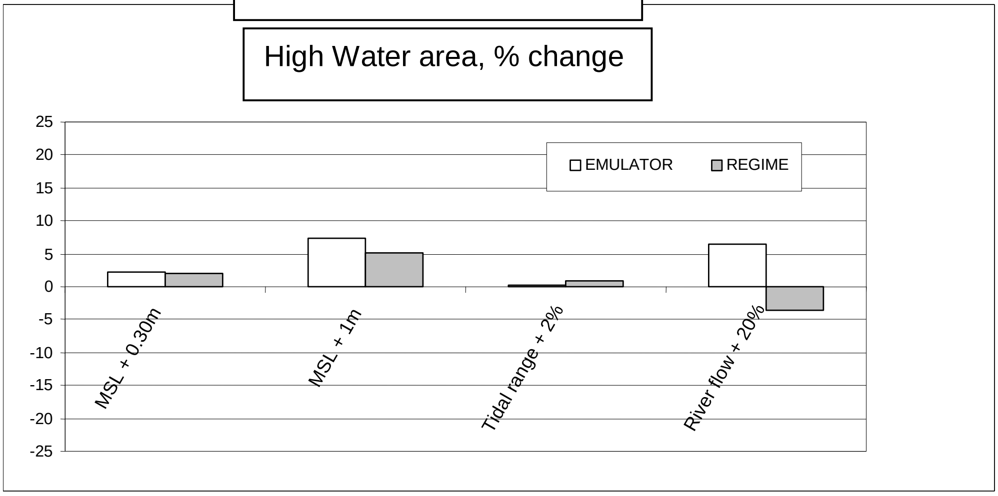
For a (20 per cent) increase in river flow, the Emulator for the Dee is less sensitive than in the Mersey, but very sensitive in the Ribble. This probably corresponds to respective over- and under-estimation of LW volume and area.

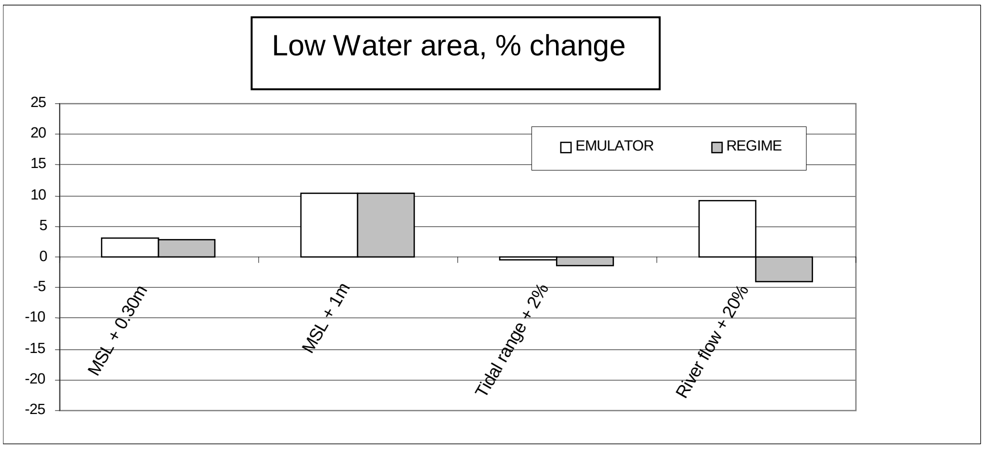
The mean (spring-neap) suspended sediment flux into the Dee is estimated by the “2.5-D” model as 24,900 tonnes per tide for the Dee and 7,120 tonnes per tide for the Ribble; both much less than the Mersey. These values increase as expected with increased tidal range (i.e. currents) and strongly with wind-(wave) enhanced bed stress; the flux decreases with raised MSL in the Dee but increases in the Ribble (as for the Mersey). Sediment deposited (per tide) in the Dee is ~10 per cent of “flux in”; ~14 per cent in the Ribble. There is little change over the different scenarios in the Ribble, but deposition in the Dee decreases markedly with raised mean sea level. Infill times to baseline HW level are respectively 555, 685 years for the Dee, Ribble (subject to the same *caveat* as for the Mersey; deposition would change before infill is substantial). These values are comparable with those of the Emulator for the Dee, longer for the Ribble.

### 5.6 Southampton Water

Scenarios were run with the Hybrid Regime model and the Emulator. Discrepancies between them, and changes altogether, are relatively small (the difference between HW and LW areas and volumes is relatively small for Southampton Water). Hybrid Regime model estimates for LW (HW) volume increase in Southampton Water are ~ 8 per cent (7 per cent) per metre MSL rise; ~ 10 per cent (5 per cent) per metre MSL rise for LW (HW) area increase; intertidal area decreases by ~ 10 per cent (‘coastal squeeze’; figure 5.6). Indeed the Hybrid-Regime mean LW depth decreases with MSL rise and the HW depth increase is much less than MSL rise; infill is predicted in contrast with most of the other estuaries.

High Water area, % change





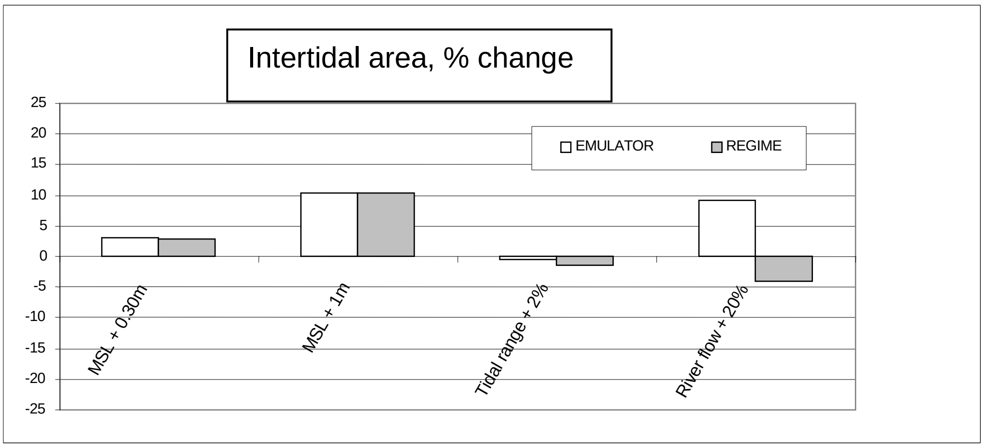


Figure 5.6. Southampton Water responses to changed MSL, tidal range and river flow.

Changes for (2 per cent) greater tidal range are less than 2 per cent, but intertidal area increases. For increased freshwater flow the Emulator gives a substantial increase in HW and LW volume and area, whereas the Hybrid Regime model predicts a decrease except for HW area. This contrast is probably because the Emulator predicts deepening with constant side slope, whereas the Hybrid-Regime morphological response to increased river flow is more specific; the estuary widens but deepens only locally.

Emulator estimates of Southampton Water flushing time and infill time are relatively long: 14.9 days (see note to table 5a), 765 years respectively.

### <u>5.7 Tamar</u>

This was run only with the Emulator. Relative to the other estuaries, the representation of the Tamar is fairly deep with moderate tidal range and HW/LW ratios. Accordingly, LW (HW) volume increase at ~ 32 per cent (19 per cent) per metre MSL rise, and LW (HW) area increase at ~ 15 per cent (9 per cent) per metre MSL rise, are moderate compared with other Emulator predictions. Changes for (2 per cent) greater tidal range are at most 2 per cent. However, (20 per cent) increased freshwater gives an increase in HW and LW volume and area, up to 21 per cent for LW volume. Estimated flushing time and infill time are 11.5 days (see note to table 5a), 619 years respectively

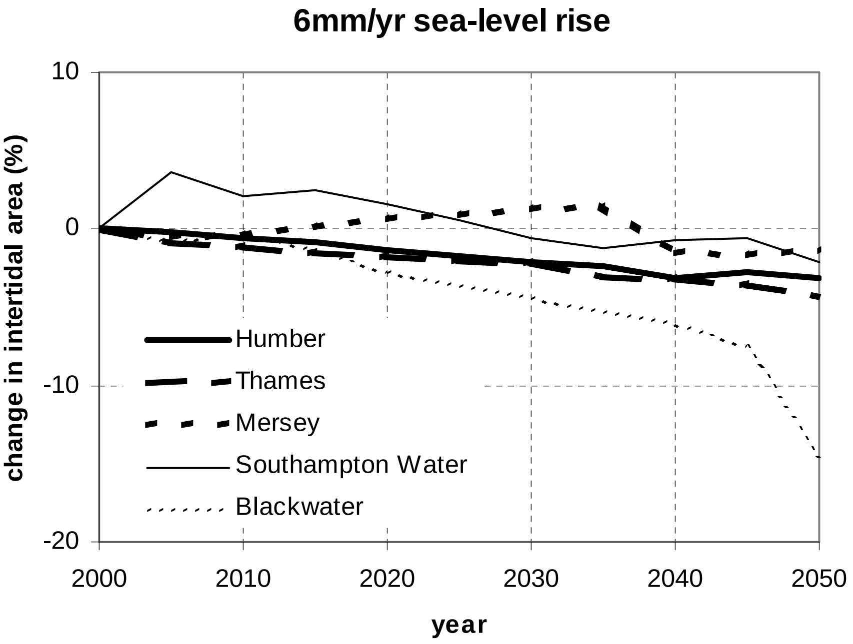
## 6. Discussion

Some trends are inevitable in models (Emulator, “2.5-D”) that do not evolve the morphology. LW and HW areas and volumes, the tidal prism and fluxes of water at the mouth will increase with raised MSL. The Emulator mean depth increases by half the rise in MSL. Intertidal and saltmarsh areas will increase or decrease with raised MSL as cross-sections are convex or concave (and hence cannot change with the triangular section assumed by the Emulator). Increased tidal range increases HW volume and area, intertidal area, the tidal prism, fluxes of water at the mouth and suspended sediment concentrations; LW volume and area must decrease. Increased river flow increases LW volumes and areas (in fact the Emulator does evolve, increasing depth in response to increased river flow and so strengthening this trend of increased LW volumes and areas). These trends form a reference against which to infer effects of evolving morphology.

LW volumes and areas are typically more sensitive to raised MSL, increased tidal range and river flow than are HW volumes and areas (aside from any question about rigid structures constraining HW area). This is simply that effects in shallow water are relatively large. The same argument suggests greater sensitivity of shallow estuaries in general. [However, initial estuary depth may be dependent on the tidal and river-flow regime (as supposed in the Emulator and Hybrid-Regime approaches); depth is not then an independent factor against which to compare sensitivity].

Hard structures may limit HW area. With MSL rise, unless the estuary fills in to compensate, LW area increases and consequently intertidal area decreases. This is a finding of the Hybrid Regime model (over the whole 50 years) common to all five estuaries on which it was run (Thames, Blackwater, Humber, Mersey, Southampton Water); the Blackwater is an extreme case (figure 6a). However, ASMITA predicts loss of Thames intertidal area only if infill lags *accelerated* MSL rise.

Mean depths in most estuaries should increase as MSL rises, according to the Hybrid Regime model. However, this depth increase is comparable with MSL rise only for high waters in the Thames, Blackwater and Humber, and infill with MSL rise may be more prevalent than the Hybrid-Regime results suggest. Indeed, ASMITA shows infill in the Thames eventually keeping pace with any likely MSL rise rate. The Hybrid Regime model predicts substantial infill for the Mersey, where scope for infill is known historically and accords with the "2.5-D" and Emulator predictions of a relatively short infill time. For Southampton Water, Hybrid-Regime HW area appears to be relatively unconstrained and allows an increase in shallow-water area as MSL rises.



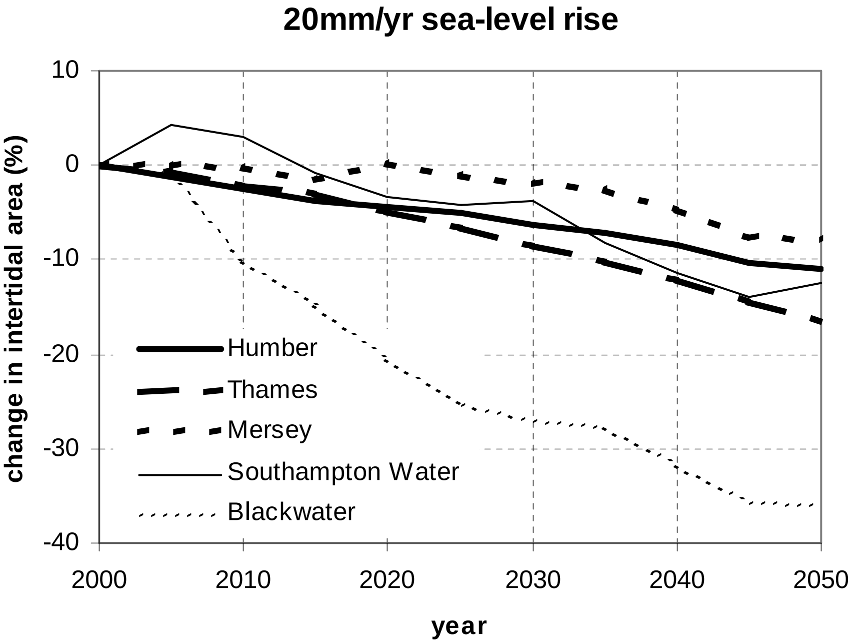


**Figure 6a Hybrid Regime model predictions of intertidal area change with sea-level rise**

For most of the estuaries, intertidal change with increase in tidal range is limited to O(2 per cent) [in the Hybrid Regime model; figure 6b]. An exception is Southampton Water which has large gains peaking in 2025 and a net gain of almost 4 per cent over the 50 years. The 2025 peak appears to be related to the position of relatively shallow bed slopes. The Thames Estuary is predicted to lose 5 per cent of intertidal area over the 50 years.

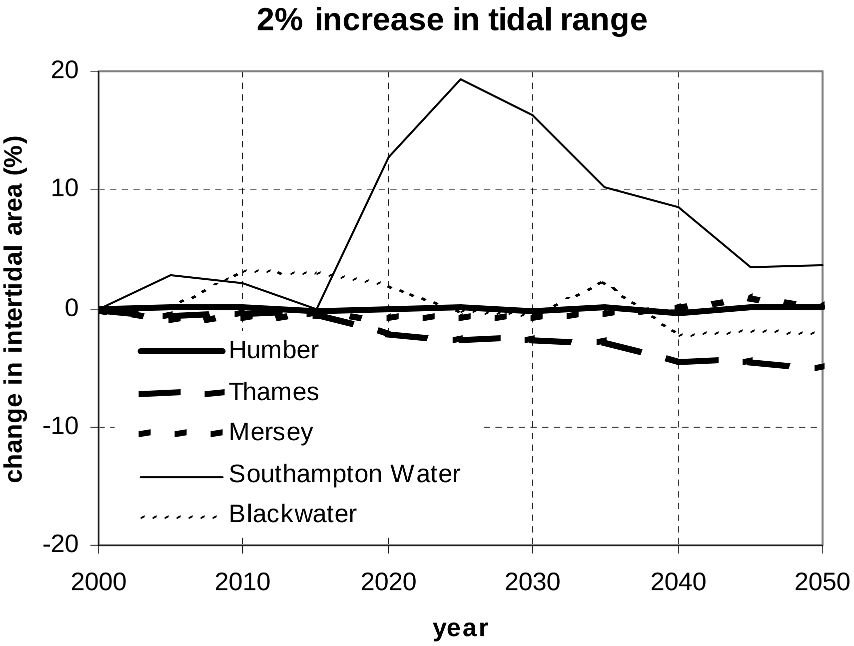


**Figure 6b Hybrid Regime model predictions of intertidal area change with tidal range**

River-flow is a strong factor in Emulator predictions, through the predicted increase in mean depth as river flow increases. The Hybrid-Regime predictions are more discriminating (figure 6c). The Humber and Thames estuaries are least sensitive to a change (20 per cent increase) in river flow, probably because these are large estuaries and experience much variability in river inflow. The Mersey is predicted to experience a loss in intertidal area with increased river flow. The Blackwater appears sensitive; initial loss of intertidal area is followed by a gain.

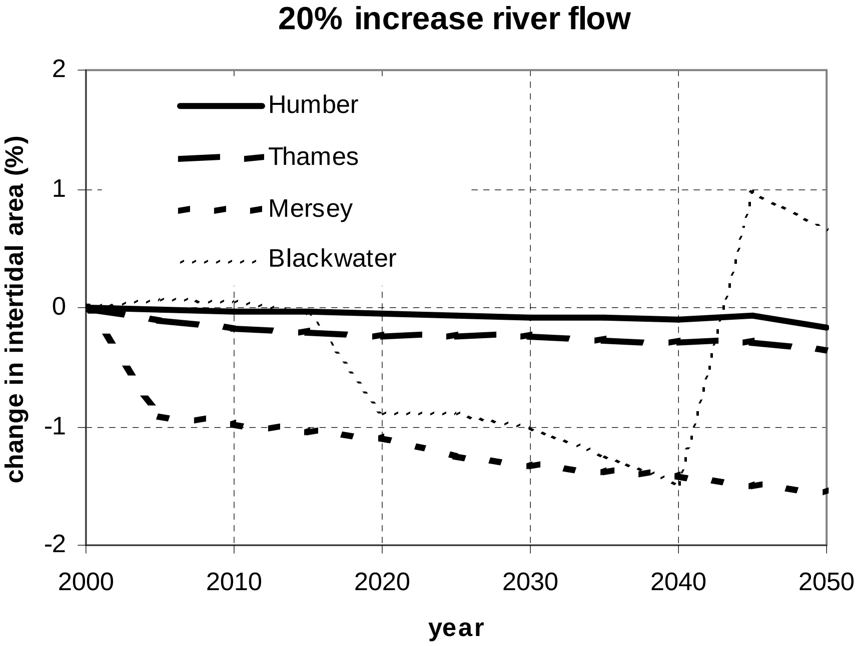


**Figure 6c Hybrid Regime model predictions of intertidal area change with river flow**

Estimates of flushing time (by the Emulator; see note to table 5a) vary from a few days to a few weeks. They do not correlate with estuary size; they depend also on tidal range and river flow. Infill times are much longer because concentrations of transported sediment are low; infill times lengthen in response to rising MSL, and shorten for increased mean river flow. The Thames, Humber and Mersey flushing times are shorter than the 15-day spring-neap cycle; Prandle *et al.* (2005) indicate that longer flushing times would provide longer-term persistence of marine-derived nutrients.

We have presented results from alternative morphological prediction tools founded on very different concepts. All are important for developing an ensemble of possible future scenarios. Where the models are in agreement, this provides confidence in results. Differences under particular test conditions can often be explained by model limitations, e.g. the Emulator's simplified estuary form, most models' lack of wave processes. In such circumstances, the confidence levels for specific outputs should be applied when synthesising the results. For example, the Emulator is not suited to assessing changes in intertidal area. The Hybrid-Regime approach can predict a decrease in intertidal area with sea-level rise ('coastal squeeze'; perhaps too often predicted), an increase with increased tidal range, and usually a small decrease in intertidal area with increased river flow; to maintain its regime state the estuary widens and deepens to accommodate the additional flow resulting in the loss of intertidal area. ASMITA also provides intuitively correct results (loss of intertidal area if infill lags accelerated sea level rise). Of these three, ASMITA was the only model able to reproduce the current trend of increase in Thames intertidal area for present MSL rise ~ 2mm/yr. Annex D *Intercomparison of models predicting estuarine morphology* has more detail about the respective characteristics and merits of models.

## 7. Conclusions

LW volumes and areas invariably increase for raised MSL, as for the most part do HW volumes and areas, but less so. Accordingly, intertidal area decreases in the Hybrid Regime model, in all five estuaries where it was run (Thames, Blackwater, Humber, Mersey, Southampton Water; over the whole 50 years); the Blackwater decrease is large. ASMITA predicted a smaller loss of Thames intertidal area. For the present rate of sea level rise, both HTA and ASMITA predicted an increase in Thames intertidal area.

Hybrid-Regime results do not suggest infill keeping pace with sea-level rise, except for the Mersey, where scope for infill is known historically and the “2.5-D” model and Emulator predict a relatively short infill time. ASMITA predicts that the Thames Estuary will attain a new dynamic equilibrium on a comparable time scale.

Likely effects of realistic changes in tidal range (e.g. +2 per cent) are relatively modest. A 20 per cent increase in river flow gives only O(2 per cent) changes in LW and HW areas and volumes in the Hybrid Regime model, but the Mersey and Blackwater lose substantial intertidal area. [The Emulator predicts much greater increases in areas and volumes].

Estimated flushing times relating to river flow and saline intrusion length are between six days and three weeks. Estimated infill times range from 182 years (Mersey) to 765 years (Southampton Water); most suggest enough sediment input for the morphology to keep up with sea-level rise; however, estuarine dynamics typically determine otherwise, as above.

Best practice when attempting to predict long-term changes in estuaries is to validate models against historic change. Successful validation gives some confidence that a model predicts the key processes controlling morphological change, despite uncertainty inherent in model predictions. Care is required when interpreting results from any one model. Inherent unpredictability in bed-morphology, and limitations of routines updating the bed, can produce questionable results. Model results should be compared with alternative techniques, to help establish the validity of predicted morphologies. If validation data are lacking, generation of an ensemble of possible outcomes is likely to become best practice for such predictions. Importantly, predicted morphological trends should be consistent (in a broad sense) with the results of bottom-up models.

The results provided show the sensitivities of different estuaries to a range of climate change scenarios, and that not all estuaries can be expected to respond in the same manner.

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