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Predicting long term estuary evolution using regime theory

Adrian Wright and Ian Townend

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PREDICTING LONG TERM ESTUARY EVOLUTION USING REGIME THEORY

Adrian Wright and Ian Townend

ABP Marine Environmental Research Ltd

Abstract

There is ever increasing pressure to better predict the possible future morphological evolution of estuaries over long time periods (decades to centuries), owing to a variety of commercial, social and environmental reasons and to inform the development of sustainable management policies. Due to the highly complex nature of estuaries, conventional 2 and 3 dimensional numerical models struggle to describe the large number of parameters needed to fully predict the morphological response to changing environmental conditions.

In order to address this requirement a hybrid modelling approach is proposed comprising of a 1-dimensional process based model to describe the detailed hydrodynamic conditions combined with a system goal 'Regime' morphological relationship. This hybrid modelling approach uses the tools developed under the current UK Estuaries Research Program Phase 2. To provide a flexible interface between hydrodynamics and such regime relationships, a program has been developed, referred to as the 'Shell' interface. This tool is then applied to the English Severn Estuary, predicting the 100year evolution following the addition of potential realignment sites and accounting for sea level rise.

Introduction

Our interest in the morphological evolution of estuaries stems from the need to predict and quantify the future impact of our present actions. There are also socio-economic drivers to predict the impact of sea level rise and changing climate. The use of numerical models to predict the likely estuarine response to sea level rise, engineering works etc, is now common. However, recent studies have shown that current morphological models struggle to accurately predict long-term changes in estuary morphology over periods of decades [5, 8]. In addition, complex 2 and 3-dimensional morphological modelling is often computationally inefficient and extremely difficult to parameterize, and this hinders the use of such models when looking at a large number of scenarios and sensitivities.

In order to predict the likely shape of future estuary geometry it is proposed that a regime approach be adopted. Regime theory assumes some form of equilibrium relationship between certain morphological parameters, such as width, or depth and hydraulic parameters such as hydraulic slope, discharge, or flow velocity. Where sufficient historic data are available, these relationships can be used to explore aspects of the estuary development over time [1, 2]. Increasingly, however, regime theory is being used in conjunction with hydrodynamic models to create a form of hybrid model that can iterate to an equilibrium state.

This paper sets out to describe the application of a hybrid regime model, looking at the issue of sea level rise in combination with the influence of potential managed realignment sites using the tools developed under the current UK Estuaries Research Program termed the 'Shell' interface.

'Shell' Interface

Conceptual Design

As part of the UK Estuaries Research Program Phase 2 (ERP2) funded by the UK Environment Agency and the Department for Environment, Food, and Rural Affairs (DEFRA) a number of research tools have been developed. One of the tools has been termed the Shell interface.

The Shell interface is designed to allow users to readily link hydrodynamic results from a 1-dimension (1D) hydrodynamic model to regime relationships. The Shell has been designed to work within a Microsoft Windows environment and is written in the program language Visual Basic and Matlab. The Interface is designed as a series of forms that allow the user to select a type of regime algorithm and couple this to a specific model simulation. In addition, a number of routines have been incorporated that provides the user with additional information about the estuary under investigation; this includes intertidal area and tidal asymmetry. The code has been written in a modular format with an open architecture approach to allow other users to add to and develop upon the existing routines.

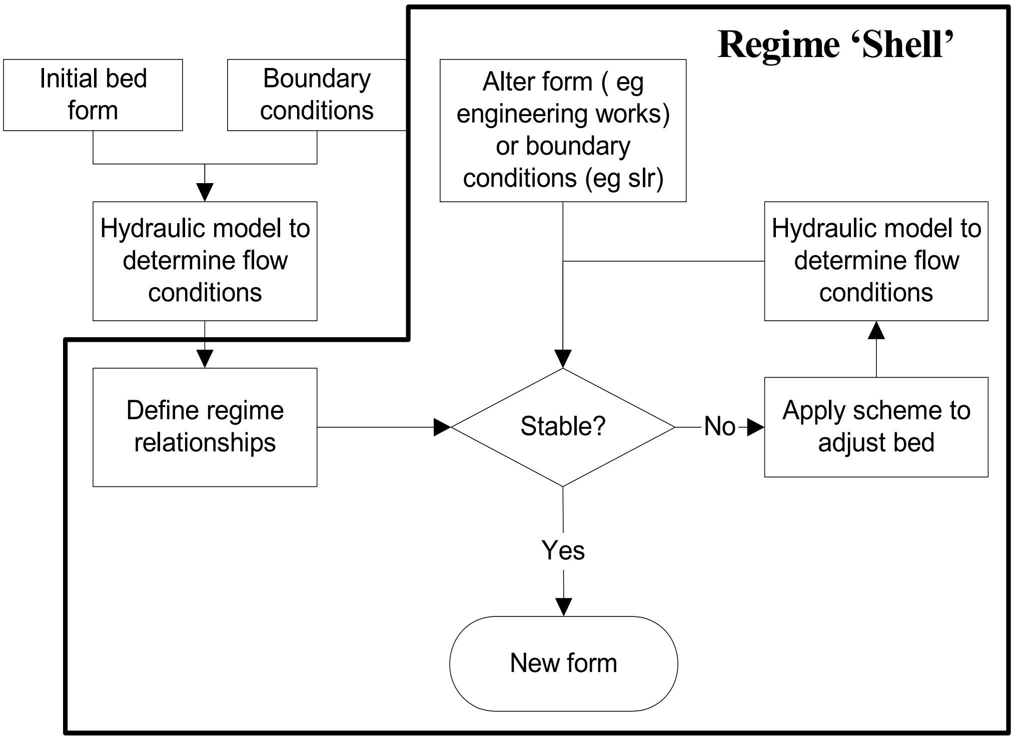

Figure 1 Flow diagram showing the process undertaken to perform a hybrid regime analysis. The Shell interface provides a mechanism to control this process in one standard interface

Regime Theory for Estuaries

Regime theory predicts how the estuary will respond to changes in either the estuary form (reclamation, engineering works, etc) or the forcing conditions (sea level, tidal range, etc) in order to return to the existing regime condition. There are two basic assumptions to regime theory:

- The estuary will achieve some form of equilibrium state
- The existing estuary form can be characterized by some function that describes the equilibrium relation.

Regime theory was first described by Langbein (1963) who concluded the following relationships involving top width, hydraulic depth and average cross sectional velocity:

$B \propto A_{Qmax}^{p} \qquad H \propto A_{Qmax}^{q}$

Where, B, A, H, and Q_{max} are top width, cross-sectional area, mean hydraulic depth and maximum discharge. The constants (p, q) are obtained from fitting to the results of the initial model run.

These exponents form the basis of regime theory for use in estuaries. Within the Shell interface, the regime condition is defined as the initial estuary geometry and hydrodynamic conditions; based on the assumption that the current estuary geometry is in a stable equilibrium. The existing regime can be defined in terms of a power law relationship between the maximum discharge during the tidal cycle and the simultaneous cross-sectional area of flow. The power law relationship is assumed to represent the equilibrium condition prior to the change in forcing conditions.

An alternative approach is to use a polynomial description of the maximum discharge and cross-section area. The use of a polynomial description allows for a greater freedom of mathematical description of the estuary regime. For example, the cross-sectional area at maximum discharge may not follow the form of a power curve due to the specific nature of the estuary in question [4].

Thus far it has been assumed that the relationship between estuary geometry is based on the maximum discharge through the cross-section. However, it may be better to represent the relationship of the estuary morphology in terms of cross-sectional area at maximum velocity. The Shell interface allows the user to select either peak discharge or velocity as the means to characterize the estuary regime.

In deriving the regime relationship between peak discharge and simultaneous cross-sectional area, there may be a large degree of scatter. Validation exercises for the Shell interface on estuaries along the East Coast of England have shown a poor relationship between the relationships as described above. To overcome this, a number of options have been implemented within the Shell interface. These are:

- Iterate the model (Figure 1) with no change in the forcing conditions until the fit of the characteristic regime equation is within a specified limit (typically about 5%).

- Assume the initial estuary is in a regime state and use the existing form to define the new estuary geometry. Each cross-section is adjusted according to the individual cross-sectional regime state rather than forcing all sections to a single regime relationship.

Morphological Adjustment

Morphological updating of the cross-sections within the Shell interface occurs if the regime condition for that particular cross-section is not met. The update procedure has a number of conditions applied, and assumes some physical constraints, these include:

- The cross-section geometry is not adjusted above the maximum water elevation; this high water value will typically vary along the estuary.

- A horizontal and vertical limit may be applied to the individual cross-sections preventing adjustment beyond a specified extent. This extent may be defined by a variety of objects such as a Holocene surface, sea walls, cliffs, bridge piers and so on.

- The cross-section adjustment routine uses a linear stretching (vertically and horizontally) approach. No variation in the flow velocity over the section is considered. The routine adjusts the section according to the required width and cross-sectional area, based on the regime parameters.

- The new cross-section geometry forms the basis of the next iteration of the hydrodynamic model. If the regime criterion has not been achieved then another iteration of the hydrodynamic model is performed (Figure 1). This iterative process continues until the change in successive cross-sectional geometries has converged to within a specified margin of the regime criteria.

- To ensure the correct morphological width adjustment, the cross-sections are extended beyond the point of any potential adjustment, i.e. where the land elevations are significantly greater than the maximum water level. If the intertidal area is not included within the 1D cross-sectional description then this may lead to an over deepening (if not restricted by the underlying geology) of the cross-section.

Geological and Physical Constraint

In order to understand any future morphological response to sea level rise, engineering works and so on, the sub littoral geology and physical constraints of the estuary need to be considered. The underlying clay, bedrock or other hard substrata can prevent the estuary from widening or deepening. Equally, the physical constraints imposed on the estuary, i.e. sea defence walls; quay walls etc, will also prevent the estuary geometry changing. Long-term predictions must take these factors into account before any future morphological adjustments can be determined. The importance of the constraints is highlighted by the work undertaken for the Severn Estuary Coastal Habitat Management Plan (CHaMP), which showed the significance of the physical constraints in preventing development of intertidal areas under a range of sea level rise scenarios [8]. Without the constraints in place the estuary continues to widen, where in reality this would be prevented from happening by the presence of physical constraints. The application of the physical constraints is essential particularly when considering issues such as coastal squeeze, estuary rollback and so on.

Model Application

A hybrid regime model of the Severn Estuary was constructed to investigation how the estuary evolves as a result of a 100year increase in mean sea level. In addition, a number of potential managed realignment sites were included (Table 1) to investigate their influence on the estuary morphology and hydrodynamics. The 1D model was constructed using the Danish Hydraulics Institute (DHI) software Mike11 and consisted of 495 cross-sections (Figure 2). The location for the flood plain areas was derived from the mapping of the unconstrained intertidal areas and GIS screening to establish those areas that could potentially be re-aligned [3]. In addition to the realignment scenarios (Table 1), a number of sensitivity runs were undertaken to establish the hydrodynamic response of the estuary to the morphological adjustments (Table 2) via the regime analysis.

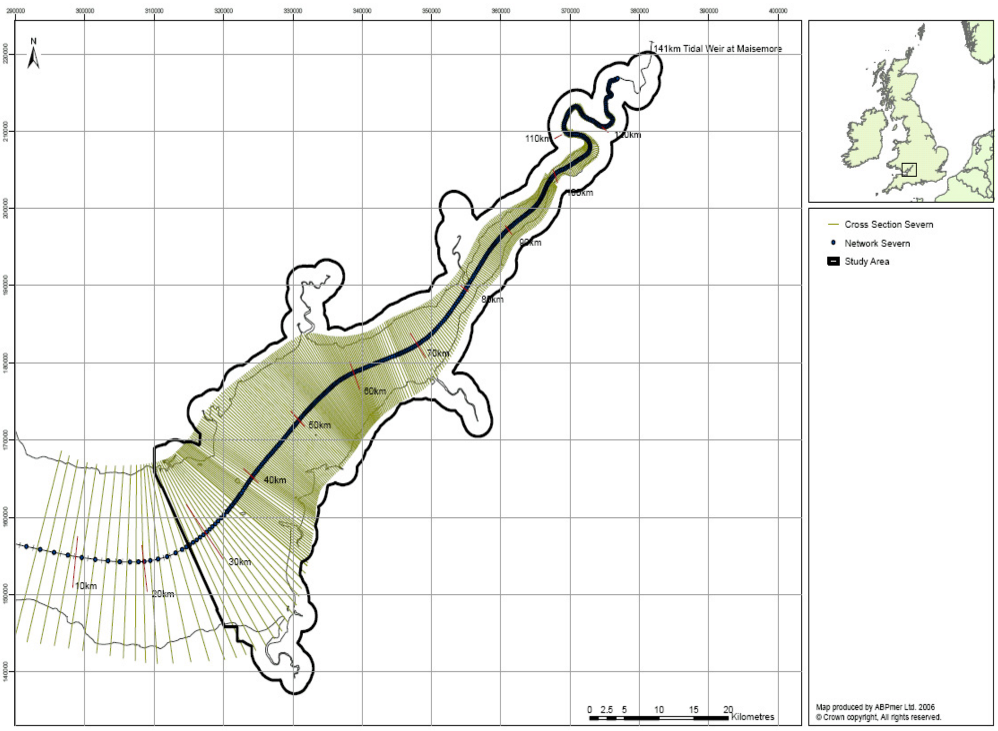

Figure 2 **Schematic of the 1D model setup for the Severn Estuary, South West Coast of England. The cross-sections extend beyond the high water line and include the upper intertidal.**

Table 1 **Scenario conditions applied within the 1D hybrid regime modelling of the Severn Estuary.**

Scenario ID	Scheme
Baseline	2105 Simulation with No Realignment Schemes
All	All realignments
A	Outer estuary
B	Outer middle estuary
C	Middle upper estuary
D	Upper estuary

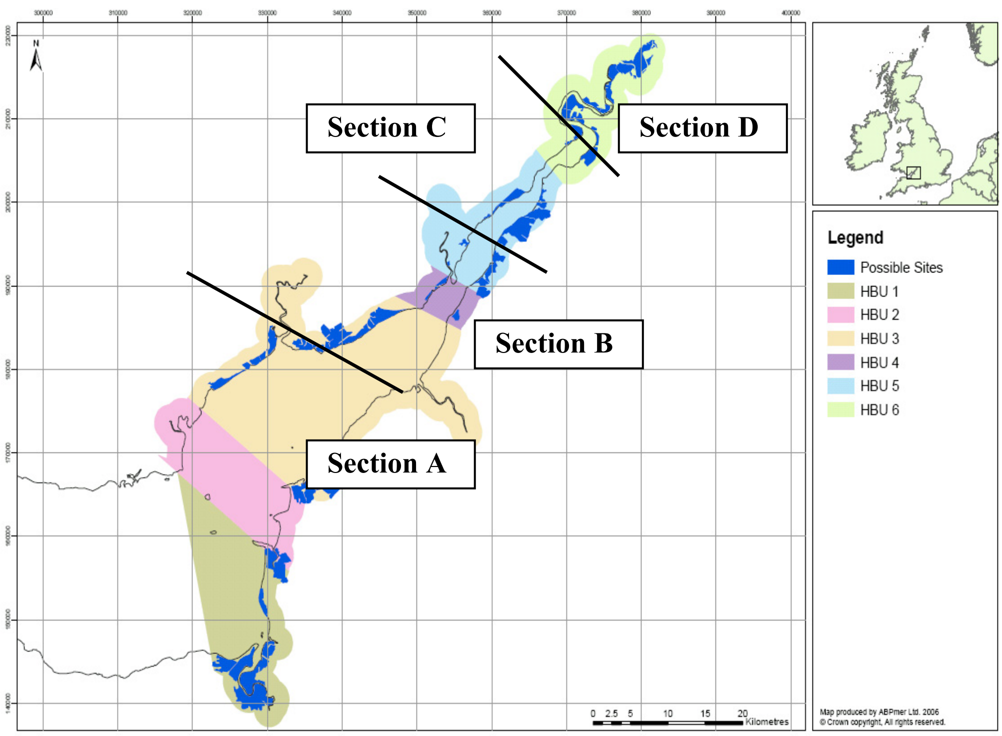

Figure 3 Proposed managed realignment sites along the Severn Estuary. The estuary was divided into 4 sections A-D.

Mean sea level at the driving water level boundary was increased to account for sea level rise for the 100year epoch. Sea level was assumed to rise by 6mm per year based on the guidelines from the UK Climate Impacts Programme (UKCIP) and guidance from DEFRA.

The Severn Estuary is situated on the South West Coast of England; it is a highly dynamic environment with one of the largest tidal ranges in the world. A regime analysis of the Severn Estuary provides a good validation of the Shell interface, particularly, given the large spatial and temporal scales. The exercise to establish the possibly future morphological response of the estuary under the chosen forcing conditions provides a good benchmark in which other similar studies could be conducted using the Shell Interface.

Table 2 Additional sensitivity scenarios considering the setup of the regime model for the Severn Estuary. In examples where realignment scenarios are included, all site locations have been used.

Sensitivity Scenario
With Realignment Sites, Completely Constrained Middle Estuary Section
With Realignment Sites, No Constrained Middle Estuary Section
With Realignment Sites, No Morphological Adjustment
No Realignment Sites, Completely Constrained Middle Estuary Section

Modelling Results

Existing Conditions

In order to understand any future evolutionary change in estuary morphology the existing hydrodynamic conditions must first be established (Figure 1). Underlying regime theory is the assumption that the existing estuary state is in a stable regime. If the estuary is in a period of rapid change or instability then regime modelling is unsuitable.

The consideration of the existing regime state is derived from the examination of the existing hydraulic parameters before the addition of the potential managed realignment sites and the increase in mean sea level is applied. The stability of the existing estuary layout was determined by comparison with the form of the estuary from a previous time [3]. Alternatively, the estuary stability may be determined by comparison to a theoretical state, for example by comparing tidal prism and cross-section area [7].

Morphological Response

Realignment sites in the upper and lower sections of the Severn Estuary result in a lowering of peak water levels (Schemes All, A, B and D). Realignment sites within the middle upper part of the estuary (Section C) result in an increase in peak water levels upstream of the realignment areas (Figure 3).

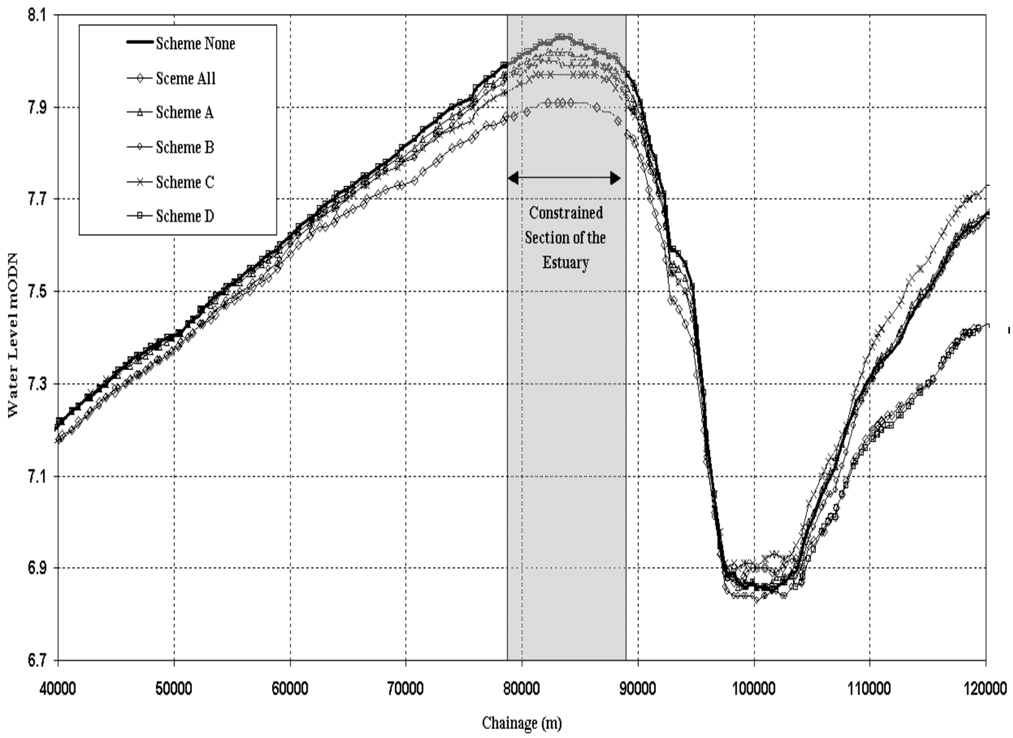

Figure 3 The maximum water levels along the Severn Estuary for the different potential managed realignment scenarios using the 2105 increase in mean sea level.

The change in peak water elevations after running the sensitivity scenarios (Table 2) is show in (Figure 4). The results show a marked difference in the estuaries response to the presence of the constrained section of the estuary. Allowing the middle sector of the estuary to evolve results in a continual increase in peak water levels upstream. The existing middle sector acts as a control point within the estuary, by constraining this section the peak water levels are accurately reproduced. By comparing the results from the scenario with no morphological adjustment suggests that the hydrodynamic model may potentially under predict peak water levels in the upper part of the estuary.

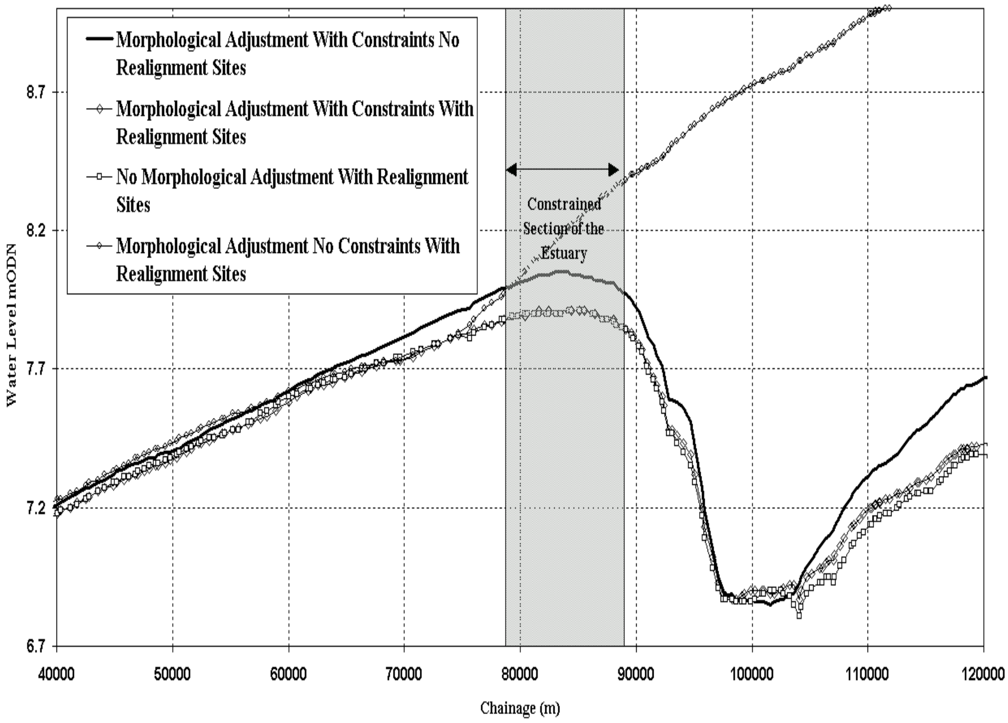

Figure 4 Maximum water levels along the Severn Estuary using the 2105 increase in mean sea level for a number of different regime modelling scenarios.

Discussion

The results from the hybrid regime modelling of the Severn Estuary have provided some interesting insights into the hydrodynamic effects of morphological adjustments and potential managed realignment positions along the estuary. The results of this exercise are summarised below

- Realignment sites in the upper middle section of estuary (Section C, Figure 3) result in an increase in peak water levels. This may be significant in terms of flood management. Realignment sites in the upper section of the estuary (Section D) result in a significant lowering of peak water levels at the upper section of the estuary.

- Results from the sensitivity analysis show the importance of accurately predicting the morphological response of the estuary through the application of the physical constraints. By not considering the constrained sections of the estuary there is the potential to inaccurately predict the future morphological response of the estuary.

- By not considering potential morphological adjustments may result in an under estimation of peak water levels. This may be significant when considering issues of flood defence.

- The regime analysis of the realignment schemes under a 100year epoch water level condition was run successfully using the Shell interface tool. This exercise has proven the potential usefulness of hybrid regime modeling using the Shell interface.

Further Work

Further improvements to the morphological update procedure and regime algorithms within the Shell interface are currently being addressed, these include:

- The section adjustment routine takes no account of the variation of flow through the section. Work is being undertaken to represent some form of physical representation of the flow through the cross-section.

- Time-scales, work is being undertaken to consider how sediment information can be incorporated within a regime equation. In particular, methods to establish how sedimentation and erosion rates can be considered to determine the length of time an estuary will take to establish its predicted form.

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References

ABP Research, 1999. Historic analysis of Humber morphology, Humber Estuary Geomorphology Studies - Stage 2, Binnie, Black & Veatch for the Environment Agency, ABP Research, Southampton, Report No: R.839. [1]

ABPmer, 2003. Historical analysis of Humber estuary morphology*,* Report for Environment Agency, North East Region, ABP Marine Environmental Research Ltd, Southampton, Report No: R.1005 1-16. [2]

ABPmer 2005. Severn Estuary CHaMP Morphological Assessments Part A: Regime Modelling, Date. ABP Marine Environmental Research Ltd. Report No. R.1225a. [3]

Dennis JM, Spearman JR, Dearnaley MP, 2000, The development of a regime model for prediction of the long-term effects of civil engineering activities on estuaries, Phys. Chem. Earth (B), 25(1), 45-50. [4]

Haigh I, Norton P, Townend IH, 2004, Understanding and predicting morphological change in the inner Humber Estuary, In: 29th International Conference on Coastal Engineering, ASCE, New York, 4. [5]

Langbein WB, 1963, The hydraulic geometry of a shallow estuary, Bulletin of Int Assoc Sci Hydrology, 8, 84-94. [6]

Price, D and Norton, P. 2000. Emphasis Consortium Phase 1B – Modelling Results. MAFF Report, Contract CSA 4938, Project FD1401. [8]

Wright, A. P and Townend, I. 2006. Predicting Intertidal Change in Estuaries. 41st Defra Flood and Coastal Management Conference. [9]

NOTES

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HR Wallingford Ltd
Howbery Park
Wallingford
Oxfordshire OX10 8BA
UK

tel +44 (0)1491 835381
fax +44 (0)1491 832233
email info@hrwallingford.co.uk

www.hrwallingford.co.uk