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PREDICTING INTERTIDAL CHANGE IN ESTUARIES

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Key Words
Regime theory, hybrid modelling, morphological updating, numerical model, sea level rise

Abstract
There is an increasing need to better predict possible future morphological behaviour of estuaries, over timescales of decades to centuries to improve and support the development of sustainable shoreline management polices. Whist models to examine short-term, site specific, changes are well developed, the ability to make predictions over time-scales of 10-100 years is less well advanced. Therefore, this has formed a primary focus of the Estuary Research Programme funded partly by DEFRA and the Environment Agency (EA). One approach to this problem entails combining the level of detail available from the well established hydrodynamic process based models (bottom-up methods), with some system goals, determined from various equilibrium relationships (often referred to as top-down methods). This hybrid modelling approach has recently been applied to good effect to support the SMP geomorphological studies on the Humber (Keiller & Young, 2005) and is currently being used as part of the assessment for the Severn Coastal Habitat Management Plan's (CHaMP).

The approach of hybrid models to these two estuaries, in conjunction with detailed analysis of the historic data, has revealed how much of the variation in intertidal area is due to the nodal tidal cycle (an 18.6 year cyclic variation in the tidal range). This means that a reduction in area over a 10-year period is part of a cycle that will restore the area during the next 10 years. Such changes must, however, be superimposed on the underlying response to sea level rise.

Introduction
This paper briefly describes the work undertaken for the Environment Agency as part of the Severn Coastal Habitat Management Plan (CHaMP) to draw out the management implications that follow from the predicted changes in estuary morphology following changes in mean sea level (msl). The objective of the study was to estimate the change in intertidal habitat over a period of 100 years. The study considered 4 representative years 2005 (baseline condition) 2025, 2055 and 2105. An increase of 6mm per year was used as the rate of sea level rise, based on the DEFRA and EA guidelines for the West Coast of the UK.

In addition to the increase in msl the effect of the lunar nodal cycle was superimposed. This 18.6 yearly nodal amplitude represents the alignment of the earth, moon and sun, during which time there is a change in the amplitude of the tidal range. For this study, the nodal amplitude was determined using long-term tidal records obtained at the port of Avonmouth. Analyses of the mean annual low waters and high waters clearly show this 18.6 yearly cycle. Figure 1 illustrates the change in tidal amplitude over 100 years within the Severn Estuary. Considering just the nodal cycle (i.e. ignoring sea level rise) results in a change in intertidal area for the Severn Estuary of approximately ±400ha based on the baseline 2005 elevations.

Values for the Humber estuary show a similar change in tidal range and variation in intertidal area.

The consideration of the nodal amplitude is an important aspect of long-term model predictions. For example, during certain phases of the nodal cycle the decrease in tidal range can be equal to the rate of sea level rise, therefore, during this phase of the nodal cycle there is very little increase in msl. The reverse is also true during the upward phase of the nodal cycle, making the effects of sea level rise more severe.

The Study Area

The Severn Estuary is the largest in the UK, it lies on the South West coast and it is notable for having an extremely large tidal range 12.2m over a mean spring tide. This investigation covers the areas from Minehead to the confluence at Minterworth, Figure 1 shows the extent of the 1D model and positions of the cross sections. The outer limit (mouth) of the estuary was chosen primarily by the natural shape and geology at that location.

The estuary supports a diverse and large number of wildlife and is designated under a number of directives including European Marine Site, Special Protection Area, Ramsar Site and so on. The area is of extreme importance and as such warrants consideration of the long-term effects of climate change. This is particularly true considering the extensive intertidal zone and the effects from coastal squeeze as a consequence of climate change.

Methods

In order to predict the new morphological shape of an estuary after a perturbation two approaches are typically adopted. The first makes use of a detailed 2/3-dimensional numerical modal investigation, often referred to as a 'bottom-up' approach. This approach requires the user to run a complex hydrodynamic model to simulate the tidal and sediment characteristics. Over short temporal and/or spatial scales this approach can provide answers on the effect of local perturbations. However, long-term (decadal) morphological changes require long simulation times and a good understanding of the sediment characteristics within the system, something which is often not well known. In addition, process based models have shown poor success in reproducing long-term changes in morphology extrapolating from short-term morphological predictions (D. Price and P. Norton, 2000) Investigations using morphological scale factors on the Humber estuary showed a poor fit to the observed changes (ABPmer 2000). This again, reinforces the notion that current morphological models do not reproduce the physics with sufficient accuracy capable of predicting long-term (10-100years) morphology.

The second approach involves using a 1D hydrodynamic model combined with empirical relationships that relate the hydrodynamics with the morphology of the estuary, this is referred to as 'Regime Theory'. Regime theory is a more simplistic approach to estimating change in estuary morphology without the physics associated with 2/3-dimensional bottom-up modelling. This "hybrid" (1D model coupled to empirical relationships) forms the basis of the results presented here.

A regime model predicts how the estuary will respond to a perturbation in order to return to a "regime" state. In most cases the assumption is made that the current estuary geometry is in a stable form or regime. 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 the 1D hydrodynamic tidal flow model.

In essence, regime theory relates discharge, cross-section area, width and the mean hydraulic depth. Calculating the relationship between these parameters for the initial conditions and then reapplying the relationships after a perturbation form the basis of how a new morphological geometry is obtained. Figure 3 illustrates the steps undertaken to establish the existing and new morphological shape.

'Shell' Interface

Under the Estuaries Research Program an initiative was setup to establish an interface between existing 1D models, and the empirical relationships needed within traditional and more current regime theory. This was termed the 'Shell' interface. The Shell allows the user to couple an existing hydrodynamic simulation with empirical regime relationships, without the need to export and interpret the hydrodynamic data. The advantage of such systems is that the difficult task of coupling modelling results with regime algorithms has been simplified and different hydrodynamic conditions can be rapidly tested.

The "Shell" interface represents a major step forward in providing a simple, easy to use and robust method to employ regime calculations. The code is written as a modular interface, which is designed to allow the addition of different modular components. Thus, additional algorithms can be simply added to the existing code. Currently, the interface has been developed to work using the DHI Mike11 software and the HR Wallingford Software InfoWorks.

Cross Section Updating

Cross-sections are adjusted to meet the new area required to satisfy the regime relationship. However, the adjustment of the section is only made below the maximum water level. In addition, the option is available to define fixed surfaces. This utility can be used to represent the influence of solid geology and structures, such as sea walls, bridge piers and so on. The adjustment routine limits where on a cross-section the erosion is allowed to take place. Figure 4 shows the adjustment made for a selected cross-section of the Severn Estuary.

The application of physical constraints is critical to determine the new morphological shape of the estuary. Without the application of physical constraints the cross-section top widths are widened under the influence of sea level rise, resulting in gains of intertidal area. In reality, physical constraints prevent some sections from widening, therefore, at these locations the section can only deepen to maintain the regime cross sectional area, providing of course, that this is not prevented by a physical constraint. In a case where the cross sectional area is required to increase to meet the regime condition but cannot widen, the section area must deepen if possible. As a consequence, there will be a loss of intertidal area. However, a section that increases in area and has no physical constraint may gain or lose intertidal area, depending on the aspect ratio of the section.

The section geometry is adjusted to the meet the requirements of the regime relationships but takes no account of any condition in flow across the section. It is noted that a further improvement in the adjustment routine would involve this consideration. Also, if sediment type was known, a further improvement would involve a threshold of motion based on the sediment erosion threshold. This could be applied either as a single representative value, or on a section-by-section basis.

Hydrodynamic Model Configuration

Figure 1 shows the configuration of the cross sections used in the hydrodynamic model of the Severn Estuary. The model consisted of 495 cross sections, intertidal coverage was obtained from high resolution LIDAR and NextMap data. Although no limitation is placed on the number of sections used, as a rule of thumb, the greater the number of sections the better the resolution of predicted intertidal change. Ultimately, the new cross-section geometries are converted to a x,y,z depth file. This file is interpolated onto a grid, so that an estimate of intertidal and subtidal habitat can be made, this provides the basis for examining the change between the years investigated.

The model boundary was derived from an existing ABPmer calibrated model. The model was calibrated against predicted and measured water level gauges along the estuary. Changes in the nodal tide were scaled from the predicted nodal cycle at Avonmouth and applied at the model water level boundary. A typical mean spring neap tidal period was chosen, the regime calculations were performed using a representative tidal sequence extracted from the hydrodynamic model.

Regime configuration

In order to make long-term predictions in the Severn Estuary particular attention was given to defining the physical constraint. This information was gathered from a number of sources including the National Flood and Coastal Defence Database, Ordinance Survey Data and the British Geological Society. The hydrodynamic model was run with the increase in msl and tidal amplitude.

At each iteration (not a time step) the convergence or the discharge at each section is checked. If the difference is less than 2% then it is assumed that no further changes need to be made and the cross-section is consistent with the preliminary forcing conditions. If the difference in discharge at a given section is greater than 2%, another iteration is required and the cross-section is adjusted according to the regime relationship. This iterative process is not a time step, therefore, provides no estimate of the time scales for the regime condition to be reached. Algorithms developed under the DEFRA/EA funded FD2106 contract are currently being investigated in order to address this issue.

Key Findings

The hybrid modelling exercise using regime theory established the following:

- The 2025 prediction showed a smaller then expected change in estuary geometry, the mean change in bed elevation was 0.1m, with a predicted loss of approximately 600ha. Figure 6 highlights the areas of intertidal change predicted using a 20-year water level boundary. The estuary did not significantly alter due to a number of reasons:
  - The phase in the nodal cycle represented by the year 2025 is at a low point with smaller amplitudes. This indicates that under a 2025 tidal condition only the upper reaches of the Severn Estuary are likely to experience change in estuary geometry.
  - The majority of sections met the 2% convergence criteria adopted for the regime analysis. Therefore, only small adjustments to the cross-section area were required
- The 2055 result showed a significant change in bed elevations throughout the estuary. The regime exercise predicted an average bed change of -0.21m. This represents a loss of approximately 1100 ha of intertidal area. Figure 7 illustrates the intertidal areas that have changed using a 50-year water level condition. The loss of area is due to a number of reasons:
  - An increase in msl of 0.3m
  - The physical constraints prevent the estuary from widening to meet the required regime. Therefore, the estuary deepens to meet the regime requirements.
- The 2105 simulation showed the greatest change in bed elevation throughout the Severn Estuary. The average elevation change was –0.32m and represents a loss of intertidal habitat of 2100 ha. This is approximately 10% of the total intertidal area for the whole estuary. Figure 8 shows the intertidal areas that have changed using a 100-year water level condition. The 2105 shows the greatest change because:
  - The nodal cycle was at a higher amplitude than seen during the other years of the investigation.
  - By 2105 msl has increased by 0.6m and this represents a significant change in the tidal prism. With a greater volume of water entering the system, the estuary volume will need to increase to maintain the regime relationship.

- The effects of the physical constraints are seen most significantly in the 2105 simulation. The cross-sections are unable to widen beyond the position of the physical constraints.

Conclusion

This study has shown how detailed regime analysis coupled with a 1D numerical model has improved our understanding of the likely change in the Severn Estuary morphology over the next 100-years. This study has provided an insight into the mechanisms required to predict likely changes over decades that can be performed in a relatively short space of time.

The regime shell tool developed under the Estuaries Research Programme, provides a mechanism to couple existing 1D numerical models with regime theory under a simple and easy to use interface. Initial investigations using the Humber and Severn Estuaries have demonstrated this to be an extremely effective tool. Initial comparisons with historical data and other methods of estimating long-term change (ASMITA) suggest that the predictions are of the correct order of magnitude, although, more work is needed to further validate this approach.

One of the most revealing aspects of this investigation is seen when comparing the influence of maximum water levels using a 100 year sea level rise with a baseline and predicted 2105 bathymetry.

Figure 5 shows how by not including the predicted change in morphology the water levels are some 30cm higher. This highlights the importance of such an approach when looking at other long-term environmental impact.

Management Implications

Although there may be some scepticism between researchers into the usefulness and accuracy of regime theory, it provides a tool which when used in combination with historical analysis and expert geological interpretation can provide useful insights into the possible outcomes of future changes such as sea level rise on environmentally sensitive areas.

References

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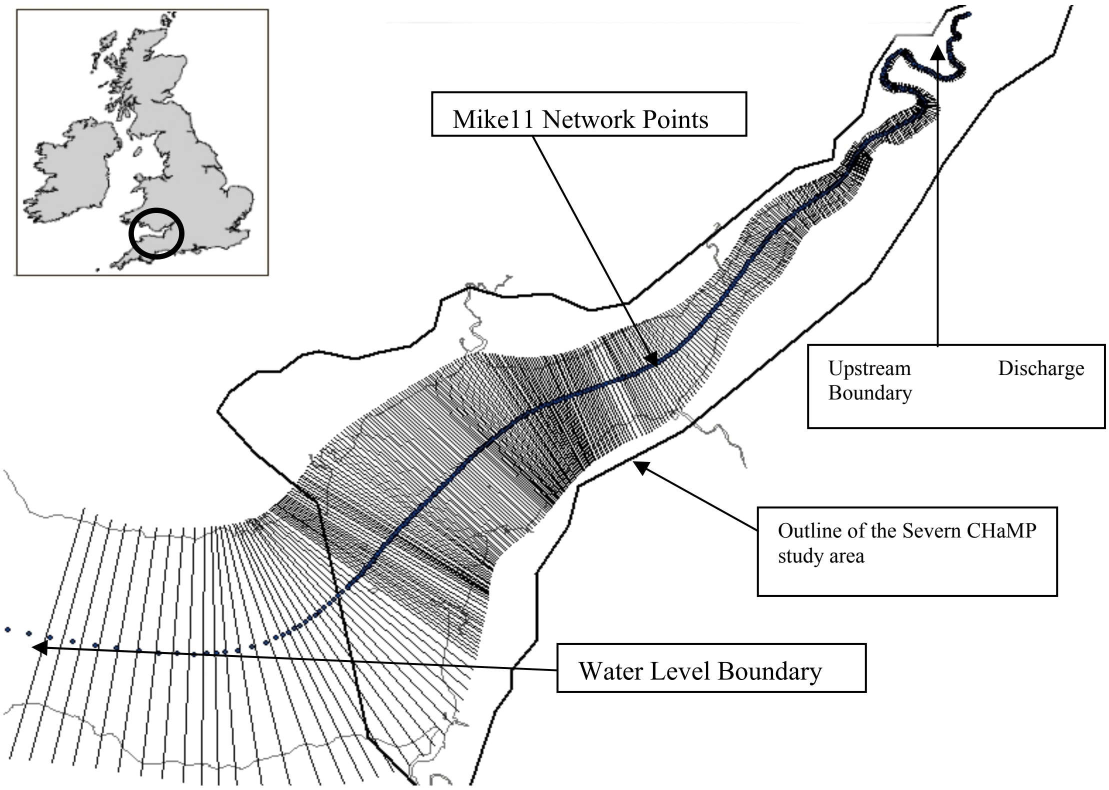

Figure 1 Location of the study area, also shown are the cross-section positions used in the 1D hydrodynamic model.

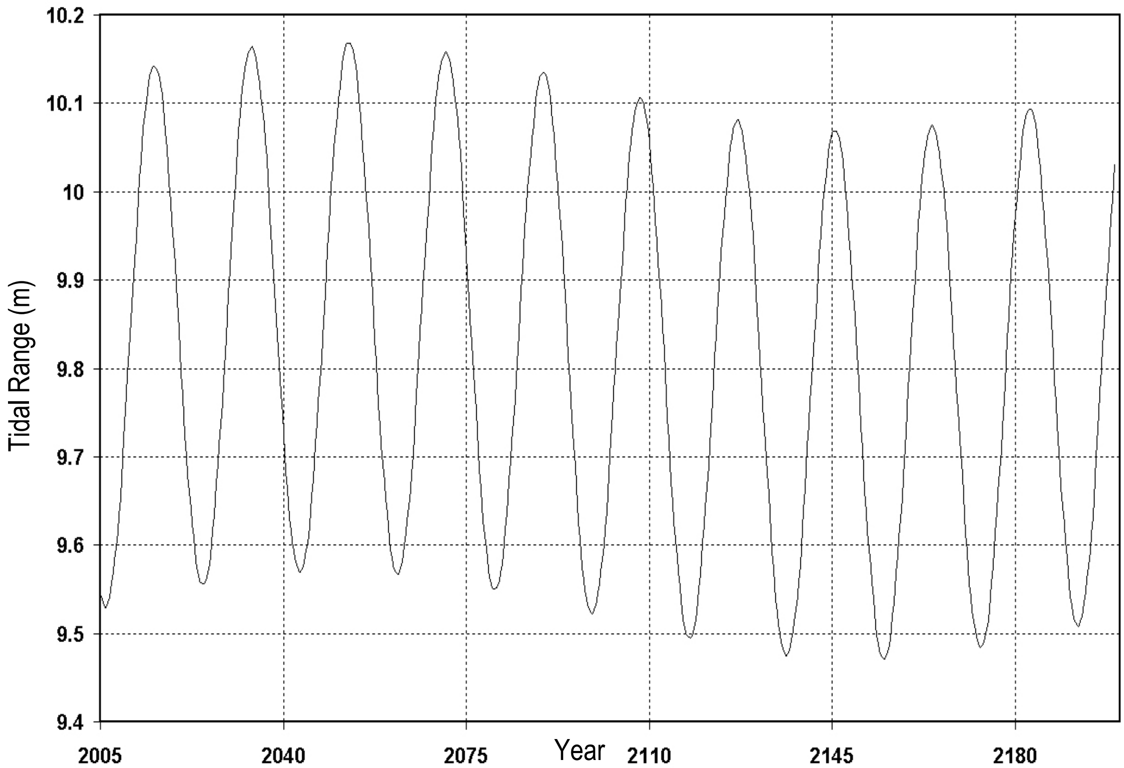

Figure 2 Change in tidal range due to the 18.6 yearly nodal cycle calculated at Avonmouth, Severn Estuary.

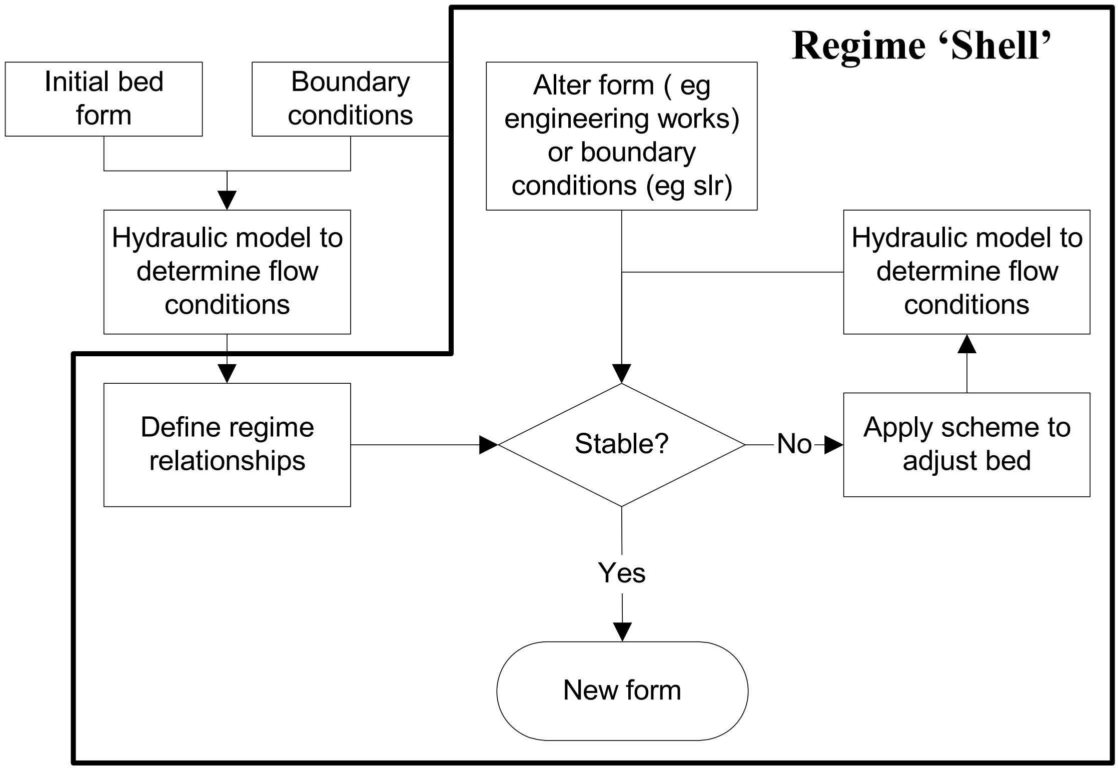

Figure 3 Flow diagram illustrating how the Shell interface couples the hydrodynamic model with the empirical regime relationships.

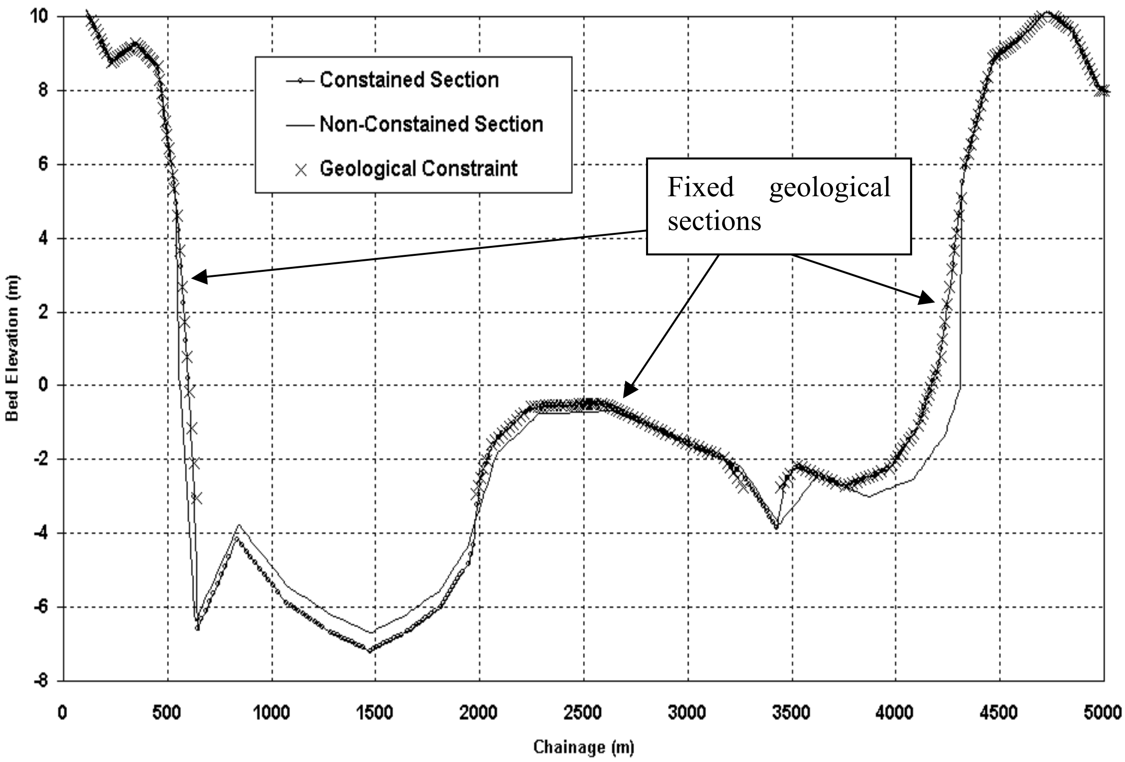

Figure 4 Example of the adjustment of a cross-section having met the required regime criteria. The section shape is significantly altered with the presence of physical constraints.

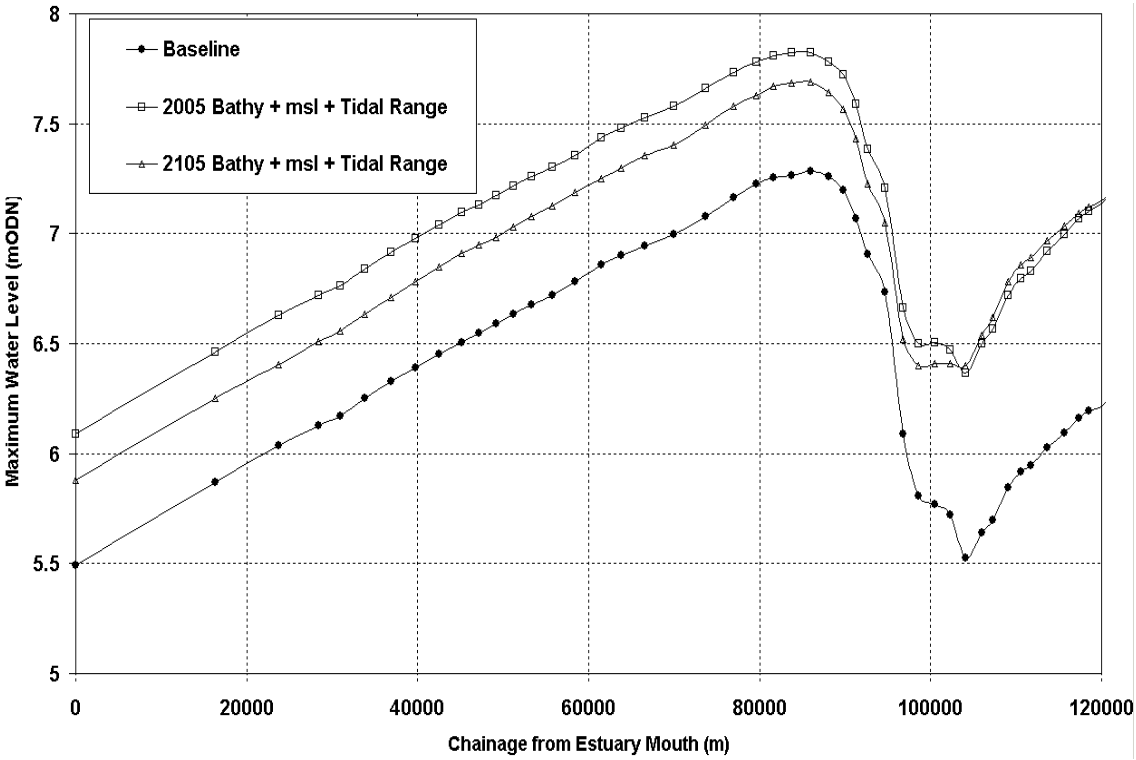

Figure 5 Change in maximum water levels along the Severn Estuary, the difference in water levels with and without the morphological adjustment is shown for the 2105-year water level using bathymetry from the 2005 and 2105 regime scenario.

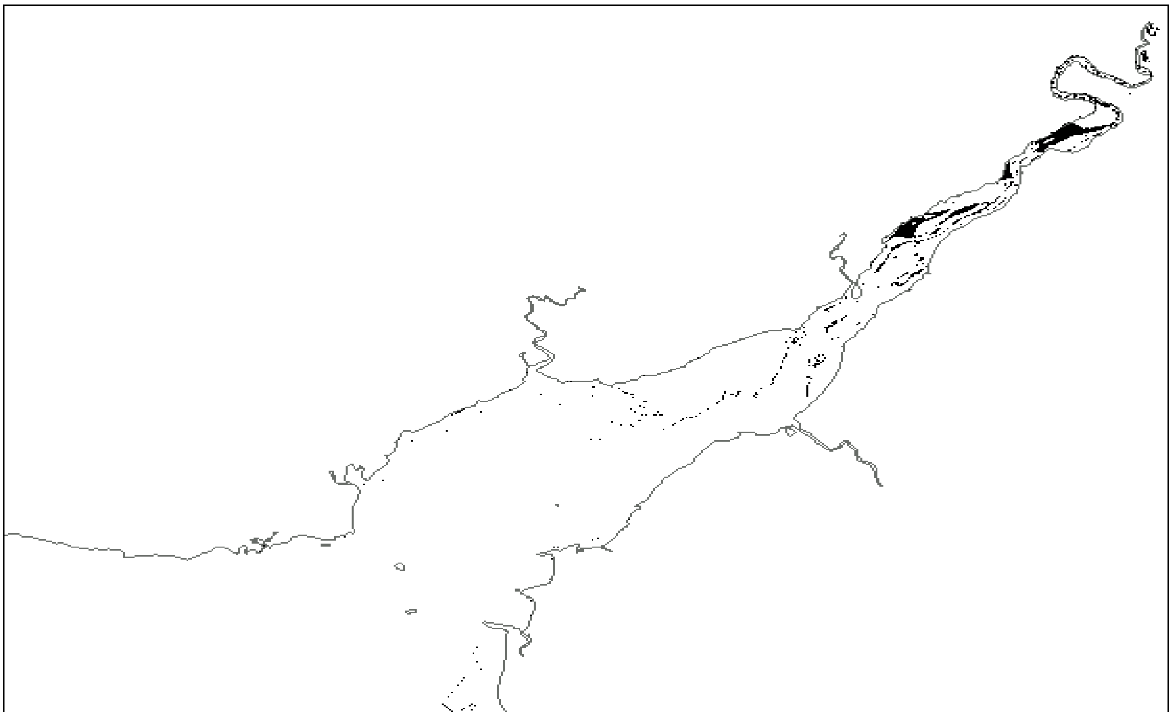

Figure 6 Predicted change in intertidal area using a 20-year water level condition. The areas in black indicate where there is a predicted loss of intertidal area.

Figure 7 Predicted change in intertidal area using a 50-year water level condition. The areas in black indicate where there is a predicted loss of intertidal area.

Figure 8 Predicted change in intertidal area using a 100-year water level condition. The areas in black indicate where there is a predicted loss of intertidal area.

NOTES

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