An abbreviated version of this note was published in the MAFF River & Coastal Engineering Conference Proceedings (Pontee & Townend, 1999). The note has subsequently been updated to take account of the EMPHASYS study findings (EMPHASYS Consortium, 2000).

CAUSE-CONSEQUENCE MODEL

Introduction

Perhaps the most difficult aspect facing any approach to understanding estuarine morphology is the lack of any clear cause-effect hierarchies. Within an estuary, form and process are inextricably linked and there are no obvious dependent and independent variables or clear cause-effect hierarchies. This results in the potential for small changes to have far reaching effects. Although the size and shape of an estuarine channel is a response to tidal processes, the tidal discharge is itself dependent on the morphology of the estuarine channel, since this determines the overall tidal prism. One possible constraint on the estuarine system is the tidal length of the estuary, which is dependent on the macro-scale slope of the coastal plain, the fluvial discharge, and the tidal range in the nearshore zone. Additionally, in some specific cases, further constraints to the closed cause-effect relationship may include geological or, in some cases, anthropogenic controls on estuary width or depth, such as existing urban areas or harbour facilities.

As a consequence, when developing plans for estuary management, it is important to retain a clear estuary wide perspective, even when addressing seemingly local issues. This is of course made more complex by the superposition of external influences, such as sea level rise and changes in storminess, which impose changes on a variety of spatial and temporal scales.

The purpose of the cause-consequence model is to map the possible routes from a particular causal action and the resultant changes to the system (primarily in terms of changes in form/morphology). Both actions and induced changes can take place on one or more spatial and temporal scales. As a consequence, it is difficult to map all the possible routes in a simple flow diagram. A matrix approach has therefore been adopted, where a number of matrices form several layers to the model with defined links between layers. This is summarised in Figure 1, where there are five layers:

i) The first matrix defines the spatial scale of action;
ii) The second is for the temporal scale of action;
iii) The various response models that could be used to compute the changes forms the third layer;
iv) Possible changes to different attributes makes up the fourth layer; and
v) The time scale of any response is the final layer.

The first two combine to define the inputs to the response model, in conjunction with relevant boundary conditions and constraints on the system. It is not the case, however, that every spatial scale of a particular causal action combines with every temporal scale of the action. In most cases a sub-set is all that needs to be considered. Typically actions that are spatially on a large scale (estuary/external), also have long-term time scales of action.

Figure 1. Estuary cause-consequence model

CAUSE OF CHANGE

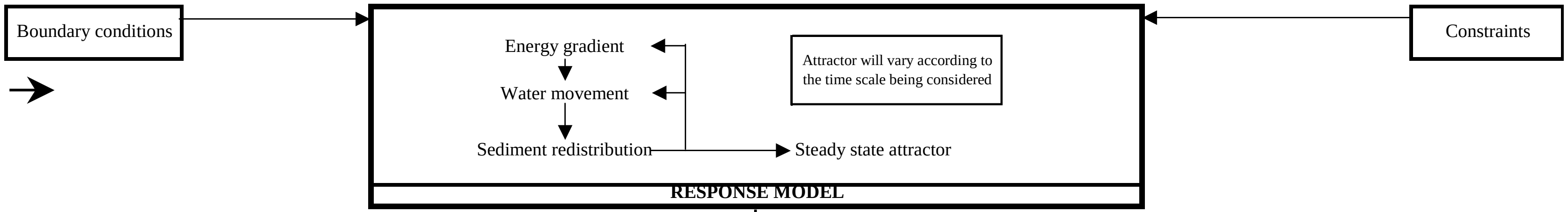
Layer 1

Spatial Scale of Action		Energy: 1 Freshwater flow	2 Tides	3 Mean Sea Level	4 External surface waves	5 Local wind waves	6 Meteorological surge	7 Bio-chemical flux	Sediment: 8 Terrestrial	9 Marine	Management Action: 10 Barrage	11 Barrier	12 Dredging	13 Fauna	14 Flora	15 Intake or outfall	16 Jetty or pier	17 Reclamation	18 Sea defences	19 Sea disposal	20 Training works	21 Managed realignment	22 Intertidal recharge
Local	Lc					✓		✓			✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Estuary	Es					✓		✓			✓	✓	✓	✓		✓		✓	✓	✓	✓	✓	✓
External	Xt	✓	✓	✓	✓		✓	✓	✓	✓													

Layer 2

Time Scale of Action		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
Sh	short-term (<=tidal cycle)	•	•		•	•		•	•	•													
Md	medium-term (seasons/years)	•	•	•	•	•	•	•	•	•				•	•								
Lg	long-term (10-100 years)	•	•	•	•	•	•	•	•	•						•							
Int	intermittent	•			•	•	•	•	•	•		•	•							•			•
Fx	fixed (in human terms)										•	•				•	•	•	•		•	•	

Layer 3



Layer 4

Action results in changes to:

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
Estuary size	sz																						
Estuary shape	sh																						
Estuary location	loc																						
Intertidal form	if																						
Subtidal form	sf																						
Habitat extent	hx																						
Population	pop																						

Layer 5

Time Scale of Response		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
Sh	short-term (<=tidal cycle)																						
Md	medium-term (seasons/years)																						
Lg	long-term (10-100 years)																						
Int	intermittent																						
Fx	fixed (in human terms)																						

CONSEQUENCES

Causes of Change

The *causes of change* have been grouped into three classes; namely the energy throughputs, the sediment imports/exports and the potential management actions within the estuary. For each *cause* there will be one or more relevant *spatial* and *temporal* scales.

Spatial Scales

The *spatial scales* (level 1) are subdivided into three:

Local - Typically the immediate vicinity of the action, possibly extending as far afield as a reach of the estuary;

Estuary - An action that occurs throughout the estuary, although not necessarily uniformly; and

External - Causes of change that take place outside the estuary but give rise to changes in the boundary conditions of the system.

Time Scales

The subdivision of the *temporal scale* (level 2) seeks to reflect different types of event as well as their duration. For changes that happen progressively or cyclically over a period of time, three subdivisions have been adopted:

Short-term - Covers actions that take less than a tidal cycle or repeat on a time-scale of this duration or less;

Medium-term - Relates to seasonal or annual changes;

Long-term - Progressive changes over decades or centuries, including trends and cycles.

To these are added two further classes to cover non-continuous events and single actions:

Intermittent - Changes that happen episodically (e.g. storms) or infrequently (e.g. accidents);

Fixed - One off actions that, in the context of management (50-100 year time horizon), do not change with time and may, therefore, be considered constant or fixed.

Combining Space and Time Scales

As noted above the space and time matrices do not explicitly define the links between the two. In general the number of links will be less than every possible combination that could be drawn from the possible options (see Figure 1). The way in which they combine, can also be illustrated by a matrix for each causal action. Two examples serve to illustrate this point. The first is a case where only a subset needs to be considered, whereas in the second example all combinations need to be addressed, although some grouping may be possible. A complete analysis for all causal actions is given in Appendix 1.

i) Freshwater Flows

Possible combinations of space and time scales of action for the 'freshwater flow' cause of change:

	Short	Medium	Long	Intermittent	Fixed
Local					
Estuary					
External	✔	✔	✔	✔	

The cases to be examined for freshwater flows are therefore:

Spatial scale		*Temporal scale*
External	+	Long
External	+	Intermittent

In the context of **morphological change** persistent actions on a short or medium time scale provide the boundary conditions for the response model. It is the long term and intermittent changes which are most likely to result in direct changes in form

ii) Local Wind Waves

Possible combinations of space and time scales of action for the 'local wind-wave' cause of change:

	Short	Medium	Long	Intermittent	Fixed
Local	✔			✔	
Estuary	✔	✔	✔	✔	
External					

The cases to be examined for wind waves are therefore:

Spatial scale		*Temporal scale*
Local	+	Short
Local	+	Intermittent
Estuary	+	Short/Med/Intermittent
Estuary	+	Long

Short, medium and intermittent time scales are generally used for process-based studies. The long-term time scale makes more use of climatic trends and cycles to evaluate changes.

Response Model

The response model is actually a collection of computational models, rules and subjective judgements that provide the link between the causal actions and the resultant changes in the estuary. It is essentially a toolbox that can evolve as new knowledge, techniques and computational models become available. The cause-consequence model enables developments from the various research disciplines to be introduced in a consistent way. The overall framework for identifying change remains unaltered but the tools used to establish the various responses can be updated when necessary. As such the approach may be considered as an embryonic estuary management system. Given the acknowledged need for research into long-term geomorphological behaviour, the tools available at present are limited. The following sections endeavour to set out what is currently possible.

Models

There is no one model that can be used to predict the changes of interest. Instead there are a variety models that address specific processes, or provide some form of parametric scaling. Some can be used on their own, whereas others have to be interactively linked together.

As with any scientific investigation, data analysis forms an important building block to understanding changes that have gone in the past and aspects of behaviour. In general, two approaches have been taken to the prediction of morphological change in estuaries, namely the application of process based models (referred to as "bottom-up" methods) and a variety of techniques based on behavioural system concepts (referred to as "top-down" methods). The latter often define a goal based on some form of equilibrium concept. By combining the top-down target state, with process models run at individual time steps, it is possible to set-up a goal-seeking iteration to find possible outcomes. This is often referred to as the "hybrid" method. There are then a number of related models and methods which use the output from the hydrodynamic and morphological models as a basis of making predictions about dependent properties such as water quality, benthic communities, bird/fish populations and so forth.

The following tables summarise the range of analysis techniques and models available and give an indication of their current state of development and what they are used for. Further details and some pointers to the relevant literature are given in the Analysis and Modelling Guide.

i) Data analysis methods

Method	Status [1]	Use
Holocene analysis	A	To identify long-term changes (over last 10,000 years), particularly periods of marine transgression and regression, as context for contemporary changes
Accommodation space	A	Defines changes in sediment storage capacity (i) over Holocene time scale and (ii) based on existing capacity
Historical analysis	A	To establish what changes have taken place (natural and anthropogenic) and identify any trends or cycles.
Saltmarsh analysis	A	Historical analysis of changes in saltmarsh coverage over time and related to changes in sea level, tidal conditions and/or exposure.
Statistical, spatial and time series analysis techniques	A	Provides information on the dynamics and complexity of the system, particularly dominant components of change, trends and cycles
Sediment budget analysis	A	Defines the balance between sediment inputs, outputs and sources/sinks within the estuary
Expert geomorphological analysis	A	To rationalise information from different sources, with an understanding of how different landforms evolve, in order to predict future change.

ii) Regime and equilibrium "top-down" methods

Method	Status	Use
Regime relationships	D	Allows the current shape and hydraulic characteristics to be related to defined equilibrium relationships
Form analysis	A	Simple description of estuary shape that provides an indication of likely behavioural characteristics
Tidal asymmetry analysis	D	Provides an indication of areas of sediment convergence/divergence and whether the system as a whole is flood or ebb dominant
Intertidal form analysis	R	Defines the shore profile and provides an indication on the erosional/accretional character of the foreshore
Estuary translation (rollover)	R	Estimates the vertical and horizontal movements of the

[1] Status: A = available/established; D = under development; R = being researched; C = concept only

Method	Status	Use
		estuary as a whole due to changes in sea level

iii) Process based "bottom-up" methods

Method	Status	Use
Hydrodynamic modelling	A	To establish water levels, discharge, current speed and direction, waves, density currents and secondary circulation patterns
Advection-diffusion models	A	To predict the movement and dispersion of a constituent (particle matter or solute), given an initial concentration field (e.g. dispersion of a heat from a power station outfall)
Sediment transport	A	To estimate sediment movement and hence areas of erosion and accretion
Particle Tracking	A	To map the movement of individual particles (a useful visualisation technique)
Morphological bed-updating models	D	To estimate changes in estuary form based on rates of erosion and accretion. The inclusion of dynamic updating within the model provides a feedback between form and hydraulics/sediment transport

iv) "Hybrid" techniques that combine "top-down" and "bottom-up" methods

Method	Status	Use
Coupled hydraulic and regime relationships	D	To estimate changes in estuary form based on an assumed equilibrium relationship between form and hydraulics
Coupled hydraulic and entropy relationships	R	To estimate changes in estuary form based on the assumption that the system will strive to do minimum work
Coupled hydraulic and energy relationships	A	Maps bed shear stresses and compares them with erosion thresholds, as a basis for assessing where erosion is likely to occur
Uniform sediment flux or sediment balance	A	To estimate changes in estuary form based on the assumption that the sediment flux will reach an ebb/flood balance.
Behaviour models	D	To estimate some aspect of overall behaviour based on a simplified relationship derived from the use of more detailed process models

v) Related modelling and analysis topics

Method	Status	Use
Water quality	A	To examine the advection and dispersion of suspended matter, dissolved oxygen and contaminants
Sediment quality	A	To examine the movement of contaminants attached to the sediment and the potential impact on water quality
Ecosystem	R	Aims to describe the spatial distribution of species and how populations may change over time by describing the interactions between physical, chemical and biological components. Often considers specific range of interests (e.g. bird/fish populations, benthic communities, etc).
Socio-economic	R	Aims to describe how institutional, social and economic factors will drive changes to human use in and around estuaries and hence alter the pressures and impacts that need to be addressed

This wide-ranging set of methods each makes different contributions to the prediction of change in the estuary system. The following table summarises the methods listed above into a set of generic methods and ascribes the type of output each can provide, with reference to the consequences listed in Figure 1.

Generic Method	Type of Output
Historical data analysis	Very dependent on data type and coverage. Can be used to examine how individual parameters change over varying space and time scales, as well as relationships between parameters – sea level change, bathymetric change, suspended load v's temperature, etc
Flow	Local and estuary wide hydraulic changes – water levels , velocities, density gradients, etc
Waves	Local and estuary wide wave activity – wave height, period and direction
Erosion/deposition	Local and estuary wide changes in erosion and accretion rates – bed level changes
Morphology	Changes in form of whole estuary or specific features such as the intertidal – bed level changes, or shape changes in plan or section
Estuary transgression	Movement of estuary system – shape changes (width, depth, meanders)
Dispersion	Redistribution of solute or particulate matter, locally and estuary wide
Ecosystem	Changes in habitat extent or population distribution (invertebrates, fish, birds, etc)

Boundary Conditions

Many of the attributes discussed above, as causes of change, also constitute the boundary conditions to any modelling or analysis exercise. In general these need to be specified in a manner consistent with the spatial and temporal scales of the application. One of the major difficulties in applying some of the methods listed above is that suitable data to define the boundary conditions is often not available. For instance, on the Humber, a vast quantity of sediment moves in and out of the estuary on every tide. However, there are no records of how the sediment supply from the North Sea may have changed over time. This is therefore a particular difficulty in constructing historic sediment budgets to help validate predictive models. In such circumstances the usual course of action is to seek some form of surrogate measure. For instance, for marine sediments this may be found in the Holocene sediment record within the estuary.

Constraints

Some aspects of the problem may be considered fixed, in the context of estuary evolution. In terms of initial setting such constraints include the drainage basin in which the estuary is set and the solid (non-erodible) geology. To this it may be necessary to add other “fixed points” in the system, which might include coastal conurbations, bridge piers, training walls, etc.

Consequences

The focus of the cause-consequence model is on geomorphological changes, or changes consequent on morphological changes. As with the causes, these can have different spatial and temporal scales. For management purposes, we need to be able to quantify the changes at least to within some range, or order of magnitude. Depending on the models available this may be a quantitative estimate. For long-term predictions however it is more likely to be some envelope of possible behaviour. This in itself may be useful, as it provides an indication of the potential room that the system may require in the future.

Resultant Changes

Morphological changes of primary interest include the size, shape and location of the estuary and the form of specific features such as banks and channels within the estuary. The intertidal and subtidal forms also have a particular importance because they influence habitat extent and hence the distribution of communities and species of flora and fauna.

Time Scale of Change

For local short-term changes, the available models are able to provide reasonable indications of timescale over which a particular change will take place. Longer-term predictions are more difficult and raise issues such of data reduction and development of a suitable morphological time scale. The time scales identified for the response, on level 5 in Figure 1, are the same as those used to define the time scale of the action on level 2.

Summary

To determine the changes for a particular action usually requires several of these methods to be used. Using the spatial and temporal scales identified for each action (Appendix 1), the table below (Table 1) maps the methods that could possibly be used and the outputs that are possible for each case. However, the choice of methods invariably depends on the data available, opportunities to collect further data, available budget and the specific scope of the problem to be studied (see the EMPHASYS Guide for some suggestions on how to evaluate these aspects).

There are significant limits to the predictions that can be made using the models currently available. Many of the top-down and hybrid models do not, however, deal with specific scenarios. Instead they provide diagnostic tools, which allow an understanding of the estuaries geomorphology to be developed. A degree of interpretation and subjective judgement may then be required to reach conclusions as to how the system will evolve. Drawing the disparate results together then requires a degree of synthesis. This often makes use of a conceptual model as a basis for summarising the overall conclusions reached from the various studies. Ongoing research is likely to progressively supplement both the range of tools available and the way in which results are integrated.

References

Pontee NI, Townend IH, 1999, An estuary cause-consequence model, In: 34th MAFF Conference of River and Coastal Engineers, MAFF, London, pp. 5.2.1-5.2.17

EMPHASYS Consortium, 2000, Modelling Estuary Morphology and Process; Final Report, Estuary Research Programme, Phase 1, HR Wallingford, Wallingford TR 111, pp193

Table 1. Summary of generic models applicable to different causes of change

Cause of change	Spatial scale	Temporal Scale	Data Analysis Methods							Regime and Equilibrium "Top down" Methods					Process Based "Bottom up" Methods					Hybrid Methods		Related Modelling and Analysis Topics				Consequences (see Figure 1)
			Holocene Analysis	Accommodation Space	Historical Analysis	Saltmarsh Analysis	Statistical, Spatial and time series analysis	Sediment Budget Analysis	Expert Geomorphological Analysis	Regime Relationships	Form Analysis	Tidal Asymmetry Analysis	Intertidal Form Analysis	Estuary Translation (rollover)	Hydrodynamic Models	Advection-Diffusion Models	Sediment Transport Models	Particle Tracking (Lagrangian) Models	Morphological (bed updating) Models	Coupled Hydraulic and State Models (Regime, TD+BU)	Coupled Hydraulic and Condition Models (entropy, energy, sediment balance)	Water Quality	Sediment Quality	Ecosystem	Socio-Economic	
Freshwater	Xt	Lg			x	x	x		x	x		x								x	x					Sz, sh, loc, hx, pop
	Xt	S/M/Int					x								x	x	x		x			x	x	x	x	Sz, sh
Tide	Xt	S/M					x								x		x		x			x	x	x		Sz, sh
	Xt	Lg			x		x		x	x		x								x	x					Sz, sh, loc, hx, pop
Sea level	Xt	Md					x								x		x		x							Sz, sh
	Xt	Lg	x	x	x	x	x	x	x	x		x		x						x	x			x	x	Sz, sh, loc, hx, pop
External waves	Xt	S					x						x		x		x		x			x	x			Sz, sh
	Xt	M					x						x		x		x		x			x	x	x		Sz, sh, hx
	Xt	Lg					x		x	x											x				x	Sz, sh, hx
	Xt	Int					x		x						x		x		x			x	x			Sz, sh
Local waves	Lc	S					x						x		x		x		x			x	x			Sz, sh
	Lc	Int					x		x				x		x		x		x			x	x			Sz, sh
	Es	S					x								x		x		x			x	x			Sz, sh
	Es	M					x								x		x		x			x	x	x		Sz, sh, hx
	Es	Lg					x		x	x											x				x	Sz, sh, hx
	Es	Int					x		x						x		x		x			x	x			Sz, sh
Surge	Xt	M					x								x		x		x						x	Sz, sh
	Xt	Lg			x		x		x	x											x			x	x	Sz, sh
	Xt	Int					x		x						x		x		x						x	Sz, sh
Bio-chem flux	Lc	S/Int					x								x	x	x					x	x	x		Pop
	Lc	M					x								x	x	x					x	x	x		Pop
	Lc	Lg					x		x																	Pop
	Es	M					x								x	x	x					x	x	x	x	Pop
	Es	Lg					x		x																x	Pop
	Es	Int					x								x	x	x					x	x	x		Pop
	Xt	M					x								x	x	x					x	x	x		Pop
	Xt	Lg					x		x																	Pop
	Xt	Int					x								x	x	x					x	x	x		Pop
Terrestrial seds	Xt	S					x	x					x		x	x	x	x	x			x	x			Sz, sh, hx
	Xt	M				x	x	x					x		x	x	x	x	x			x	x	x		Sz, sh, hx
	Xt	Lg	x	x	x		x	x	x	x											x			x		Sz, sh, hx
	Xt	Int					x	x							x	x	x	x	x							Sz, sh, hx
Marine seds	Xt	S					x	x					x		x	x	x	x	x			x	x			Sz, sh, hx
	Xt	M					x	x					x		x	x	x	x	x			x	x			Sz, sh, hx
	Xt	Lg	x	x	x	x	x	x	x	x											x					Sz, sh, hx
	Xt	Int					x	x							x	x	x	x	x							Sz, sh, hx
Barrage	Lc	Fx												x	x		x		x							Sz, sh
	Es	Fx								x	x	x			x		x		x	x	x	x	x	x	x	Sz, sh, loc, hx, pop
Barrier	Lc	Fx													x		x		x			x	x		x	Sz, sh
	Es	Int										x			x		x		x							Sz, sh, loc, hx, pop
Dredging	Lc	Int			x			x							x	x	x	x	x							Sz, sh
	Es	Int			x	x		x		x	x	x		x	x	x	x	x	x			x	x	x	x	Sz, sh, loc, hx, pop
Fauna	Lc	M													x									x		Hx, pop
	Es	M													x									x	x	Hx, pop
Flora	Lc	M				x									x							x	x	x		Hx, pop
	Lc	Lg																				x	x	x		Hx, pop
Intake/outfall	Lc	Fx													x	x		x				x	x	x		Sz, sh, hx, pop
	Es	Fx													x	x		x				x	x	x	x	Sz, sh,, hx, pop
Jetty or pier	Lc	Fx													x		x		x						x	Sz, sh
Reclamation	Lc	Fx													x		x		x							Sz, sh
	Es	Fx								x	x	x		x	x		x		x	x	x			x	x	Sz, sh, loc, hx, pop
Sea defences	Lc	Fx													x		x		x							Sz, sh
	Es	Fx								x	x	x		x	x		x		x	x	x			x	x	Sz, sh, loc, hx, pop
Sea disposal	Lc	Int			x			x							x	x		x								Sz, sh, hx, pop
	Es	Int			x	x		x							x	x		x				x	x	x	x	Sz, sh,, hx, pop
Training works	Lc	Fx													x		x		x							Sz, sh
	Es	Fx								x					x		x		x	x	x			x	x	Sz, sh, loc, hx, pop
Managed realignment	Lc	Fx											x		x		x		x							Sz, sh, loc, hx, pop
	Es	Fx		x	x	x		x	x	x	x	x		x	x		x		x	x	x	x	x	x	x	Sz, sh, loc, hx, pop
Intertidal recharge	Lc	Int											x		x	x	x	x	x							Sz, sh, loc, hx, pop
	Es	Int			x	x		x	x	x	x	x			x	x	x	x	x	x	x	x	x	x		Sz, sh, loc, hx, pop

Note: The short hand notation used in the above table is explained in Figure 1.

Appendix 1 - Combinations of Space and Time Scales for Individual Causal Actions

1. Freshwater Flow

	Short	Medium	Long	Intermittent	Fixed
Local					
Estuary					
External	✔	✔	✔	✔	

Spatial scale		*Temporal scale*
External	+	Long
External	+	Intermittent

In the context of **morphological change** persistent actions on a short or medium time scale provide the boundary conditions for the response model. It is the long term and intermittent changes which are most likely to result in changes in form

2. Tides

	Short	Medium	Long	Intermittent	Fixed
Local					
Estuary					
External	✔	✔	✔		

Spatial scale		*Temporal scale*
External	+	Short/Medium
External	+	Long

Whilst a single tide is the main period of action, there can be significant variations between spring and neap tides, which can have a significant influence on the overall form of the estuary

3. Mean Sea Level

	Short	Medium	Long	Intermittent	Fixed
Local					
Estuary					
External		✔	✔		

Spatial scale		*Temporal scale*
External	+	Medium
External	+	Long

Inter-annual variations may have a small effect but the main variation of interest will be the longer-term isostatic and eustatic changes. (Note: strictly speaking this should be relative sea level change as it is assumed to include any tectonic, settlement or other changes in land elevations).

4. External Wind Waves

	Short	Medium	Long	Intermittent	Fixed
Local					
Estuary					
External	✔	✔	✔	✔	

Spatial scale		*Temporal scale*
External	+	Short/Med./Intermittent
External	+	Long

Short, medium and intermittent time scales are generally used for process-based studies. The long-term time scale makes more use of climatic trends and cycles to evaluate changes.

5. Local Wind Waves

	Short	Medium	Long	Intermittent	Fixed
Local	✔			✔	
Estuary	✔	✔	✔	✔	
External					

Spatial scale		*Temporal scale*
Local	+	Short
Local	+	Intermittent
Estuary	+	Short/Med./Intermittent
Estuary	+	Long

Short, medium and intermittent time scales are generally used for process-based studies. The long-term time scale makes more use of climatic trends and cycles to evaluate changes.

6. Meteorological Surge

	Short	Medium	Long	Intermittent	Fixed
Local					
Estuary					
External		✔	✔	✔	

Spatial scale		*Temporal scale*
External	+	Medium/Intermittent
External	+	Long

Estuary wide, medium and intermittent time scale effects have been grouped because they would be investigated in the same way.

7. Bio-chemical Flux

	Short	Medium	Long	Intermittent	Fixed
Local	✔	✔	✔	✔	
Estuary		✔	✔	✔	
External		✔	✔	✔	

Spatial scale		*Temporal scale*
Local	+	Short/Intermittent/Med.
Local	+	Long
Estuary	+	Medium/Intermittent
Estuary	+	Long
External	+	Medium/Intermittent
External	+	Long

Short/medium/intermittent events are likely to be treated in a similar way at all three space scales

8. Terrestrial Sediment Input

	Short	Medium	Long	Intermittent	Fixed
Local					
Estuary					
External	✔	✔	✔	✔	

Spatial scale		*Temporal scale*
External	+	Short/Medium
External	+	Long
External	+	Intermittent

Estuary wide, short and medium time scale effects have been grouped because they would be investigated in the same way. In this case, it can again be argued that short and intermittent time scales could be similarly combined.

9. Marine Sediment Input

	Short	Medium	Long	Intermittent	Fixed
Local					
Estuary					
External	✔	✔	✔	✔	

Spatial scale		*Temporal scale*
External	+	Short/Medium
External	+	Long
External	+	Intermittent

Short and medium time scale effects have been grouped because they would be investigated in the same way. Sediment carried in by the daily tide would be the main short-term event but this may be altered intermittently by additional sediment inputs from the adjacent coast (e.g. due to a cliff fall). Hence intermittent is simply a variant of short.

10. Barrage

	Short	Medium	Long	Intermittent	Fixed
Local					✔
Estuary					✔
External					

Spatial scale		*Temporal scale*
Local	+	Fixed
Estuary	+	Fixed

Local effects are likely to give rise to rapid adjustments (e.g. local scouring), whereas estuary wide changes are likely to take significantly longer (see O'Conner *et al*, 1990)

11. Barrier

	Short	Medium	Long	Intermittent	Fixed
Local					✔
Estuary				✔	
External					

Spatial scale		*Temporal scale*
Local	+	Fixed
Estuary	+	Intermittent

Local effects will cause rapid adjustments but estuary wide effects are only likely when the barrier is in operation (assuming the structure is not too intrusive when in its non-operational position) and even these may be quite short lived.

12. Dredging

	Short	Medium	Long	Intermittent	Fixed
Local				✔	
Estuary				✔	
External					

Spatial scale		*Temporal scale*
Local	+	Intermittent
Estuary	+	Intermittent

Capital, maintenance and extraction dredging generally occur at undefined intervals, although some maintenance dredging operations are almost continuous and might be considered as short-term.

13. Fauna

	Short	Medium	Long	Intermittent	Fixed
Local		✓			
Estuary		✓			
External					

Spatial scale		*Temporal scale*
Local	+	Medium
Estuary	+	Medium

Introduced changes might include oyster or mussel beds, which have a seasonal time scale. In some estuaries such farming might be sufficiently extensive to have an estuary wide effect

14. Flora

	Short	Medium	Long	Intermittent	Fixed
Local		✓			
Estuary					
External					

Spatial scale		*Temporal scale*
Local	+	Medium

Generally, introduced flora will be localised, although wider colonisation is possible as has been the case following the introduction of *Spartina* in a number of estuaries around the UK.

15. Intake or Outfall

	Short	Medium	Long	Intermittent	Fixed
Local					✓
Estuary			✓		
External					

Spatial scale		*Temporal scale*
Local	+	Fixed
Estuary	+	Long

Whilst the impacts due to structure are most likely to be localised, the effect of inputs, such as nutrients or heat, could give rise to new bio-chemical fluxes, which induce change over a longer time scale.

16. Jetty or Pier

	Short	Medium	Long	Intermittent	Fixed
Local					✓
Estuary					
External					

Spatial scale		*Temporal scale*
Local	+	Fixed

Unlikely to have more than a local effect in most cases.

17. Reclamation

	Short	Medium	Long	Intermittent	Fixed
Local					✔
Estuary					✔
External					

Spatial scale		*Temporal scale*
Local	+	Fixed
Estuary	+	Fixed

The location of the reclamation within the estuary and any change in tidal prism determines the scale of influence. Some may only have a local effect but in most cases it is prudent to check the estuary wide impact.

18. Sea Defences

	Short	Medium	Long	Intermittent	Fixed
Local					✔
Estuary					✔
External					

Spatial scale		*Temporal scale*
Local	+	Fixed
Estuary	+	Fixed

The main implication of defences is the loss of high water storage volume. Some alteration of the flow regime may also occur depending on the structural form of the defences.

19. Sea Disposal

	Short	Medium	Long	Intermittent	Fixed
Local				✔	
Estuary				✔	
External					

Spatial scale		*Temporal scale*
Local	+	Intermittent
Estuary	+	Intermittent

Although sea disposal of waste is now prohibited, dredged spoil continues to be dumped at sea and in estuaries. The latter may however benefit the system by redistributing sediment to the intertidal. Consequently whilst the dumping is local, there may be estuary wide effects.

20. Training Works

	Short	Medium	Long	Intermittent	Fixed
Local					✔
Estuary					✔
External					

Spatial scale		*Temporal scale*
Local	+	Fixed
Estuary	+	Fixed

The location of the training works within the estuary and any changes to the channels determines the scale of influence. Some may only have a local effect but in most cases it is prudent to check the estuary wide impact

21. Managed Realignment

	Short	Medium	Long	Intermittent	Fixed
Local					✓
Estuary					✓
External					

Spatial scale		*Temporal scale*
Local	+	Fixed
Estuary	+	Fixed

The location of the realignment within the estuary and any change in tidal prism determines the scale of influence. Some may only have a local effect but in most cases it is prudent to check the estuary wide impact.

22. Intertidal recharge

	Short	Medium	Long	Intermittent	Fixed
Local				✓	
Estuary				✓	
External					

Spatial scale		*Temporal scale*
Local	+	Intermittent
Estuary	+	Intermittent

The magnitude of a recharge can vary from large placements of sediment through to so called trickle charging of small amounts of material. They type of material can also vary from sand to fine silt. The location of recharge within the estuary and any change in tidal prism determines any wider influence. Some may only have a local effect but in most cases it is prudent to check the estuary wide impact.

Appendix 2 - Example of an Application of the Cause-Consequence Model

When studying a particular causal action, it will normally be necessary to apply several models, or analyses, to develop a range of predictions covering the various form parameters. To illustrate the methodology, the following example considers the application of a single model, as just one component of the overall process. The potential (not actual) long-term sediment demand is considered using an entropy model (Dun and Townend, 1997) to identify the most probable state, in conjunction with historic siltation rates to estimate the likely timescale of change.

Action: Sediment input

Spatial scale: Estuary wide

Temporal scale: Long-term

Response models: 1-D flow model, energy/entropy model, and historical volumetric analysis.

Consequences:

a) spatial - volume of estuary and degree to which existing cross-sections along the length of the estuary are likely to change with time

b) timescale – estimate of likely timescale of changes identified

See Dun and Townend, 1997 for further details of the findings.

References

Dun R, Townend I H, 1997, Studies to examine the contemporary morphological evolution of the Humber estuary, 32nd MAFF Conference of River and Coastal Engineers, Keele University, paper F.1.1-11, Ministry of Agriculture Fisheries and Food, UK