



Integrated modelling of an estuarine environment: an assessment of managed realignment options

Dave Shepherd, Tim Jickells, Julian Andrews, Rachel Cave,
Laure Ledoux, Kerry Turner, Andrew Watkinson,
John Aldridge, Steve Malcolm, Ruth Parker and Emma Young

March 2005

Integrated modelling of an estuarine environment: an assessment of
managed realignment options:

Tyndall Centre Technical Report No. 21

Project T2.41

D. Shepherd, T. Jickells, J. Andrews, R. Cave, L. Ledoux, R. Turner, A. Watkinson

Tyndall Centre, School of Environmental Sciences, University of East Anglia

J. Aldridge, S. Malcolm, R. Parker, E. Young,

CEFAS Laboratory, Lowestoft

D. Nedwell,

Department of Biology, University of Essex

Overview of Project Outcomes

This overview briefly summarises the work done under this project. The attached technical report is a summary paper that is in the advanced draft stage of preparation for submission to the journal *Estuarine and Coastal Shelf Science*.

This project aimed to improve methodologies for fully assessing the costs and benefits of managed realignment of coastal defences, particularly by including the value of carbon storage and the attenuation of nutrient fluxes. To this end we have successfully built a coupled hydrodynamic and biogeochemical model of the Blackwater Estuary (our demonstration site) and used this with plausible realignment scenarios to estimate changes in carbon and nutrient fluxes. These have then been incorporated into an environmental economics assessment of managed realignment to evaluate the full cost and benefits.

The specific stages of the work involved the following steps.

1. Work with CEFAS to obtain two models, one hydrodynamic and the other biogeochemical.
2. Set up these models and merge them.
3. Develop an algorithm for denitrification within the models
4. Initialise and validate the models for the Blackwater estuary
5. Develop one managed realignment strategy for the Blackwater as a demonstration
6. Estimate total nitrogen fluxes in the Blackwater
7. Estimate changes in nitrogen fluxes associated with denitrification from managed realignment strategy
8. Offline of the model estimate changes in carbon, nitrogen and sediment burial in the estuary associated with managed realignment. Compare sediment burial changes to offshore supply
9. Conduct a cost benefit analysis of managed realignment in the estuary for the selected scenario using existing information from other projects
10. Incorporate effects of changes in C and N fluxes from managed realignment into cost benefit analysis.
11. Write final report and an interdisciplinary paper incorporating all aspects of this work.

The project has basically met its primary objectives. A companion ecological study in this area was not funded reducing our ability to link ecological effects into the analysis and cuts in funding meant that we only considered one realignment scenario. We also had several changes of personnel with Young, Ledoux and Cave moving to new posts. Despite this we achieved all our objectives. The model and economic analysis can be refined, but we have been able to demonstrate the application of the entire methodology at this demonstration site.

We believe this project represents a valuable contribution to components of the development of the Tyndall coastal simulator and to research into the sustainable management of coastal ecosystems in general - Tyndall Research Theme 4. The requirement for interdisciplinary work across the fields of physical, biogeochemical and socioeconomic science has been demonstrated and realised. There is considerable potential for further work and we have already secured funding from the Environment Agency via the COMCOAST project to continue research in this general area.

Key words/phrases

Sea level rise, carbon storage, nitrogen storage, Blackwater, managed realignment

Final report T2.41

The Effects of Managed Realignment on the Cycling and Storage of Nutrients, carbon and sediments in Estuaries

D. Shepherd¹, T. Jickells^{1*}, J. Andrews¹, R. Cave¹, L. Ledoux¹, D. Burgess¹, R. Turner¹, A. Watkinson¹, J. Aldridge², S. Malcolm², R. Parker², E. Young², D. Nedwell³

1. School of Environmental Sciences, University of East Anglia, Norwich, NR4 7TJ, UK.
2. CEFAS Laboratory, Pakefield Road, Lowestoft, NR33 0HT, UK.
3. Dept. Biology, University of Essex, Wivenhoe Park, Colchester, CO4 3SQ, UK.

1. Introduction

Coastal and estuarine management strategies in the UK have for many centuries, focussed on the building of flood protection dikes and the drainage of wetland systems. However, against a background of rising sea levels due to climate change, the cost of maintaining and improving sea defences around the entire coast has caused policy makers to consider the long term benefits of this strategy. In recent years therefore, the focus has moved towards managing coasts in a more dynamic manner, protecting areas of high value, whilst allowing coastal processes to proceed relatively unhindered elsewhere.

Coastal and estuarine wetlands provide both habitat and a self sustaining flood defence. The biodiversity and functional value of wetland habitats is widely recognised, and the UK government has commitments under the European Union Habitats Directive to follow a no-net-loss policy within large designated areas (Crooks and Turner, 1999). The ability of intertidal areas to attenuate wind wave height has been established and there is increasing evidence that they can also attenuate tidal amplitude (Pethick, 2002), hence providing sustainable coastal defence. Managed realignment, where coastal defences are breached allowing previously reclaimed land to be subjected to tidal flooding, has therefore become increasingly attractive as an integral part of coastal and estuarine management strategy.

There are four main drivers for the identification of potential realignment sites:

- 1 - Mitigation sites for a development where habitat will be lost
- 2 - Compensation for natural habitat loss (potentially due to coastal squeeze/sea level rise)
- 3 - Compliance with EU Habitats or other directives for creation of habitat
- 4 - Cost-effective flood defence strategy for a particular area.

These have been incorporated into several management strategies, the main one being the Shoreline Management Plans (SMPs), created in 1996/7, which identify options for the coastline mainly in terms of socio-economics, infrastructure, land-use and coastal processes where this information is available. An example of the protocol followed for a given site is as an option assessment for a given area of land (Pethick, 2003). This involves appraisal of the various options on a site-by-site basis and may involve looking at the history, geology and geomorphology of a site and using numerical modelling to assess/predict sediment budgets and morphological/profile change which would occur if the site was realigned. The option of managed realignment is then set in the context of other options such as 'do nothing' (hold the line) or other options, and hence a suitable option is recommended. This approach relies heavily on expert judgement and is focussed on identifying the sustainable option in terms of hydrodynamics and coastal processes. However, other considerations such as the practicality of removal of the flood embankments and economic considerations have also to be added in due course. In this case habitat creation assessment is undertaken separately. The exact approach may differ between sites, but the overall criteria examined are common to most sites.

Ultimately, rational evaluation of management options requires a full understanding of *all* the environmental roles played by environments lost and created by managed realignment and an evaluation of the economic value of *all* the services provided by these environments. These benefits can then be set against the engineering costs associated with maintaining current sea defences and compared to the net value of environments lost through managed realignment (opportunity costs). Constanza et al. (1997) argued that nutrient (nitrogen and phosphorus) cycling represents the major environmental service from coastal areas, and although controversial (Turner et al., 1998) it does serve to emphasise the importance of considering nutrient cycling and also sediment transport in developing coastal management strategies. This is further supported by Andrews et al. (2000) and Jickells et al. (2000) who have shown in the Humber Estuary, U.K., that loss of intertidal environments can markedly reduce the trapping of carbon and nutrients within the estuary. This trapping arises through a combination of sedimentation, primary production and denitrification predominantly in intertidal areas, so the loss of intertidal area directly impacts storage capacity. Since loss of intertidal area due to reclamation has been so extensive in recent centuries it implies that recreation of wetlands could significantly reduce fluxes of nitrogen and phosphorus into the North Sea. Andrews et al. (2000) calculated that >90% of intertidal areas have been lost in the Humber estuary UK and Jickells et al. (2000) estimated that nitrogen and phosphorus fluxes

into the North Sea could be reduced by more than 50% and 25% respectively if all the intertidal areas were restored.

The UK is committed to a 50% reduction in inputs of nitrogen and phosphorus to areas of the North Sea that are suffering from pollution. This obligation under the OSPAR Convention has yet to take effect for the UK. The EC Nitrates from Agriculture Directive (the "Nitrates Directive") requires the establishment of Nitrate Vulnerability Zones where "good agricultural practice" is adopted to reduce the loss of nitrogen as a contribution to reducing eutrophication pressures. Progress to this target by the UK (and other European countries) has been slow and control of emissions, particularly of nitrogen from agricultural sources, is proving costly and difficult. Creation of wetland environments, effectively allowing the natural nutrient cycling capability of the ecosystem to function, offers a mechanism to reduce eutrophication pressures on the North Sea and meet treaty obligations. Storage potential for organic carbon has also been reduced by reclamation. Andrews et al. (2000), for example, show that organic carbon storage has been reduced by more than 99% by reclamation in the Humber estuary, UK. Managed realignment would restore some of this storage potential by increasing overall sedimentation within the estuary. Such storage may in the future need to be valued in terms of carbon credit/taxation schemes.

The calculations of Andrews et al. (2000) and Jickells et al. (2000) were simplistic. The processes leading to nutrient and sediment storage in estuaries are highly non-linear, particularly for denitrification which depends on nitrate concentration (Nedwell et al., 1999). Using the Blackwater/Colne estuary, Essex, UK as a case study, we have developed a more sophisticated methodology based on a full numerical estuarine model, incorporating established and robust hydrodynamic and transport models, and established socio-economic techniques. We have quantified physical changes and estimated associated economic values in environmental services associated with changes in nutrient, sediment and carbon storage arising from managed realignment. The methodology can be adapted to other estuaries by reconfiguring the model, and we have identified some general guidelines concerning the implication of managed realignment for environmental services for estuaries in general. These can then be applied in other systems to evaluate the costs and benefits of various managed realignment options.

2. Blackwater/Colne Estuary

The Blackwater/Colne estuaries are situated in Essex in the East of England, an area characterised by low-lying land adjacent to the coast and subject to both climate-driven and isostatic sea-level rise. Annual relative sea-level rise has been estimated at 6mm yr^{-1} (NRA, 1994) and the Essex coast has been identified as having an "extreme" risk of shoreline erosion (Foresight 2004). Land reclamation began in Roman times and continued from the 15th century. After suffering a devastating flood in 1953, a coastal-defence system was established in Essex comprising 400 km of seawalls (Emmerson et al., 1997). Although heavily defended, the Blackwater/Colne estuary is relatively natural, having lost only 21% of intertidal area to reclamation, the smallest proportion among the Essex estuaries. This compares with 88% loss in the nearby Crouch estuary (Townend and Pethick, 2002). However the ratio of saltmarsh to mudflat is only slightly greater than for the Crouch, suggesting that prior to reclamation, salt marsh was not as extensively developed as elsewhere in Essex, with greater expanses of mudflat instead. The reasons for this are unclear but are probably due to geological constraints (English Nature, 2002). Quaternary terrace gravels limit channel width at Bradwell/Mersea so that the channel widens upstream. The islands of Osea and Northey along with steep valley sides force the estuary to subdivide producing large areas of mudflat with little or no saltmarsh. In effect, there is a process of natural coastal squeeze, exacerbated by the effects of reclamation and flood embankments. The Colne appears relatively stable (English Nature, 2002) - despite being the smallest estuary in Essex it has the largest area of salt marsh, having suffered little from the effects of reclamation. It is also free of the geological constraints which affect the Blackwater. However, despite the relatively small areas of reclaimed land available for restoration, the high cost of repairing or replacing the aging sea defences coupled with the pressures of sea -level rise have encouraged alternative approaches to coastal management to be considered.

The Blackwater and Colne are hypernutrified estuaries receiving significant loads of nitrogen from the catchments and from sewage inputs at Maldon and Colchester (Nedwell et al., 1999). Action is being taken under relevant EC Directives to reduce the load of nutrients from urban waste water and agriculture but recent designation of the area under the 'Habitat's' Directive together with the development of a local Essex Estuaries Initiative may increase pressure for further reductions in nutrient input. Management strategies have been proposed to provide sustainable flood defence and experiments are underway on the use of managed re-alignment of the coast (at Tollesbury, Orplands, Northey Island and Abbots Hall)

to mitigate flood risk. Preliminary results are available for nutrient exchange between the estuary and the reclaimed areas but have not been set in the context of the overall estuarine processing and fluxes of nitrogen (Emmerson et al., 1997).

In addition to several nature designations, the estuary is also a valuable asset in terms of heritage, landscape and marine environment, as well as recreation, tourism, fishing, agriculture and riverside industry.

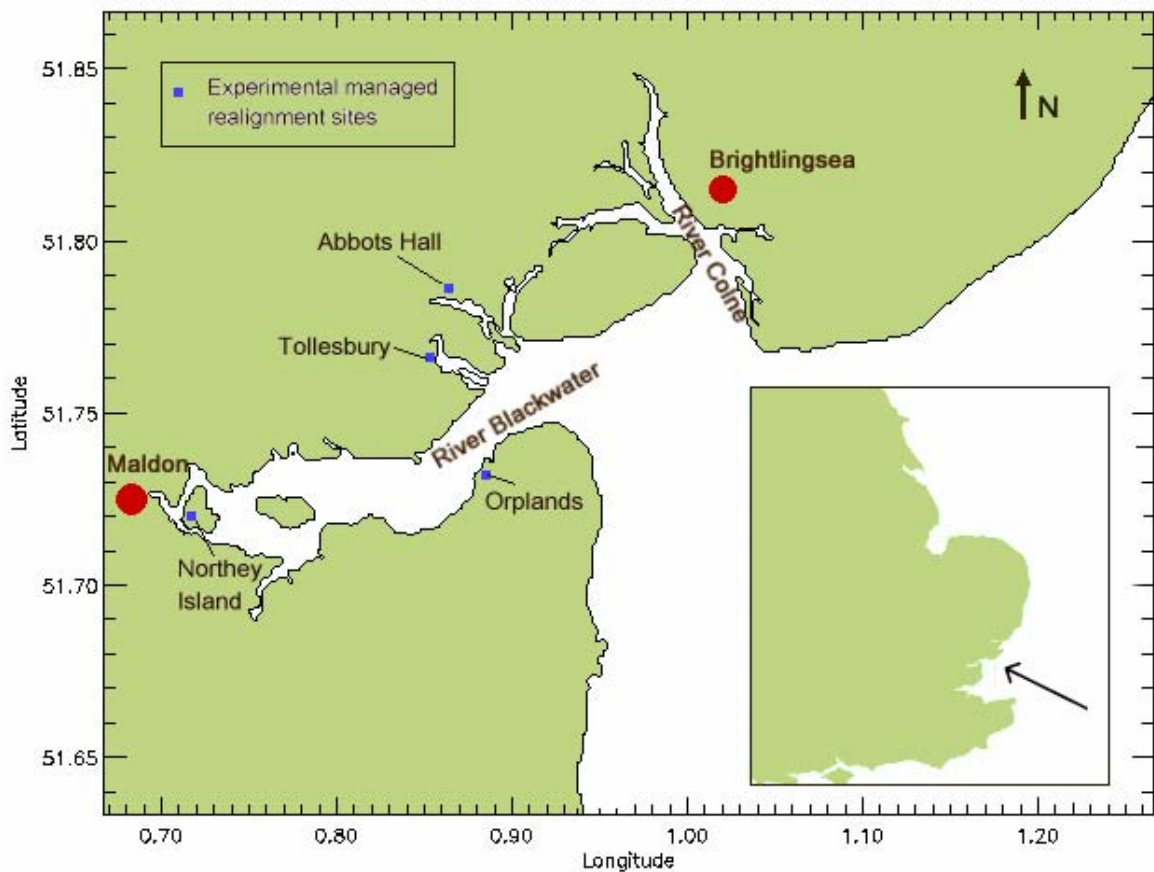


Figure 1. Location of Blackwater/Colne Estuaries

The Blackwater/Colne estuary was chosen for this study primarily because of the hydrodynamic, water quality, and biogeochemical data available, as well as the existence of highly monitored experimental realignment schemes. This enabled initialisation and validation of the numerical models. Although the loss to reclamation, and hence the potential for realignment, may be less than some other estuaries (e.g. the Crouch) this only means that estimates of potential increased nutrient removal will be conservative.

3. Hydrodynamic Model

Water velocity fields for the Blackwater/Colne estuaries were simulated using the PRISM hydrodynamic model developed at the Proudman Oceanographic Laboratory. The model has been widely reported in the literature (e.g. (Aldridge and Davies, 1993; Davies and Aldridge, 1993) and only a brief description is given here. Standard shallow water equations are solved on a finite difference grid in the horizontal, with an optional 3D capability based on a spectral approach in the vertical. The model has been extensively validated for the Irish Sea (Aldridge and Davies, 1993; Davies and Aldridge, 1993; Davies and Lawrence, 1994)). For this study, tidal forcing using 4 harmonic components was used to yield elevation and depth averaged flow fields at 30 minute intervals for subsequent transport calculations. The computational domain comprised 419 x 257 numerical grid points, giving a grid size of 101m x 98m (Figure 2). This configuration allowed a reasonable spatial resolution of the coastline and a reasonable temporal resolution of tidal currents whilst maintaining computational efficiency. The effect of spatially varying bed friction has been shown to have little effect on tidal currents (Aldridge and Davies, 1993) and hence a uniform bed friction was used. Freshwater inputs to the estuary via the two main rivers, the Colne and the Blackwater, were specified as a constant discharge equal to the mean flow for winter months.

Validation of the model comprised comparison of tidal amplitude and phase with observational data and comparison of velocity with flow gauge data (Appendix I).

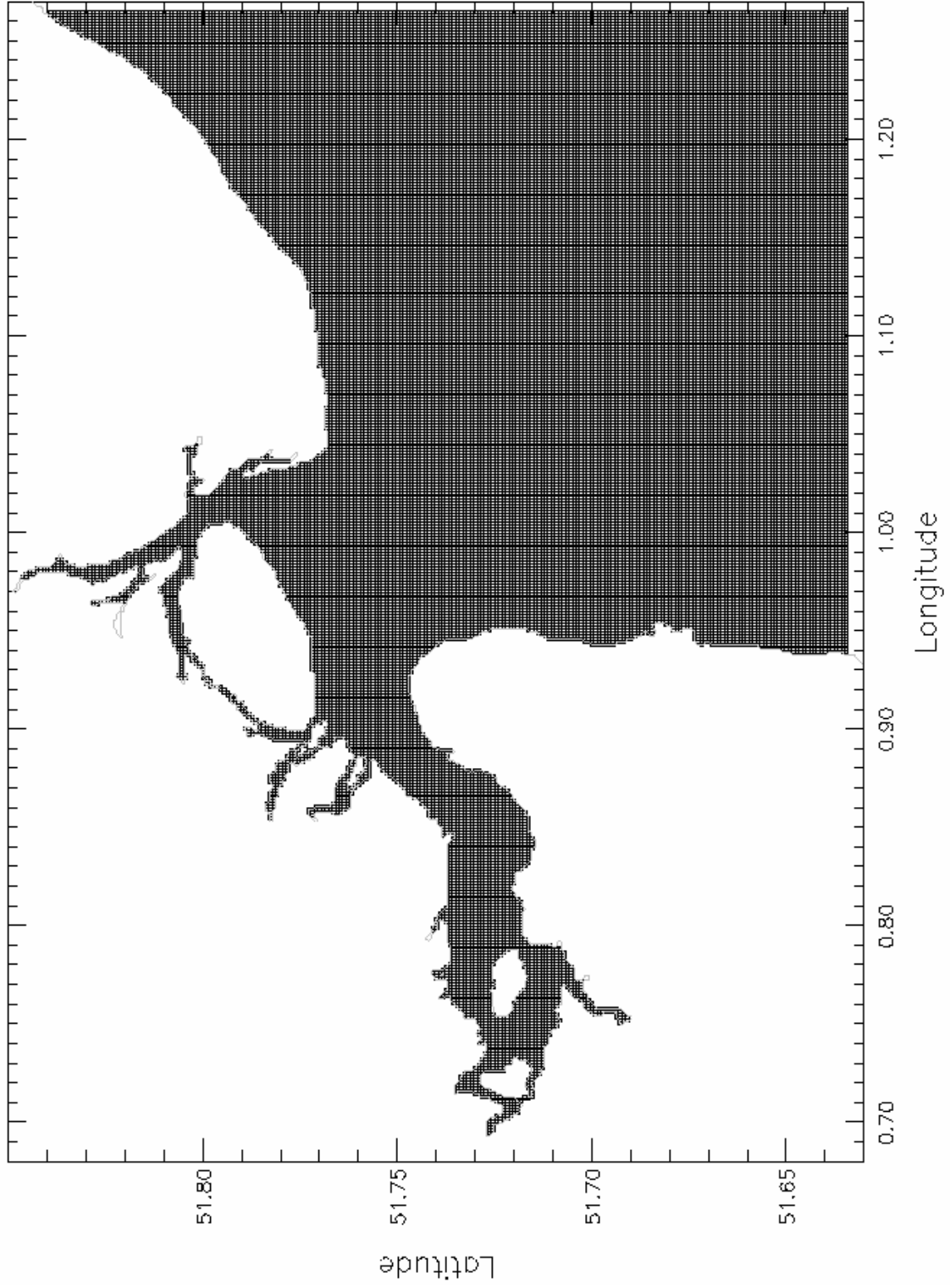


Figure 2. Computational Grid of the Blackwater-Colne Model

3.1 Transport Model

Simulation of the transport of nutrients within the estuary by advection and diffusion processes was accomplished using the COSE transport model described by Aldridge et al. (2003). The model is capable of dealing with movement of material in both dissolved and particulate (sediment bound) phases, with transfer of contaminants between phases, and allowance for simultaneous transport of a number of sediment classes. All transport equations are solved using a conservative finite volume scheme on a regular, spherical polar grid. Budgets are calculated at each time step to ensure exact (within rounding error) conservation of material. Care is taken that the input flow and elevation fields exactly conserve mass to avoid the generation of spurious concentration gradients. An operator splitting approach is used, with horizontal advection and diffusion processes solved in the first half time step and the vertical processes in the second half. Horizontal advection is implemented using the non-diffusive positive definite scheme of Smolarkiewicz (1984). Vertical shear dispersion, scaling on the product of depth mean velocity and depth, is included in the transport equations. Sediment erosion and deposition, bed mixing, and contaminant exchange processes use standard implicit finite difference formulations. The model was used in its 2D form on the same computational grid as used to generate the current fields.

Nutrient inflows to the estuary were specified as mass per unit time at the same grid location as the river inputs to the hydrodynamic model. Boundary conditions were open sea concentrations on the East and South boundaries and zero on the West and North boundaries (upstream of the river point sources). A uniform initial concentration was specified throughout the computational grid.

Validation of the model was accomplished using salinity, since the available observational data was comprehensive. Detailed plots of salinity simulations may be found in Appendix II.

3.2 Carbon, Nitrogen and Phosphorus Burial

Burial of organic rich sediments within an estuary acts as a sink for carbon, nitrogen and phosphorus (Jickells et al., 2000). In addition, degradation of organic carbon within the sediment can exhaust available oxygen, allowing the use of alternative electron acceptors, particularly nitrate, i.e. the process of denitrification. The fate of denitrified nitrate can be complicated but in a nitrate-rich system such as the Blackwater, N_2 and N_2O will be the dominant products leading to an overall reduction in nitrate transport offshore (Nedwell et al.,

1999). It should be noted that estuarine denitrification can be a significant source of the greenhouse gas N_2O .

The area of intertidal sediment where we assume sediment burial can take place was estimated with and without the realignment scenarios. We then assumed sedimentation rates (see below) and from this calculated sediment storage in mudflats and saltmarsh, assuming bulk density of 1.6 for mudflat and 2.6 for saltmarsh (Parkes, 2004). The distinction between the two habitats was based on elevation relative to the tidal frame. The bulk sedimentation rate was converted to C, N and P storage using average C, N and P concentration from the East of England which Parkes (2004) has shown to be applicable throughout large areas of the UK east coast.

Estimation of sedimentation rates within the estuary after realignment is subject to considerable uncertainty. Estuaries are thought to adjust to sea-level rise by erosion of intertidal areas in the outer estuary and deposition of these sediments in the inner estuary. In this way, the estuary moves landwards as sea level rises. Additional sediment from marine sources allows the estuary to also move upwards and so maintain its position within the tidal frame (Pethick, 1998). This additional marine derived sediment represents the net sink for carbon, nitrogen and phosphorus as described above.

The current rate of sea level rise in the Blackwater/Colne estuaries is 6mm a^{-1} (NRA, 1994) and therefore sedimentation rates of 6mm a^{-1} might be expected. However, whilst accretion rates in the Tollesbury experimental site have reached 7.1 mm a^{-1} in the creek margins and 3.3 mm a^{-1} in the marsh interior (Cahoon et al., 2000) and some estuaries are known to have accreted at high rates in the past, there is as yet, little evidence that such rates could be sustained *throughout* the estuary over *decadal* timescales. Long term sustained accretion rates in other estuaries have been measured at $1\text{-}2\text{ mm a}^{-1}$ and Pethick's (1998) calculation of the Blackwater's sediment budget corresponds to a 4mm a^{-1} sedimentation rate when averaged over the whole estuary. The potential effect on the sediment budget of the Blackwater/Colne estuaries of wide scale managed realignment is unclear.

We have therefore based our calculations on two sedimentation rates. The first, 1.5 mm a^{-1} corresponds to the long term sustainable rate observed elsewhere. The second, 6mm a^{-1} corresponds to the upper limit which *may* be achieved during the immediate post-realignment phase. Tables 2 and 3 show the quantity of nutrients buried annually for the two sedimentation rates.

3.3 Denitrification

Nedwell et al. (1999) have demonstrated in the Colne estuary and elsewhere that denitrification is a strong function of nitrate concentration. A Michaelis Menton equation was fitted to the data presented by Nedwell et al. (1999) for the relationship between sediment denitrification and nitrate concentrations. This relationship was used to describe denitrification rate in the model. Modelled nitrate concentrations within the water column were allowed to diffuse into the sediments in the model based on a fixed exchange rate of water between the water column and the porewater zone. Within the sediments, denitrification was allowed to take place throughout the upper 10 cm according to equation according to the Michaelis Menton equation described above:

$$\text{denitrification rate} = V_{\max} \left(\frac{N}{N + k_N} \right)$$

where N is nitrate concentration (Kg m^{-3}), $k_N = 0.002 \text{ Kg m}^{-3}$ and $V_{\max} = 2.41\text{E-}6 \text{ Kg m}^{-2} \text{ hr}^{-1}$. Alternative and more complex formulations to describe all the processes considered are of course possible. Our goal was to determine the relative importance of the various processes and hence allow further research activity to focus on key processes and uncertainties.

3.4 Simulations

The Blackwater/Colne estuary was the target of a demonstration project to provide tools to identify potential sites suitable for habitat creation by managed realignment. The project was funded jointly by DEFRA FCD and the EA (FD1917 – Suitability Criteria for Habitat Creation). In order to provide realistic scenarios for managed realignment areas within the Blackwater and Colne system, information derived from this project was adapted to drive model assessment of areas suitable for habitat creation. Criteria of a site that are required to make a site suitable for habitat creation (salt marsh or intertidal flat) were addressed in this project. The main controlling feature for habitat suitability is elevation and a rough application of the elevation thresholds for salt marsh and intertidal flat were applied across the Blackwater/Colne region. The selection process was implemented using a GIS. The details are summarised in Table 1. Other environmental criteria such as slope and proximity of colonising species as well as political and socio-economic criteria were not applied and therefore the area available for setback has been over-estimated. However, this was deemed acceptable for the intended purpose of studying the potential impact on nutrient cycling within

the estuary. Present day bathymetry and the setback bathymetry with potential areas of mudflat and saltmarsh are shown in Figures 3 and 4.

Water flow and nutrient transport were simulated for a 6-month winter period driven by hydrological and chemical data from the winter of 1995/96 (October - March). River inputs for the Colne and Blackwater were specified as the mean winter flow ($3.29 \text{ m}^3 \text{ s}^{-1}$ and $1.09 \text{ m}^3 \text{ s}^{-1}$ respectively). Mean nitrate input rates were calculated for winter months from Environment Agency data and specified in the model as constant values of 0.0333 Kg s^{-1} and 0.0109 Kg s^{-1} respectively. Offshore boundary and background nitrate concentrations were calculated from CEFAS survey data and specified in the model as $3.45\text{E-}4 \text{ Kg m}^{-3}$ - $3.53\text{E-}4 \text{ Kg m}^{-3}$ and $3.5\text{E-}4 \text{ Kg m}^{-3}$ respectively. The simulations were conducted for both the existing and setback scenarios.

The hydrodynamic model output depths and currents for the entire computational domain at half hourly intervals. The transport model output water column and porewater nitrate concentrations at 30 minute intervals and cumulative totals of nutrients entering and leaving the domain as well as total denitrified at 40 second intervals.

As explained in Section 2.3, it is essential that the current and depth fields produced by the hydrodynamic model conserve mass otherwise spurious concentration gradients arise during transport simulations. This presented a problem when applying the model to an estuary since the hydrodynamic model does not fully conserve mass when wetting and drying takes place in intertidal grid cells. In this preliminary study the modelling procedure was adapted to circumvent this problem. This was achieved in two stages. First the hydrodynamic simulations were conducted to provide information on all wetting and drying instances during the 6 month simulation period. The bathymetry was then modified to a minimum depth criterion such that no drying would occur. The hydrodynamic simulations were repeated with the modified bathymetry. Nutrient transport simulations were conducted on the second flow fields, but the information on wetting and drying from the first simulations was used to prevent nutrient transport within grid cells at times when they would be dry.

3.5 Results

Outcomes of the results pertinent to cost benefit analysis (see below) are summarised in Tables 2 and 3 in terms differences of C, N and P stored. Simulations results are shown in Appendices.

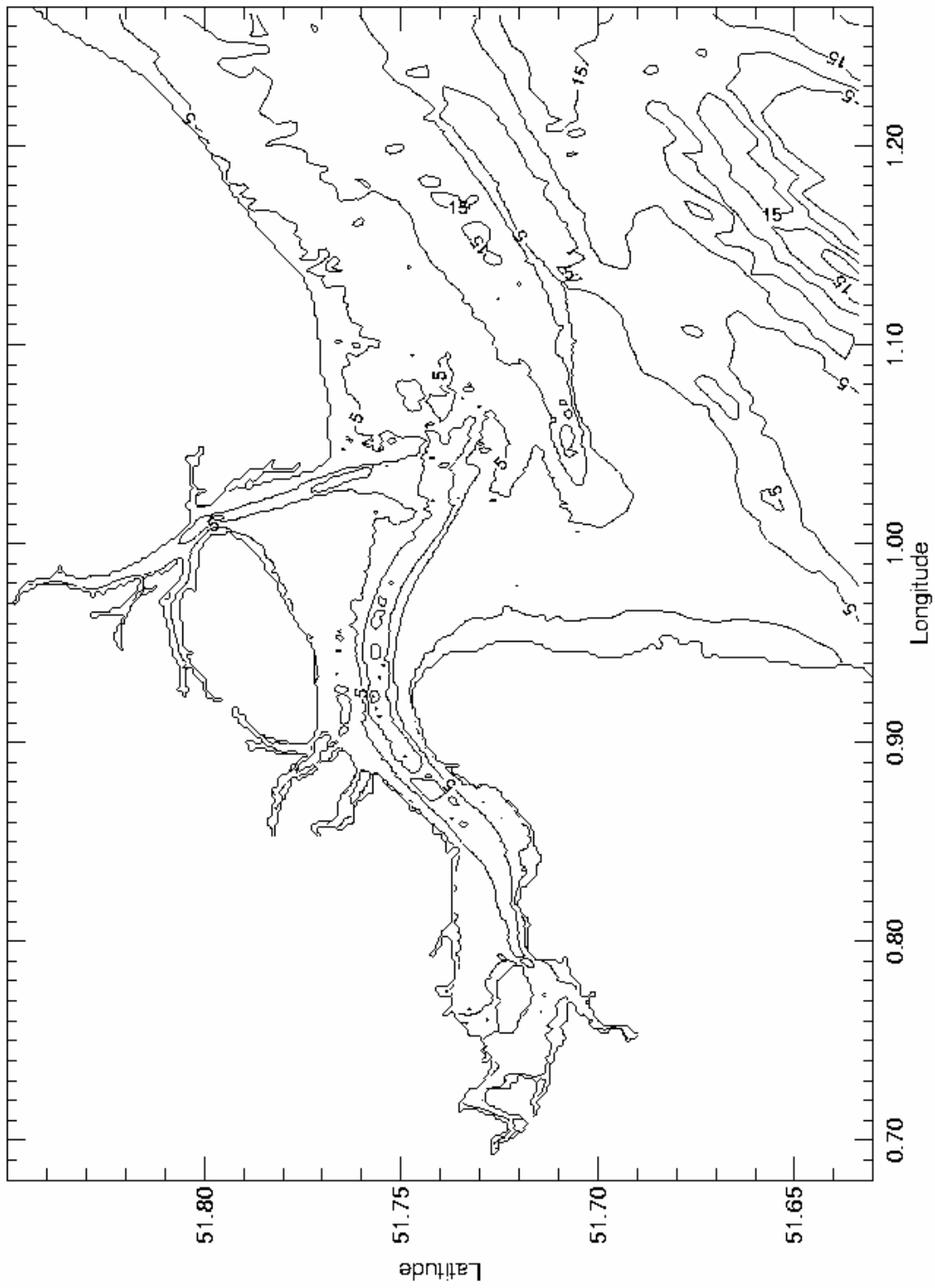


Figure 3. Bathymetry of Blackwater-Colne

Table 1: Suitability criteria for salt marsh and mudflat creation

Habitat	Criteria/layer	Criteria information	Thresholds applied	Data source
Saltmarsh	Elevation	Elevation must be suitable for salt marsh vegetation colonisation. The minimum elevation should be around the level of <i>MHWN in the location of the proposed site</i> , or at a level that would experience 450-500 tidal inundations per year.	MHWS - MHWN	EA LIDAR data (mOD).
Mudflat	Elevation	For intertidal mudflats or sandflats to develop, the site needs to be at an elevation between low spring tides and the level at which salt marsh develops, i.e. the site should experience at least 450-500 tidal inundations per year, or be below MHWN.	MHWN - MLWS	EA LIDAR data (mOD).

(MHWS = mean high water spring; MHWN = mean high water neap; MLWS = mean low water spring)

4. Cost Benefit Analysis

Both costs and benefits can result from managed realignment. An appraisal process is thus required to identify and evaluate potential options and to identify the one that most closely satisfies the defined project objectives. For flood and coastal defence projects the following are important:

- reducing the risks to people and to the developed and natural environment from flooding and coastal erosion;
- identifying a solution that is technically sound and most fit for its purpose;
- being environmentally acceptable and sustainable;
- ensuring best value for money from a national perspective.

Cost benefit analysis (CBA) provides a framework in which the economic efficiency of potential realignment schemes is assessed. It involves identifying and measuring, in monetary terms, as many of the costs and benefits as possible that relate to a particular project (Pearce, 1983). This helps determine whether a project will produce a net gain or loss in economic welfare for society as a whole (Edwards-Jones et al., 2000). In CBA all the pros and cons of a project are translated into monetary terms. As a rule, a project is efficient if total benefits exceed total costs, and in the context of flood defence can be used to identify the most

environmentally and economically suitable sites for realignment (Spurgeon, 1998). However, the monetary impacts represent only a sub-set of the total costs and benefits of the management realignment schemes, as translating all the costs and benefits of a policy scenario into monetary terms can be impractical or not meaningful. CBA thus provides an aid to decision making: the most cost efficient option may not be the most appropriate on other grounds (Pearce, 1983).

The main stages of undertaking a CBA are.

1. Defining details of each scheme, including a 'do nothing' option (DEFRA, 2001c).
2. Determination of the spatial and temporal scales of the analysis (Spurgeon, 1998).
3. Identification of the costs and benefits and their monetary values. Monetary value may be based on market value (or replacement cost) for assets such as power lines (Pilcher et al., 2002). To enable valid comparisons, all monetary values must refer to a common point in time – the base year. A standard 'discount rate' is applied so that costs and benefits incurred over the operation life of projects with varying time scales can be compared (DEFRA, 2001a).
4. The economic efficiency of options is assessed through comparing either their 'benefit-cost ratios', i.e. the present value of benefits divided by the present value of costs, or their 'net present values', i.e. the present value of benefits less the present value of costs (DEFRA, 2001b).
5. A sensitivity analysis should be included within a CBA, to assess the impact on the benefit cost ratio and/or net present value of changes in the values of central parameters, e.g. the value of costs and benefits or the discount rate. By examining the impact that increasing cost (or reducing benefit) may have on the net present value, the break-even point can be determined whereby the scheme would be no longer justifiable.

This process was applied to the managed realignment schemes in the Blackwater Estuary to assess whether a net benefit was produced.

Uncertainty regarding future economic development and climate change (DEFRA, 2001a) means there are an infinite number of possible futures for coasts. To help reduce uncertainty and aid decision-making, a number of managed realignment scenarios are usually developed based on the foresight scenarios.

In the Blackwater, based on the physical simulations (see above), two scenarios were used: one with no realignment and the other including realigned defences. The “hold the line” scenario (HTL) refers to retention of existing flood defence, i.e. the “do nothing” scenario. This forms the reference point to compare the benefits and costs of managed realignment. The managed realignment scenario was based only on creating the maximum area of inter-tidal habitat. This raises a number of potential conflicts with the current uses of the land due to be converted into inter-tidal habitat. Although quite sophisticated criteria can be developed to analyse this (e.g. Coombes 2003), the resources available to us allowed only a simple approach. However, to make our approach more realistic, the cost of maintaining flood defences for Maldon were included. Details of the realignment areas are shown in Tables 2 & 3 for the two sedimentation rates chosen.

Table 2: Details of realignment areas for a sedimentation rate of 1.5mm y⁻¹

Scenario	Length of defences before realignment (km)	Length of hard defences after realignment (km)*	Length of realigned defences (km)	Amount of intertidal habitat created by realignment (ha)	Estimated tonnes of Carbon stored each year (Andrews et al, 2000)	Estimated tonnes of Nitrogen stored each year	Estimated tonnes of phosphorus stored each year
Hold-the-line	170	170	0	0	0	0	0
Realignment	170	10	160	5320 2950 (saltmarsh) 2370 (mudflat)	2354.4	281.2	146.1

Table 3: Details of realignment areas for a sedimentation rate of 6mm y⁻¹

Scenario	Length of defences before realignment (km)	Length of hard defences after realignment (km)*	Length of realigned defences (km)	Amount of intertidal habitat created by realignment (ha)	Estimated tonnes of Carbon stored each year (Andrews et al, 2000)	Estimated tonnes of Nitrogen stored each year	Estimated tonnes of phosphorus stored each year
Hold-the-line	170	170	0	0	0	0	0
Realignment	170	10	160	5320 2950 (saltmarsh) 2370 (mudflat)	9417.7	876.8	584.4

Before 2003 the assessment of flood defence schemes was based on a 50 year time span. With the introduction of new Treasury Guidance (HM Treasury, 2003), it was recommended that the appraisal period should reflect the physical life (with maintenance) of the longest-lived asset within the scheme. For flood and coastal defences, it was determined that for most schemes involving major earthworks, concrete and masonry structures, a 100 year timeframe is appropriate (DEFRA, 2003) and is adopted here.

4.1 Determining monetary costs and benefits of each scheme

A subtle but important issue in CBA when aggregating benefits is that of double-counting, i.e. where a benefit (or a cost) is included twice within the evaluation process and therefore gains more importance within the final decision than it deserves. Double-counting is a particular issue in this Blackwater case study. The functions of wetland ecosystems such as intertidal habitats are highly multi-functional, with many benefits (and costs) being dependent on a combination of functions, and those benefits or costs being distributed both within and outside the wetland ecosystem. If each of the functional values provided by a wetland ecosystem was to be identified separately, and then attributed to the underlying functions, there is the likelihood that benefits will be double counted. For instance, Barbier (1994) notes that if the nutrient retention function is integral to the maintenance of biodiversity, then if both functions are given monetary values separately and these values are then aggregated, this would double count the nutrient retention which is already 'captured' in the biodiversity value. Furthermore, some functions might also be incompatible, such as water extraction and groundwater recharge, so that combining these values would overestimate the feasible benefits to be derived from the ecosystem. Benefits need therefore to be explicitly allocated between functions.

In evaluating policy options for wetlands, it is essential to establish all these linkages to ensure that all benefits and costs are included correctly within the decision-making process. Using the example given in Barbier (1994), the decision-maker may consider both biodiversity and water quality (relating to nutrient retention) to be important and include both within the MCA. Thus the same value will be included twice. However, it is imperative that before the process of choosing the preferred option occurs, the potential for double counting is recognised.

In this Blackwater study, to avoid the double-counting issue the CBA focuses on independent goods and services produced by the intertidal habitat. As only partial evaluation of benefits-derived are included, the CBA underestimates of the total economic value of the managed realignment schemes.

4.2 Costs of Realignment

In determining the total costs of implementing the realignment schemes a number of costs must be taken into account. In addition to the initial capital costs incurred in the physical realignment of the defences, there are also the costs of maintaining the newly realigned defences over the time span of the project. The costs of maintaining the existing defences as

well as the realigned defences must also be considered. This can be included as a cost incurred on all the schemes dependent on the length of defences remaining, or can be considered as a benefit – the reduced cost of maintaining hard defences relative to realigned ones. For simplicity, in this CBA, these maintenance costs are included as costs. The conversion of the land lying seaward of the realigned defences into intertidal habitat will result in a loss of value from its former land-use - the opportunity cost.

As the Blackwater managed realignment scheme involves retreat to the level of the indicative flood plain/highest spring tide, no secondary defences are required. The quoted capital costs of realignment are an average including the creation of secondary defences; thus the values used are an over-estimate.

Maintenance costs assume the defences are currently at the 1 in 100 year flood standard, however it is likely that many of these defences will be coming to the end of their design life of 50 years. Thus, further costs could be incurred by replacing existing defences currently in unsatisfactory condition. However, we had no access to data on the condition of the existing defences. To generate a conservative estimate of the managed realignment scheme we have assumed that all the defences offer a satisfactory level of defence.

A summary of costs involved in the Blackwater managed realignment include the following.

Capital Costs - *the costs of realigning the defences.*

- Based on average costs for other UK realignment schemes **£811,893/Km** (Dixon, 2003).

Cost of land – *the value of the land to be converted into intertidal habitat.*

- Most land identified for conversion is undeveloped and primarily used for agriculture. A number of methods can be used to determine the value of this land. In this study the opportunity cost of the land was used as this is the true economic cost of converting the land into intertidal habitat. All the land previously protected by the flood defences which would be converted into inter-tidal habitat was assumed to be grade 3 agricultural land to develop a conservative estimate of the cost. Agricultural subsidies were accounted for using the method of Dickie and Pilcher (2001).

Predominant grade of land	Average price (£/ha)	Average price taking into account subsidies x0.3 (£/ha)
Grade 1	7,033	2,110
Grade 2	7,033	2,110
Grade 3	7,941	2,382
Grade 4	5,310	1,593
Grade 5	5,310	1,593

Maintenance Costs - Ensuring that the defences are maintained at a satisfactory level.

Debate exists over the costs of maintaining the non-realigned defences.

1. The Environment Agency estimates the cost of maintaining the Humber flood defences at £1,200/km/yr (Edwards, 2002, personal communication).
This figure was compared to other maintenance costs identified and found to be considerably lower than the majority of figures suggested.
2. The highest maintenance costs were £5,000 km/yr (e.g. Bowers, 2000, cited in Dickie and Pilcher, 2001; NRA, 1992b, cited in King and Lester, 1995).

In this study the higher value of **£5,000** was applied to provide a conservative estimate.

We also assumed (despite possible future sea-level rise) that no increased cost of raising, maintaining or providing additional defences would be required. Our cost estimate is thus a minimum. To consider these additional costs, the CBA included an increase in maintenance costs of 2% per year, over the time horizon of the analysis.

Further costs may also be incurred if the realigned defences do not offer the same level of flood protection as that provided by the existing defences. For the purpose of this case study, it was assumed that the overall standard of protection that would be provided by the realignment schemes would be as good as that provided by the defences before they were realigned.

4.3 Benefits of Realigning

The quantification of scheme benefits should encompass all relevant social welfare gains that can be assigned to the introduction of the new investment. However, there is an ever present danger of double counting inherent in such exercises (see above). In the case of managed

realignment in the Blackwater Estuary, extension of the area of intertidal habitat will provide enhanced carbon and nutrient storage capacity and hence improved water quality in the estuary, as well as providing landscape/amenity, recreation and biodiversity/habitat benefits.

In order to avoid double counting, only one composite environmental benefit value has been included within the CBA -“*habitat creation benefit*”. Therefore, the nutrient storage functional benefit has not been valued independently. The improved water quality impact will be interpreted by the public as an increase in general environmental amenity and will be encompassed by any valuation of the general environmental gain (landscape, amenity, recreation and habitat augmentation) likely to be connected to managed realignment.

We have, however, included one extra independent benefit value estimate to cover the *carbon sequestration* function that extended intertidal areas would generate. This function and its value are not encompassed by the composite environmental value estimate as it is provided independently of the other “environmental” goods and services.

A summary of the benefits of realignment is given below.

Carbon Sequestration

- Carbon credits can be generated from the creation of habitats that sequester carbon and used to offset taxes on greenhouse gas emissions imposed by the Kyoto Protocol. Various figures have been suggested for the monetary value that may be placed on carbon credits, two possible approaches exist. (1) An estimation (in monetary terms) of the environmental damage done per tonne of carbon equivalent emitted into the atmosphere - the “damage cost avoided” by storing rather than releasing a given quantity of carbon equivalent units. (2) Based on the price of pollution permits* to represent the economic value of the likely carbon abatement costs incurred by polluters – relates to the abatement costs avoided per tonne of carbon stored.
- In this case, the first approach has been undertaken with a cost of £7/tc which is at the lower end of estimates (Pearce, 2003; Tol et al.. 2000)

Value of created intertidal habitat

- Many of the values that intertidal habitats provide in terms of, for example recreation, are difficult to quantify in monetary terms. Moreover, few studies have quantified these benefits and those that have suffer from ‘limited

transferability’, i.e. many studies value wetlands and intertidal habitats in their own right which do not equate to a price per hectare value.

A summary of values for composite environmental habitats are shown below.

Study	Quoted value	£/ha/year
Brooke (1992)	£18,500/ha/yr (1992)	22,920
Costanza <i>et al</i> (1997)	US\$9,990/ha/yr (1994)	7,752
WWF (2004) (function)	US\$907/ha/yr	614
Woodward & Wui (2003)	US\$306/acre/year (1990)	574
WWF (2004) (Wadden Sea)	US\$211/ha/year (2003)	122

- Due to the variability of figures used in the literature (Table above), a range of the conservative figures (£122-574/ha/yr) were used in this Blackwater study, comparison with the Dutch Wadden Sea being thought most appropriate.

4.4. Assessment of economic efficiency and standardising costs and benefits

To estimate the net present value of providing defence for each of the scenarios, the present value of all the costs were subtracted from the present value of all the benefits. This involves ensuring that all the costs and benefits are standardised into present values, taking into account the fact that the figures used are from studies undertaken in different years and some costs and benefits are one-offs and others occur over the life of a projects.

As the values which have been obtained for the various costs and benefits are based on previous studies and projects which have been undertaken over a number of years, these figures do not take into account inflation. To enable a comparison of the costs and benefits on equal terms, it is necessary to convert them all as if they were to occur in the same year. All of the values used in the cost-benefit analysis were standardised to the financial year 2001-2002 (see Table 4) using GDP deflators recommended by HM Treasury (<http://www.hm-treasury.gov.uk/>). This process allows for the effects of changes in price to be removed.

Table 4: The values used to estimate the costs and benefits of realignment before and after standardising to the financial year 2001-2002 by using GDP deflators recommended by HM Treasury (<http://www.hm-treasury.gov.uk/>).

Item	Value of item at time of reference	Year value relates to	Value of item after adjustment to the financial year 2001-2002
Capital costs of realignment (realigning defences)	£811,893/km	2001-2002	£811,893/km
Opportunity costs (Grade 3 land)	£2,382/ha	2001-2002	£2,382/ha
Maintenance of non-realigned defences (max estimate)	£5,000/km/yr	2000	£5,127/km/yr
Replacement costs	£618,000/km	2001	£618,000/km
General habitat creation benefits	US\$211/ha/yr– US\$306/acre/y	2003/1990	£122-574/ha/yr
Carbon sequestration benefits	£7/tonne CO ₂ e	2000	£7.18/tonne CO ₂ e

4.5 Present value

The costs and benefits of managed realignment were estimated on the basis that realignment would be implemented at the start of the time period for each scenario. In order to compare all the costs and benefits of the managed realignment schemes which occur at different time periods, it was necessary to determine the present values of each of the costs and benefits. For one-off impacts, such as the capital costs involved in the realignment schemes, the present value is simply the monetary cost or benefit. For impacts occurring over the time-frame of the project, for example the maintenance costs and the benefits from habitat creation, these flows of values must be discounted to their present values to enable a comparison between like and like. In discounting the values for the Blackwater Estuary, a declining discount rate was applied following the Treasury Guidance for project appraisal as shown in Table 5.

Table 5. Declining schedule of discount rates used in project appraisal (HM Treasury, 2003):

<i>Period of Years</i>	<i>0-30</i>	<i>31-75</i>	<i>76-125</i>	<i>126-200</i>	<i>201-300</i>	<i>300+</i>
Discount Rate	3.5%	3.0%	2.5%	2.0%	1.5%	1.0%

Following CBA convention, the project is initiated in year 0 with one-off costs and benefits occurring only in this year, with the continuing costs and benefits occurring in each subsequent year of the project. These were then discounted over the project time span to determine the present values. The impact of an extended appraisal period combined with a lower discount rate is to increase the weight of the costs and benefits accruing in the future.

Thus, to explore the impacts of time span on the policy decisions, in addition to the 100 year timeframe, 25 and 50 year scales were also assessed.

4.6. Results of the cost benefit analysis

The length of time that it would take to implement realignment and for an intertidal habitat to mature was not considered because it is difficult to predict how long these processes may take. For the purpose of this investigation, benefits were taken into account from the start, i.e. year 0. This however, represents an over estimation of the benefits, as there is always some delay before the habitat becomes well established.

Table 7. Net present Values of Providing Flood Defence for the managed realignment scenario as compared to the Hold-the-Line scenario for the Blackwater Estuary

a) With sedimentation rate of 1.5 mm/yr

Scenario	25 years	50 years	100 years
HTL	-90013988.57	-66189110.02	-46643352.65
Managed Realignment	-18994744.67	-33651662.85	-59644256.9
Net Present Value	-71019243.90	-32537447.17	13000904.25

b) With sedimentation rate of 6 mm/yr

Scenario	25 years	50 years	100 years
HTL	-89164560.95	-64931945.30	-45038112.7
Managed Realignment	-18994744.67	-33651662.85	-59644256.9
Net Present Value	-70169816.29	-31280282.46	14606144.2

In this study, the different scenarios considered over a range of time-spans produce a range of benefits. Most important:

- 1) The longer the time-span the greater the benefits, with all scenarios producing positive benefits over the 100 year period. These are deemed economically efficient.
- 2) The HTL scenario represents an overall cost to society.

The analysis also shows that under the recommended 100 year time span for project appraisals (DEFRA, 2003), the managed realignment scheme produced positive economic

benefit, regardless of whether the sedimentation level was assumed to be either 1.5 or 6 mmyr^{-1} .

The majority of the costs relate to the capital cost of realignment and replacing unsatisfactory defences. These costs are incurred in the first year. As a consequence of this distribution of costs, managed realignment schemes are shown to be more cost effective if they are considered over long periods of time, such as 50 and 100 years, rather than 25 years. This enables the benefits of habitat creation and carbon sequestration from the creation of inter-tidal habitat to be considered. This shows the impact of changing the project appraisal length in the Green Book (H.M. Treasury, 2003).

Using a lower value for the benefits of habitat creation has a dramatic effect on the net present values of all the schemes, with the managed realignment scheme being economically inefficient relative to the HTL scenario. The value of habitat creation has a significant impact as to whether a project should be adopted through the appraisal system. Meanwhile reducing the costs of realignment by 50% to take into account the lack of secondary defences, produces net benefits over the 50 year time-span in addition to the 100 year time-span.

A full consideration of caveats to the CBA, including over and under estimation issues are given in Appendix IV.

5. Conclusions

This case study has demonstrated clearly that managed realignment options in the Blackwater/Colne estuary will enhance C, N and P burial in the newly accreted sediments and allow extra microbial metabolism of dissolved nitrate, attenuating flux to the southern North Sea. Cost-benefit analysis (CBA) demonstrates that managed realignment provides positive economic benefit, regardless of whether the sedimentation rate is assumed to be either 1.5 or 6 mmyr^{-1} .

In a wider sense this case study has outlined how CBA of managed realignment schemes should be undertaken elsewhere so that the potential cost of realignment can be better understood. Improving the CBA requires better information on likely costs and benefits, particularly the 'average' capital costs for realignment, the effect of sea level rise on maintenance and replacement costs of existing defences and the monetary value of the benefits that may be received from intertidal habitat creation.

References

Aldridge J. N., Davies A. M., 1993. A High-Resolution 3-Dimensional Hydrodynamic Tidal Model of the Eastern Irish Sea. *Journal of Physical Oceanography* 23, 207-224.

Aldridge J. N. et al., 2003. Transport of plutonium (Pu-239/240) and caesium (Cs-137) in the Irish Sea: comparison between observations and results from sediment and contaminant transport modelling. *Continental Shelf Research* 23, 869-899.

Andrews J. E. et al., 2000. Origin, abundance and storage of organic carbon and sulphur in the Holocene Humber Estuary: emphasizing human impact on storage changes. In: Shennan I., Andrews J. (Eds.), *Holocene Land-Ocean Interaction and Environmental Change around the North Sea*. Geological Society, London, Special Publications, London, 166, pp. 145-170.

Barbier, E.B. (1994) Valuing Environmental Functions: Tropical Wetlands. *Land Economics*, 70 (2): 155-173.

Cahoon D. R. et al., 2000. Vertical accretion versus elevational adjustment in UK saltmarshes: an evaluation of alternative methodologies. In: Pye K., Allen J. R. L. (Eds.), *Coastal and estuarine environments: sedimentology, geomorphology and geoarchaeology*. The Geological Society, London, Special Publications, 175, pp. 223-238.

Coombes, E.G., (2003). *Habitat creation and loss within the Humber Estuary, and the associated environmental and economic costs and benefits*. M.Sc. by Research Dissertation, University of East Anglia, Norwich, UK.

Costanza R. et al., 1997. The value of the world's ecosystem services and natural capital. *Nature* 387, 253-260.

Crooks S., Turner R. K., 1999. Integrated coastal management: Sustaining estuarine natural resources. In: (Eds.), *Advances in Ecological Research*, Vol 29. *Advances in Ecological Research*, 29, pp. 241-289.

Davies A. M., Aldridge J. N., 1993. A Numerical-Model Study of Parameters Influencing Tidal Currents in the Irish Sea. *Journal of Geophysical Research-Oceans* 98, 7049-7067.

Davies A. M., Lawrence J., 1994. The Response of the Irish Sea to Boundary and Wind Forcing - Results from a 3-Dimensional Hydrodynamic Model. *Journal of Geophysical Research-Oceans* 99, 22665-22687.

Department for Environment, Food and Rural Affairs (DEFRA), (2001a). *FCDPAG1 Flood and Coastal Defence Project Appraisal Guidance: Overview*. <http://www.defra.gov.uk/environ/fcd/pubs/pagn/fcdpag1.pdf>

Department for Environment, Food and Rural Affairs (DEFRA), (2001b). *FCDPAG3 Flood and Coastal Defence Project Appraisal Guidance: Economic Appraisal*. <http://www.defra.gov.uk/environ/fcd/pubs/pagn/fcdpag3/default.htm>

Department for Environment, Food and Rural Affairs (DEFRA), (2001c). FCDPAG5 *Flood and Coastal Defence Project Appraisal Guidance: Environmental Appraisal*. <http://www.defra.gov.uk/enviro/fcd/pubs/pagn/fcdpag5.pdf>

Department for Environment, Food and Rural Affairs (DEFRA), (2003). *Flood and Coastal Defence Project Appraisal Guidance: Economic Appraisal: Supplementary Note to Operating Authorities. REVISIONS TO ECONOMIC APPRAISAL PROCEDURES ARISING FROM THE NEW HM TREASURY "GREEN BOOK"*. <http://www.defra.gov.uk/enviro/fcd/pubs/pagn/FCDPAG3supplementv3.pdf>

Dixon, M., (2003). Personal communication, Department for Environment, Food and Rural Affairs.

Edwards-Jones, G., Davies, B. and Hussain, S., (2000). *Ecological Economics an Introduction*, p.30-31, 84-97, 121-138, Blackwell Science.

Emmerson R. H. C. et al., 1997. Tidal exchanges between Orplands managed retreat site and the Blackwater Estuary, Essex. *Journal of the Chartered Institution of Water and Environmental Management* 11, 363-372.

HM Treasury (2003) *"The Green Book" Appraisal and Evaluation in Central Government*. London: The Stationery Office.
http://www.hm-treasury.gov.uk/media/785/27/Green_Book_03.pdf
http://www.hm-treasury.gov.uk/media/54C/E8/Green_Book2_03.pdf

Jickells T., 1998. Nutrient Biogeochemistry of the Coastal Zone. *Science* 281, 217-222.

Jickells T. et al., 2000. Nutrient fluxes through the Humber estuary - Past, present and future. *Ambio* 29, 130-135.

English Nature, 2002. Essex Coast and Estuaries Coastal Habitat Management Plan.

Nedwell D. B. et al., 1999. Nutrients in estuaries. In: Nedwell D. B., Raffaelli D. G. (Eds.), *Advances in Ecological Research Estuaries*, Vol 29. ACADEMIC PRESS INC, San Diego, *Advances in Ecological Research*, 29, pp. 43-92.

NRA Anglian Region, 1994. Blackwater Catchment Management Plan: Consultation Report.

Parkes, D. (2004) *Storage and Cycling of Organic Carbon and Nutrients in Holocene Coastal Sediments*. Ph.D. Thesis University of East Anglia.

Pearce, D.W., (1983). *Cost-Benefit Analysis*, (second edition). Macmillan Education Ltd., p.1-4.

Pearce, D.W. (2003). The Social Cost of Carbon and its Policy Implications, *Oxford Review of Economic Policy*, 19: 362-384.

Pethick J. S., 1998. Coastal management and sea level rise: a morphological approach. In: Lane S., Richards K. S., Chandler J. (Eds.), *Landform monitoring, modelling and analysis*. Wiley, London, pp.

- Pethick J. S., 2002. Estuarine and Tidal Wetland Restoration in the United Kingdom: Policy Versus Practice. *Restoration Ecology* 10, 431-437.
- Pethick J. S., 2003. Option Assessment: Rewalls, East Mersea. University of Newcastle. pp. 46
- Pilcher, R., Burston, P. and Davis, R., (2002). *Seas of Change*, A RSPB report.
- Smolarkiewicz P. K., 1984. A fully multidimensional positive definite advection transport algorithm with small implicit diffusion. *Journal of Computational Physics* 54, 325-362.
- Spurgeon, J., (1998). The Socio-Economic Costs and Benefits of Coastal Habitat Rehabilitation and Creation. *Marine Pollution Bulletin*, 37 (8-12): 373-382.
- Tol, R.S.J., S. Fankhauser, R.G. Richels and J.B. Smith (2000), 'How Much Damage Will Climate Change Do? Recent Estimates', *World Economics*, 1 (4), 179-206.
- Townend I., Pethick J. S., 2002. Estuarine flooding and managed retreat. *Philosophical Transactions, Royal Society of London. (A)* 360, 1477-1495.
- Turner R. K. et al., 1998. Ecosystem services value, research needs, and policy relevance: a commentary. *Ecological Economics* 25, 61-65.

The inter-disciplinary Tyndall Centre for Climate Change Research undertakes integrated research into the long-term consequences of climate change for society and into the development of sustainable responses that governments, business-leaders and decision-makers can evaluate and implement. Achieving these objectives brings together UK climate scientists, social scientists, engineers and economists in a unique collaborative research effort.

Research at the Tyndall Centre is organised into four research themes that collectively contribute to all aspects of the climate change issue: Integrating Frameworks; Decarbonising Modern Societies; Adapting to Climate Change; and Sustaining the Coastal Zone. All thematic fields address a clear problem posed to society by climate change, and will generate results to guide the strategic development of climate change mitigation and adaptation policies at local, national and global scales.

The Tyndall Centre is named after the 19th century UK scientist John Tyndall, who was the first to prove the Earth's natural greenhouse effect and suggested that slight changes in atmospheric composition could bring about climate variations. In addition, he was committed to improving the quality of science education and knowledge.

The Tyndall Centre is a partnership of the following institutions:

- University of East Anglia
- UMIST
- Southampton Oceanography Centre
- University of Southampton
- University of Cambridge
- Centre for Ecology and Hydrology
- SPRU – Science and Technology Policy Research (University of Sussex)
- Institute for Transport Studies (University of Leeds)
- Complex Systems Management Centre (Cranfield University)
- Energy Research Unit (CLRC Rutherford Appleton Laboratory)

The Centre is core funded by the following organisations:

- Natural Environmental Research Council (NERC)
- Economic and Social Research Council (ESRC)
- Engineering and Physical Sciences Research Council (EPSRC)
- UK Government Department of Trade and Industry (DTI)

For more information, visit the Tyndall Centre Web site (www.tyndall.ac.uk) or contact:

- External Communications Manager
- Tyndall Centre for Climate Change Research
- University of East Anglia, Norwich NR4 7TJ, UK
- Phone: +44 (0) 1603 59 3906; Fax: +44 (0) 1603 59 3901
- Email: tyndall@uea.ac.uk

Recent Tyndall Centre Technical Reports

Tyndall Centre Technical Reports are available online at
http://www.tyndall.ac.uk/publications/tech_reports/tech_reports.shtml

Warren, R. (2002). **A blueprint for integrated assessment of climate change**, Tyndall Centre Technical Report 1.

Gough, C., Shackley, S., Cannell, M.G.R. (2002). **Evaluating the options for carbon sequestration**, Tyndall Centre Technical Report 2.

Köhler, J.H. (2002). **Modelling technological change**, Tyndall Centre Technical Report 3.

Goodess, C.M. Osborn, T. J. and Hulme, M. (2003) **The identification and evaluation of suitable scenario development methods for the estimation of future probabilities of extreme weather events**, Tyndall Centre Technical Report 4.

Stemmers, K. (2003) **Establishing research directions in sustainable building design**. Tyndall Centre Technical Report 5.

Macmillan, S. and Köhler, J.H., (2004) **Modelling energy use in the global building stock: a pilot survey to identify available data**, Tyndall Centre Technical Report 6.

Adger W. N., Brooks, N., Kelly, M., Bentham, S. and Eriksen, S. (2004) **New indicators of vulnerability and adaptive capacity**, Tyndall Centre Technical Report 7.

Skinner, I., Fergusson, M., Kröger, K., Kelly, C. and Bristow, A. (2004) **Critical Issues in Decarbonising Transport**, Tyndall Centre Technical Report 8

Gill, J., Watkinson, A. and Côté, I (2004). **Linking sea level rise, coastal biodiversity and economic activity in Caribbean island states: towards the development of a coastal island simulator**, Tyndall Centre Technical Report 9.

M. N. Tsimplis (2003). **Towards a vulnerability assessment for the UK coastline**, Tyndall Centre Technical Report 10.

Berkhout, F., Hertin, J. and Arnell, N. (2003). **Business and Climate Change: Measuring and Enhancing Adaptive Capacity**, Tyndall Centre Technical Report 11.

Palutikof, J. and Hanson, C. (2004) **Integrated assessment of the potential for change in storm activity over Europe: Implications for insurance and forestry**, Tyndall Centre Technical Report 12

Jenkins, N., Strbac G. and Watson J. (2004) **Connecting new and renewable energy sources to the UK electricity system**, Tyndall Centre Technical Report 13

Levermore, G, Chow, D., Jones, P. and Lister, D. (2004) **Accuracy of modelled extremes of temperature and climate change and its implications for the built environment in the UK**, Tyndall Centre Technical Report 14

Levermore, Bristow, A., Pridmore, A., Tight, M., May, T., Berkhout, F. and Harris, M. (2004) **How can we reduce carbon emissions from transport?** Tyndall Centre Technical Report 15

Brown, K., Boyd, E., Corbera-Elizalde, E Adger, W. N. and Shackley, S (2004) **How do CDM projects contribute to sustainable development?** Tyndall Centre Technical Report 16

Few, R. (2005) **Health and flood risk: A strategic assessment of adaptation processes and policies**, Tyndall Centre Technical Report 17

Dutton, A. G., Bristow, A. L., Page, M. W., Kelly, C. E., Watson, J. and Tetteh, A. (2005) **The Hydrogen energy economy: its long term role in greenhouse gas reduction**, Tyndall Centre Technical Report 18

Shackley, S., Bray, D. and Bleda, M., (2005) **Developing discourse coalitions to incorporate stakeholder perceptions and responses within the Tyndall Integrated Assessment**, Tyndall Centre Technical Report 19

Dlugolecki, A. and Mansley, M. (2005) **Asset management and climate change**, Tyndall Centre Technical Report 20

Shepherd, D., Jickells, T., Andrews, J., Cave, R., Ledoux, L, Turner, R., Watkinson, A., Aldridge, J. Malcolm, S, Parker, R., Young, E., Nedwell, D. (2005) **Integrated modelling of an estuarine environment: an assessment of managed realignment options**, Tyndall Centre Technical Report 21