Has Loss of Accommodation Space in the Humber Estuary Led to Elevated Suspended Sediment Concentrations?

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***Abstract*- The role of anthropogenic modification of the Humber estuary (England, UK) is examined in the context of its exceptionally high suspended sediment concentrations (SSCs). Loss of accommodation space through land claim for agriculture over the past 1,000 years has led to the evolution of channel that may be described as a tidal canal. We explore some relevant analogues in order to determine whether any correlation exists among the degree of narrowing, the extent of tidal propagation, and the persistence of elevated SSCs. Several examples are shown of estuaries whose tidal range and SSC have been manipulated by anthropogenic changes to their geometry. It is postulated that this modern form has resulted in increased tidal propagation and that elevated sediment loads within the Humber Estuary have been influenced by a loss of accommodation space. We propose that should this association be substantiated then accommodation space should be regarded as a significant 'ecosystem function' in regulating suspended sediment concentrations and water quality.**

Our analysis highlights a suite of ecosystem services that include the regulation of tidal range as well as of SSC. It provides the basis for a broader approach to coastal management in which the role of accommodation space is given a higher profile from an engineering perspective. A wider suite of biochemical benefits may also arise in the aftermath of substantial realignments, emphasising the broader relationship between managed realignment, sediment availability and ecological functioning.

Keywords*- *Accommodation Space; Suspended Sediment Concentrations; Tidal Propagation; Managed Realignment; Ecosystem Services

I. INTRODUCTION

Most estuaries in the UK and Europe have been substantially modified, with substantial areas of former tidal floodplains (accommodation space) protected from flooding by sea walls. This has been a gradual process over hundreds or in some cases thousands of years. This means that although we now look upon our estuaries as behaving in a particular manner they may not have done so in the same way in the past. This is emphasised by Townend [1] who described the mechanisms involved in building a conceptual model for estuary change.

The loss of accommodation space would have removed considerable volume from the spring tide in particular, thus affecting tidal symmetry. These losses would also have removed the main areas where suspended sediments might be absorbed and removed from the system.

Suspended sediment concentrations in modern estuaries vary considerably depending upon a combination of fluvial and marine sources as well as the degree to which sediments are re-suspended during the tidal cycle. In estuaries that enter the North Sea around English shores, the majority of the sediment is supplied from coastal and nearshore sources as a consequence of cliff and bed erosion (e.g. [2]).

If there are limited places for this sediment to be deposited, or the wave and tidal regime is unfavourable to deposition, then the sediment must go somewhere else. In some cases such as the Bay of Fundy (Nova Scotia, Canada), it does so by remaining in suspension within the estuaries concerned. Elsewhere, it is exported offshore. Where suspended sediment levels are exceptionally high, there is a biological response. Primary productivity is limited (e.g. the Severn Estuary, UK) and the biology of the water column is dominated by zooplankton. We assume that this has always been the case, but this may not be so.

Management and conservation of sediment supply is a growing concern. On the one hand, estuaries in temperate zones with high suspended sediment concentrations can suffer significant water quality problems during summer months when there is insufficient flushing combined with raised water temperatures. Conversely, sediment conservation is a potentially important issue in the development of greater resilience to sea level rise and increased storminess [3]. Managed realignment and creation of new accommodation space is largely regarded as a partial solution with the main focus being on nature conservation and the 'ecoststem services' that derive from new habitat. In this paper, we explore the possibility that accommodation space itself may have more important regulating influences and that the space itself should be regarded as an important 'ecosystem function'.

In order to test this possibility, we have explored the possible responses to anthropogenic changes in the Humber estuary using analogues to highlight possible mechanisms that could have influenced changes over time. We have no empirical evidence that suspended sediment concentrations within the Humber estuary have actually changed, although it is possible that this might be determined by investigating the biological record in the sediments of the estuary. Our analysis is therefore presented as a potential stimulus to new work that would be highly relevant to development of new strategies to manage estuaries in the face of rising sea levels. The following account is therefore a highly conceptual model that is intended to provoke debate and new lines of thinking.

II. THE HUMBER ESTUARY

The Humber estuary is one of the largest estuaries in England and drains around a fifth of England's land mass [4]. It is formed by the confluence of two major rivers, the Trent and Ouse, but also drains several minor rivers such as the Ancholm, Hull, and Freshney. Its modern form is unusual because its inter-tidal zone is dominated by mudflats and sandbanks, with comparatively little saltmarsh [5].

Tidal influences within the Humber estuary on the east coast of England extend as far inland as Cromwell Weir (Trent) and Naburn Weir (Ouse), and mean tidal range varies from 5.7 m (Spurn) to 7.4 m (Saltend) and 6.9 m (Hessle) [6] (see Figure 1 for locations). Suspended sediment concentrations (SSCs) in the Humber Estuary (UK) are amongst the highest in the UK and are also noteworthy in a global context. For example, Uncles et al. [7] report the Humber to have the third highest depth-mean SSC among the 48 estuary systems they analysed. Turbidity maxima are frequently quoted as occurring around Trent Falls [8], but higher depth-averaged maxima are reported much further upstream within the Trent and Ouse [9]. Sources of sediment are discussed by Townend and Whitehead [2] who show that the majority of sediment derives from the Holderness coast and marine sources, with the fluvial contribution being less than 5% of the total.

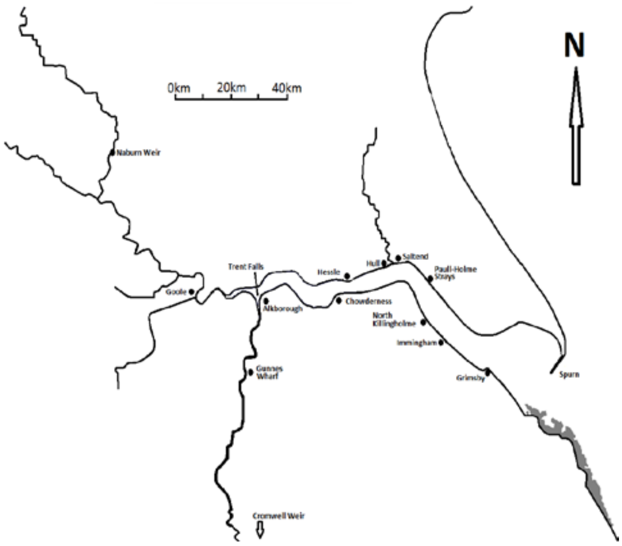

Fig. 1 Location of key locations around the Humber Estuary

Uncles et al. [7] use an empirically based model to demonstrate a consistent relationship between the length of tidal intrusion and tidal range, and provide an explanation for the tendency of longer estuaries with bigger tidal ranges to be both better mixed and more turbid. They show that very long, slowly flushed estuaries are unlikely to lose significant quantities of suspended sediment over single tides or during periods of high freshwater discharge, and therefore sediment loads increase over time. The Humber Estuary provides an important model for this analysis.

Accommodation space around the Humber has reduced progressively since Roman times, with the most significant losses taking place well before the 20th Century. Its overall evolution falls into two clear stages.

- Prior to the Roman period (43 AD to 410 AD) the Humber Estuary and associated coasts comprised a mosaic of freshwater wetlands and tidally inundated river valleys that evolved through the development of peats and marine sedimentation in response to post glacial sea level rise. During this period a substantial sink was available to absorb marine-sourced sediment and extensive freshwater and brackish marshes would have regulated freshwater input by acting as stores of fresh water and sinks for suspended sediments.

- Although some higher tidally inundated wetlands were claimed by creating sea walls during the Iron Age and Roman times, archaeological evidence suggests that a more significant period of change occurred from the 11th Century onwards. Flood banks were created and tidal wetlands were gradually turned into dry ground for agriculture. For example, the saltmarshes within the southern Vale of York on the north bank (as far inland as the confluence of the Rivers Derwent and Ouse) were largely lost to flood banks by the 13th Century [10]. Major wetlands within the Ancholme Valley and between the

Rivers Trent and Ouse were mainly drained for agricultural and other purposes in the 17th Century. Industrialisation and further land claim in the 19th and early 20th Centuries consolidated this loss and led to a substantial hardening of the defences. A number of power stations now line the banks of the tidal reaches, using the fast-flowing waters of the tidal rivers as effective cooling water; and, of course, the dredged channels also provide excellent facilities for importing the raw materials required. As a result of these changes, the Humber Estuary has reduced in extent from 550,000 ha to 11,000 ha since the 11th Century [11].

These modifications have reinforced the natural evolution of a funnel-shaped estuary and mean that in places the estuary might almost be described as a tidal canal with mudflats or a narrow fringe of saltmarsh or reedbeds. This morphology differs so substantially from its original form that modern decision-makers arguably overlook the processes of regulation associated with its original form, and base their management decisions on conceptual models that fail to take them into account. We herein offer a new conceptual model based on the proposal that high degrees of canalisation within longer estuaries such as the Humber system contribute to greater tidal propagation, and this in turn raises SSCs. Furthermore, this influence is set to increase in conjunction with relative increases in mean sea level. The aims of this paper are threefold. First, we aim to show the degree to which canalisation of the Humber may be connected with raised levels of SSC due to the loss of accommodation space. Secondly, we use analogues with other estuaries to show how the processes in one estuary are similar to those in others that have the same hydraulic characteristics. Finally, we investigate whether the changed hydrodynamics of a system such as the Humber could be responsible for the particular sediment regime found within it.

III. RELEVANT MODERN MANAGEMENT

The relative absence of saltmarsh within the Humber Estuary [5, 11] means that flood defences are vulnerable to undercutting and to overtopping [12]. Despite remarkably elevated sediment loads, many mudflats are eroding and the toes of many flood banks require reinforcement (Photographs 1 and 2). This erosion contributes to the overall sediment budget of the estuary [2].

Photograph 1 Foreshore at North Killingholme depicting lowered mudflats in from of the sea wall which is partially protected by debris from previous rock armour

Photograph 2 Foreshore at Barton on Humber in which the toe of the sea wall has been extended in response to foreshore lowering. Debris from previous rock armour lies on the upper foreshore

The limited extent of saltmarsh (1419 ha reported in Buck [13], which includes the Lincolnshire coast) is directly related to the absence of accommodation space [5] and this is amply demonstrated by the rate of accretion within managed realignment sites at Paull-Holme Strays, Chowderness and Welwick. At Paull-Holme Strays for example, initial accretion was around 300 mm in the first year. This rapid accretion can be largely attributed to the high concentrations of SSC in the Humber system, bearing in mind that much lower rates have been recorded at other realignment sites such as Tollesbury on the Blackwater Estuary (Essex, England) [5]. Nevertheless, it has been shown that any sediment accretion can be considered to be long lasting and permanent [14].

The Humber Estuary also provides a focus for considerable economic activity, with three major ports (Hull, Grimsby & Immingham, and Goole), together with several smaller enterprises such as North Killingholme Haven and Gunnes Wharf [15]. Parts of the outer Humber, especially the Sunk Dredged Channel, are maintained at an artificial depth to allow access by some of the largest ships in the World. Annual maintenance dredging volumes vary considerably (Figure 2). Dredged sediment is returned to the estuary relatively near to the point of dredging, and this management is supported by the nature conservation agencies because it limits the loss of sediment.

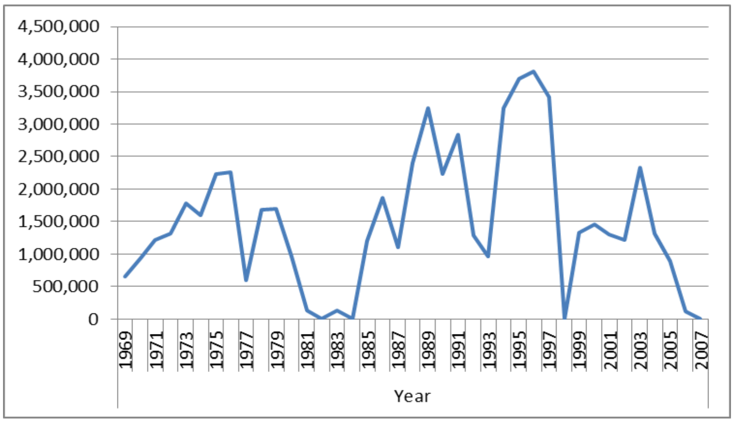

Fig. 2 Maintenance dredging (cubic metres) from the Sunk Dredged Channel, Humber Estuary [after ABP [29]

IV. THE RELEVANCE OF ANALOGUES

Analogues that can help to explain critical pathways in one system may be used to develop a conceptual model for others. For the case of the Humber Estuary, we have selected a series of analogues in order to explore the relationship between SSC and the loss of accommodation space. The relevance of each example to the impact of changes to accommodation space on tidal propagation and associated SSC is described in the sections that follow.

Analogue 1. Channel deepening to allow access for navigation within long tidal rivers such as the Elbe Estuary (Germany) [16], the Ems (The Netherlands/Germany) [17], the Western Schelde (The Netherlands/Belgium) [18] and the Seine (France) [19] has been shown to have increased tidal propagation, resulting in elevated high tides. This is especially well demonstrated in the Elbe Estuary where successive deepening between 1870 and 2009 has led to an increase of some 50 cm tidal propagation at St Pauli (tidal range increased from 1.9 m to 3.1 m) [20]. In the Seine, increased tidal currents cause sediment, which previously would have remained in the estuary, to be deposited in shelf mud zones off the estuary mouth [19]. This analogue shows how, in the absence of a mechanism to absorb increased tidal energy, an increase in water depth reduces friction and allows the incoming tide to travel upstream at a faster rate than it did prior to channel deepening.

Analogue 2. Progressive channel deepening to improve navigation access to the Meyer shipyard at Pappenburg has increased the tidal range of the Ems Estuary from 5.7 m in 1985/86 to 7.4 m in 1994 [21]. The estuary has subsequently changed from a relatively clear water estuary to one that has extremely high sediment loads has occurred. This change is referred to in Germany as 'tidal pumping'. In this extreme case sediment mobilisation on the flood tide reaches a critical level where it remains in suspension throughout the tidal cycle. This analogue shows how increased tidal propagation within a largely canalised estuary can lead to greatly elevated SSC under certain circumstances.

Analogue 3. The 'hypertidal' Severn Estuary is well known for its extremely high tidal range, which fluctuates markedly over the spring-neap cycle. On spring tides, SSC within the water column is relatively uniform because the estuary is generally very well mixed; whereas on neap tides it forms fluid mud in deeper channels that can be anoxic [22]. Its sediment budget is primarily driven by the deposition and erosion of existing sediments rather than new inputs [23], and comparatively little new sediment arrives from either fluvial or offshore sources. The extreme fluctuations in the distribution of SSC have been associated with tidal propagation. This analogue provides evidence that SSC in hypertidal estuaries of this kind can be substantially influenced by the spring-neap cycle. It is important to bear in mind that the Severn Estuary has been modified by loss of accommodation space and the question whether high SSC occurring in 'closed' systems is influenced by the absence of accommodation space and its capacity to absorb suspended sediment, thereby reducing the amount of available sediment. This may be an influential factor in the difficulties [23] experienced in achieving a balanced sediment budget for the Severn Estuary.

Analogue 4. The Petitcodiac River in New Brunswick, Canada forms part of the Bay of Fundy, and is known locally as 'The Chocolate River' on account of its exceptionally high sediment loads derived from local red sandstones. This estuary lies within a shallow valley and has a tidal range of 9 metres; it was renowned for its tidal bore which is reported to have been of the order of 2 metres in height on the biggest tides. The construction of the Moncton Causeway in 1968 has led to substantial reductions in the tidal prism from approximately 450m m^3 to around 200m m^3 and to rapid sedimentation, reducing the width of the river from 1 km in 1968 to just 80 m by 1998 [24]. This analogue illustrates the way estuaries with high SSC respond to substantial changes in the tidal prism when the length of the estuary is shortened rather than narrowed, as also occurred in the Konkoure estuary in Equatorial Guinea [25]. High levels of (initially) sub-tidal sedimentation are followed by inter-tidal mudflat and saltmarsh development. This is a reversible state as has been shown on the Petitcodiac River where the former causeway was partially re-opened in April 2010. The sluice gates within the Moncton causeway have been opened as a first stage in a more complex programme that includes proposals for replacing part of the causeway by a bridge. The response to the tidal river has been rapid: the former saltmarsh downstream has started to erode as the channel widens and deepens in response to a significant increase in the tidal prism (approaching 20.4 MCM initially but subsequently reduced to 17.6 MCM by sediment accumulation within the former headpond) [26].

Analogue 5. Channel deepening within Southampton Water (UK) in 1996-7 to improve access to the port of Southampton was undertaken using a pre-cut followed by use of a trailer hopper suction dredger several days later. The cutting process coincided with a big spring tide and fine white sediment was lifted and placed on the foreshore where it formed a layer of whitish material to a depth of up to 10-20 cm. This episode is significant because saltmarshes within Southampton Water are mainly eroding and contributing sediment to the overall sediment budget of the estuary (data published on ABPmer's online estuaries guide [27]). It shows how the tide can lift unconsolidated sediments when they are available, and that once the source of sediment has been dispersed (either naturally or through removal by dredging), SSCs then return to their previous levels. We must emphasise, however, that in each case we are not arguing that this particular process has happened in the Humber estuary.

Analogue 6. Studies into the 18.6 year Lunar Nodal Cycle have shown that its influences on sedimentation within the Western Schelde Estuary (The Netherlands/Belgium) can be detected in the morphological evolution of the estuary [28]. This study is important because it shows how natural fluctuations in tidal heights can govern rates of sedimentation.

Analogue 7. The Alkborough managed realignment project at the confluence of the Trent and Ouse within the Humber Estuary has been designed to create temporary accommodation space to absorb storm surges and thus to reduce tidal propagation upstream. This is a relatively large-scale realignment by modern standards (up to 350 ha) but is extremely small in the context of the natural floodplain of the Humber Estuary. It is an important analogue because it shows how tidal propagation can be reduced by increasing accommodation space, and this in turn suggests that reducing accommodation space in the upstream sections of an estuary can effectively increase tidal propagation.

Analogue 8. Studies into the response of the Humber estuary to managed realignment have shown how realignments in the outermost parts of the estuary will lead to elevated tides upstream. This study shows how changes to different parts of an estuary may have very different consequences. In the case of the Humber such changes reinforce the funnel shape of the estuary but this may not be the case everywhere (e.g. those estuaries where the mouth is more constrained).

V. DEVELOPMENT OF A CONCEPTUAL MODEL

Our model depends partially upon an analysis of the Holocene evolution of the Humber Estuary, but is especially linked to anthropogenic changes.

During the Holocene transgression (10,000 – 1,600 BP [29]) the Humber river basin filled with a mixture of marine and peaty deposits, with peats overlain by estuarine sediment where sea levels rose and extended tidal influences into former freshwater wetlands. Modelling of this period of coastal evolution has indicated that sea levels were in the order of 2.5 m lower in the mid-Holocene than they are today [30]. Coastal evolution progressively led to the creation of wetlands and infrequently inundated intertidal areas that were attractive to early human settlers, and there is extensive archaeological evidence of small communities settling on drier ground by the bronze and iron ages (see maps [10]). These communities were small and are unlikely to have had significant physical impact on the estuary until they started to counter tidal inundation by constructing flood banks.

With the commencement of the construction of flood banks, accommodation space associated with the tidal estuary was constrained by sea walls and drainage of the associated freshwater wetlands (Figure 3). The archaeological evidence suggested that these influences were most significant in two phases between the 11^{th} and 17^{th} Centuries [10] and that by the start of the 18^{th} Century the modern form of the estuary had been largely established. This loss of accommodation space would have had a significant influence on SSC in three respects:

a) In the absence of a natural sink, less sediment is absorbed into saltmarshes during spring tides and therefore more sediment is available for mobilisation within the estuary channels. This sediment either remains within the system or is exported offshore during an ebb tide.

b) The former extent of accommodation space means that the tidal prism of the estuary has been substantially reduced on the biggest spring tides with corresponding influences on the degree of tidal asymmetry between flood and ebb tides at different locations, giving the estuary greater potential for flood dominance.

c) The natural development of a funnel-shaped estuary has been reinforced by creation of sea walls that give the estuary its modern form. This reinforcement means that the processes that are observed today cannot be considered comparable to those existing 300 or 1,000 years ago. Thus, we cannot say with certainty what SSC may have been in the 9th Century.

Fig. 3 Extent of floodplain around the Humber Estuary, which represents the former extent of accommodation space

These combined influences allow the following conceptual model to be constructed:

Stage 1. The construction of seawalls leads to the loss of accommodation space and reinforcement of the funnel-shape of the modern estuary, and this in turn leads to a greater funnelling of tides and relatively small increases in tidal propagation. Increases in tidal propagation mean that the elevation of the saltmarsh to the seaward side of seawalls increases above their original levels. Progressive increases in saltmarsh height mean that additional land claim is possible so that eventually the majority of saltmarsh is converted to agricultural land.

Stage 2. Provided that constrictions are not established so as to create an artificial throttling effect, and the mouth is not narrowed, sea wall construction can increased canalisation will lead to further elevations in tidal water levels; consequently flood embankments have to be reinforced and improved. The Alkborough analogue points to a converse mechanism where loss of accommodation space leads to funnelling and increased tidal propagation.

Stage 3. As tidal propagation increases, sediment is retained in suspension for more of the tidal cycle. Several analogues demonstrate this. The Severn Estuary and Petitcodiac River represent extremes of ‘natural’ systems. Elevated SSC in the Ems Estuary illustrates the role anthropogenic change can have in some estuaries. We suggest that when the sea walls were first built they progressively constrained the tidal waters and reinforced the natural funnel shape. This in turn led to increased tidal propagation and to associated increases in SSC. Critically, the mouth was not constrained sufficiently to compensate for the enhanced funnelling effects on tidal propagation.

Stage 4. Relative increases in mean sea level elevate water levels within the estuary, and this effect in turn means that friction is reduced; facilitating increased tidal propagation, exacerbated by anthropogenically induced tidal propagation. Long-term monitoring of sea levels at various locations on the British coast have demonstrated ongoing sea level rise since the mid-19th Century, and even greater influences can be expected if relative sea level rise follows projected trajectories [31].

Stage 5. Increased tidal energy and shorted residence times mean that saltmarshes and mudflats erode rather than accrete, adding sediment to the available pool. This in turn means that there is more potential for sediment to be mobilised. SSCs therefore increase, even though neither of the usual sources of sediment (fluvial and marine sources) supplies proportionately more sediment to the available pool.

VI. APPLICATION

The model proposed by Uncles et al. [7] is based on modern estuarine forms, many of which have been highly constrained by a loss of accommodation space. The Humber is an obvious example and others within the chosen suite such as the Western Schelde (Belgium/The Netherlands) and the Gironde (France) have also lost much of their accommodation space and are effectively canalised. Consequently, whilst the Humber in its modern form carries some of the highest SSC amongst the analysed samples, it is suggested that anthropogenic factors could have had an important bearing on modern SSCs, and that accommodation space potentially provides an important regulatory role in limiting any progressive increases in SSC.

Significant increases in accommodation space in the upper section of the Humber would have the complementary impacts of reduced tidal propagation and of bringing SSCs closer to ‘natural’ levels. This in turn has the potential to improve water quality and therefore to benefit fisheries, both within the coastal zone and amongst anadromous species. The primary drawback of such an approach is that significant realignments lead to a reduction in sediment mobilisation on the flood tide and absorption of sediment whilst new saltmarshes are formed. The latter is significant in the context of the overall sediment budget, whilst the former will have a bearing on the degree to which sediment is delivered to new realignment sites.

The restoration of accommodation space through the realignment of flood banks has been applied widely in Europe over the past 20 years; but the majority of examples are on a small scale [32]. It has an important role in flood risk management but is more frequently cited as a wildlife management tool and generates considerable local opposition because of the perception that it is driven by a conservation agenda. Realignment is the focus of interest for its role in carbon sequestration [33-35] and consequently it is seen as a potentially important 'ecosystem service'. Our conceptual model raises the possibility that accommodation space itself should be regarded as a critical 'ecosystem service'. Furthermore, accommodation space gains importance as a critical sink for sediment in shorter estuaries that are unable to form a natural feedback loop to retain sediment eroded from existing stores of fine sediment.

The temporary storage of sediment on intertidal zones during spring tides has been shown to be a factor in the overall budget of sediment in the Humber [36]. Measurements of sediment surface elevation made by light sensitive devices inserted in the intertidal mud bank showed that spring tides generally produced a net tidal increase in sediment on intertidal mud banks at Blacktoft, near the confluence of the Trent and the Ouse. These sediment deposits were remobilised by locally generated wind waves, which caused higher shear stresses to occur at the sediment surface. The relationships between sediment elevation, tidal range and wind speed are far from predictable in that there is considerable scatter, but at least it is possible to say that it is likely that spring tides, and by implication higher water levels generally, will lead to increased sediment storage on inter tidal zones.

It seems likely that any canalisation that occurs as a result of the presence of raised flood banks at the sides of the channel will also cause the rapid response of the sediments in the system to fluvial flood events, even relatively small ones [37]. This point may be illustrated by considering the observed SSC at Burringham, located near the town of Scunthorpe on the tidal R. Trent. Figure 4 shows the effect of a sudden increase in fresh water flow from the low flow level of around 30 to 75 and then 130 m^3/s (25 Aug and 1 Sep, respectively) in terms of the rapid reduction in SSC, which fails to recover to the same level by the second set of spring tides that peak on 5 Sep. as shown. This is clearly a result of the sudden flushing of the turbidity maximum downstream at this time. Moreover, there are likely to be influences to the sediment regime in the channel caused by fresh water flow rates that are supplemented by effluent water from major sewage treatment works at large cities such as Birmingham, Nottingham etc. [38]; in the Trent these maintain the fresh water flow at a minimum of around 30 m^3/s even after prolonged periods of dry weather.

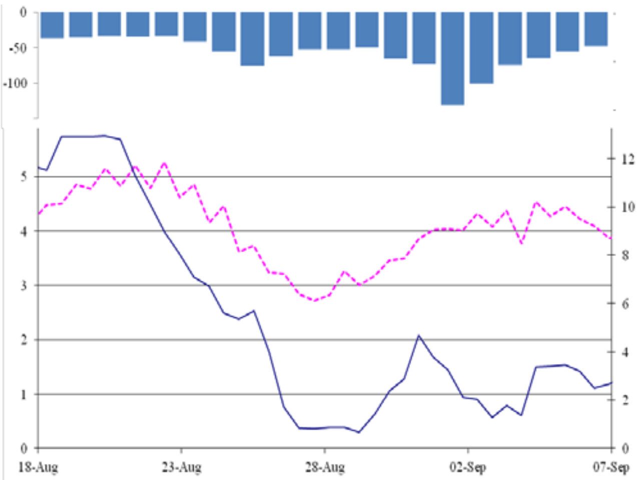

Fig. 4 Peak tidal water level in m above ordnance datum at Burringham (dashed line, left axis), mean flood tide SSC in grams per litre at Burringham (solid line, right axis), and daily mean fresh water flow measured at the tidal limit at North Muskham, River Trent, Aug/Sep 1997

VII. CONCLUSIONS

A conceptual model that explains the relatively high suspended sediment concentrations in the Humber Estuary has been developed using a suite of analogues from Europe and North America. The model highlights the importance of accommodation space as a regulator not only of tidal propagation but also potentially of suspended sediment concentrations and therefore of water quality. It therefore follows that current attention to 'ecosystem services' could be extended to cover a broader suite of engineering and biochemical benefits derived from managed realignment.

This model highlights the degree to which modern estuary forms have diverged from those that existed prior to the major human influences over the last 1,000 years. It follows that greater attention needs to be given to the relationship between managed realignment and sediment availability. In some estuaries realignment may act as an important sink for limited sediment supplies. Elsewhere, realignment may change tidal propagation and hence the sediment available to maintain and build existing mudflats and saltmarshes as well as to build new inter-tidal environments that provide natural energy attenuation.

Increasing the range of 'ecosystem functions' arising from accommodation space has the potential to influence the way managed realignment is presented to the wider public. Many coastal communities regard realignment as an unacceptable loss of hard-won assets that is primarily advocated for nature conservation management reasons. Extending the suite of explicit benefits has the potential to make managed realignment more socially acceptable, especially if a broader suite of engineers recognise its potential and the need for greater attention to benefits that are not specifically focussed on wildlife.

REFERENCES

[1] Townend, I.H., 2004. Identifying change in estuaries. Journal of Coastal Conservation 10: 5-12.

[2] Townend, I. & Whitehead, P. A preliminary net sediment budget for the Humber Estuary. The Science of the Total Environment 2003; 314-316: 755-767.

[3] Morris, R.K.A., 2012. Managed realignment – a sediment management perspective. Ocean & Coastal Management 65 (2012) 59-66.

[4] Freestone, D., Jones, N., North, J., Pethick, J. , Symes, D. & Ward, R., 1987. The Humber Estuary: environmental background. University of Hull & Shell UK Ltd. 55pp. http://www.hull.ac.uk/iecs/pdfs/shell.pdf (Accessed 05 January 2013).

[5] Morris, R.K.A., Reach, I.S., Duffy, M.J., Collins, T.S. & Leafe, R.N. Forum: On the loss of saltmarshes in south-east England and the relationship with Nereis diversicolor. Journal of Applied Ecology 2004; 41: 787-791.

[6] Humber Management Scheme. http://www.humberems.co.uk/humber/(Accessed 24 February 2012).

[7] Uncles, R.J., Stephens, J.A. & Smith, R.E. The dependence of estuarine turbidity on tidal intrusion length, tidal range and residence time. Continental Shelf Research 2001; 22: 1835-1856.

[8] Pontee N.I., Whitehead P.A. & Hayes C.M. The effect of freshwater flow on siltation in the Humber Estuary, north east UK. Estuarine, Coastal and Shelf Science 2004; 60: 241-249.

[9] Mitchell, S.B. Discussion on 'The effect of freshwater flow on siltation in the Humber Estuary, Northeast UK' by Pontee NI, Whitehead PA and Hayes CM (ECSS vol. 60, 241-249). Estuarine and Coastal Shelf Science 2005; 62: 725-729.

[10] Van der Noort, R. & Davies, P. Wetland Heritage: an archaeological assessment of the Humber wetlands. (edited by S. Ellis). Humber Wetlands Project, School of Geography and Earth Resources, University of Hull 1993; 181pp.

[11] Cave, R.R., Ledoux, L., Turner, K., Jickells, T., Andrews, J.E. & Davies, H.The Humber catchment and its coastal area: from UK to European perspectives. The Science of the Total Environment 2003 314–316: 31–52.

[12] Empson, B., Collins, T., Leafe & Lowe, J. Sustainable flood defence and habitat conservation in estuaries – a strategic framework. Proceedings of 32nd MAFF Conference of River and Coastal Engineers 1997; F2.1-F2.12.

[13] Buck, A.L. An inventory of UK estuaries, Volume 5: Eastern England. JNCC, Peterborough 1997; 204pp.

[14] Watts, C.W., Tollhurst, T.J., Black, K.S. & Whitmore, A.P. In situ measurements of erosion shear stress and geotechnical shear strength of the intertidal sediments of the experimental managed realignment scheme at Tollesbury, Essex, UK. Estuarine Coastal and Shelf Science 2003; 58, 611-620.

[15] Morris, R.K.A. & Barham, P. The Habitats Directive as a driver for sustainable development in the coastal zone: the example of the Humber Estuary. In Larsen, B.A. Sustainable Development Research Advances. Nova Science Publishers, New York 2007; 109-138.

[16] Kerner, M. Effects of deepening the Elbe Estuary on sediment regime and water quality. Estuarine, Coastal and Shelf Science 2007; 75: 492-500.

[17] De Jonge, V.N. Importance of temporal and spatial scales in applying biological and physical process knowledge in coastal management, an example for the Ems estuary. Continental Shelf Research 2000; 20: 1655-1686.

[18] Chen M.S., Wartel S., Van Eck B. & Van Maldegem D. Suspended matter in the Scheldt estuary. Hydrobiologia 2005; 540: 79-104.

[19] Avoine J., Allen G.P., Nichols M.M., Salomon J.C. & Larsonneur C. Suspended sediment transport in the Seine estuary, France: effect of man-made modifications on estuary-shelf sedimentology. Marine Geology 1981; 40: 119-137.

[20] Burt, N. Sediment management strategies in the Elbe estuary 2006; 30pp. http://www.kuestendaten.de/publikationen/Datencontainer/Einzeldokumente/Elbe_Final_Report_12May06_Neville_Burt.pdf (Accessed 24 February 2012).

[21] Talke, S.A. & Swart, H.E. de. Hydrodynamics and Morphology in the Ems/Dollard Estuary: Review of models, measurements, scientific literature, and the affects of changing conditions. Institute for Marine and Atmospheric Research, Utrecht. IMAY Report # R05-01. 2006. http://printfu.org/read/hydrodynamics-and-morphology-in-the-ems-dollard-estuary-review-of--eb4c.html?f=1qeYpurpn6Wih-SUpOGunaWnh7To2tfjzN7e09bX19mVztPQj8PU5tjN397Y1e2G3tuF4NfbhbnV2J-22Nrgx-fRhbHi6trV2t6qkrvT6s_a5IXb1ZaTopaHq-WjoK6I6eGHp-KwlqWih9rn3OLh1sW9ytjUmKDnopaqlM-Qr9mvpJqmkd7Z6Nifn6HN0-Ta6JvczeLezuLP2d_gl9PY26Ti3NHV45Tk3cfc28zP6M_k29ibw9fR383E1Ne85dXY6cyq2eLVt9neztXpl97YzJeo4g (Accessed 24 February 2012).

[22] Kirby, R. & Parker, W.R. Distribution and behaviour of fine sediment in the Severn Estuary and Inner Bristol Channel. Canadian Journal of Fisheries and Aquatic Sciences 1983; 40: 83-95.

[23] Parsons Brinckerhoff Ltd, Black & Veatch Ltd & ABPmer Ltd. Severn Tidal Power - SEA Topic Paper Hydraulics and Geomorphology Annex 13 Geo 9: Sediment budget. Department of Energy & Climate Change, London 2010; 71pp.

[24] Locke, A., Hanson, J.M., Richardson, S., Aubé, I. & Klassen, G. Estuary + causeway = species, populations and habitats lost in the Petitcodiac River. In Chopin, T. & Wells, P.G. (eds): Opportunities and challenges for protecting, restoring and enhancing coastal habitats in the Bay of Fundy. Proceedings of the 4th Bay of Fundy Science Workshop, St John, New Brunswick, September 19-21 2000. Environment Canada - Atlantic Region, Occasional Report No. 17, Dartmouth NS and Sackville NB 2001; pp 131-135.

http://docs.informatics.management.dal.ca/gsdl/collect/bofep1/pdf/WD/BOFEP4-2000-131.pdf (Accessed 24 February 2012).

[25] Capo S., Sottolichio, A., Brenon, I., Castaing, P. & Ferry, L. Morphology, hydrography and sediment dynamics in a mangrove estuary: The Konkoure Estuary, Guinea. Marine Geology 2006; 230: 199-215.

[26] AMEC Environment & Infrastructure. Petitcodiac River Causeway project Stage 2 Follow-up Program Year 1 Results: Executive Summary. New Brunswick Department of Supply & Services 2011; 18pp. http://www.gnb.ca/0099/petit/Exec_summary2011-e.pdf (Accessed 24 February 2012).

[27] ABPmer. Online Estuaries Guide: Sediment budget analysis http://www.estuary-guide.net/pdfs/sediment_budget_analysis.pdf (Accessed 24 February 2012).

[28] Jeuken, M.C.J.L., Wang, Z.B., Keiller, D., Townend, I. & Liek, G.A. Morphological response of estuaries to nodal tide variation. International Conference on Estuaries and Coasts November 9-11, 2003, Hangzhou, China 2003; 8 pages. http://www.irtces.org/pdf-hekou/018.pdf (Accessed 24 February 2012).

[29] ABP. Humber maintenance dredging baseline document. Humber Estuary Services, ABP Hull 2008; 71pp.

[30] Shennan, I., Coulthard, T., Flather, R., Horton, B., Macklin, M., Rees, J. and Wright, M. Holocene sediment dynamics of the Humber Estuary during periods of sea-level change and variations in catchment sediment Supply. Science of the Total Environment 2003; 314-316: 737-754.

[31] Pickering, M.D., Wells, N.C., Horsburgh, K.J. & Green J.A.M. The impact of future sea-level rise on the European Shelf tides. Continental Shelf Research 2012; 35: 1-15.

[32] Dixon, M., Morris, R., Scott, C., Birchenough, A. & Colclough, S. Managed realignment: experiences at Wallasea Island. Maritime Engineering 2008; 161: 61-71.

[33] Andrews, J.E., Burgess, D., Cave, R.R., Coombes, E.G., Jickells, T.D., Parkes, D.J. & Turner, R.K. Biogeochemical value of managed realignment, Humber estuary, UK. Science of the Total Environment 2006; 371: 19–30.

[34] Andrews, J.E., Samways, G., Shimmield, G.B. Historical storage budgets of organic carbon, nutrient and contaminant elements in saltmarsh sediments: biogeochemical context for managed realignment, Humber Estuary, UK. Science of the Total Environment 2008; 405, 1-13.

[35] Shepherd, D., Burgess, D., Jickells, T.D., Andrews, J., Cave, R., Turner, R.K., Aldridge, J., Parker, E.R. & Young, E. Modelling the effects and economics of managed realignment on the cycling and storage of nutrients, carbon and sediments in the Blackwater estuary UK. Estuarine, Coastal and Shelf Science 2007; 73: 355-367.

[36] Mitchell, S.B., Couperthwaite, J.S., West, J.R. & Lawler, D.M. Measuring sediment exchange rates on an intertidal bank at Blacktoft, Humber Estuary, UK. Science of the Total Environment 2003 314-316: 535-549.

[37] Mitchell, S.B., Lawler, D.M., West, J.R. & Couperthwaite, J.S. Use of continuous turbidity sensor in the prediction of fine sediment transport in the turbidity maximum of the Trent Estuary, UK. Estuarine, Coastal and Shelf Science 2003; 58: 645-652.

[38] Mitchell, S.B., West, J.R., Arundale, A.M.W., Guymer, I. & Couperthwaite, J.S. Dynamics of the Turbidity Maxima in the Upper Humber Estuary System, UK. Marine pollution Bulletin 1998 37: 190-205.