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Development of a coastal vulnerability index: a geomorphological perspective

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Summary

Sustainable coastal resource management requires the safeguarding and transmission to future generations of a level and quality of natural resources that will provide an ongoing yield of economic and environmental services. All maritime nations are approaching this goal with different issues in mind. The UK, which has a long history of development and flood protection in coastal areas, has chosen to adopt shoreline management, rather than coastal management, so placing coastal defence above all else as its primary and statutory objective. This paper aims to provide a geomorphological perspective of long-term coastal evolution and seeks to compare the UK approach with wider interpretations of coastal management. Based on a literature review, it is argued that coastal management (CM) and shoreline management, as a subset of CM, should share the same ultimate objectives, which are defined by many authorities as sustainable use. The objectives, both strategic and pragmatic, which follow from such an aim may appear to conflict with a reading of many of the texts for international and national CM or designated area management which emphasizes stability rather than sustainability. The result is that coastal defence is seen not merely as a means to an end but as an end in itself. It is argued within this paper that sustainable use of the coast, however, demands both spatial and temporal flexibility of its component systems, and management for change must therefore be the primary objective. Response of the natural system to independent forcing factors must be encouraged under this objective, whether such forces are natural or anthropogenic. In achieving such an objective the concept of shoreline vulnerability may prove useful. A simple and preliminary Vulnerability Index is proposed, relating disturbance event frequency to relaxation time (the time taken for the coastal feature to recover its form). This index provides a first order approximation of the temporal variability that may be expected in landform components of the shoreline system, so allowing management to provide more realistic objectives for long-term sustainability in response to both natural and artificial forces.

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Introduction

Coasts are highly dynamic and geomorphologically complex systems, which respond in a non-linear manner to extreme events. Thus, in coastal management (CM) there is a critical need to understand the geomorphological spatial and temporal aspects of coastal system response to perturbation. While a vast literature exists detailing specific system responses to perturbations, the tools to measure and communicate aspects of societal and environmental vulnerability has been largely neglected. Only once we can measure vulnerability can we then inform policy makers of the underlying causes and the potential for ameliorating such vulnerability (Adger 1999).

To date the concept of, and research into, vulnerability have been driven by global issues of climate change and its impact on environmental and social systems. Prominent amongst definitions of vulnerability is that of the Intergovernmental Panel on Climate Change (IPCC), according to whom vulnerability defines 'the extent to which climate change may damage or harm a system; it depends not only on system sensitivity but also the ability to adapt to new climatic conditions' (IPCC 1996). Sensitivity in this particular climatic context refers to the degree to which a system will respond to a change in climatic conditions. The concept of vulnerability, of course, extends across a whole range of spatial scales including those at which coastal systems function. Here vulnerability may be defined as the exposure of social (and environmental) systems to stress as a result of the impacts of environmental change (see Adger 1999). This environmental change may be some combination of natural or anthropogenic forcing factors.

In focusing on the coast specifically, CM aims, through holistic management for sustainable development, to maintain a socially desirable mix of coastal zone products and services for current and future generations (Bower & Turner 1998). At the same time, through adequate planning and control, CM must combine the maintenance of an optimal level of environmental integrity, functioning and resilience, with reducing the level of vulnerability of coastal systems, and hence local populations, to catastrophic events and change. Thus assessment and planning to minimize vulnerability is a critical and central element within CM (Townend 1990).

By way of guidance on assessment of risk and vulnerability to sea-level rise the Coastal Zone Management Sub-Group (CZMS) of the IPCC suggested a common methodology based on a seven step process (IPCC, CZMS 1992):

(1) delineate the case study and specify the sea-level rise boundary conditions;
(2) inventory the study area characteristics;
(3) identify relevant development factors;
(4) assess physical changes and natural system responses;
(5) formulate response strategies and assess their cost and effects;
(6) assess vulnerability profile and interpret results; and
(7) identify relevant sections to determine long-term ICZM planning.

This process, particularly step four, is often difficult to complete in attempting to assess physical change and environmental response. As Capobianco *et al.* (1999) discussed in a modelling perspective for integrated assessment, 'most large-scale coastal problems concern complex geomorphic systems like estuaries, deltas and tidal inlets. The amount of sediment which circulates within these systems is often large compared with the exchange of sediments with neighbouring systems. A variety of processed-based models may be applied to such systems, producing useful results from a diagnostic point of view. However, their predictive value remains limited, either because they only describe a residual transport field and ignore morphodynamic interactions, or because they only include some of the relevant physical processes.' In this way, process-level modelling fails to account sufficiently for both the larger temporal and spatial scales that are associated with natural system evolution.

The objectives of this paper are to clarify the roles of coastal and shoreline management and place them, along with the understanding of coastal change, in the context of sustainable resource utilization. Based on the wide recognition that management must incorporate temporal and spatial change, this paper concludes with suggestions for the creation of a simple and preliminary first order Vulnerability Index to aid identification of (1) whether a coastal system is under threat of failure because of human perturbations, or (2) whether the change in coastal configuration of concern is part of a natural or quasi-natural cyclical readjustment and will in time return to a stable and resilient state.

Shoreline management

From the point of view of each maritime nation, the development of coastal management strategies is largely a response to existing problems within domestic coastal areas. In the UK, many lowland shoreline boundaries were delineated clearly into marine and terrestrial components, by the *ad hoc* construction of flood embankments to 'improve' coastal floodplain areas. The present coastal configuration reflects this unregulated pre-20th century development, with, in England alone, over 860 km of soft cliffs protected from erosion (23% of the coastline) and in excess of 1259 km of sea-defences protecting 2347 km^2 of embanked lowlands from flooding (Barne *et al.* 1996). It is on these coastal floodplains that over 5% of the population live (more than 2 million people) and 50% of the highest grade agricultural land is found. The remaining coastal natural resources in the UK are suffering from a sustained net decline, largely related to coastal squeeze of intertidal habitats (Carpenter & Pye 1996). Given the long history of dyke construction, strengthening property rights on the landward side of this boundary have shaped, limited and confined the subsequent developing UK coastal zone management strategy into one principally of shoreline management, namely flood protection in low-lying areas and protection from erosion of soft cliffs.

In England and Wales, shoreline management is technically the responsibility of the Ministry of Agriculture, Fisheries and Food (MAFF), but MAFF delegates to its operating authorities, namely local maritime district councils on high, potentially eroding, coasts and the Environment Agency for low, potentially flooding coasts. These authorities, while they have a duty to consider the nature conservation implications of their management activities, nevertheless regard it as their primary duty to reduce risks to people and property (MAFF 1993). Thus, although shoreline management may be seen as a sub-set of coastal management it possesses a very different set of aims and objectives. The aim of CM, as, for example, set out by the UK Department of Environment (DoE) in its strategy for the management of the coast (DoE 1993), is to achieve sustainable use of the coastal environment, while that of shoreline management is to achieve shoreline stability. Although the distinction between these two aims may appear slight, nevertheless it is argued here that it is in fact fundamental.

Sustainable use of the coast

Sustainability is now the dominant paradigm for the proposed management of the world's coastal, and other, environmental systems. The advancement of this paradigm reflects growing and widespread political awareness of the need to manage the global environment (of which coastal zones are a key component) in a more holistic manner (WCED 1987; FAO 1992; OECD 1997). The scientific and policy literature abounds with definitions of sustainable development reflecting the broad range of world-views and the depth of debate over what sustainability means and whether it can be achieved. The most familiar of the many interpretations of sustainable development is the Brundtland definition: 'Sustainable development that meets the needs of the present without compromising the ability of future generations to meet their own needs' (WCED 1987).

Two of the major issues to which such a definition has given rise are, first, the confusion it engenders between the concepts of sustainability and permanence and, second, the implication that the needs of the present generation may indeed be met as a right (Turner 1993). Far from implying permanence, it can be argued that the primary objective of a sustainable use policy must be management for change. It is only when the natural system is allowed time and space to develop naturally that true sustainability will be engendered. This concept has become known as 'strong sustainability', while the alternative view, that of merely preserving existing capital assets is referred to as 'weak sustainability' (Pearce & Warford 1993; Turner 1993; O'Riordan 1995; Crooks & Turner 1999). Weak sustainability is that in which the overall stock of natural capital, both natural and human-made, be maintained, although allowing possibilities of unlimited substitution between different forms of capital. Theoretically, substitution may be between one ecosystem form and another, or comparable functionality or via technological advancement. However, complete substitution is not always possible, and it is questionable whether human-made advances can compensate fully for the loss of natural capital systems beyond critical threshold criteria. Strong sustainability is that in which the total stock of natural capital is non-declining, because of uncertainties over substitution possibilities and the adoption of a precautionary approach, and the ecosystem is allowed to function in as natural a manner as possible both for functional and ethical reasons.

The tendency, especially amongst shoreline managers, to adopt the former weak sustainability definition rather than strong sustainability may be, in some measure, attributable to a reading of the various documents providing guidance or outlining legislation for coastal areas. In many cases, temporal change at the coast is seen as the converse of sustainable use and, moreover, such change is often explicitly defined as erosion or deposition (sometimes even referred to as degradation). For example Chapter 17 of Agenda 21 (UN 1992) states that: 'Current approaches to the management of marine and coastal resources have not always proved capable of achieving sustainable development and coastal resources and the coastal environment are rapidly being *degraded and eroded* in many parts of the world' (UN 1992, para 17.3). 'As concerns physical destruction of coastal and marine areas…priority action should include control and *prevention of coastal erosion and siltation* due to anthropogenic factors' (UN 1992, para 17.29).

The Ramsar Convention includes the following enjoinder to guard against change: 'Each contracting party shall arrange to be informed at the earliest possible time if the ecological character of any wetland in its territory has changed, is changing or is likely to change as the result of technological developments, pollution or other human interference' (Ramsar 1971, Article 3:2).

These statements raise two major propositions. First, erosion and siltation should be seen, not as degradation, but as natural responses to external changes leading to a steady state which should be encouraged by managers who wish to achieve strong sustainability. Second, these changes to the coastal system may, as acknowledged in the excerpts given above, be due to anthropogenic causes as well as natural causes, but the primary response of the system is identical in both cases. Cumulative anthropogenic forcing factors may, however, accelerate the process of coastal change and 'trip' positive or negative domain changes not previously encountered. Whilst this is the case, it is also clear that attempting to stifle the response of a natural system to anthropogenically-induced changes may reduce system resilience further, so emphasizing the negative impacts of human intervention without allowing the system time to adjust to such modification.

Anthropogenic inputs

Instead of continuing this anthropophobic attitude, humankind should view itself as an integral part of the coastal system: anthropogenically-introduced changes are perfectly acceptable as long the impacts changes are understood and the temporal nature of infrastructure in the coastal zone is recognized. The coastal system must be given sufficient time, space and materials (usually in the form of sediments) to adjust to a new equilibrium state. Given this change from one equilibrium change to another, attempts to re-engineer the former coastal system will result in reduced resilience as this now lies within a non-equilibrium state. Thus, for example, introduction of a hard coastal defence in order to protect an important asset may lead to the reshaping of adjacent shorelines; this is a process which may take several decades to achieve but will eventually result in a new, stable, coastal morphology into which the artificial element has been incorporated. Examples of such incorporation include many of the 18th century fishing harbours around the UK coast that now appear to be moulded into their coastline but which, initially, presented a major disruption to natural processes.

This *laissez faire* approach to the development of strong sustainability is appealing, but it may involve the loss of existing infrastructure, natural, industrial or urban, found on adjacent coastlines, which may be threatened by erosion, deposition, flooding or other processes set in motion by the introduced change. Building 'permanent' infrastructure on eroding unstable cliffs, which supply sediment to downstream coastal lowlands, is a clear indication of the impacts of inappropriate development. Such losses may be considered unacceptable, but, in order to assess whether or not to proceed with coastal defence construction there is a need to first be able to predict the medium to long-term effects of any modifications to the natural system. Unfortunately we do not, at present, possess such predictive power for the medium to long-term development of coastal morphology. A strong sustainable coastal system is, therefore, one which cannot be designed since prediction of an optimum morphology is not possible and, since managers are forced to continue making adjustments to the coastal system a protectionist philosophy of weak sustainability is constantly adopted.

Monitoring for sustainable use

There is, however, a middle road that may be adopted, allowing progression towards strong sustainable utilization of coastal systems that function with a mix of anthropogenic and natural inputs. Careful monitoring of the coastal system can be used to fine-tune anthropogenic inputs so that progressive deterioration of natural and human assets is avoided while at the same time allowing the system to change in response to variations in inputs. This implies that, while prediction or design of sustainable coastal systems is not possible, it is possible to recognize an unsustainable system and take appropriate remedial action. This middle road considers the attainment of sustainable coastal systems as a process not as a plan, a process that manages change in the coastal system.

The recognition of an unsustainable coastal system is, however, more complex than may at first be supposed. Deterioration cannot be equated simply with erosion as suggested in Agenda 21 (UN 1992); the erosion of a sand dune or salt marsh may be part of the internal functioning of the wider coastal system, allowing it to adjust to changes in energy or sediment caused by natural or anthropogenic factors. Alternatively, the progressive loss of coastal landforms such as dunes, marshes or mudflats may be seen as deterioration, in that the resulting system is less capable of responding to imposed changes. The problem facing coastal managers is to be able to distinguish between progressive deterioration and system adjustments to changing inputs.

Temporal change in coastal systems

Natural coastal systems have to respond to constantly changing environmental conditions that are imposed by such factors as tidal cycles, wave action or biological seasonality (Carter 1988). If perturbed, a coastal system in equilibrium with environmental conditions will accommodate a disturbance unless a critical threshold level is exceeded. A coastal system in an unstable state will, by contrast, not return to its pre-disturbance state. Many of these low-level, quasi-continuous changes in the environment do not result in morphological changes in the coast, since their energy levels lie below the threshold strength of the coastal form (Pethick 1996). In most cases, this threshold coastal strength has developed as a direct response to such environmental inputs, for example, as in the depositional mudflat environment, so that a short-term balance is achieved between environmental inputs and system response. Infrequent but high-energy events such as extreme storms may, however, exceed this threshold strength and cause changes in the coastal morphology (Pethick 1996). If such large disturbance events were to persist, such change would represent a natural development towards a sustainable form, but since they are relatively rare, they are separated by periods of low energy during which the coast can recover from the effects of the extreme event. This period of recovery, often referred to as the relaxation time of the system (Fig. 1*a*), is crucial to the long-term sustainability of the coast, since, if insufficient time elapses for recovery between threshold events, the coast will suffer progressive change (Fig. 1*b*). Thus, after perturbation a coastal system may fluctuate about a stable state equilibrium, be out of equilibrium or be approaching a new equilibrium, depending on its initial status and the size of the disturbance. The ratio between relaxation time and the return interval for threshold events, referred to here as the Vulnerability Index, provides an important measure of the manner in which coastal landforms respond to imposed changes and can allow assessment of the potential for long term progressive change in the system:

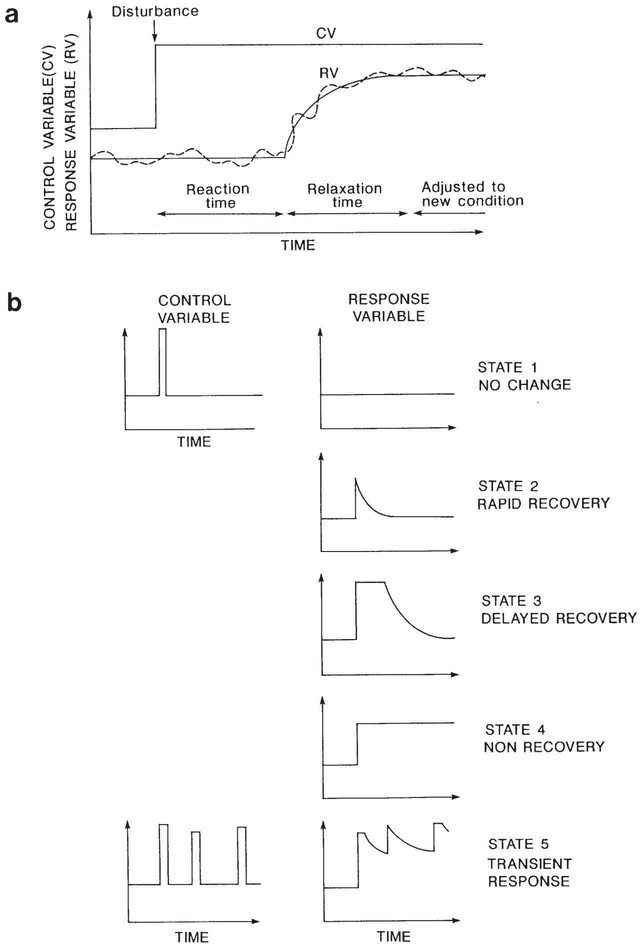

Figure 1 (*a*) A diagrammatic representation of response to a step-like change in control variable, where the solid line of the response curve indicated the mean condition about which fluctuations occur (dashed line). (*b*) Diagrammatic representation of potential coastal responses to large storm events (after Knighton 1998).

Vulnerability Index = relaxation time/return interval (1)

A coastal vulnerability index

Despite the crucial importance of the assessment of change in coastal systems (such as the seven step 'common methodology' for assessment of coastal vulnerability; IPCC, CZMS

1992), no extensive research has been undertaken into the response of these landforms to imposed change. Table 1 shows some documented estimates of the return intervals and corresponding relaxation times of a range of coastal forms. These data are collected from locations around the world and it must be borne in mind that event frequency will be highly variable by geographical area and by the local exposition of the sites. Given that so much effort is related to short term, site-specific studies obtaining appropriate data for the construction of a generic vulnerability index at present is difficult. Nevertheless, by way of example, a vulnerability index constructed from such data (Table 1) provides a first order indication of the sensitivity of the landform to slight changes in its environment. Construction of a vulnerability index for specific coastal regions will need locally specific data, the monitoring requirements of which are discussed below.

Small scale coastal landforms

Using the examples within this preliminary index, salt marshes in southeast England were shown by Pethick (1992) to suffer surface erosion under vegetation cover only during rare events when a high tide is combined with storm-wave conditions. The return interval for such an event was calculated as being >30 years, but the marsh recovered from the erosion by rapid deposition in less than 5 years (Pethick 1992). The vulnerability index of this saltmarsh of 6.0 (Table 1) suggests that an increase in the return interval of such storm events or a decrease in the deposition rate would not result in progressive deterioration of the marsh system. The marsh system may thus be described as robust.

On the other hand, sand dunes located in high-energy environments and with relatively slow recovery time, have a vulnerability index close to 1.0 (Table 1). This implies that even slight random variation in the return interval of erosive wave events could mean that re-erosion of the foredune ridge may occur before the system has recovered fully from previous erosive events. However, the opposite is also true, in that a slight increase in the return interval of threshold events can allow the sand dune system to prograde seaward. This sensitivity may explain why sand dune systems are commonly observed with eroding seaward margins and yet with extensive dune ridges landwards (e.g. Carter 1988).

Sand dune vulnerability

A vulnerability index and its component data could be used as the basis for interpretation of databases assembled as part of monitoring programmes based on remote, terrestrial or marine sources. Simple observation of the temporal variability of coastal landforms is insufficient to allow assessment of long-term deterioration; instead, temporal changes in each landform must be assessed in conjunction with the expected behaviour as indicated by the vulnerability index. Based on the discussion above, observation of erosion of the foredune ridge in a sand dune system need not be taken as an indication of long-term deterioration of the system. The sensitivity of sand dunes to slight random changes in environmental conditions means that such change is to be expected and may continue for several years before a period of accretion ensues. By way of example, Ritchie and Penland (1990) documented storms to induce erosion on the Louisiana barrier coast dunes with a return interval of eight years, yet the dunes recovered within four years. Similarly, Orford *et al.* (1999) attributed long-term dune erosion at Inch Spit, SW Ireland, to extreme storm events (30–50 year frequency) with intervening periods of recovery. The Inch study highlighted the fact that small, annual and sub-decadal scale erosion events had little influence on dune field stability in the system concerned. These examples also serve to highlight the site-specific nature of the vulnerability index for which locally referenced data must be collected.

Saltmarsh vulnerability

Observations of the continued erosion of a salt marsh should be cause for greater concern than those of a sand dune system, since the high vulnerability index of this landform implies that only relatively massive changes in the return interval of erosive events, or the ability of the marsh to recover from such events, can result in progressive loss of the marsh surface. Determining whether observations of erosion are progressive or merely part of a periodic adjustment to

Table 1 Example Vulnerability Indices for a range of coastal features. * Recovery refers to the form of the cliff itself not the location of the form.

Shoreline	*Event Frequency (yr)*	*Relaxation time (yr)*	*Vulnerability index*	*Example*
Cliffs	10^0–10^3	>10^0–10^3	1	Brunsden & Chandler (1996)*; Moon and Healy 1994
Beaches	1	0.7	1.5	Bascom (1954); Gunton (1997)
Sand dunes	8	4	2	Ritchie and Penland (1990); Orford *et al.* (1999)
Mudflats	2	1	2	Pethick (1996)
Spits	500	50	10	De Boer (1988)
Salt marshes	33	5	6	Pethick (1992)
Estuaries	100 000	10 000	10	Metcalfe *et al.* (2000)
Shingle ridges	10–100	1–10	10	Forbes *et al.* (1995); Orford *et al.* (1995)

storm damage is, however, extremely difficult in this case due to the time intervals involved. The probability of a measurement of the aerial extent of a salt marsh falling in a period of recovery from storm damage is 0.16 (five years in 30 years; Pethick 1992) Comparison of a single measurement taken during this period of five years when a reduced marsh area is present, with one taken during a previous stable period when marsh area would be at a maximum, would immediately, but mistakenly, be construed as marsh deterioration. Repeated annual observations over at least 10 years would be needed to establish a progressive change in marsh extent.

It is clear that monitoring coastal landforms such as salt marshes requires that the periodicity of measurement be carefully adjusted to fit the vulnerability index and the relaxation time period of the landform. Monitoring programmes, which do not incorporate such periodicity, may result in erroneous conclusions and stimulate coastal managers to take wholly inappropriate defensive action resulting in a reduction in the ability of the marsh to respond to future events.

Beach vulnerability

Similar conclusions could be made in the case of beaches, the high vulnerability index of which implies robustness of response to environmental changes. Recovery of beaches after storm events can take hours and thus gives an apparent permanence to this highly volatile environment. Cyclical changes on beach morphology may take place with seasonal change (Gunton 1997). Beach erosion that is not matched by such recovery must therefore be taken as an indication of a major environmental shift that is leading to progressive deterioration. Such changes are often ascribed to anthropogenic interference in the system, particularly to sediment inhibition by coastal defence works that can significantly increase the relaxation time of adjacent beach systems (Cooper *et al.* 2000).

Large-scale coastal landforms

Large-scale coastal landforms, such as estuaries, respond to environmental changes in the same way as do the smaller-scale forms already discussed. The difference in spatial scale, however, is reflected in the temporal scale of such adjustments and, since the smaller-scale forms are nested within the larger systems, this means that a complex series of internal responses is set up.

Estuaries

Monitoring and assessment of the long-term sustainability of larger coastal landforms such as estuaries or cliffed coasts presents much greater problems than the smaller-scale marshes, beaches or sand dunes, although speculative relaxation times and event return intervals for such large-scale systems (Table 1) may indicate some of the issues involved. Estuaries for example are a response to the change in postglacial sea level and in many cases, especially those estuaries with high sediment loads, appear to have achieved a form of steady state in the 10 000 years of the Holocene period. Assuming that such major changes in sea level have taken place only in inter-glacial periods, the return interval for the threshold event here may be as long as 100 000 years. This would mean that the vulnerability index for such estuaries could be 0.1, well within the range for landforms that are much smaller in scale and this implies that slight changes in sea level or deposition rates would have no long-term progressive impact on the estuarine system.

Open coasts

At the opposite extreme, rocky cliffed coastlines also respond to major changes in sea level, again perhaps with an inter-glacial return interval, but here the strength of the cliffs prevents any rapid response to such changes, so that the relaxation time is extremely long. In some cases, cliff erosion appears to have continued throughout the last inter-glacial period, implying that the relaxation time of these large-scale hardrock systems is greater than the threshold return interval, and that the vulnerability index might be <1.0. If this is the case, then continued erosion of cliff coasts may be expected during the present inter-glacial period, despite the negative feedback in the system whereby widening abrasion platforms reduce incident wave energy at the foot of the cliff.

Nested responses

In both these cases the large-scale landform, whether estuary or open coast, has nested within it a number of smaller-scale forms such as beaches, shingle ridges, sand dunes, mudflats or marshes. Each of these components must respond to the changes in environment that result from the adjustment of the larger unit and adjustment of its own. Thus, beaches located on a cliff coast must respond to the gradual changes in sediment supply and wave energy that are imposed upon them as the cliffs recede and abrasion platforms widen. It may be speculated that the gradual, world-wide erosion of beaches that has been noted over the past 100 years (Bird 1985) could be a response to this large-scale change in environment. If this is so, then the causes of the present observed deterioration in many beaches (Bird 1985) may be internal to the larger system and not exclusively to any recent changes in environmental inputs.

In the case of estuarine systems, the robustness implied by the high vulnerability index means that if the system reaches an age at which it has recovered from its postglacial sea level shock, further minor changes in energy or sediments will become less significant. To the small-scale components of the estuary, however, these environmental changes may represent major shifts in the environmental conditions and the components will respond accordingly. Thus, an increase in sea level may be expected to increase the joint probability of wave and tide events that threaten salt marshes and intertidal mudflats. The result may be a progressive decrease in intertidal area, such as is now being observed (Viles & Spencer 1995) in many coastal areas. Although the change in sea level itself may not affect the wider estuary system directly, such reduction in the intertidal zone may have an indirect effect by widening the estuary at a given point.

Monitoring and management

It is apparent from these examples that the recognition of progressive change in coastal systems depends to a large extent on the ability to determine the periodicity of regular adjustments to threshold events for coastal landforms and to interpret any longer periods of change as deterioration. Provision of a suitable database, the measurement periodicity of which is designed to coincide with coastal adjustments and which will therefore allow such interpretation, must be seen as a major challenge for the immediate future. The rigorous requirements of such a database call into question the utility of infrequent or randomly-spaced observations. For this reason, many types of remote sensing which depend upon cloud cover or tidal states can only be used if they are combined with more frequent and regular terrestrial observations. Such a monitoring programme, composed of a variety of different types of observation, could be devised to allow minimum cost commensurate with maximum temporal cover.

Identification of deterioration, as opposed to adjustment, is the primary goal of monitoring and the complexities of such an assessment have been outlined here in an introductory way. If progressive changes in a coastal system are suspected, then identification of possible causal factors is necessary before any remedial action may be taken. Heightened vulnerability of a coastal landform, reflected by a decrease in index value towards 1.0, may be caused by one or both of two groups of factors, namely a decrease in return intervals of energy events or an increase in the length of the response time of the landform (Eq. 1). This is of course a geomorphological perspective and it must borne in mind that social vulnerability may stem from habitation in locations where disturbance occurs on a low frequency and high magnitude basis. Here shortening of relaxation time in coastal landform recovery may well induce a chain of additional damages and disturbances that increase social vulnerability. Progressive change in a natural system cannot be defined as deterioration, since eventually some new steady-state form will be attained. Progressive change that is due to anthropogenic causes may, however, be defined as deterioration and here interference in natural coastal systems can have three effects:

- An increase in the frequency or magnitude of energy inputs (waves or currents). This may be caused by such modifications as an increase in water depth due to dredging, or channel straightening or reclamation in an estuary (e.g. Inglis & Kestner 1958; Price & Kendrick 1963; O'Connor 1987).
- A decrease in the sediment supply to a coastal area caused by coastal defence of eroding cliffs, aggregate dredging, fluvial dams, or loss of sediment-trapping vegetation due to pollution (e.g. Ly 1980; Carter 1988; Stanley & Warne 1993).
- A decrease in the area available for coastal landform development. This is perhaps the most prevalent cause of system deterioration and can involve such structures as reclamation banks for agriculture, coastal defences, estuarine training walls, or port and harbour constructions (e.g. Bird 1985; Carpenter & Pye 1996).

In each case, such interference results in a lowering of the vulnerability index until the critical threshold is attained when progressive deterioration is initiated. In the case of extremely responsive landforms, for instance sand dunes, such a process may be initiated by relatively small changes in the environment. In other cases such as beaches, major changes must be introduced before deterioration is affected. These considerations may allow a more positive approach to the introduction of artificial elements into coastal systems. It is not necessary to attempt to return to some ideal natural system in order to provide a sustainable coastal morphology. Anthropogenic changes can be introduced as long as the impacts allow the vulnerability index to remain above the critical threshold. This means more careful management is required in treatment of sensitive coastal areas but less so in robust areas. In cases where progressive deterioration is noted, then it will be necessary to adjust anthropogenic impacts to a safe level, rather than remove the impact altogether.

Conclusions

This paper has attempted to provide a deterministic approach to the problems involved in the attainment of a geomorphologically-sustainable coastal system. This approach is based upon recovery-time vulnerability for coastal landform at given geographical locations. Human interference upon the resilience of the natural system must be viewed much in the same way as any other driving force of environmental change. This is not to say that all human-induced activity in coastal systems is acceptable, but that given the means to determine deterioration in system geomorphological vulnerability the possible need to adapt management strategies to reduce social vulnerability becomes apparent.

The prediction of a sustainable coastal morphology over long time periods must remain an elusive goal for the present; instead, it is recommended that a programme of monitoring is initiated which allows the identification of coastal deterioration in time for remedial action to be taken. This implies that the attainment of sustainable coastal systems is more of an ongoing process than the implementation of a well-defined plan. Such a programme does not entail protectionism or preservation but is intended to manage change in the coastal system so that it is allowed to adjust to the various environmental changes that occur, both natural and human. In order to determine the levels at which human interference might be sustainable, a vulnerability index, to be based upon site-specific data, is proposed that would allow the sensitivity of coastal landforms to be assessed and to which monitoring results could be referred.

Coastal systems are remarkably robust, and can tolerate major changes in environmental conditions before they begin to suffer long-term deterioration. The task that faces society over the next few years is to provide a carefully constructed research base that is capable of defining the precise limits of such tolerances, only then will we be able to utilize our coastal resources in a sustainable manner over the long term.

References

Adger, N.W. (1999) Social vulnerability to climate change and extremes in coastal Vietnam. *World Development* **27**: 249–269.

Barne, J.H., Robson, C.F., Kaznowska, S.S., Doody, J.P., Davidson, N.C. & Buck, A.L., eds. (1996) *Coasts and Seas of the United Kingdom. Region 11. The Western Approaches: Falmouth Bay to Kenfig*. Peterborough, UK: Joint Nature Conservation Committee (JNCC): 210 pp.

Bascom, W.H. (1954) Characteristics of natural beaches. *Proceedings of the 4th Conference on Coastal Engineering*, pp. 163–180. Victoria, Australia: Institute of Engineers of Australia.

Bird, E.C.F. (1985) *Coastal Changes: A Global Review*. Chichester, UK: Wiley.

Bower, B.T. & Turner, R.K. (1998) Characterising amd analysing benefits from integrated coastal management (ICM). *Ocean and Coastal Management* **38**: 41–66.

Brunsden, D. & Chandler, J.H. (1996) Development of an episodic landform change model based upon the Black Ven Mudslide, 1946–1995. *Advances in Hillslope Processes: Volume 2*, ed. M.G. Anderson & S.M. Brooks, pp. 869–896. Chichester, UK: John Wiley.

Capobianco, M., DeVriend, H.J., Nicolls, R.J. & Stive, M.J.F. (1999) Coastal area impacts and vulnerability assessment: the point of view of a morphodynamic modeller. *Journal of Coastal Research* **15**: 701–716.

Carpenter, K. & Pye, K. (1996) Saltmarsh change in England and Wales – its history and causes. Environment Agency R & D Technical report W12, HR Wallingford Ltd. and Foundation for Water Research, Marlow: 181 pp.

Carter, R.W.G. (1988) *Coastal Environments: An Introduction to the Physical, Ecological and Cultural Systems of Coastlines*. London, UK: Academic Press: 614 pp.

Cooper, N.J., Leggett, D.J. & Lowe, J.P. (2000) Beach profile management, theory and analysis: practical guidance and applied case studies. *Journal of the Chartered Institution of Water and Environmental Management* **14**: 79–88.

Crooks, S. & Turner, R.K. (1999) Coastal zone management: sustaining estuarine natural resources. *Advances in Ecological Research* **29**: 241–291.

De Boer, G. (1988) History of the Humber coast. In: *A Dynamic Estuary: Man, Nature and the Humber*, ed. N.V. Jones, pp. 16–30. Hull, UK: Hull University Press.

DoE (1993) *Managing the Coast: A Review of Coastal Management Plans in England and Wales and the Powers Supporting Them.* London, UK: HMSO.

FAO (1992) Sustainable development and the environment. Unpublished report, Food and Agriculture Organization, Rome.

Forbes, D.L., Orford, J.D., Carter, R.W.G., Shaw, J. & Jennings, S.C. (1995) Morphodynamic evolution, self-organisation, and instability of coarse clastic barriers on paraglacial coasts. *Marine Geology* **126**: 63–85.

Gunton, A. (1997) Upper foreshore and sea wall stability, Jersey, Channel Islands. *Journal of Coastal Research* **13**: 813–821.

Inglis, C.C. & Kestner, F.J.T. (1958) The long-term effects of training walls, reclamation and dredging on estuaries. *Proceedings of the Institution of Civil Engineers* **9**: 193–216.

IPCC (1996) *Second Assessment Report: the Science of Climate Change*. Cambridge, UK: Cambridge University Press: 564 pp.

IPCC, CZMS (1992) *Global Climate Change and the Rising Challenge of the Sea*. Geneva, Switzerland: Meteorological Organization and the United Nations Environment Programme.

Knighton, D. (1998) *Fluvial Forms and Processes*. London, UK: Arnold: 383 pp.

Ly, C.K. (1980) The role of the Akosombo Dam on the Volta river in causing coastal erosion in central and eastern Ghana (west Africa). *Marine Geology* **37**: 323–332.

MAFF (1993) Strategy for Coastal Defence in England and Wales (No. PB1471). Unpublished Report, Ministry of Agriculture, Fisheries and Food and the Welsh Office, HMSO, UK.

Metcalfe, S.E., Ellis, S., Horton, B.P., Innes, J.B., McArthur, J., Mitlehner, A., Parkes, A. Pethick, J.S., Rees, J., Ridgway, J., Rutherford, M.M., Shennan, I. & Tooley, M.J. (2000) The Holocene evolution of the Humber Estuary: reconstructing change in a dynamic environment. In: *Holocene Land–Ocean Interactions and Environmental Change around the North Sea,* ed. I.Shennan & J. Andrews, pp. 97–118. London, UK: Geological Society, Special Publication **166**.

Moon, V.G. & Healy, T. (1994) Mechanisms of coastal cliff retreat and hazard zone delineation in soft flysch deposits. *Journal of Coastal Research* **10**: 663–680.

OECD (1997) *OECD Policy Approaches for the 21st Century*. Paris, France: Organization for Economic Growth and Development.

O'Connor, B.A. (1987) Short and long term changes in estuary capacity. *Journal of the Geological Society, London* **144**: 187–195.

Orford, J.D., Carter, R.W.G., Jennings, S.C. & Hinton, A.C. (1995) Processes and timescales by which a coastal gravel-dominated barrier responds geomorphologically to sea-level rise – Story Head Barrier, Nova Scotia. *Earth Surface Process and Landforms* **20**: 21–37.

Orford, J.D., Cooper, J.A.G. & McKenna, J. (1999). Mesoscale temporal changes to foredunes at Inch Spit, south-west Ireland. *Zeitschrift für Geomorphologie* **43**: 439–461.

O'Riordan, T., ed. (1995) *Environmental Science for Environmental Management*. Harlow, UK: Longman: 369 pp.

Pearce, D. W. & Warford, J.J. (1993) *World Without End: Economics, Environment and Sustainable Development*. Oxford, UK: Oxford University Press: 440 pp.

Pethick, J. S. (1992) Salt marsh geomorphology. In: *Salt marshes: Morphodynamics, Conservation and Engineering Significance,* ed. J.R.L. Allen & K. Pye, pp. 41–62. Cambridge, UK: Cambridge University Press.

Pethick, J.S. (1996) The geomorphology of mudflats. In: *Estuarine Shores: Evolution, Environment and Human Health*, ed. K.F. Nordstrom & C.T. Roman, pp. 185–211. Chichester, UK: John Wiley.

Price, W.A. & Kendrick, M.P (1963) Field and model investigation into the reasons for siltation in the Mersey Estuary. *Proceedings of the Institute of Civil Engineering* **24**: 473–518.

Ramsar (1971) *Convention on Wetlands of International Importance* *especially as Waterfowl Habitat*. Paris, France: United Nations Educational, Scientific and Cultural Organization (UNESCO).

Richie, W. & Penland, S. (1990) Aeolian sand bodies of the south Lousianna coast. In: *Coastal Dunes*, ed. K.F.Nordstrom, N.P. Pusty & R.W.G. Carter, pp. 105–27. Chichester, UK: John Wiley.

Stanley, D.J. & Warne, A.G. (1993) Nile Delta: recent geological conditions and human impact. *Science* **260**: 624–634.

Townend, I.H. (1990) Frameworks for shoreline management. *International Navigation Association (PIANC-AIPCN) Bulletin* **71**: 72–80.

Turner, R. K. (1993) Sustainability: principles and practice. In: *Sustainable Environmental Economics and Management,* ed. R.K. Turner, pp. 3–36. London, UK: Bellhaven Press.

UN (1992) *Agenda 21. Rio: United Nations Programme of Action from Rio.* New York, USA: United Nations Publication.

Viles, H. & Spencer, T. (1995) *Coastal Problems: Geomorphology, Ecology and Society at the Coast*. London, UK: Edward Arnold: 350 pp.

WCED (1987) *Our Common Future*. Oxford, UK: Oxford University Press: 398 pp.