HRPP 331

Application and inter-comparison of estuary morphological models

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Reproduced from a paper presented at
42nd Defra Flood and Coastal Management Conference
University of York
3rd to 5th July 2007

APPLICATION AND INTER-COMPARISON OF ESTUARY MORPHOLOGICAL MODELS

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Key Words: Estuary, Morphology, Model

Abstract

The Defra/EA project FD2107 has involved the development of hybrid estuary morphological 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 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. The development and initial application of a hybrid regime model, carried out as part of the FD2107 project, is described in more detail by Wright and Townend (2006).

This paper expands on the earlier work and presents the results of applying regime-based models to a wider range of UK estuaries (Humber, Blackwater, Thames, Southampton Water and Mersey) for a range of possible future climate scenarios. The reliability of the model predictions of future morphology is a key issue that has also been assessed as part of the investigation through the inter-comparison of alternative modelling approaches (eg. hybrid, bottom-up and top-down).

Further demonstration of the proposed approach is provided through the application of standard hydrodynamic techniques using the predicted future estuary morphologies. The potential change in future flood risk within the selected estuaries can thus be evaluated. Through this approach it is has also been possible to assess the relative sensitivity of the estuaries to climate change and furthermore to identify regions within individual estuaries which are likely to be most at risk from future flooding.

Summary

Hybrid modelling techniques provide a useful means for the prediction of future change in our estuaries but care is required when applying such methods in isolation. The concept of generating an ensemble of possible outcomes is likely to become an established part of best practice when attempting to predict long-term changes within our estuaries.

At this stage the results provided based on regime theory should be interpreted with caution since the bed updating algorithms and assumptions of sediment availability are subject to ongoing development which may lead to improved accuracy of such predictions. The results are thus provided as a demonstration of techniques that are currently under development, to be made available to practitioners on completion of the research studies.

The results provided show the sensitivities of different estuaries to a range of climate

change scenarios and show that not all estuaries can be expected to respond in the same manner. It is acknowledged that care is required in the interpretation of results from any individual model. As in the case of the regime model applied to the Blackwater Estuary, the unusual form of the estuary and limitations of the bed-updating routines can produce questionable results. For this reason model results should ideally be compared with alternative techniques, such as the analytical emulator, to help establish the validity of predicted future morphologies.

A further key finding is the indication that applying a fixed bed model for the assessment of future flood risk in the Humber Estuary can potentially lead to an over-prediction of future flood levels.

Introduction

Over the next 50 years Global Climate Change (GCC) is expected to significantly affect mean sea levels, storminess and river flows, which will inevitably impact on future flood risk. Modified flood probabilities can be readily calculated by incorporating the various 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’ (Prandle, 2005).

FD2107 involves the development and application of top-down, bottom-up, hybrid, inverse and analytical models. The overall objective is to provide ensemble outputs, indicating the range of likely outcomes of morphologies and associated flood risks. Subsequent assessment against observational data sets will help translate possibilities to probabilities. The project covers a range of UK estuaries, although comparisons are limited here to a selection including the Thames, Mersey and Humber

Methods

Regime Modelling

A regime model predicts how the estuary will respond to a perturbation in order to return to a ‘regime’ state. For this to be possible it is necessary to assume that the current estuary geometry is in a stable, or regime form. The existing regime is defined in terms of a power law relationship between the maximum discharge during the tidal cycle and the cross sectional area. Discharge information is obtained from a 1D hydrodynamic tidal flow model. A typical representation of an estuary in the 1D model applied to the Humber Estuary is provided in Figure 1.

In essence, regime theory relates discharge, cross-sectional area, width and the mean hydraulic depth. Calculating the relationship between these parameters for the initial conditions and then re-applying the relationships after a perturbation form the basis of how a new morphological geometry is obtained. Technical details of the morphological updating routines, for example, are provided in earlier work (Wright & Townend, 2006).

Analytical Emulator

The Analytical Emulator (AE) is largely based on the simplification of the one-dimensional equation of axial momentum propagation (Prandle, 2006), and has recently been used to partly explain how estuarine bathymetries have developed in response to tidal and riverine inputs (Prandle et al. (2006)). A number of general rule-based morphological explicit expressions were derived by Prandle (2004) which included a description of estuarine depth in terms of the river flow and channel side slope. A version modified by Manning (2007a) allowed time-averaged river flow (Q_{f_mean}) input values to estimate the average estuary depths (D_{mean_AE}):

$$D_{mean\_AE} = 12.8\ (Q_{f\_mean} * a_{mean})^{0.4} * M$$

In order to apply the analytical emulator for the Work Package 2.7 (WP2.7) aspects of FD2107, which dealt with: “Intercomparison and evaluation of model predictions for 2050 morphologies," AE baseline conditions were acquired from the newly enhanced Future-Coast database of UK estuaries (Manning, 2007b). A mean estuary depth (D_{mean_data}) was computed for a specific estuary and this value was compared with the AE derived value (D_{mean_AE}). Also a mean side slope (a_{mean}) was estimated from the database. The difference between the two depth values was applied to the D_{mean_AE} baseline, to provide a good starting position and from this the calibration scaling coefficient M could be determined. D_{mean_AE} is equivalent to a mean sea level (MSL) datum. The AE computations assumed the estuary cross-section was triangular, and input values of estuary length (L) and a_{mean} were provided by the database. This allowed the AE equations for W_{mean_AE} and D_{mean_AE}, and associated channel bathymetry, to be solved to a reasonable degree of accuracy (i.e. at a 95% level of statistical confidence).

Test Conditions

A key stage within the FD2107 project has involved the inter-comparison of model predictions in terms of predicted morphologies for 2050. As part of this inter-comparison work, a range of test conditions was applied leading to an ensemble of model results which were then used to assess the sensitivities of morphological predictions for the various techniques applied. The tests conditions considered here are summarised below:

- 0.3m increase in mean sea level (6mm/yr)
- 1.0m increase in mean sea level (20mm/yr)
- 2% increase in tidal range
- 20% increase in river discharge

These conditions were defined prior to issue of the latest government guidelines (Defra, 2006). A more extensive range of test conditions has been considered within the study including, for example, storage areas to represent managed realignment within the estuary. However, a limited range of test conditions is presented here which can be accommodated by both the AE and regime approaches.

Regime Model Application

The key characteristics of the estuaries considered here are provided in Table 1. Note that the absence of saltmarsh for the Thames Estuary is due to the location of the seaward boundary which does not include the areas of saltmarsh along the North Kent and Essex coastlines of the outer estuary.

Table 1 Physical characteristics of selected estuaries (source: Future-Coast database)

Estuary	Area (ha)	Area of intertidal (ha)	Area of marsh (ha)	Shore length (km)	Channel length (km)	Tidal range (m)	Mean river flow (m^3/s)	Max. river flow (m^3/s)	Width at mouth (m)
Humber	64800	45500	1419	675.5	144.7	6.0	233.74	1683.6	7500
Thames	20000	13510	-	232.0	82.5	6.5	92.49	572.7	2100
Mersey	18600	11810	847	102.9	15.6	8.9	67.11	717.8	1525
Soton Water	3975	1376	355	109.8	20.2	4.0	18.10	34.9	1980
Blackwater	4830	2780	1103	107.5	21.2	4.6	3.76	49.9	2850

For the assessment of potential future morphological change within the selected estuaries, the predicted percentage change in intertidal area is considered in each case. It should be noted that the rates of habitat loss provided have been calculated using a spatially varying water surface and a dynamic estuary morphology. As a consequence it may not be appropriate to make direct comparisons with previous estimates obtained using alternative methodologies.

Scenario 1 - 6mm/yr sea-level rise

Figure 2 shows how the Humber and Thames estuaries respond in a similar manner to sea-level rise with a consistent rate of loss in intertidal area of less than 0.1% per year. Intertidal areas within the Mersey Estuary are predicted to increase over an initial period of 35 years since this can be accommodated within the form of the estuary. However, by 2050 there is predicted to be a small net loss of intertidal area. Southampton Water also shows an initial trend of increasing intertidal area although the capacity of the estuary is exceeded after 2025 leading to a small net loss by 2050. The response of the Blackwater Estuary is quite different from the other estuaries as it appears to experience a consistently higher rate of intertidal loss, in excess of 0.15% per year, over the initial period of 45 years followed by a rapid increase over the next 5 years. Care is required in the interpretation of these findings and the response of the Blackwater could be due to the unusual form of the estuary and limitations of the morphological updating routines used in the current version of the regime model as applied here.

Scenario 2 – 20mm/yr sea-level rise

In Figure 3, the higher rate of sea-level rise shows broadly the same trends in intertidal response as found with the lower rate of sea-level rise. Over the 50 year period considered, this exaggerated rate of sea- level rise is predicted to result in intertidal losses of between 7-17% for four out of the five estuaries. However, the Blackwater is an exception to this general trend involving a much greater extent of intertidal loss of up to 35% over the 50 years. From this assessment it would therefore appear that the Blackwater is particularly sensitive to accelerated rates of sea-level rise.

Scenario 3 – 2% increase in tidal range

For most of the estuaries there is limited response in terms of intertidal change as a result of the moderate increase in tidal range, as shown in Figure 4. The exceptions are Southampton Water which over a 50 year period is predicted to have a net gain in intertidal area of almost 4%. The high rates of predicted gain in intertidal area which peaks in 2025 appears to be a related to the position of relatively shallow bed slopes relative to the modified tidal frame. Conversely, the Thames Estuary is predicted to loose 5% of intertidal area over the 50 year period.

Scenario 4 – 20% increase in river flow

Figure 5 shows that the Humber and Thames estuaries are least sensitive to a change in river flow, probably because these are larger estuaries and frequently experience a high degree of variability in river inflow. The Mersey is predicted to experience a loss in intertidal area with increased river flow. Once again the Blackwater appears to be particularly sensitive to future changes in environmental conditions although after an initial period of intertidal loss, in the longer term there is predicted to be a net gain in intertidal area of 0.6% over the 50 year period.

Emulator Application

Baseline conditions

A mean tidal range (midway between spring and neap tides) was used for the main modelling scenario comparison and analysis undertaken for the Mersey, Humber and Thames estuaries. A summary of the database and AE derived values are listed in Table 2. The AE baseline bathymetry for the Mersey Estuary was 1.11 x 10^9 m^3 at high water, with a tidal prism of 1 x 10^9 m^3. This corresponded to W_{mean_AE} and D_{mean_AE} of 8138 m and 7.5 m, respectively. The area at

HW was 19,400 Ha, of which 69% reverted to intertidal flats at LW.

Demonstrating an AE baseline high water volume of 2.5 x 10^9 m^3, the 144.7 km long Humber Estuary HW bathymetry was more than double that of the Mersey, which was nearly an order of magnitude shorter in length (L_{Mersey} = 15.6 km). The AE estimated Humber W_{mean_AE} of 2.9 km and D_{mean_AE} of 5.5 m, resulted in a mean tidal range prism volume of 2.2 x 10^9 m^3. The longer Humber Estuary displayed a high water surface area of 61,811 Ha, three times that of the Mersey. At low water, 36% was still inundated (i.e. 64% was intertidal), a decrease of 5% from the Mersey.

With an overall tidal channel length of 82.5 km, the Thames Estuary falls midway between the longer Humber and shorter Mersey. The analytical emulator computed a D_{mean_AE} of 6.4 m which was also midway between the other two estuaries under consideration, but a significantly narrower estuary-mean channel width of just 1600 m. The AE baseline high water volume for the Thames was 9 x 10^8 m^3, with a tidal prism of 1 x 10^9 m^3. This HW volume was just 19% smaller than Mersey, but a factor of three smaller than Humber. The Thames HW area of 19,325 Ha was very similar to the Mersey, but at just a 63% coverage, had a similar intertidal region to that of the Humber.

Table 2 AE input parameters and results for the Mersey, Humber and Thames estuaries

Estuary	Scenarios	Mean channel side slope (a_{mean}) From *Database*	Channel length (km) From *Database*	D_{mean_AE} (m)	W_{mean_AE} (m)	Area of intertidal at HW (Ha)	Channel area at HW (Ha)	Channel volume at HW (m^3)	Channel volume at LW (m^3)	Volume of tidal prism (m^3)	mean suspended particulate concentration (mg/l)	Flushing Time (days)	In-filling (years)
Mersey	*Baseline*	0.002	15.6	7.5	8138	19396	13401	1.11E+09	1.06E+08	1.00E+09	164	7.5	182
Humber	*Baseline*	0.004	144.7	5.5	2906	61811	39523	2.51E+09	3.27E+08	2.19E+09	112	6.3	223
Thames	*Baseline*	0.008	82.5	6.4	1605	19325	12159	8.98E+08	1.24E+08	7.75E+08	127	7.0	218
Mersey	*MSL +0.30m*	0.002	15.6	7.8	8464	19905	13401	1.17E+09	1.25E+08	1.04E+09	164	7.8	189
Humber	*MSL +0.30m*	0.004	144.7	5.8	3064	64091	39523	2.70E+09	3.97E+08	2.31E+09	112	6.6	236
Thames	*MSL +0.30m*	0.008	82.5	6.7	1681	19948	12159	9.57E+08	1.46E+08	8.11E+08	127	7.3	228
Mersey	*MSL +1m*	0.002	15.6	8.5	9225	21092	13401	1.31E+09	1.74E+08	1.14E+09	164	8.5	206
Humber	*MSL +1m*	0.004	144.7	6.5	3431	69412	39523	3.17E+09	5.88E+08	2.58E+09	112	7.4	264
Thames	*MSL +1m*	0.008	82.5	7.4	1857	21403	12159	1.10E+09	2.06E+08	8.96E+08	127	8.1	252
Mersey	*50 yr extreme*	0.002	15.6	11	11978	25520	13669	1.92E+09	4.14E+08	1.51E+09	166	11.0	263
Humber	*50 yr extreme*	0.004	144.7	9	4731	88610	40313	5.17E+09	1.53E+09	3.63E+09	114	10.2	357
Thames	*50 yr extreme*	0.008	82.5	10.3	2584	27523	12402	1.82E+09	5.50E+08	1.27E+09	129	11.2	344

Emulator Results

The analytical emulator found that a 30 cm rise in MSL produced an 18.2% increase in the LW volume of the Thames Estuary, but just a 4.7% growth in the tidal prism. The shorter, but deeper Mersey saw the LW volume rise by 17.7%, with a 0.7% lesser increase in the prism than the Thames.

On raising the baseline MSL by a full 1m, the Mersey prism grew by a further 9.4%, whilst the LW volume was now 69% larger than the baseline value; this compared to a 66.4% rise for the Thames. The comparative Thames tidal prism rose by 15.7% from the baseline, which was still a larger relative increase than experienced by the Mersey.

The significantly longer Humber produced a 21.5% increase in the LW volume and a 5.4% growth in the tidal prism, in response to imposing a 30 cm rise in MSL. The additional 0.7m rise in MSL saw the Humber Estuary prism grow by a further 12.7%, whilst the LW volume was now 80% larger than the baseline value. For each MSL scenario, the Humber Estuary produced higher relative percentage increases in bathymetry than the Mersey and Thames.

The analytical emulator derived flushing time (FT) for the Mersey was 7.5 days for the baseline conditions, rising to 11 days for the extreme conditions scenario (i.e. 1 m rise in MSL, together with a 0.2 m net isostatic & eustatic MSL increase over 50 years, a 20% rise in river flow, plus the addition of the 50 year storm surge). The Thames demonstrated a 12 hour quicker baseline flushing times, but was similar to the Mersey during extreme conditions. With a baseline flushing time of 6.3 days, rising to 10.2 days for the extreme conditions, the Humber displayed faster flushing times during each scenario. Prandle et al. (2005) indicates that flushing times greater than the 15-day spring-neap cycle provide valuable longer-term persistence of marine-derived nutrients. Whereas FT values less than the principal semi-diurnal tidal period yield effective flushing of contaminants. The Mersey Estuary falls within the latter classification.

The analytical emulator initially estimated the time- and depth-averaged suspended particulate matter (SPM) concentration as 164 mg l^{-1} for the Mersey Estuary. This was 37 mg l^{-1} and 52 mg l^{-1} more turbid than the Thames and Humber Estuaries, respectively. By applying both the mean SPM and FT outputs, the analytical emulator could estimate minimum in-filling times (IFT) for an estuary (Prandle, 2004). These baseline in-filling durations extended from 182 years for the Mersey, through to about 220 years for the Thames and Humber. Generally the analytical emulator showed that IFT increased in response to rising MSL, and shortened when an estuarine system was subjected to a rise in Q_{f_mean}. For the extreme conditions scenario, the Mersey IFT would be extended by 80 years (+44%), whilst the longer Thames and Humber Estuaries would potentially see an increase in IFT of 126 years (58%) and 134 years (60%), respectively.

Model Inter-Comparison

The previous sections have described two alternative morphological predictions tools which are founded on very different concepts. Both are important for development of an ensemble of possible future scenarios. Where the models are in agreement, this provides a high level of confidence in results. Differences under particular test conditions can often be explained by model limitations as in the simplified representation of estuary form in the AE or the absence of wave processes in the case of the regime model. In such circumstances, the confidence levels for specific outputs should be applied during the process of synthesising the results. Results from such intercomparisons for Southampton Water are presented here for a combination of metrics and scenarios.

Metric 1 – Area at High Water

Figure 6 shows how results from the AE and regime approaches compare for a range of scenarios. There is a high degree of similarity between the predicted changes for the sea-level rise and tidal range scenarios but a significant difference is found with the increased freshwater flow condition for which the AE appears to be particularly sensitive whilst the regime model predicts a loss in intertidal area. The most probable explanation for this is that the regime model is more responsive than the AE, in terms of morphological change, to variations in river flow.

Metric 2 – Area at Low Water

The variation in low water for a range of scenarios is provided in Figure 7. Again both models predict similar degrees of change in most cases. As would be expected, the area at low water with sea level rise is increased but decreased with an increase in tidal range. Once again the AE suggests an increase in area at low water of a similar magnitude to the predicted increase in area at high water.

Metric 3 – Intertidal Area

The net change resulting from the predicted changes in area at high and low water provides the change in intertidal area in Figure 8. The only scenario under which the AE predicts a change in intertidal area is the increased tidal range. The reason for this is that the AE assumes a triangular representation of the estuary cross-section and therefore an offset in water level due to sea-level rise results in the same plan area change around low water as at high water resulting in no net change. The AE is therefore not suited to assessing changes in intertidal area under such conditions. The regime approach however provides intuitively correct results with a decrease in intertidal with sea-level rise, as a result of 'coastal squeeze' and an increase in area with increased tidal range. The regime approach also predicts a small decrease in intertidal area with increased river flow. To maintain its regime state the estuary has had to widen and deepen to accommodate the additional flow resulting in the loss of intertidal area.

Alternative Approaches

Within the FD2107 project, a range of other bottom-up (B-U) and top-down (T-D) approaches have been developed and applied, including inverse modelling and advanced Lagrangian particle-tracking approaches. In this context the term 'bottom-up' refers to processed-based models and 'top-down' to regime or equilibrium based approaches. In seeking to bridge the temporal and conceptual gaps between models and observations relationships between tidal energetics-sediment mobility, residual patterns of erosion and deposition-bathymetric evolution have also been explored. The inverse modelling approach seeks to derive insight into these relationships by examining how B-U model simulations need to be modified to reproduce observations. A limitation of the inverse modelling approach is the requirement for high-resolution spatial (100m or less) and temporal (5yr intervals or less) bathymetric datasets. The inverse method may not be able to predict the response of estuary morphology to future intervention but provides an alternative means of predicting future evolutionary trends that can be expected without such intervention. In this context intervention refers primarily to anthropogenic influence such as dredging activities, reclamation, flood defences and managed realignment.

Future Flood Risk

As previously stated, one of the main aims of the work carried out under FD2107 is to provide a better understanding of future flood risk which is likely to vary between estuaries. An example of the change in future flood risk is provided here for the Humber Estuary. The example compares predicted water levels along the estuary for existing conditions and for 2050 assuming initially a fixed estuary morphology followed by a further assessment which accounts for predicted changes in estuary morphology over a 50 year period. From the results presented in Figure 9 it is apparent that assuming a static bathymetry results in an over-prediction of peak water levels relative to 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 finding was also found previously in the Severn Estuary (Wright & Townend, 2006).

Acknowledgements

The authors would like to acknowledge the contribution from co-workers within the FD2107 project, in particular David Prandle, who originally developed the Analytical Emulator, as well as Adrian Wright and Richard Swift who have been instrumental in developing the hybrid regime model.

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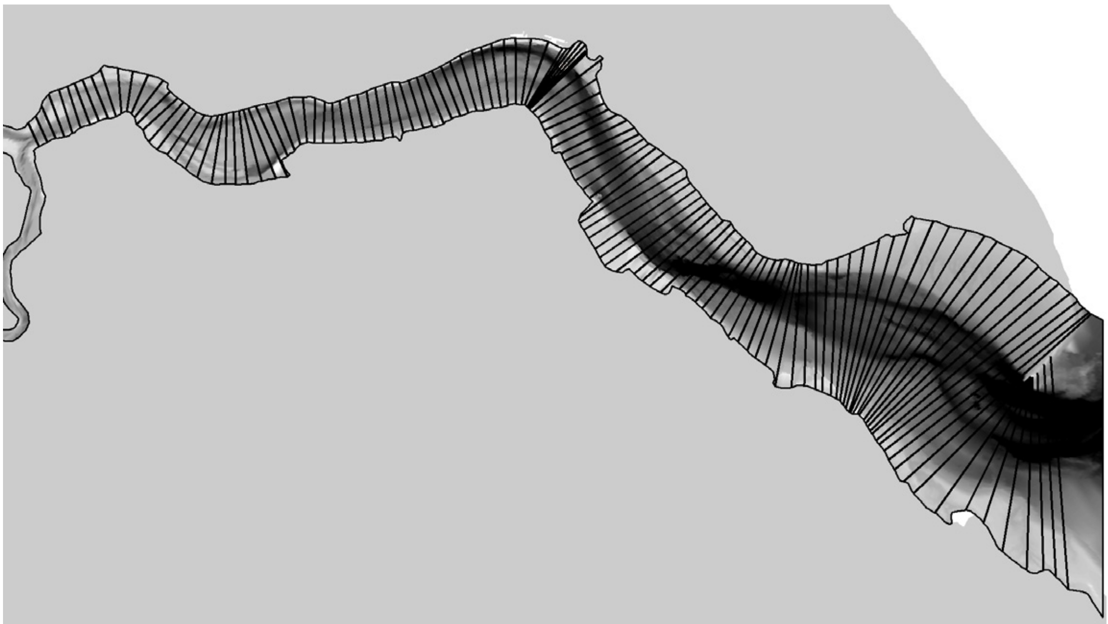

Figure 1 1D model representation of the Humber Estuary

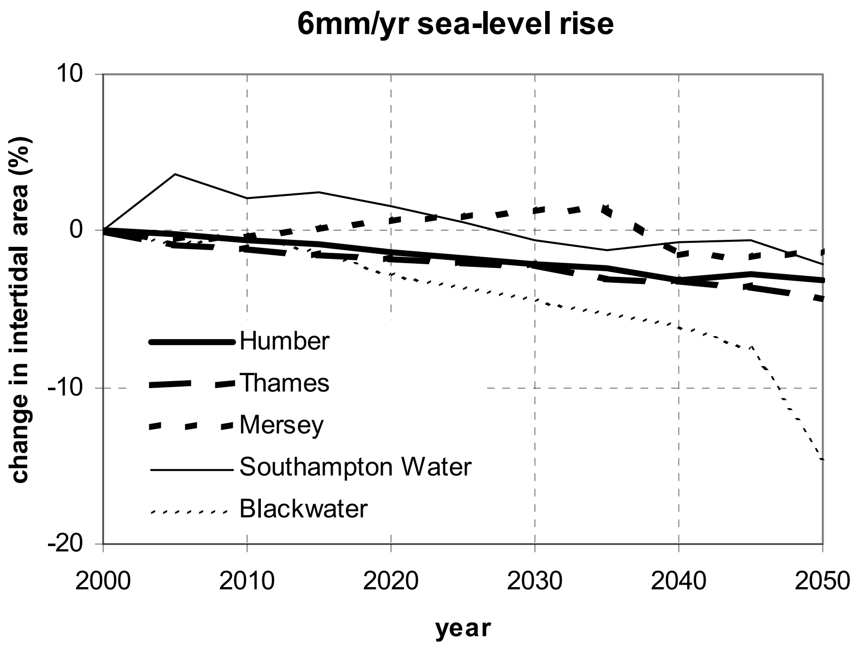

Figure 2 Change in intertidal area with 6mm/yr sea-level rise

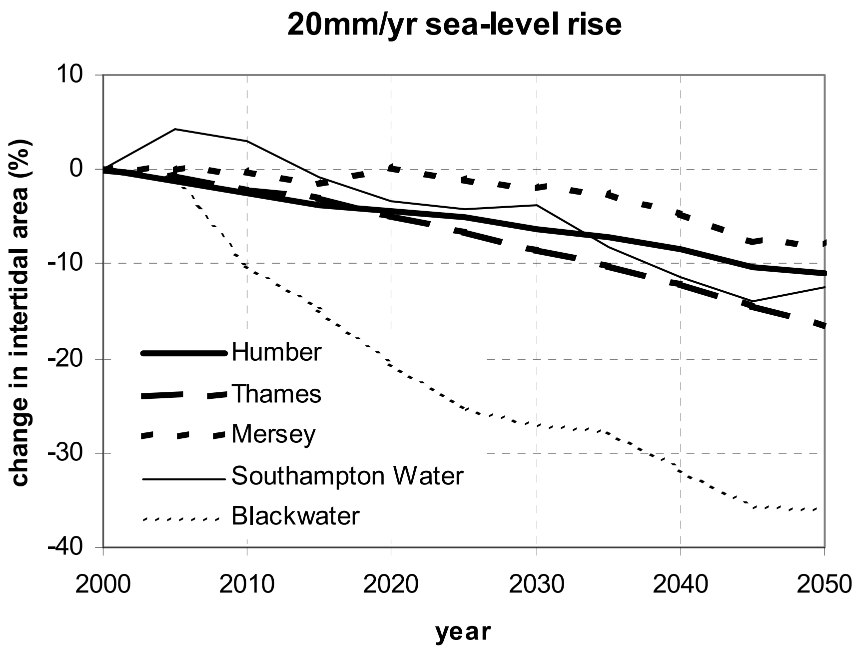

Figure 3 Change in intertidal area with 20mm/yr sea-level rise

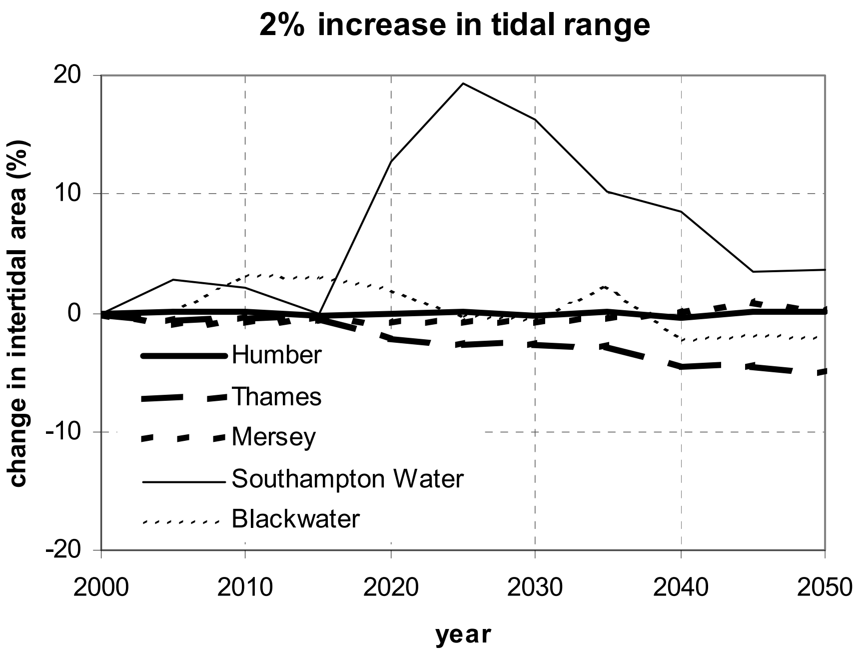

Figure 4 Change in intertidal area with 2% increase in tidal range

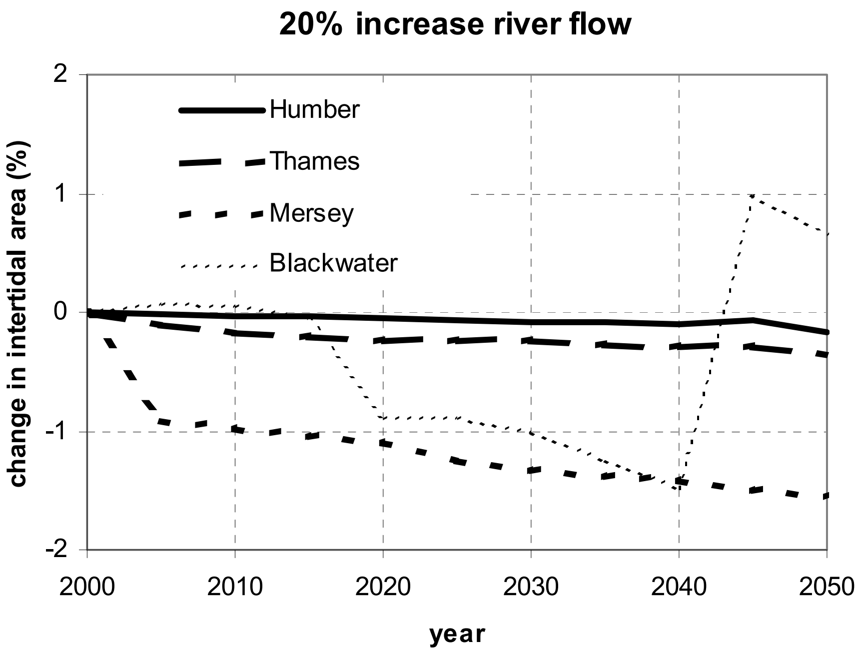

Figure 5 Change in intertidal area with 20% increase in river flow

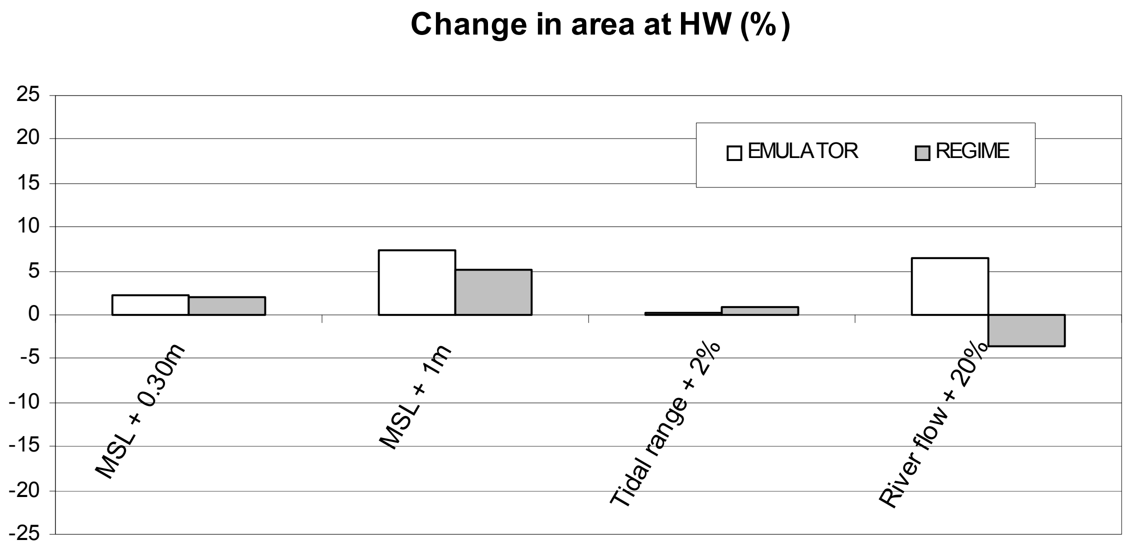

Figure 6 Change in area at high water for Southampton Water (2000 to 2050)

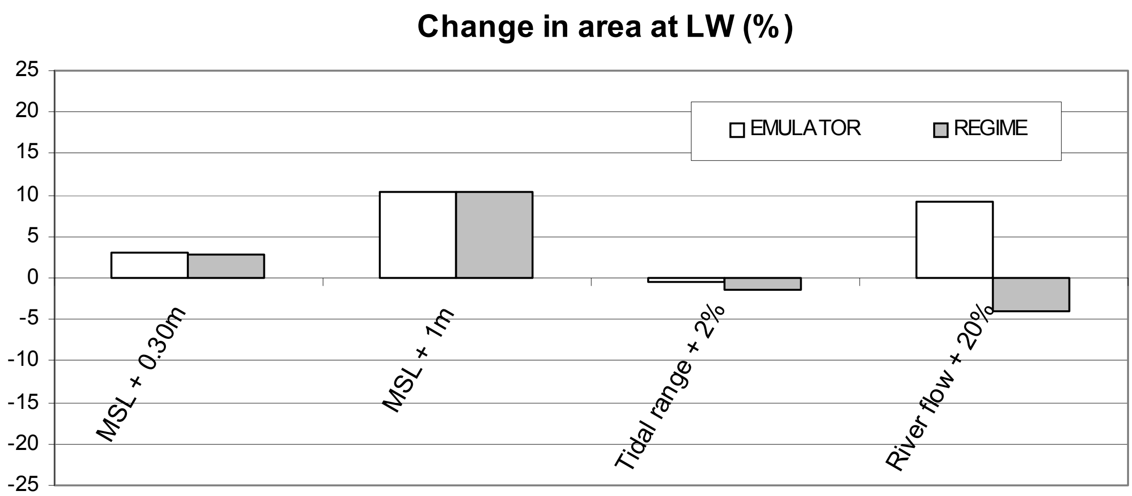

Figure 7 Change in area at low water for Southampton Water (2000 to 2050)

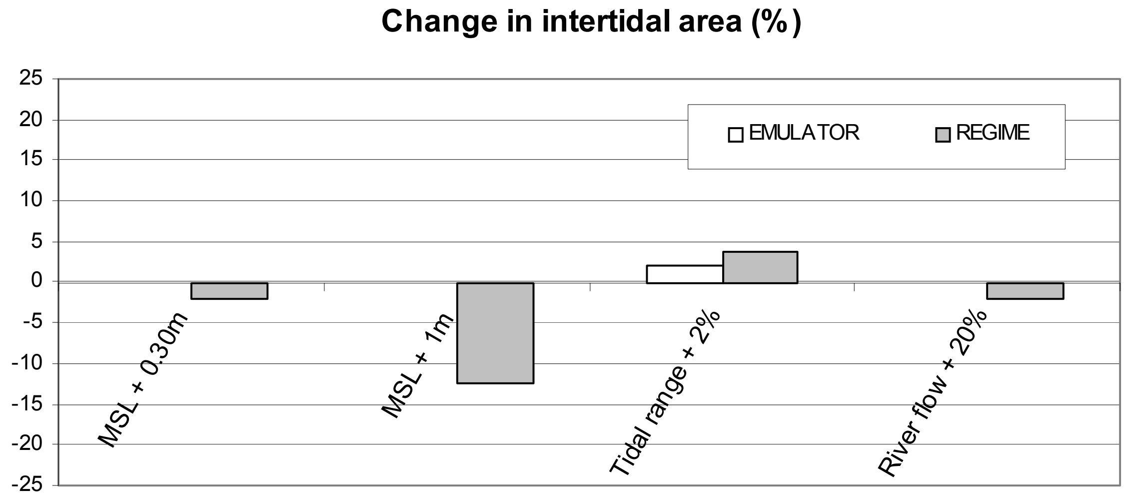

Figure 8 Change in intertidal area for Southampton Water (2000 to 2050)

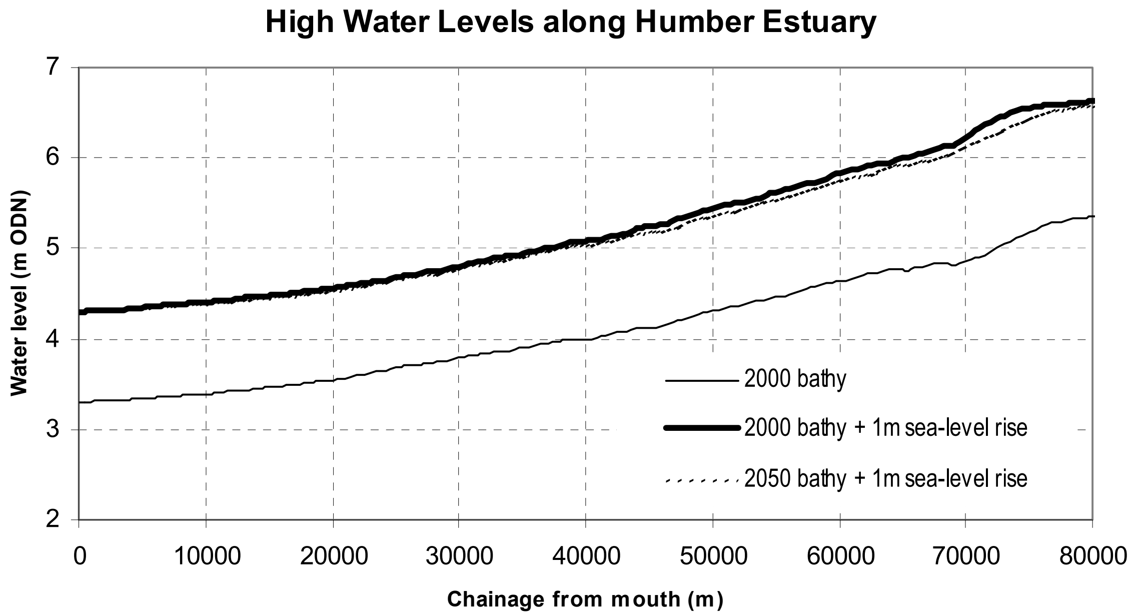

Figure 9 High water levels along the Humber Estuary

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