# ‘Methodology for Coastal Evolution and Risk Mapping’

**LIFE Environment Project 2003-2006 ‘RESPONSE’: LIFE 03 ENV/UK/000611**

# Contents

# 1 Scientific basis for RESPONSE

## 1.1 *Preamble*

RESPONSE is an EU-funded demonstration project that aims to develop a methodology for assessing the hazard and risk of climate change at the coastline.

This report gives technical guidance for application of the RESPONSE methodology and provides information on the scientific principles behind the methodology, including discussions of coastal behaviour, hazard and risk. The application of the RESPONSE methodology is described using a series of descriptive, interpretative and non-technical maps covering the south coast of England as a worked example.

## 1.2 *Introduction*

Effective responses to the challenges presented by climate change will involve scientists, decision-makers and the public, working in partnership to:

- understand how the levels of risk currently imposed on coastal communities could change in the future (i.e. risk assessment);
- communicate this risk information to decision-makers in a form that is readily accessible to a non-scientific audience (i.e. risk communication);
- evaluate the significance of the changes in risk and establishing whether current risk management strategies and policies need to be modified or replaced (i.e. risk evaluation); and
- implement the risk management strategies and policies, through a combination of state and local government funding, private investment and public participation (i.e. risk management).

The overall goal can be described as risk-based decision-making. This involves a number of distinct stages from risk assessment to risk evaluation and management (Figure 1). These stages mark a progression from technical-based activity (risk assessment) to the broader-based judgements and policies involved in evaluation and management. Although the process needs to be supported by a sound technical understanding of the risks, the management responses will be controlled or influenced by non-technical factors that will vary in significance between the European Union Member States, including:

- the cultural environment, reflecting the attitudes and values of society and their political representatives about the relative merits of public investment in risk reduction; and
- the legal and administrative framework, which provides the opportunities and constraints for undertaking risk management activities.

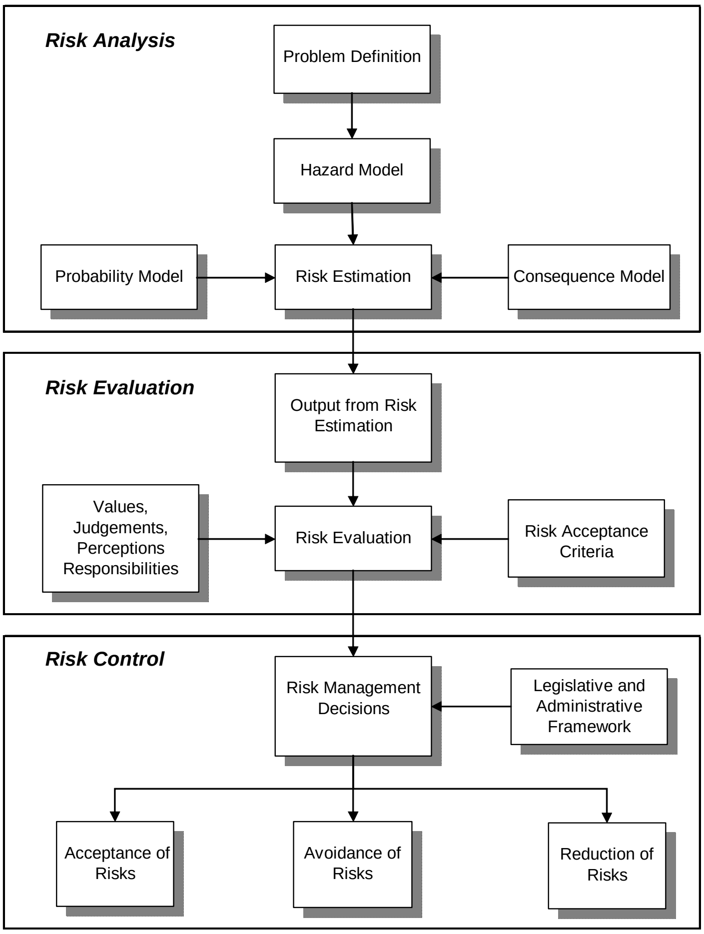



*Figure 1 The risk assessment process*

The dissemination of information between the different groups in a form that can be understood is likely to prove to be a key factor in determining the effectiveness of the management response. For this reason, the focus of the RESPONSE study has been on the interface between the scientific community and decision-makers, developing and testing methods for communicating risk information in ways in which it can be directly used in the decision-making process.

The RESPONSE study has demonstrated that *maps* are a very useful means of communicating risk information, especially to non-technical audiences. However, this is essentially the end product of a risk assessment procedure that is dependent on reliable models of coastal behaviour, hazards and consequences (Figure 2).

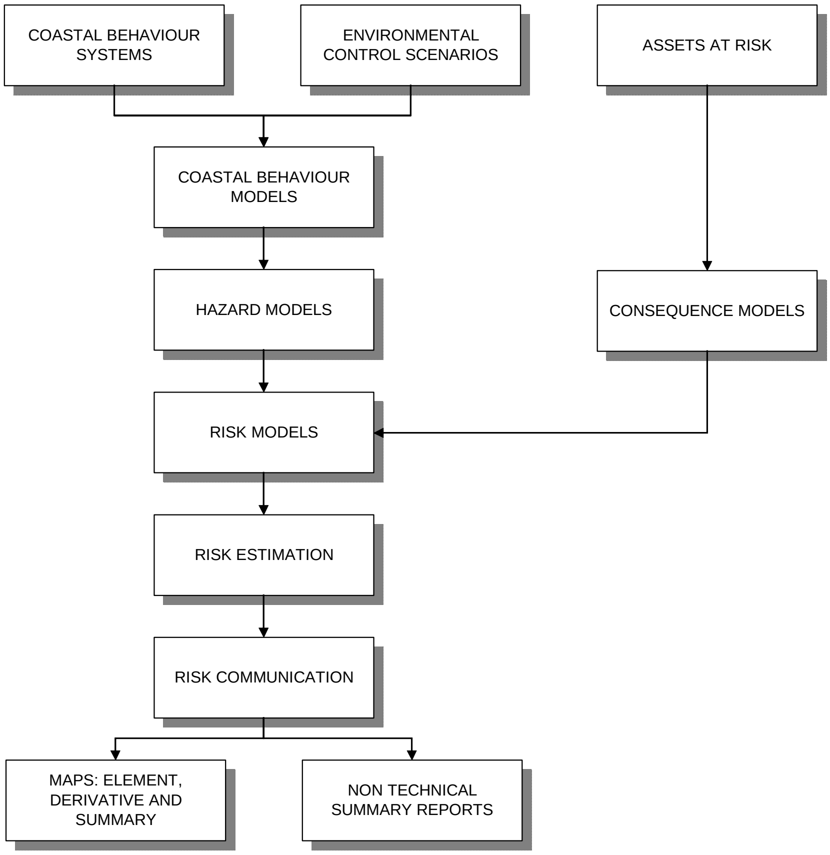



*Figure 2 The RESPONSE risk assessment procedure*

## 1.3 *Coastal Behaviour Models*

### 1.3.1 *Coastal Systems*

The key message of the RESPONSE project is that understanding the shoreline behaviour is essential for predicting the response to climate change and sea-level rise. Earth surface systems provide the framework for developing this understanding. These are conceptual models that can be used to describe how sediment and energy transfers (e.g. alongshore or onshore-offshore) provide the inter-linkages between the different landforms along a shoreline.

Earth surface systems can be defined at a range of scales. Of relevance to coastal risk assessment are:

1) sediment transport cells; the shoreline comprises a series of inter-linked units within which sediment is moved along energy gradients, from high energy sediment source areas (e.g. eroding cliffs, offshore sand banks), along sediment transport pathways (e.g. beaches) to low energy sediment stores (e.g. dunes, offshore banks). Evolution of these sediment transport cells (littoral cells) sets the framework within which individual landforms will "behave".
2) coastal behaviour systems (landform assemblages); the individual components of a sediment transport cells, such as a beach-dune system. Each system with have its own arrangement of sediment and energy source areas (inputs from adjacent sub-systems), transport pathways, storage and outputs (transfers to adjacent systems).

The influences on coastal behaviour systems (CBS) can be organised into a generalised hierarchy:

1) System environmental controls; these are climate, gravitatio, eustatic sea-level, tectonic history and the post-glacial effects of isostatic readjustment, and the existing geology and topography (i.e. boundary conditions);
2) Energy regime factors; these factors vary in response to changes in the system controls and include: rainfall, tidal range, wave climate and relative sea-level. These are the drivers of change (i.e. forcing factors).
3) System state; this is defined by the dimensions and characteristics of the landforms/elements that form the system (e.g. the beach in a cliff-beach system). It is the product of past change and sets the framework for future evolution.

This type of model provides a framework for understanding and representing the relationships between different system components. A model of a coastal cliff system is shown in Figure 3, which highlights the interactions between terrestrial (cliff) and marine (shoreline) components. Each of these two linked systems has its own environmental controls. The energy regime (forcing) factors are identified as a primary response to the environmental controls. Morphological changes to the shoreline and cliff represent the local response to variation in the forcing factors (Figure 4).

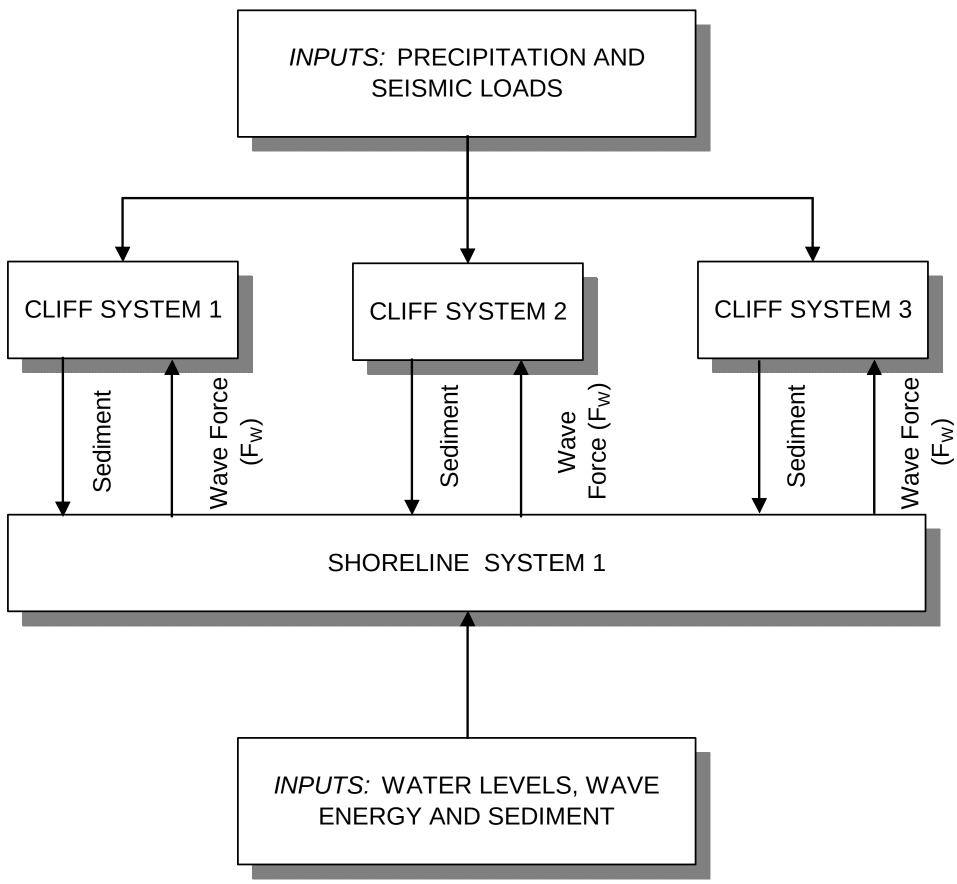



*Figure 3 A cliff system model*

1.3.2 *System Behaviour*

CBS *behaviour* describes the morphological response to variations in the balance between the forcing factors (e.g. wave energy) and the resistance of the materials. Over time, the morphology of the sub-systems represents a balance between the energy inputs and the materials. However, morphology also influences the available energy (e.g. beach height, shoreline orientation).

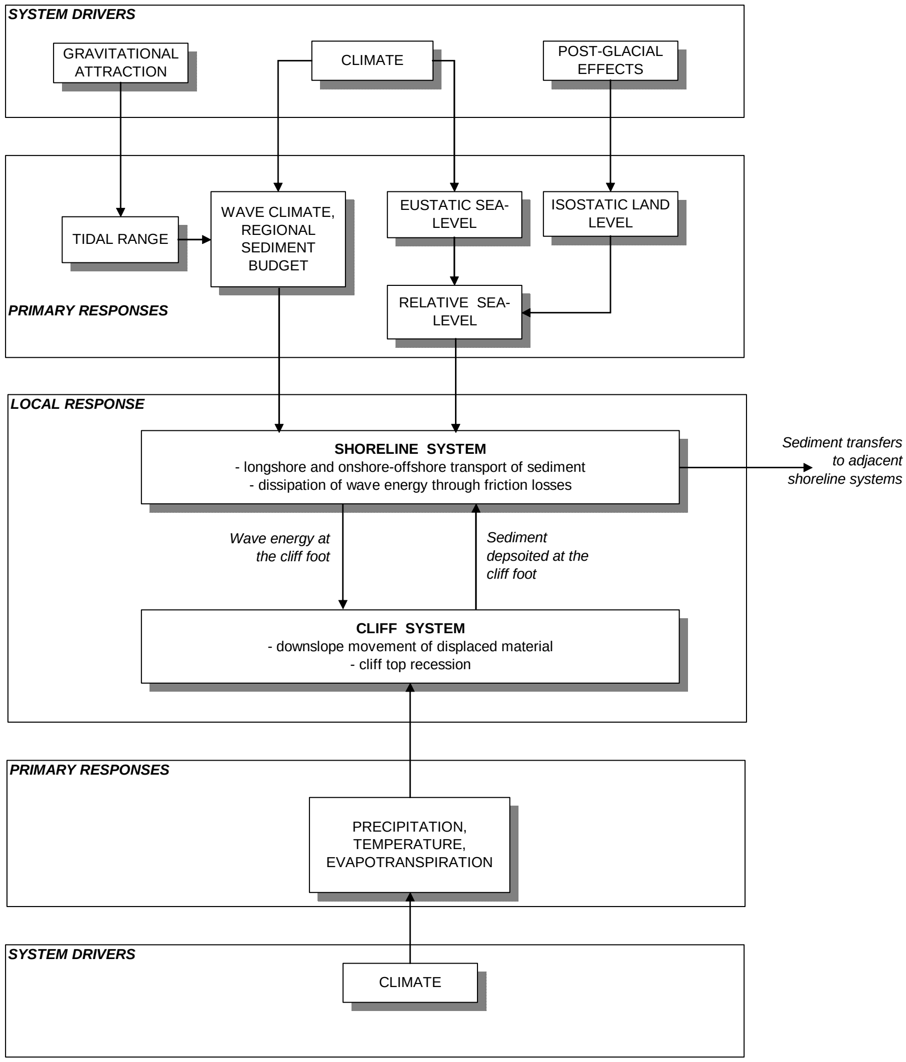



*Figure 4 Generalised hierarchy of classes and influences between the shoreline and cliff systems*

Changes in *cliff behaviour* can result from *either* changes in the energy regime or changes in system state (e.g. cliff materials, beach levels, toe protection etc.). These behaviour changes can involve a change in system state or a change in the rate of activity

(a) Change in the system state

This is change in the overall form of the landform; many landforms can occur in a limited number of robust states within which behaviour is reasonably predictable. Shingle beaches can evolve towards a series of distinct states: barrier beaches, barrier island and inlet complexes and fringing beaches. The transition between states will be associated with storm events. However, the evolving beach form (e.g. changing shoreline orientation or crest height) will also influence sediment transport processes and, hence, future beach behaviour. The constraints imposed by the geological and topographic setting (e.g. headlands and high ground inland of lagoons) will also have a major influence on the evolution pathways.

There can be considerable uncertainties associated with shingle beach evolution. However, during a storm event there is the possibility that there will be a change in beach state (Table 1; Figure 5).

*Table 1 Shingle Beach States and Evolution Pathways*

| Current State | Process | Future State |
|---|---|---|
| Barrier | Landward migration | Barrier |
| | Landward migration | Fringing beach (attachment onto hinterland slopes) |
| | Overstepping | Fringing beach |
| | Breach | Island and inlet complex |
| Island and Inlet Complex | Tidal flows | Island and inlet complex |
| | Longshore transport | Barrier (breach infill) |
| | Landward migration | Fringing beach (attachment onto hinterland slopes) |
| Fringing beach | Landward migration | Fringing beach |
| | Flooding of hinterland (rising sea-level) | Barrier |
| | Flooding of hinterland (rising sea-level) | Island and inlet complex |

Some changes are more likely than others. The likelihood that the beach will evolve along a particular pathway will be influenced by the current state of the beach system, the environmental conditions, (including the rate of relative sea-level rise and sediment availability) and the geological and topographic setting (accommodation space).

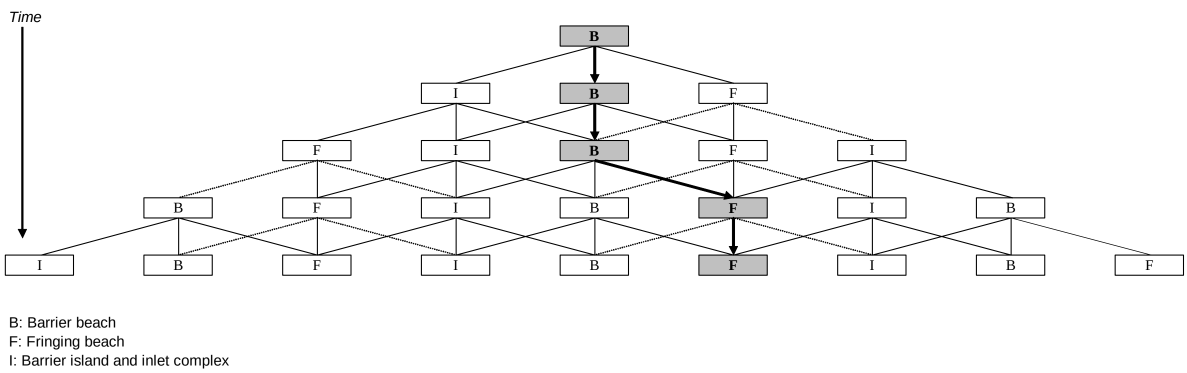



*Figure 5 Potential evolution pathways of a shingle beach system over 5 time steps (adapted from Cowell and Thom 1994).*

The chance of particular state change occurring will vary over time, as the beach form and sediment transport processes change. For example, the chance of the transition from a barrier to an island/inlet complex will vary with changes in the overwashing ratio (the proportion of waves of sufficient magnitude to generate overwash events; Figure 6). This is a function of the wave climate and the barrier crest height relative to sea-level.

Some system states are effectively evolutionary dead-ends. For example, once a fringing beach has developed at the foot of an eroding cliffline the evolutionary options are severely restricted unless the relative sea-level change (i.e. eustatic or isostatic) is sufficient to cause inundation of the hinterland and allow a new phase of barrier or island/inlet development.

(b) Changes in rate of activity

This is achieved whilst maintaining the same system state. Shingle barriers tend to respond to the energy changes associated with relative sea-level rise by "roll-over" and by increasing the crest height. Retreat is controlled by the relative significance of overtopping and overwashing events (Figure 6):

- relatively low magnitude, overtopping surge transports gravel up the beach, leading to crest height increase;
- high magnitude overwashing surge carries gravel over the crest and down the backslope where it is deposited as a series of fans. Overwashing leads to barrier retreat (roll-over).

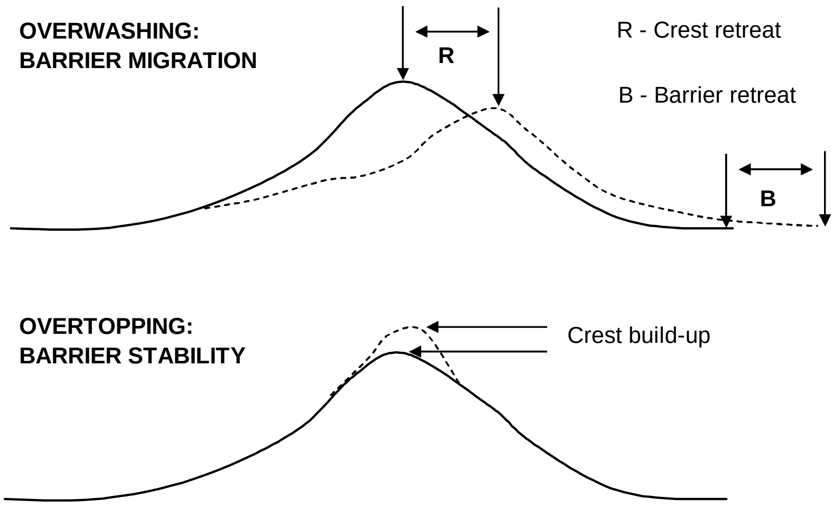



*Figure 6 Simple shingle beach overwashing and overtopping models*

The balance of these two processes controls the frequency and magnitude of roll-over events. The barrier retreat efficiency (the change in retreat rate per unit increase in the rate of sea-level rise) is related to the barrier size or barrier inertia (i.e. cross sectional area x crest height; Figure 7).

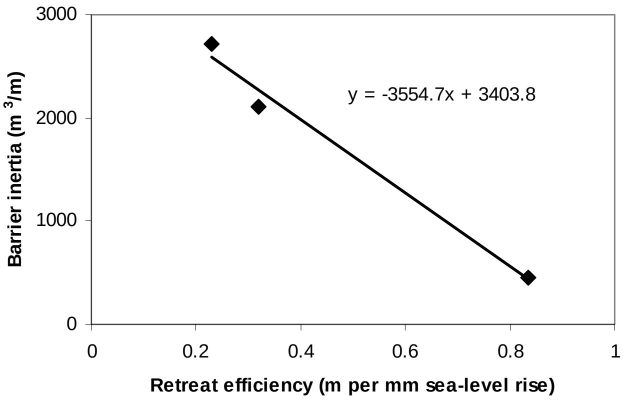



*Figure 7 Barrier retreat efficiency (from Orford et al 1995)*

System components and shoreline processes are interlinked as changes to one will influence the other. Erosion results in the release of sediment which may be deposited on the foreshore, altering the boundary conditions for the surface processes. For example, beaches control wave energy dissipation on the foreshore and, in some situations, can provide complete protection to cliffs from marine erosion. This is illustrated in Figure 8 which shows the relationship between the average beach volume (measured as the beach profile area above High Water Mark – the "beach wedge") and annual cliff recession rate for 7 profile monitoring sites on the Suffolk cliffs, UK. A range of generic behaviour types is presented in Table 2.

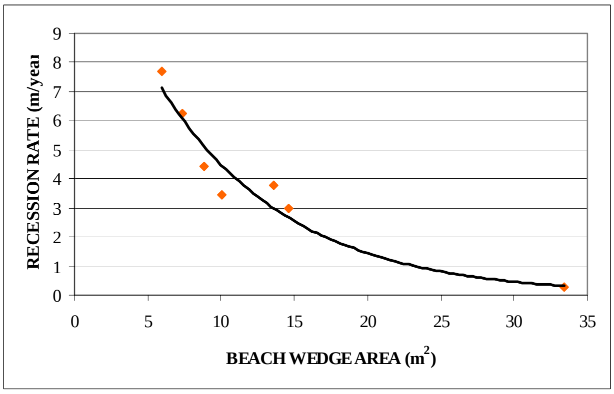



*Figure 8 Suffolk Cliffs, UK: Relationship between mean annual recession rate and mean beach volumes*

1.3.3 *CBS Response to Relative Sea-level Change*

Relative sea-level rise (RSLR) will result in an increase in wave and tidal energy arriving at the shoreline. The landward end of the shore profile (e.g. the beach face or saltmarsh cliff) would be exposed to a higher energy environment, leading to erosion. The net result could be a landward migration of the shore profile, so that the profile position and form is maintained relative to sea-level.

*Table 2 Generic coastal behaviour types*

| State | Transgressive Shoreline | Stationary Shoreline | Regressive Shoreline | Typical Conditions |
|---|---|---|---|---|
| Static equilibrium | 1. Landforms resistant to change | | | Landform resistance exceeds imposed stresses (i.e. strength > forcing) |
| Steady state equilibrium | 2a. Shorelines retreating at a constant mean rate, constant state variable (e.g. beach volumes) | 2b. Static shorelines, maintaining constant state variable (e.g. beach volumes) | 2c. Shorelines accreting at a constant mean rate, maintaining constant state variables (e.g. saltmarsh mudflat systems) | Stationary boundary conditions (i.e. constant resistance/strength and forcing) |
| Dynamic equilibrium | 3a. Shorelines retreating at a changing mean rate (i.e. accelerating or decelerating), with changing state variables (e.g. beach volumes) | 3b. Static shorelines, with changing state variables (e.g. beach volumes) | 3c. Shorelines accreting at a changing mean rate (i.e. accelerating or decelerating), with changing state variables (e.g. beach volumes) | Non-stationary boundary conditions (i.e. changing resistance/strength and/or forcing) |
| Meta-stable equilibrium | 4. Establishment of a new state (characteristic form) e.g. breakdown of a shingle barrier to a tidal inlet/barrier island system | | | Exceedence of CBS thresholds. |

Dungeness and Holderness provide examples of CBS response to relative sea level change. Figure 9 shows the acceleration in erosion along the south shore of the Dungeness shingle foreland since 1946. It is likely that these trends reflect the shoreline response to rising relative sea-levels, recorded at 1.94mm/year (1961-1993). If so, then the data suggests that erosion has accelerated at, on average, around 4cm for every 2mm of sea-level rise (i.e. 2cm per 1mm relative sea-level rise). A similar trend has developed on the eroding glacial till cliffs of Holderness, where cliff recession rates have increased since 1950 by around 2.5cm per 1mm relative sea-level rise.

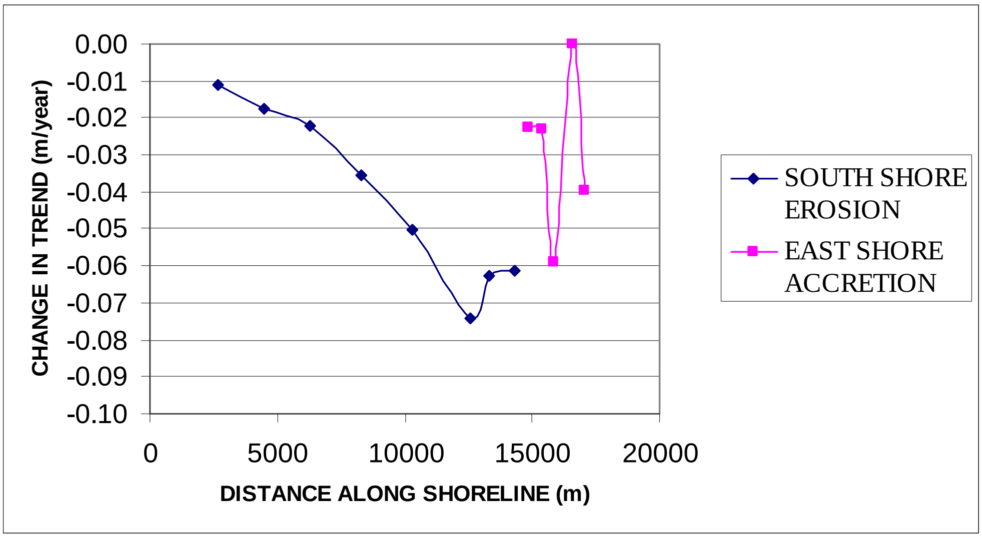



*Figure 9 Dungeness foreland, UK: Variation in the rate of erosion and accretion over time (acceleration/deceleration)*

However, other responses are possible, especially where there is an increase in sediment supply; accelerated erosion in one location will release sediment for deposition elsewhere. For example, the London Clay cliffs at Hadleigh, Essex, UK were "abandoned" around 6000BP because of the growth of a broad saltmarsh at the cliff foot; this occurred at a time when sea-level was rising at around 4mm/year. Site specific changes can only be predicted within the context of the evolution of broad-scale coastal cells and changes in sediment availability.

### 1.3.4 *Coastal Evolution Models*

Coastal evolution models provide a framework for the accurate definition of coastal hazards. By providing an explanation about the behaviour of system components, a model can be used to make predictions of future morphological changes. Examples include:

1) natural historical analogue models; models can be developed to explain the historical evolution of a system (e.g. the shoreline) in the context of the effect of changes in environmental controls. Such models tend to be qualitative and subjective, but can provide a framework for understanding long-term metastable or dynamic equilibrium responses. Examples include:

- the Coastal Behaviour Systems framework;
- the Ventnor Undercliff ground behaviour models.

2) simple empirical models; models based on the observed relationship between different system variables are widely used. For example, the O'Brien equation relates estuary tidal prism to mouth area:

$$A_m = CP^n$$

where $A_m$ is the cross sectional area ($m^2$), P the tidal prism ($m^3$), and C and n are constants.

3) mathematical models; the short-term sediment transport linkages between the elements within a system can be represented by numerical models. For example, models are capable of simulating the various processes of wave propagation, current distribution, and the resulting sediment transport in complex coastal areas.

4) probabilistic models; these methods attempt to represent the variability and uncertainty inherent in geomorphological processes. A full range of input parameters can be tested, each one weighted according to its likelihood of occurrence. This can be achieved through repeated trials involving the random sampling from an input probability distribution (i.e. "Monte Carlo" simulation).

5) system synthesis models; the CLIFFPLAN model, for example, simulates the cliff recession process including wave transformation, sediment transport, shore erosion and cliff stability. The model uses random sampling of the input parameters from probability distributions to represent uncertainty in the cliff recession process, with the output also being expressed as a probability distribution.

Coastal evolution models form the basis for the development of *hazard models* and can range in sophistication (Table 3).

*Table 3 Types of Coastal Behaviour Model*

| Type | Description |
|---|---|
| I | Broad qualitative generalisations about future behaviour (e.g. trends and state changes) |
| II | Simple quantitative models of system response (e.g. change in rate or event frequency). Examples include the Bruun Rule, probabilistic cliff recession models. |
| III | Numerical models, incorporating stochastic forcing (e.g. Monte Carlo simulation) and non-linear behaviour. |

The dominant influences of relative sea-level change and sediment availability on future coastal evolution provide a framework for developing scenarios that define future combinations of environmental controls that form the boundary conditions to coastal evolution models. These combinations could be defined as a simple matrix in which different sea-level trends and matched against varying levels of sediment availability (Table 4). Other factors that might be incorporated within these scenarios include changes in wave climate (e.g. due to changes in depression tracks across the Atlantic), tidal range and human intervention.

For further details regarding categorising the coastline into Coastal Behaviour Systems, see the tables annexed to this report.

### 1.4 Hazard Models

#### 1.4.1 *Introduction*

Hazards are defined as the potential for future events (i.e. coastal processes) to adversely affect humans and the things that people value (i.e. a situation that in particular circumstances could lead to harm). Processes operating in remote regions, away from human occupancy or use are not hazards. Amongst the most important coastal hazards are:

- flooding of low-lying coastal areas (including tsunami);
- erosion of coastal cliffs, including coastal landslide activity;
- wind blown sand in coastal dunes.

These hazards are the agents that can cause loss and contribute to the generation of risk. Although the magnitude-frequency characteristics are these hazards (e.g. the 100-year flood) are important in helping to determine risk, they are not risk, merely measures of hazardousness. References to "increased risk of wave overtopping"' or "accelerated erosion risk" are misleading, for they refer to increased likelihood of occurrence of hazards and not an increase in the scale or likelihood of adverse consequences.

*Table 4 Framework for developing coastal change scenarios, based on relative sea-level change and sediment availability.*

| **Sediment Budget** | **Relative Sea-level fall** | | **Relative Sea-level rise** | |
|---|---|---|---|---|
| | **Rapid (>2.5mm/year)** | **Slow (<2.5mm/year)** | **Rapid (>2.5mm/year)** | **Slow (<2.5mm/year)** |
| Positive (Inputs > Outputs) | | | | |
| Balanced (Inputs = Outputs) | | | | |
| Negative (Inputs < Outputs) | | | | |

Hazard models can be developed to classify the different types of hazard and quantify their future frequency and magnitude, focussing on:

- What could happen? i.e. the nature and scale of the events that might occur in the foreseeable future (scenarios). Often an important issue will be the way in which hazards develop within a system, from incubation, via the occurrence of a triggering or initiating event to the system response and all possible outcomes.
- Where could it happen? i.e. the hazard model will need to provide a spatial framework for describing variations in hazard across a site or area.

- Why such events might happen? i.e. the circumstances associated with particular events.

The hazard assessment stage of a risk assessment should not be restricted to ascertaining the magnitude and frequency characteristics of the main damaging events (e.g. the major landslide) but should, ideally, seek to identify possible sequences, or chains, of hazards that could develop from an initial event.

1.4.2 *Failure Scenarios*

Many coastal hazards arise as a result of failure of a defence system e.g. floods embankment, seawall or a barrier beach. For flood defences, generic failure modes include overtopping (i.e. water level exceeds the design crest height) or breaching (defence failure e.g. under extreme loads or progressive deterioration). Developing an understanding of the potential failure modes and pathways (i.e. the way in which an initial failure develops into a hazard) is an essential aspect of risk assessment. This will be so throughout the EC; risks will be highest where development has already occurred – these areas will usually have some form of existing defence.

A seawall breach (e.g. as a result of high wave loadings during a storm) results in renewed landsliding on the coastal slopes and subsequent renewal of cliff top recession. For a shingle barrier there may be several failure modes leading to breach and flooding of the backshore area (Figure 10 and Table 5).

*Table 5 Possible shingle barrier failure modes, pathways and outcome (see Figure 10)*

| Failure Mode | Failure Pathway | Outcome |
|---|---|---|
| Barrier erosion | Crest narrowing | Breach |
| Overtopping | Erosion of crest<br>Crest narrowing | Breach |
| Overtopping | Erosion of rear face<br>Crest narrowing | Breach |
| Seepage | Internal erosion<br>Washout of barrier material | Breach |

Failure scenarios (failure mode-pathway-outcome sequences) are often triggered by extreme conditions (e.g. wave energy or high groundwater levels). For example, combinations of extreme loadings can also be modelled, such as the joint probability of wave heights and sea water level – this approach can be used to identify a range of conditions and their likelihood under which defences can be overtopped by floodwaters. Estimates of the probability of defence failure can be made from field inspections of the defence condition. An alternative approach is to consider the fragility of the structure – fragility is the probability of its failure conditional on its loadings (e.g. wave and water levels). Fragility curves are plots of the conditional probability of failure over the complete range of loadings; the probability of failure can be determined by integrating the fragility curve over the loading distribution.

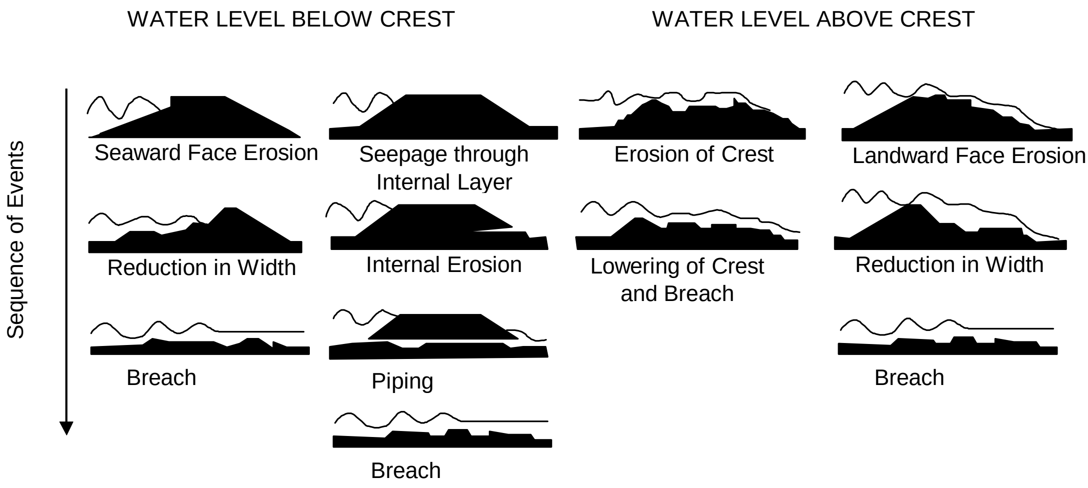



*Figure 10  Shingle barrier failure modes*

1.4.3 *Ventnor Hazard Model*

The Isle of Wight Undercliff is an extensive, coastal landslide complex with a permanent population of around 6500 located in the small towns of Ventnor, St Lawrence and Niton. Previous studies have demonstrated that there is a close association between the recorded pattern of landsliding in the Undercliff and prolonged periods of higher rainfall i.e. the occurrence of "wet years" and the resulting high groundwater levels.

A landslide hazard model has been developed for the Ventnor Undercliff (Figure 11), which invokes widespread reactivation of the system if the situation is allowed to deteriorate (i.e. do nothing). The model was used to generate 5 scenarios, based on an understanding of the causes and mechanisms of landslide behaviour, the likely reactivation sequences, an in-depth appreciation of the stability of the landslide systems, and the interrelationships between adjacent landslide units:

- Scenario 1; almost continuous creep;
- Scenario 2; an episode of significant ground movement in response to exceedence of a winter rainfall threshold level;
- Scenario 3; an episode of major ground movement in response to exceedence of an extreme winter rainfall threshold level;
- Scenario 4; the occurrence of a major landslide event within upper Ventnor; and
- Scenario 5; the establishment of active landsliding throughout the Ventnor Undercliff

It was impractical to predict reliably the scale and ground movement characteristics of these scenarios. This uncertainty has been accommodated by the definition of reference events with defined ground movement types and consequences (Table 6).

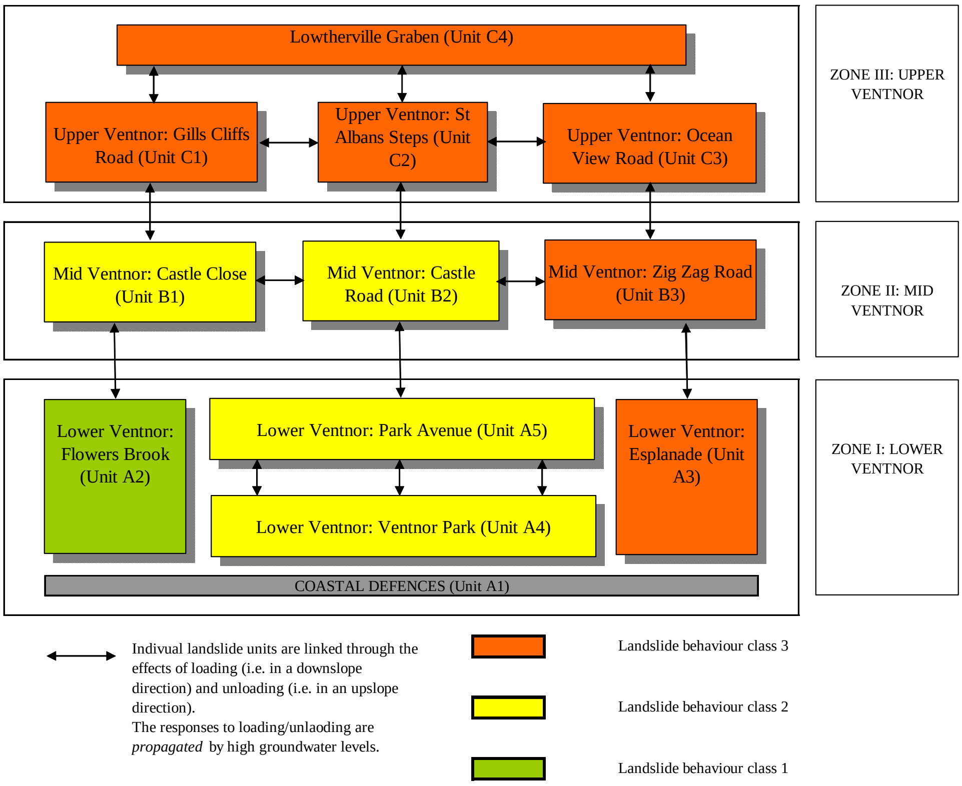



*Figure 11 Ventnor Undercliff: landslide hazard model*

*Table 6 Reference landslide reactivation events: Ventnor Undercliff*

| | Area Affected | Duration of Movement Period | Speed of Movement | Cumulative Displacement | Surface Disruption |
|---|---|---|---|---|---|
| Scenario 1 | Class 3 Landslide Units | Winter period | Very slow; up to 1.6cm/year | <0.01m | Localised minor creep, including development of tension cracks (up to 1mm wide). |
| Scenario 2 | Class 3 Landslide Units | Winter period | Very slow; up to 1.6cm/year | <0.1m | Localised creep, including development of tension cracks (up to 10mm wide). |
| Scenario 3 | Class 2 and 3 Landslide Units | Winter period | Slow; up to 1.6m/year | <1m | Widespread creep including development of tension cracks (up to 50mm wide), with evidence of localised surface displacement (<1m displacement). |
| Scenario 4 | Upper and Mid Ventnor; Landslide dimensions 250m wide and 300m long, with 250m of run out. | <10 days | Moderate; up to 13m/month | 10m | Major deep-seated landslide event, involving development of a series of displaced landslide blocks separated by steep scarp slopes and bounded by a pronounced lateral shear scarp. Widespread ground disruption within the slide area, with up to 10m surface lateral/vertical displacements and tension cracks (up to 0.5m wide). |
| Scenario 5 | Ventnor Undercliff | <10 days | Moderate; up to 13m/month | >10m | Extensive major landslide activity re-shaping the pre-existing systems and creating significant changes to the Lower and Upper Tier geomorphology. Activity includes seaward displacement and major failure of the Lower Tier ridge, formation of a new landslide geometry and failure mechanism within the Upper Tier. Widespread ground disruption, with over 10m surface lateral/vertical displacements and tension cracks (up to 1m wide). |

## 1.5 *Consequence Models*

Adverse consequences include the direct impact on people (i.e. loss of life or injury), direct and indirect economic losses and intangible losses. Direct effects are the first-order consequences that are intimately associated with an event, or arise as a direct consequence of it (e.g. destruction), while indirect effects emerge later, such as mental illness, longer-term economic problems or relocation costs.

The impact of an event is controlled by its intensity (i.e. some measure of its mass, velocity, rate of change etc.) and duration, the assets at risk, the exposure of the assets and their vulnerability to damage.

All assets occurring in an area that could be adversely affected by a hazard are known as elements at risk. These elements are extremely diverse in nature and are usually divided into the following major groupings:

1) populations; detriment is usually expressed in terms of loss of life or injury, although the longer-term consequences of physical impairment, psychological effects and ill-health can also be considered;
2) buildings, structures, services and infrastructure; the value of these physical assets can usually be determined from real estate agents or local authority tax bands for housing stock and from the owners/operators for services and infrastructure. Damage can be total or repairable (i.e. partial loss);
3) property: this includes the contents of houses, businesses and retailers, machinery, vehicles, domesticated animals and personal property.
4) activities; all activities whether for financial gain or pleasure. The main components are business, commerce, retailing, entertainment, transportation, agriculture, manufacturing and industry, minerals and recreation.
5) environment, including flora, fauna, environmental quality and amenity.

The scale of adverse consequences can be expressed qualitatively using categories such as Severe, Moderate, Mild and Negligible. Qualitative estimations can also be expressed in terms of numerical gradings or numerical scoring scales, often from 0-10, with zero meaning no observable effects and 10 signifying total destruction.

For QRA, combining the factors – assets at risk, exposure and vulnerability - enables consequence models to be developed that reflect the damage associated with particular event scenarios:

- Exposure involves being in the wrong place (i.e. the "danger zone" where a landslide impacts – the spatial probability) at the wrong time (i.e. when the landslide occurs – the temporal probability). Exposure can be expressed on a scale of 0 to 1; most buildings are permanently in the danger zone (i.e. exposure = 1), whereas other assets such as populations are dynamic with the exposure varying over time.
- Vulnerability can be defined as the potential to suffer harm, loss or detriment from a human perspective. It is a measure of the variation in level or chance of impact. This can vary between total loss (e.g. write-off of all properties or death)

to partial loss, where only a proportion of the population or assets are killed or destroyed.

In many risk assessments, vulnerability is defined as the level of potential damage, or degree of loss, of a particular asset (expressed on a scale of 0 to 1) subjected to a hazard event of a given intensity. This can also be expressed as the chance (0 to 1) of a particular level of damage, given the hazard event (e.g. the chance of a seawall breaching given a 1 in 100 year storm or the chance of a pedestrian being killed by a vehicle travelling at 30mph).

In a consequence model, both the exposure and vulnerability factors can be used to establish the predicted damages compared with a total loss event in which the assets at risk would be completely lost. Thus, for an event of a particular intensity:

Risk = Prob. (Event) x Adverse Consequence

= Prob. (Event) x (Total Loss x Exposure x Vulnerability)

In most cases it will be necessary to carry out this exercise for each of the individual elements at risk, or even each individual property:

Risk (Element 1) = Prob. (Event) x Consequence (Element 1)

= Prob. (Event) x (Total Loss x Exposure x Vulnerability)

Risk (Element 2) = Prob. (Event) x Consequence (Element 2)

= Prob. (Event) x (Total Loss x Exposure x Vulnerability)

Risk = Prob. (Event) x ∑ Consequences (Elements 1 to *n*)

This model is based on a simple, deterministic view of the adverse consequences resulting from an event. If an event of a particular magnitude or travel distance occurs, then a particular set of adverse consequences *will* result. In reality, the precise consequences can often reflect an almost unique and, perhaps, unexpected combination of circumstances that arise at the moment the event occurs and during its aftermath.

## *1.6 Risk Estimation*

### *1.6.1 Introduction*

In the UK, coastal risk assessment is usually undertaken as part of the flood and coastal defence delivery process i.e. SMPs, Strategy Studies and Scheme Appraisal. There are exceptions, of course, such as the recent assessment of individual and societal risk along the Sandown-Shanklin cliffs. Risk assessments carried out for flood and coastal defence purposes are funded by DEFRA and must be consistent with the general guidelines provided in FCDPAG 4 (Approaches to Risk). Risk-based methods, therefore, tend to be probabilistic, scenario-driven and quantitative; they support economic evaluation and, hence, take account of discounting of future values.

In other countries the requirement for risk assessment is driven by other needs. For example:

- Italy; following the Sarno landslide disaster in August 1998, the Italian Government passed new legislation on landslide and flood risk assessment and mitigation – the Landslide Risk Assessment and Reduction Act (Gazzetta Ufficiale della Repubblica Italiana, 1998). This requires Regional Governments and National River Basin Authorities to identify and map areas where landslide risk is most severe, and to take action to reduce economic damage and societal risk. The law was accompanied by a "technical document" providing a general framework and guidelines for the assessment of landslide hazard and risk (Gazzetta Ufficiale della Repubblica Italiana, 1999).
- France; the Reinforcement of Environmental Protection Act (no. 95-101; the so called "Barnier Act") encourages the development of local risk prevention plans (PPR) which determine the areas where a natural risk (flooding, avalanches, forest fires, ground movements, seismic activities and storms) is foreseeable. The objective of these plans is to map risk zones and prescribe measures of prevention. Three categories of zone had been determined: a minimal, a moderate and a high-risk zone. When a plan is drafted, the insurance company can refuse extend coverage for the risk of natural disaster to houses and buildings built in high-risk areas.

Different legislative requirements will dictate that different types of risk assessment need to be undertaken; some qualitative (e.g. France and Italy), some quantitative (e.g. the UK). At variety of scales will be relevant, from high level assessments in the UK to detailed assessments.

### 1.6.2 *Approaches to Risk Estimation*

The main approaches to risk estimation are:

- Qualitative risk estimations are those where both likelihood and adverse consequences are expressed in qualitative terms.
- Semi-quantitative risk estimations are combinations of qualitative and quantitative measures of likelihood and consequence. More usually it is probabilities of frequency that are known, or assumed, while levels of consequence remain uncertain.
- Quantitative risk estimations, where values of detriment are combined with probabilities of occurrence.

Qualitative methods are of value where the available resources or data dictate that more formalised quantitative assessment would be inappropriate or even impractical. For example, a qualitative measure of risk can be obtained by combining a measure of the likelihood of a hazard occurring with the increasing severity of consequences to provide a ranking of risk levels (Figure 12). Although rankings are value judgements, experienced specialists should be able to make realistic assessments of the likelihood of events and consequences, based on an appreciation of the landslide environment, together with knowledge of the particular site.

**Coastal instability risk**

| Consequences (land use class) | Likelihood of significant ground movement (landslide reactivation): 1:10 yr event | 1:100 yr event | 1:500 yr event | 1:1000 yr event |
|---|---|---|---|---|
| High density urban | 4 | 4 | 3 | 2 |
| Medium density urban | 4 | 3 | 2 | 2 |
| Low density urban / rural | 3 | 2 | 1 | 1 |
| Agricultural land / isolated communities | 2 | 1 | 1 | 1 |

*Figure 12. Ranking of risk levels (4 is high risk, 1 is low risk)*

Tables 7 and 8 present typical scales of hazard likelihood and consequences that could be adapted to particular circumstances. Relative risk levels can then be assigned to different combinations of hazard and consequences (e.g. Table 9). Each relative risk level should mark a step-up in the degree of threat and a change in the acceptability or tolerability of the risk. Although the designation of risk levels can appear somewhat arbitrary, they do provide a framework for making comparisons between different sites within an area.

*Table 7 Indicative measures of landslide likelihood (from Australian Geomechanics Society 2000)*

| Level | Descriptor | Description | Indicative Annual Probability |
|---|---|---|---|
| A | Almost certain | The event is expected to occur | $>\approx 10^{-1}$ |
| B | Likely | The event will probably occur under adverse conditions | $\approx 10^{-2}$ |
| C | Possible | The event could occur under adverse conditions | $\approx 10^{-3}$ |
| D | Unlikely | The event might occur under very adverse circumstances | $\approx 10^{-4}$ |
| E | Rare | The event is conceivable but only under exceptional circumstances. | $\approx 10^{-5}$ |
| F | Not credible | The event is inconceivable or fanciful | $<10^{-6}$ |

**Note:** "≈" means that the indicative value may vary by say ± ½ of an order of magnitude, or more.

*Table 8 Indicative measures of consequence (from Australian Geomechanics Society 2000)*

| Level | Descriptor | Description |
|---|---|---|
| 1 | Catastrophic | Structure completely destroyed or large scale damage requiring major engineering works for stabilisation. |
| 2 | Major | Extensive damage to most of structure, or extending beyond site boundaries, requiring significant stabilisation works. |
| 3 | Medium | Moderate damage to some of structure, or significant part of site, requiring large stabilisation works. |
| 4 | Minor | Limited damage to part of structure, or part of site, requiring some reinstatement/stabilisation works. |
| 5 | Insignificant | Little damage. |

*Table 9 Qualitative risk assessment matrix: levels of risk to property (from Australian Geomechanics Society 2000)*

| **Likelihood** | **Consequences to property** | | | | |
|---|---|---|---|---|---|
| | **1: catastrophic** | **2: major** | **3: medium** | **4: minor** | **5: insignificant** |
| A – almost certain | VH | VH | H | H | M |
| B – likely | VH | H | H | M | L-M |
| C - possible | H | H | M | L-M | VL-L |
| D - unlikely | M-H | M | L | VL-L | VL |
| E - rare | L-M | L-M | VL-L | VL | VL |
| F - not credible | VL | VL | VL | VL | VL |

Quantitative risk is generally expressed as the product of the likelihood of a hazard and its adverse consequences. Therefore, for a coastal landslide:

Risk = Prob. (Landslide event) x Adverse Consequences

Reducing risk to a single mathematical value makes it possible to compare landslide "risk" with other risks, such as flooding, in order to determine their relative significance. It follows that a 50% chance of landslide movement causing £1000 worth of footpath damage has the same "risk" as a 0.1% chance of a flood causing losses of £0.5M i.e. both have mathematical values of £500. Thus mathematically computed measures of "risk" are the same although the "perceived threats" may be rather different.

Specific Risk is the expected degree of loss due to a particular magnitude of event ($H_i$) occurring within a specified area over a given period of time.

$R_s = P(H_i)$ x (Total Loss x Exposure x Vulnerability)

*Total risk* (R) is the sum of the calculations of specific risk for the full range of potential magnitudes of events:

$R = \sum R_s$ (Events 1 …*n*)

The risks to humans are expressed in a number of different ways:

- Societal risk is the likelihood of death or injury within a society (usually a nation state or large administrative unit) due to a specified event (e.g. a landslide of particular magnitude) or a particular category of events (e.g. landsliding). It is usually defined as the product of the frequency of occurrence of a specified hazard and the number of people in a given population suffering (or likely to suffer) from a specified level of harm and is usually restricted to events potentially capable of causing large-scale loss of life, injury, etc.

- Individual risk is the likelihood of death or injury to an individual and can be calculated by dividing societal risk by the number of individuals exposed to the hazard (although there are other measures of Individual Risk).
- Group risk is the risk faced by particular groups within society, based on activity (e.g. climbers), occupation (e.g. farmers) or other relevant division (e.g. males).

The value and reliability of a risk estimation process is related to the extent that the hazards are recognised, understood and explained which is not necessarily related to the extent to which they are quantified.

Risk assessment methods can also be used to compare the level of risk (i.e. mathematical expectation value) associated with different coastal change scenarios. A variety of scenarios can be compared to highlight the range of conditions that might occur in the future, including different management options. To make this comparison it is useful to establish a baseline against which the various scenarios, including continuing with the current management practice, can be assessed. This baseline is the so-called "do nothing" option, which should involve no active landslide management whatsoever, simply walking away and abandoning all maintenance, repair or management activity.

### *1.7 Risk Communication*

Many parts of the coast are subject to risks associated with erosion or flooding. However, in many countries decision makers have often taken insufficient account of these risks. This is largely due to a lack of awareness of the physical environment and the limited availability of suitable technical information to support decision making.

One of the main problems facing coastal management is that few planners have an earth science background and few earth scientists have a planning background, and hence there is often a communication gap between the two groups. However, both groups often share a common skill: familiarity with maps. The shared background in geographical skills provides an opportunity for presenting technical information in a format that is readily appreciated by planners. However, such maps need to address planning concerns and not seek to present only specialist earth science themes.

Maps for coastal planners need to be:

- concise and clear summaries of the key earth science information as it relates to key planning issues;
- highlight potential problems so that users are aware of the factors which may restrict development opportunities in an area;
- indicate the types of planning response that may be appropriate to take account of particular physical conditions.

Coastal hazard and risk assessments should be focussed towards preparing a combination of thematic maps at a general scale, which become increasingly focused on key planning issues as they are developed from the basic factual information. The process of map preparation follows the assessment procedures outlined earlier:

- element maps; depicting factual information on specific earth science related topics;
- derivative maps; drawing on the basic data to define characteristics of particular interest;
- summary maps compiled from the element and derivative maps which highlight the general characteristics of an area in terms of, for example, the risks to development.

By and large, planners are served by summary and derived maps, whilst their technical advisors would require the greater detail presented on the element made. A wide range of maps can be custom made on specific topics and for specific audiences - the examples in the trial study areas have been selected to illustrate the issues associated with coastal processes.

These maps need to be accompanied by a written summary aimed at those not trained in the earth sciences which explains the implications of the risk assessment and the significance of the mapped units to planning and development. Table 10 presents general planning guidance for different coastal settings in the UK; this guidance indicates the types of approach that could be appropriate for similar environments on other coastal sections. This report should also highlight the limitations of this type of study, especially the uncertainties inherent in the assessment.

*Table 10 Generic planning guidance for different coastal settings in the UK*

| Settings | Development plan | Development control |
|---|---|---|
| • rapidly eroding cliffs<br>• actively unstable slopes<br>• unprotected low lying areas<br>• natural coastal defences (e.g. sand dunes)<br>• very high-high sensitivity Coasts | Areas most unsuited to development due to physical conditions. Local plan development proposals subject to major constraints. | Should development be considered it will need to be preceded by a detailed investigation, full risk assessment and/or environmental study. Many planning applications in these areas may have to be refused on the basis of potential physical problems. |
| • eroding cliffs<br>• potentially unstable slopes<br>• low lying areas with low standard of sea defences<br>• sand dunes<br>• saltmarsh areas<br>• foreshores in important sediment transport zones<br>• high-moderate sensitivity costs | Areas likely to be subject to significant constraints due to physical conditions. Local plan development proposals should identify and take account of the nature of potential problems and address the requirements for suitable coastal defences. | A site reconnaissance study will need to be followed by detailed site investigation, including a risk assessment and/or environmental study, prior to lodging a planning application. |

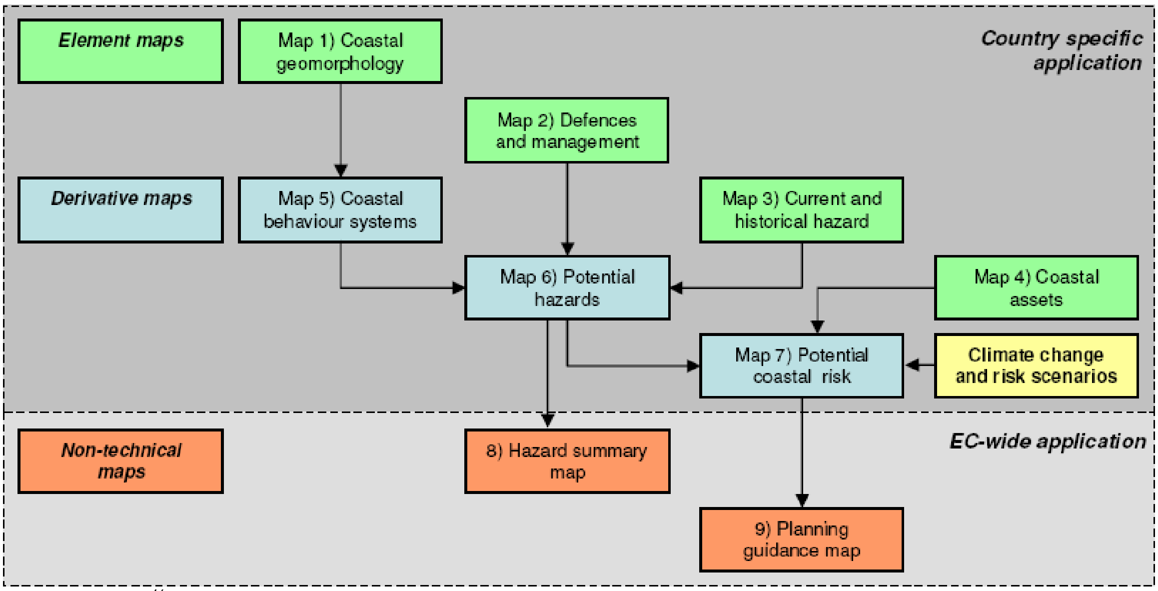
| | | |
|---|---|---|
| • areas behind eroding cliffs<br>• problem ground conditions<br>• estuaries<br>• foreshores | Areas which may or may not be suitable for development but investigations and monitoring may be required before any local plan proposals are made. | Areas need to be investigated and monitored to determine risks, sediment budget, or sensitivity. Development should be avoided unless adequate evidence of suitable conditions is provided. |

Greater detail may be presented in a technical report aimed at technical officers who need to be more aware of the physical conditions and their implications for coastal management. In this way the maps and reports can be an effective mechanism for collecting and presenting broad brush information for strategic planning, providing guidance on where potential problems may arise and areas where certain types of development may be preferred or opposed.

# 2 Project background

RESPONSE is an EU-funded demonstration project that aims to develop a methodology for assessing the hazard and risk of climate change at the coastline. The project includes a number of partner organisations from different parts of Europe who have applied the methodology to their coastlines. For the project to be a success, it is necessary for the approach to be sufficiently flexible to allow application to any stretch of the European coastline, but sufficiently rigid to allow outputs to be compared.

Central to the RESPONSE approach is the development of a series of maps that provide factual information and guidance to coastal managers (Figure 13). Maps one to four are 'element maps' that show coastal landforms and geomorphology hydrodynamic processes (Map 1), coastal defence management types and practices (Map 2), historical coastal hazards (Map 3), and coastal assets and population, and environmental assets (Map 4). These maps have then been combined to create derivative maps showing coastal behaviour systems (Map 5), and potential coastal hazards (Map 6). Production of all of these maps follows a standard approach which can be applied through out EU Member States.




*e RESPONSE maps and their associations*

Map 7 shows future coastal hazards and risk, and can be adapted to highlight the impact of various scenarios, encompassing changes induced by coastal management, climate change and sea-level. The CBU map forms the framework for the assessment of future hazard and risk, but information on coastal assets and defences is also incorporated. Map 7 shows the possible coastal risks by the year 2100 under two scenarios; that of 'business as usual', with no change in coastal management and no climate change i.e. a 'do nothing' scenario, and a 'worst case', where all coastal defences are lost and climate change is significant enough to increase the historical rate of recession. In both cases the risk of erosion, flooding and reactivation of coastal landslide complexes is assessed using a relative risk matrix that combines the economic value of coastal assets at risk and the likelihood of occurrence of each hazard that could result in the losses.

In addition to the seven EU-specific maps, additional non-technical summary maps have been produced to highlight additional possible applications of the data assembled in Maps 1 to 7. The additional maps (8 and 9) presented herein provide planning guidance and a summary of hazards, and are designed to provide additional guidance to coastal managers and planners in the UK. Because planning laws will vary across the EU, it is likely that these maps will be country-specific, the approach highlights how the data and methodology can be applied, or expanded to provide additional guidance.

The maps have been created for the RESPONSE methodology should be used to illustrate the Response approach, and should not be used in isolation. The maps have been prepared using ArcView GIS, but because of the varying quality of the input data the maps have only been used as a presentation tool and not for a spatial analysis in GIS.

# 3 Mapping methodology and interpretation

## 3.1 *Map 1. Coastal landforms and geomorphology*

### 3.1.1 *Objectives*

The first of the factor maps describes a 'system model' for the study coastline. Key elements are the forcing factors (i.e. hydrodynamics) and system state (i.e. characteristics and form of the coastline). This type of model provides a spatial framework for understanding and representing the relationships between different system components, and forms the basis for classification of Coastal Behaviour Units.

Variations in forcing factors in the system model can generate changes along the coast, and hence the impact of climate change can be investigated. Because the magnitude and frequency of energy inputs to the coastal system tend to be random and the precise nature of future climate change is unclear, uncertainty will always exist in the behaviour of the system.

### 3.1.2 *Approach*

These maps provide a representation of factual data. To avoid over-crowding the map, information is split between two maps (maps 1a and 1b) which show shoreline and hinterland elements, and offshore elements. All the information on these maps is derived from previously published data.

Map 1a provides information on the spatial distribution of landforms and the nature of beaches, hinterland and backshore systems.

Map 1b provides information on the tidal range of the coastline, structure of the coastal sediment system, including sediment cells, and key sediment stores.

Full details of the source, ownership and copyright restrictions of the data sets in all the maps are provided in Section 4 of this report.

## 3.2 *Map 2. Coastal defence management types and practices*

### 3.2.1 *Objectives*

Much of the coastline of Europe is not able to operate 'naturally' because of the impact of coastal defence structures. The distribution and nature of defences needs to be understood as they have an effect on the coastal morphology and change the impact of forcing factors. Defences have value in terms of the protection afforded to assets such as towns or agricultural land, and also in terms of the economic cost of their construction and maintenance. This is important when assessing the potential coastal risks if the defences fail. Coastal defences may degrade in the future leading to an increase in the probability of failure through time and an associated increase in the risk to the asset protected. Management policies may change in the future, with the potential for defences to be removed or realigned to allow coastlines to begin to operate naturally.

3.2.2 *Approach*

The data on Map 2 has been derived from information previously published by SCOPAC, and includes information on the specific location and type of structures and also the nature of management along the coastline. Because of the large amount of coastal defence data presented, it has been necessary to offset certain elements of the data from the coastline in order to maintain legibility.

## 3.3 Map 3. Historical coastal hazards

3.3.1 *Objectives*

Records of past and present coastal hazards highlight hotspots of activity and are a good indicator of potential hazards. Historical records provide a useful source of information on the location and nature of past and present hazards and are presented on Map 3. The map of the South Central England coast includes three types of data; precisely delimited flood envelopes showing current areas of land affected by tidal and fluvial flooding; information on the approximate locations of past coastal retreat or past landslide events from historical records; and information on the approximate current areas of active landsliding.

3.3.2 *Approach*

Flood plains are indicated by shaded polygons derived from accurate, ground-truthed outputs of numerical modelled datasets. The location of current and historical events is indicated by points on the map, which can be cross-referenced to a database which provides full information. Points have been located by grid references provided in the original database, and represent the centre point of a feature or event rather than its spatial extent. In some cases, where numerous events have occurred close to one another, points have been moved slightly to allow all the data to be clearly seen.

## 3.4 Map 4. Coastal assets and population

3.4.1 *Objectives*

As discussed above, risk is often defined as the result of combining hazards with their consequence, which may include loss of life, property or habitat. These features are presented on Map 4, which is subdivided into maps which show the human assets and population and environmental assets.

3.4.2 *Approach*

These maps provide a representation of factual data. To avoid over-crowding the map, information is split between two maps (maps 4a and 4b) which show the location of built assets, population density and environmental assets.

Map 4a locates human assets including information on main population centres, displayed in terms of population density, blue flag beaches and important industry. These data are derived from UK Government GIS data and population statistics derived from the 1990 census.

Map 4b locates environmental (natural) assets which comprise environmental designation data on Sites of Special Scientific Interest, Special Protection Areas and those which are also designated as RAMSAR sites, Areas of Outstanding Natural Beauty, National Nature Reserves, Special Areas of Conservation and candidate Special

Areas of Conservation. These data are all derived from English Nature and are fully attributed GIS layers.

## 3.5 Map 5. Coastal behaviour systems

### *3.5.1 Objectives*

Based upon the landforms present (Map 1a) and their interactions (Map 1b), it is possible to define appropriate Coastal Behaviour Systems (CBS) for the study coastline. Five CBS's have been identified that are appropriate for the South Central England coast (Table 11). These were broadly developed from the European ECUMEN classification and will largely be appropriate for the other RESPONSE coasts. Each generic Coastal Behaviour System is composed of landform elements as identified in Table 12.  Figures 14 to 19 show conceptual models describing the CBS.

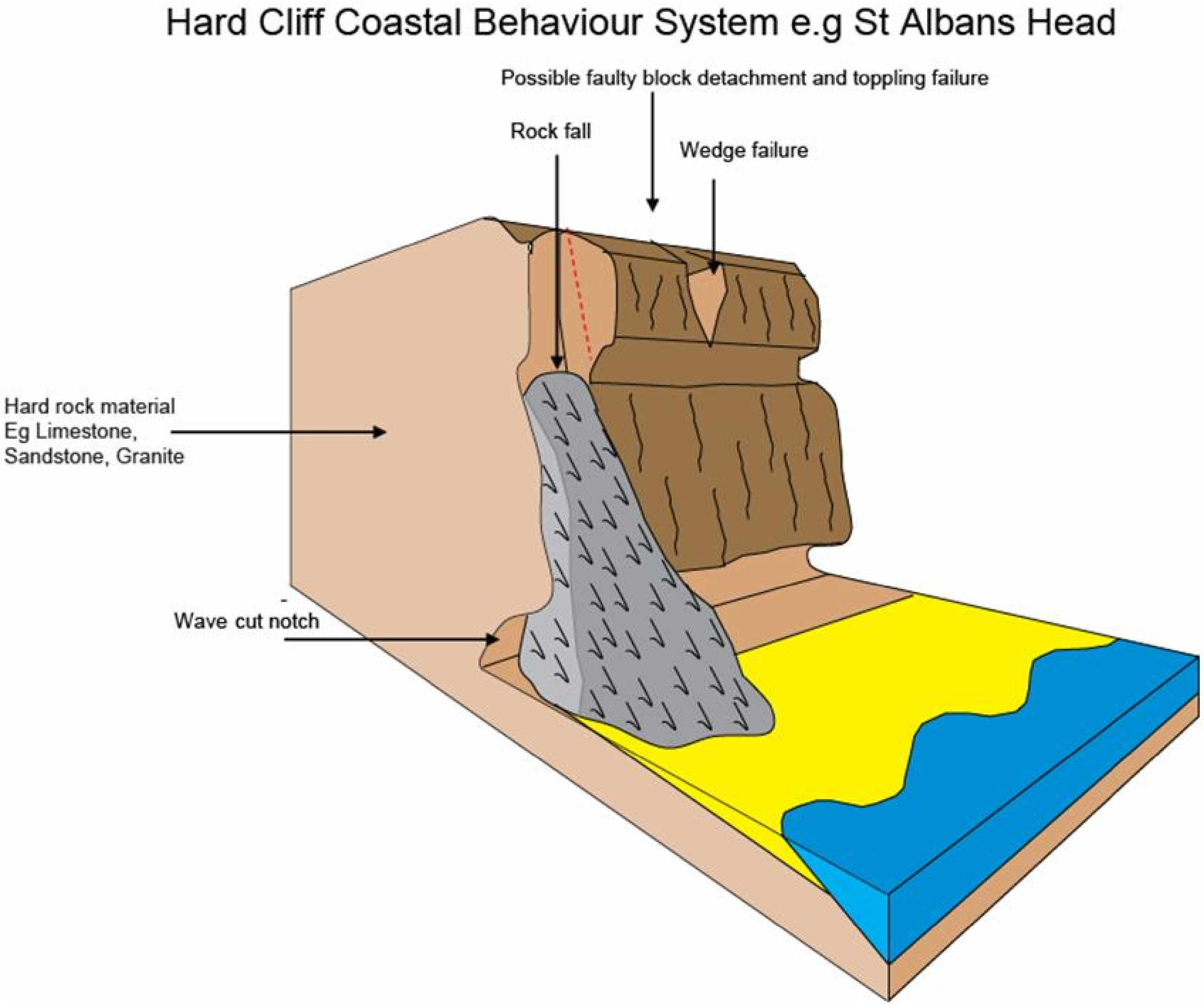



*Figure 14 Hard cliff CBS*

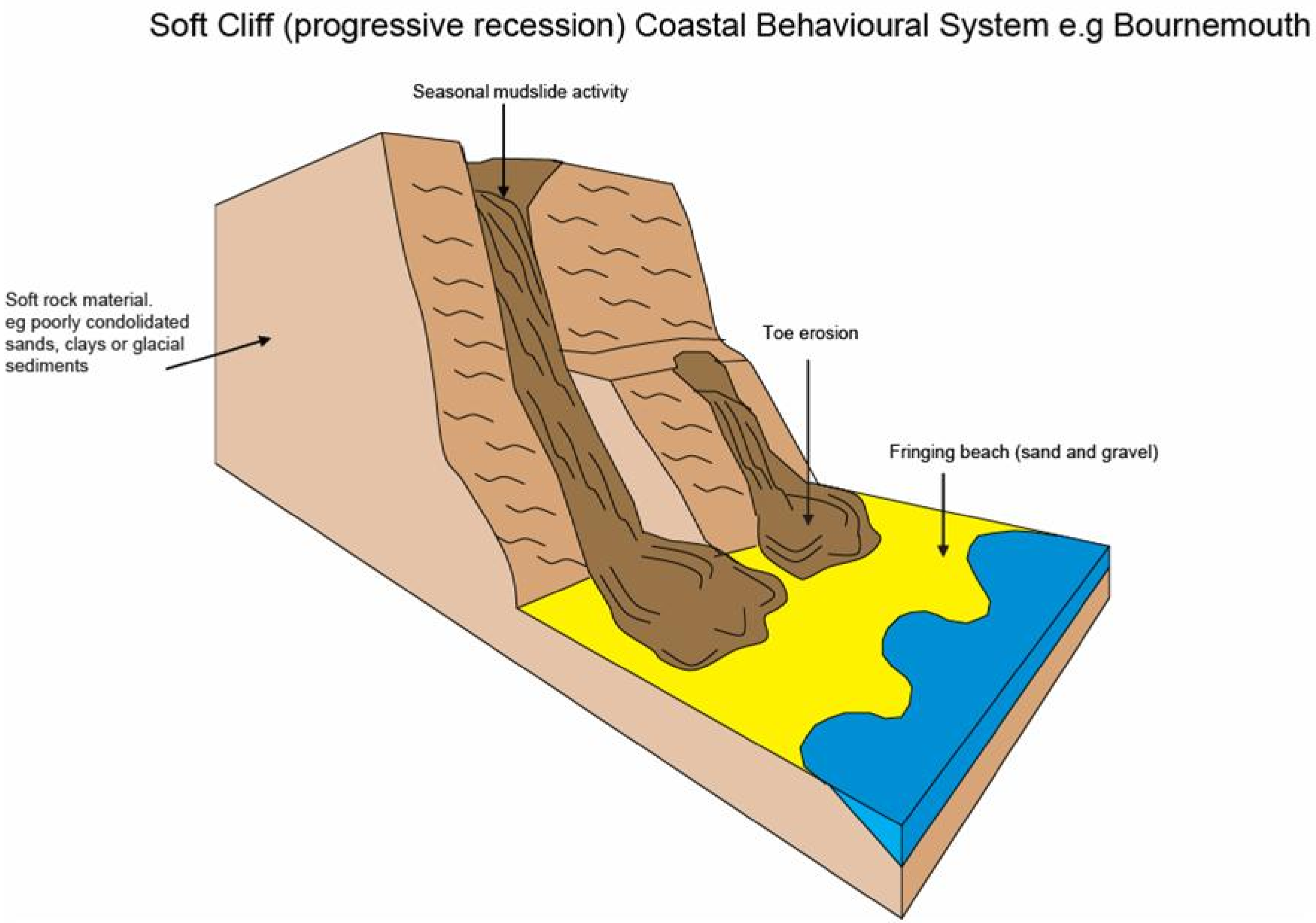



Figure 15 Soft cliff (progressive recession) CBS

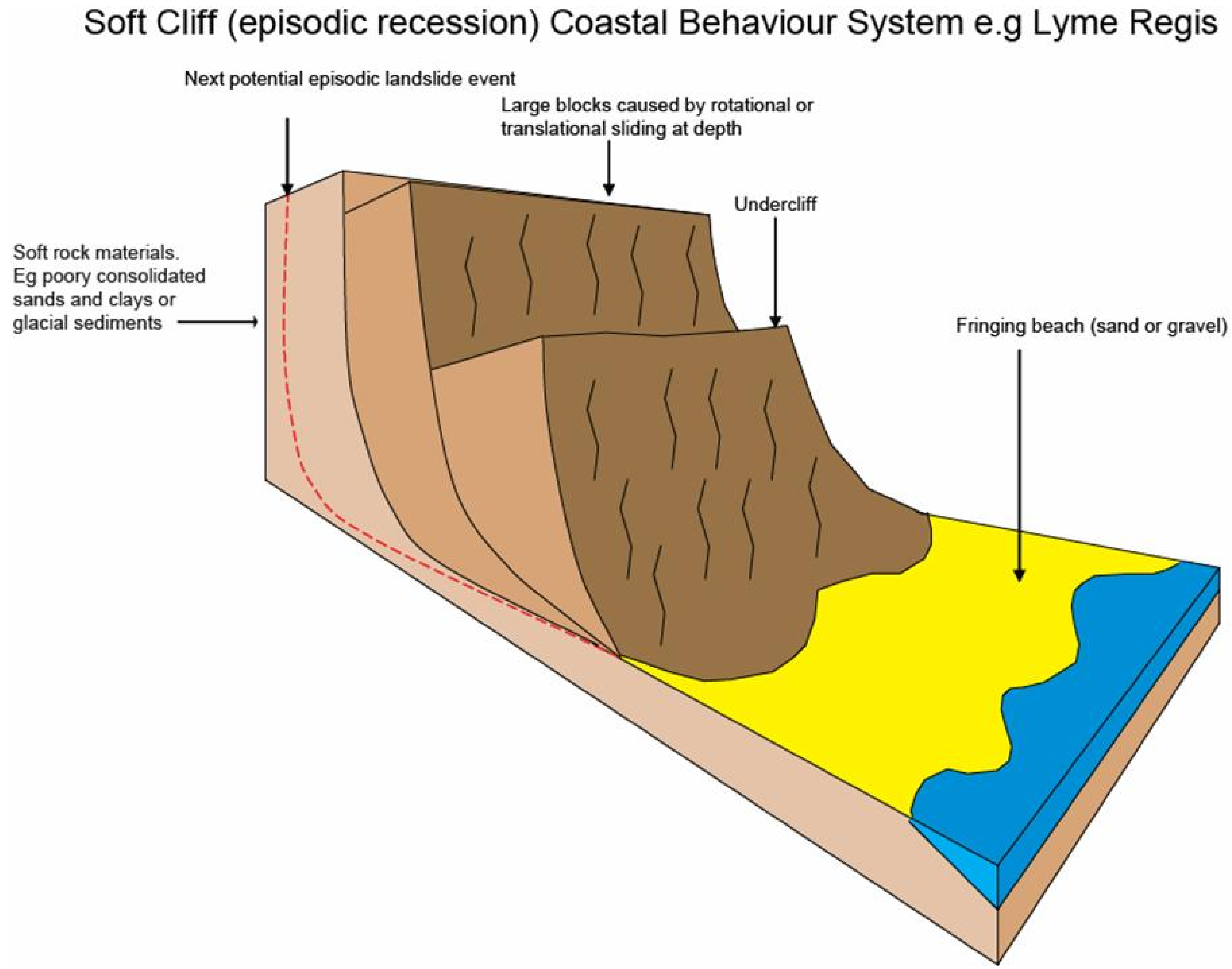



*Figure 16 Soft cliff (episodic recession) CBS*

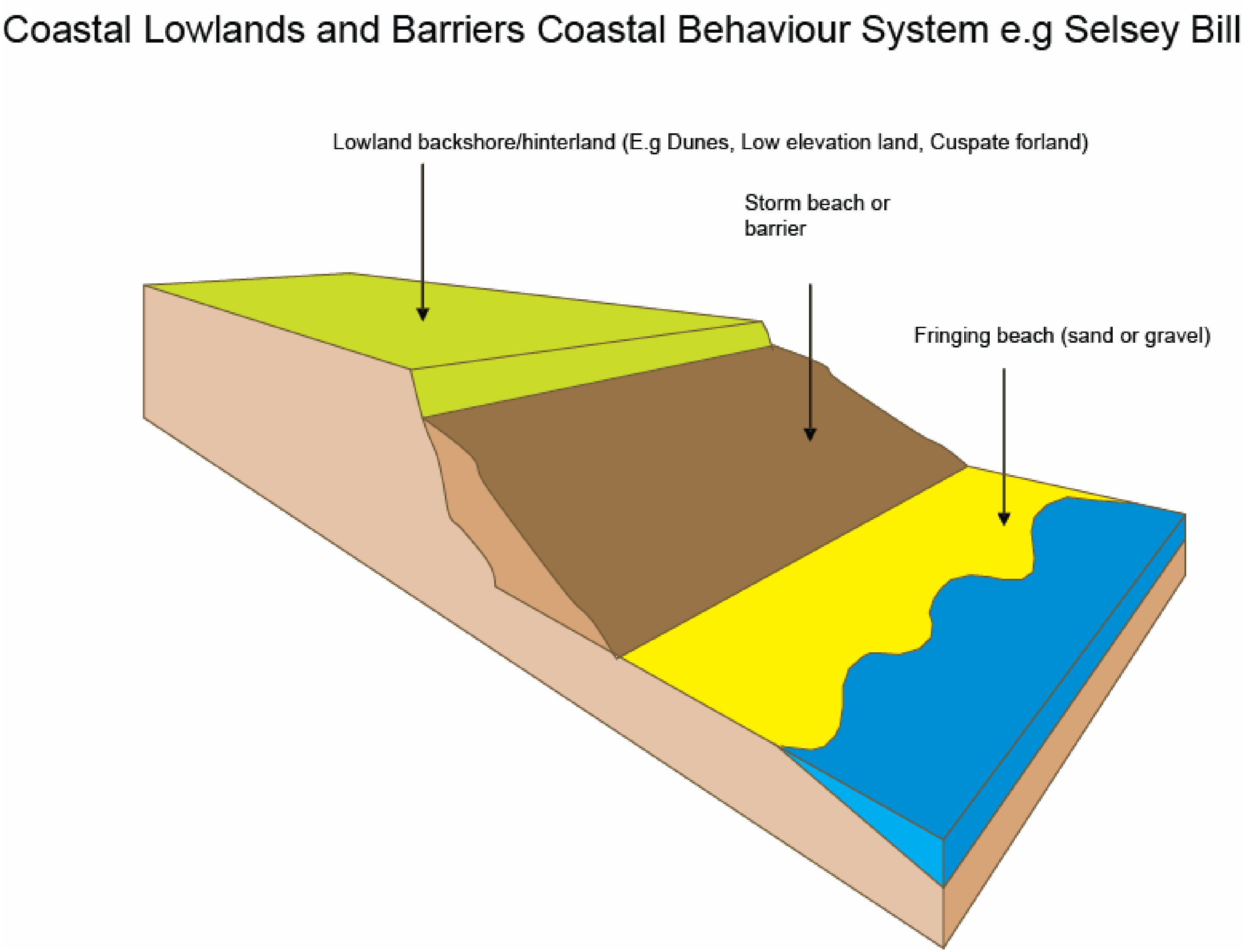



*Figure 17 Coastal lowlands and barriers CBS*

Spits, Inlets and Tidal Deltas Coastal Behaviour Systems e.g Poole Harbour

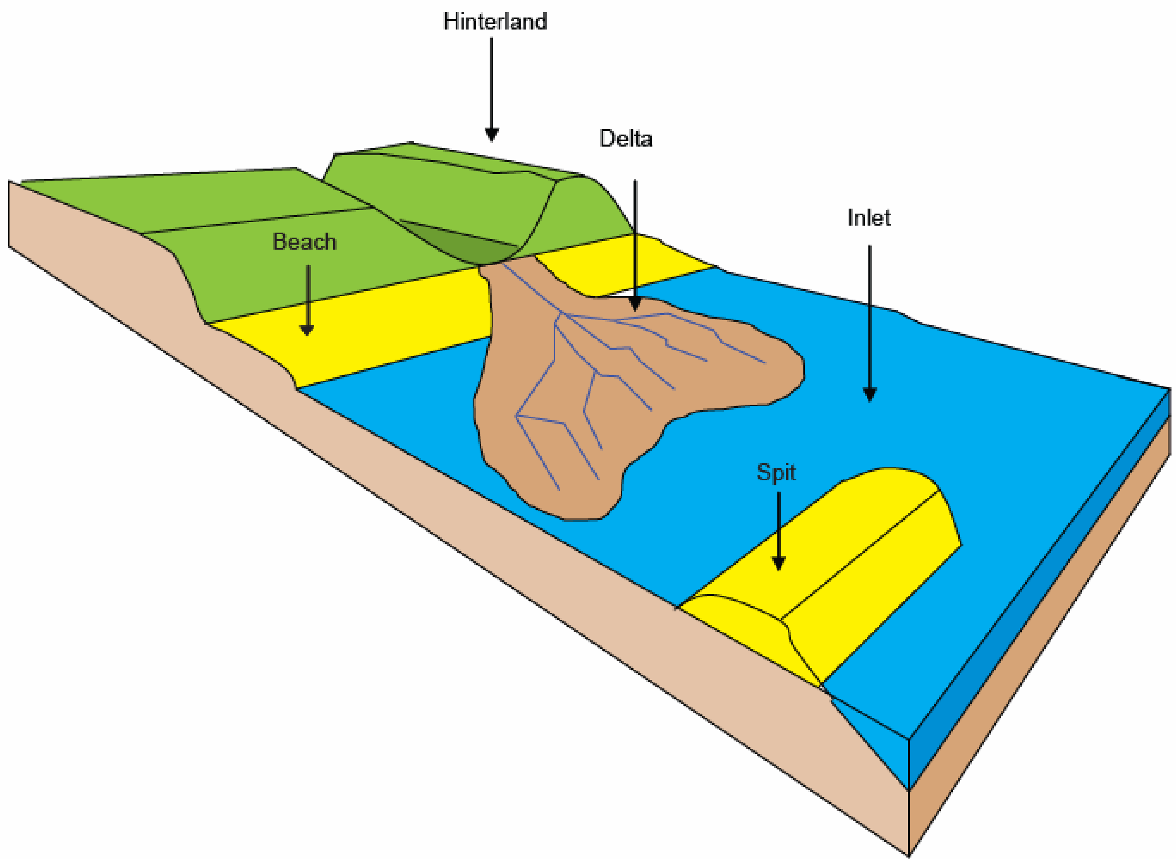



*Figure 18 Spits, inlets and tidal deltas CBS*

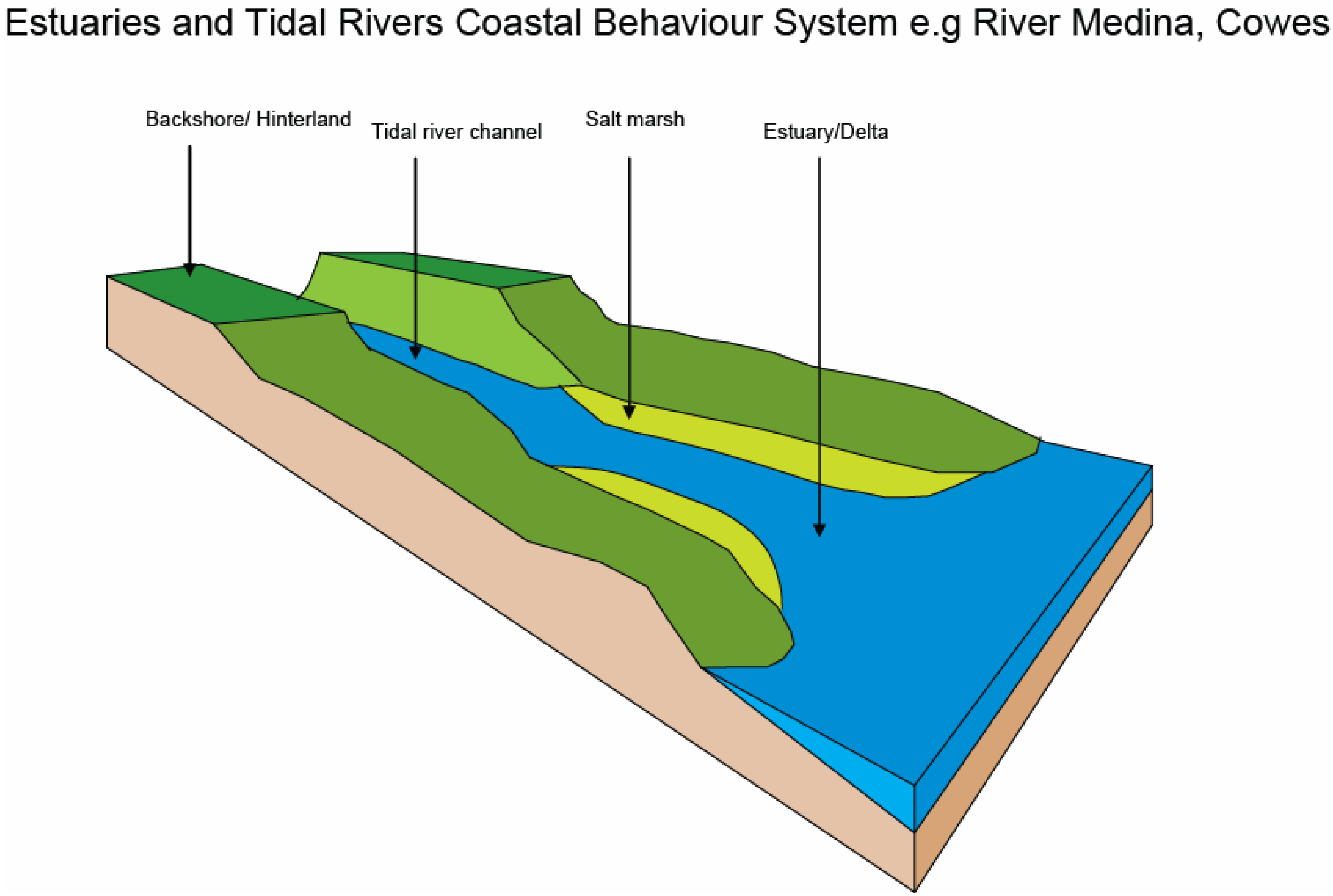
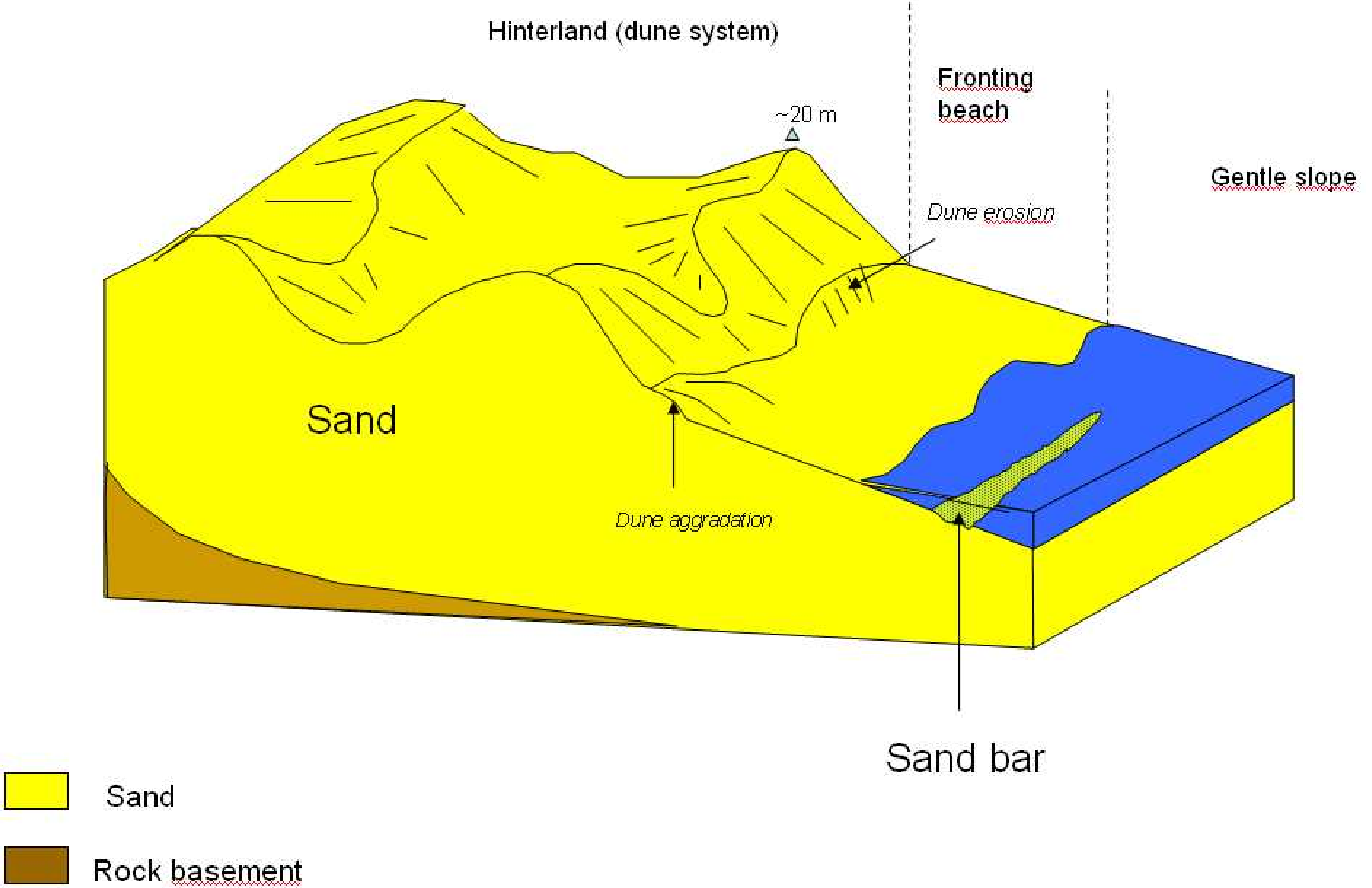



*Figure 19 Estuaries and tidal rivers CBS*

# Dune coastal behaviour system e.g sandy coast of Aquitaine



The South Central England classification has been used as the starting point for definition of CBS for the study coastlines. The landforms present along each coastline should be reviewed to consider how well they comply with the five South Central England CBS and their constituent landforms. It may be appropriate to define additional/different CBS.

Should additional CBS be required they should be determined by the coastal forms present and their generic sensitivity to climate change factors. Possible refinements include differentiation of coastal lowlands from barriers, and separate treatment of spits, inlets and tidal lagoons.

*Table 11 Broad definition of coastal behaviour systems*

| CBS | Substrate | Gradient and elevation of coastal slope | Typical hazards |
|---|---|---|---|
| Hard Cliff | hard bedrock | steep & high | Erosion |
| Soft Cliff – progressive erosion | soft bedrock | variable | Erosion |
| Soft Cliff – episodic erosion | soft bedrock | variable | Erosion and reactivation of coastal landslides |
| Coastal Lowlands and Barriers | Unconsolidated or soft bedrock | low | Flooding and erosion |
| Spits, Inlets and Tidal Deltas | Unconsolidated | low | Flooding |
| Estuaries and Tidal Rivers | Unconsolidated | low | Flooding |

*Table 12 Composition of South Central England Coastal Behaviour Systems*

| Landform Element | Shoreface | Shoreline | Backshore |
|---|---|---|---|
| Hard Cliff | Steep | Fringing boulder beach and/or shore platform | Hard Cliff |
| Soft Cliff – progressive erosion | Gentle | Fringing sand, shingle or mixed beach | Soft Cliff |

| | | | |
|---|---|---|---|
| Soft Cliff – episodic erosion | Gentle | Fringing sand, shingle or mixed beach | Soft Cliff / landslide |
| Lowlands and Barriers | Gentle | Fringing sand, shingle or mixed beach<br>Free-standing shingle barrier<br>Fronting sand or shingle beaches | Lowland |
| Spits, Inlets and Tidal Deltas | Gentle | Inlets<br>Tidal deltas<br>Free-standing shingle beach | Lowland |
| Estuaries and Tidal Rivers | Gentle | Tidal flat<br>Saltmarsh<br>Tidal river | Lowland |

*3.5.2* *Approach*

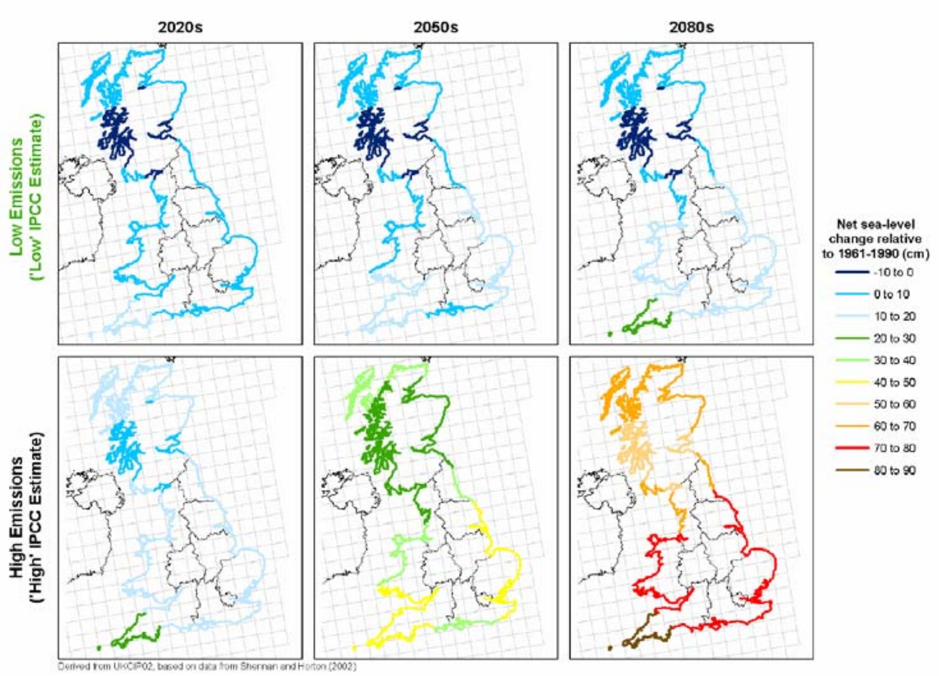
The CBS map has been development from existing data. Additional classes covering episodic and progressive erosion of the Soft Cliffs category have been added because these differences in behaviour are considered to be important over the 100 year modelling period.

### *3.6 Map 6. Potential coastal hazards (2100)*

*3.6.1* *Objectives*

Global climate change projections for the next 100 years have been published by the Intergovernmental Panel for Climate Change (IPCC, 2001). The UK benefits from higher resolution projections produced by the United Kingdom Climate Impacts Programme (UKCIP, 2002, 2005).

UKCIP suggests that sea level may rise by up to 80 cm by the 2080s (UKCIP, 2005, Figure 20) and that under the medium high scenario mean annual temperatures may rise by 4º (Figure 21) and that winter rainfall may increase by as much as 30% above today's levels (Figure 22).



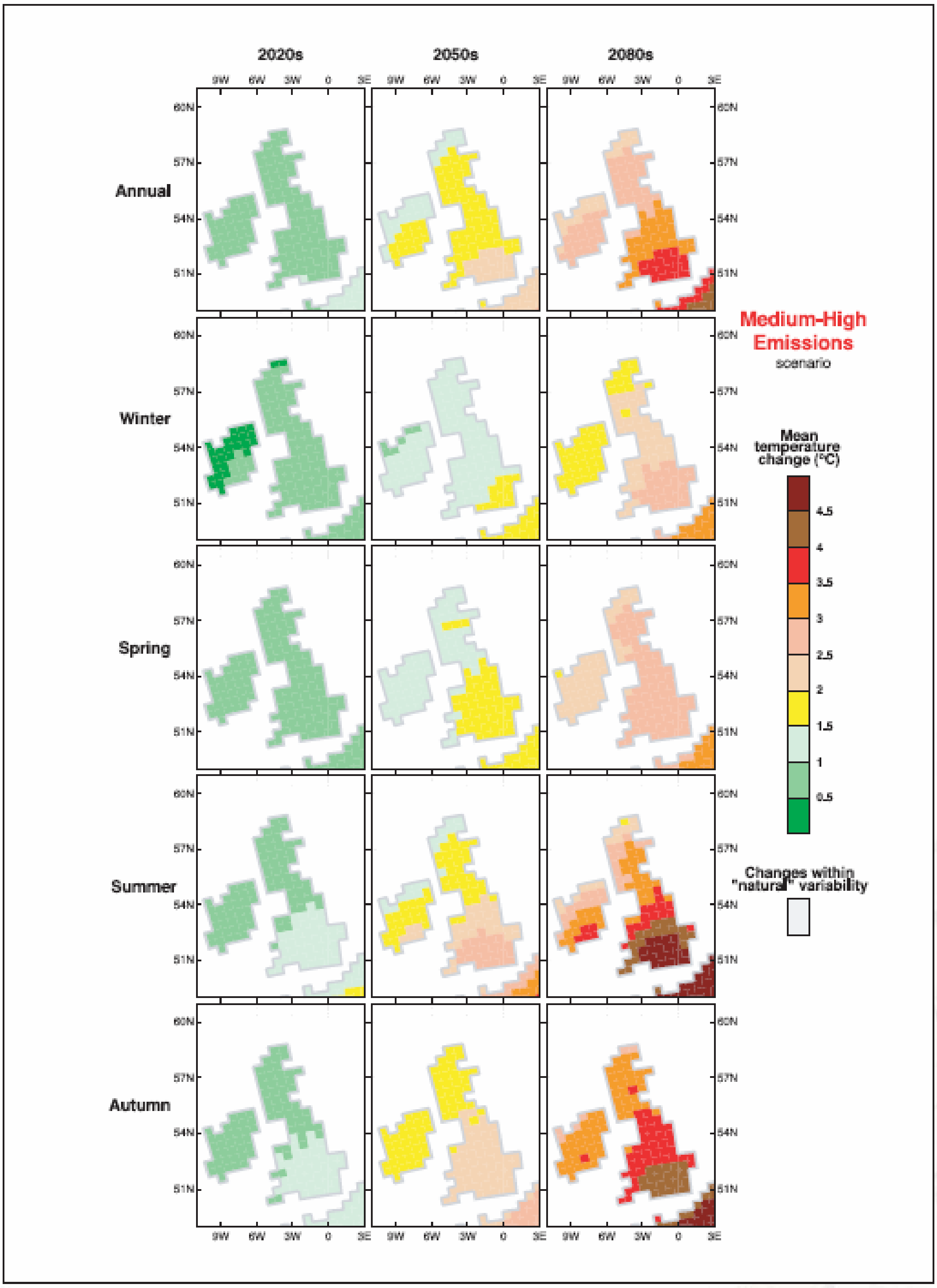



*Figure 20. Net sea-level change for the UK relative to 1961-1990 for the full range of global sea-level changes estimated by the IPCC, incorporating updated isostatic adjustment data (after UKCIP, 2005)*

*Figure 21. Change in average seasonal temperatures under the Medium High scenario, up to the 2080s(after UKCIP, 2002)*

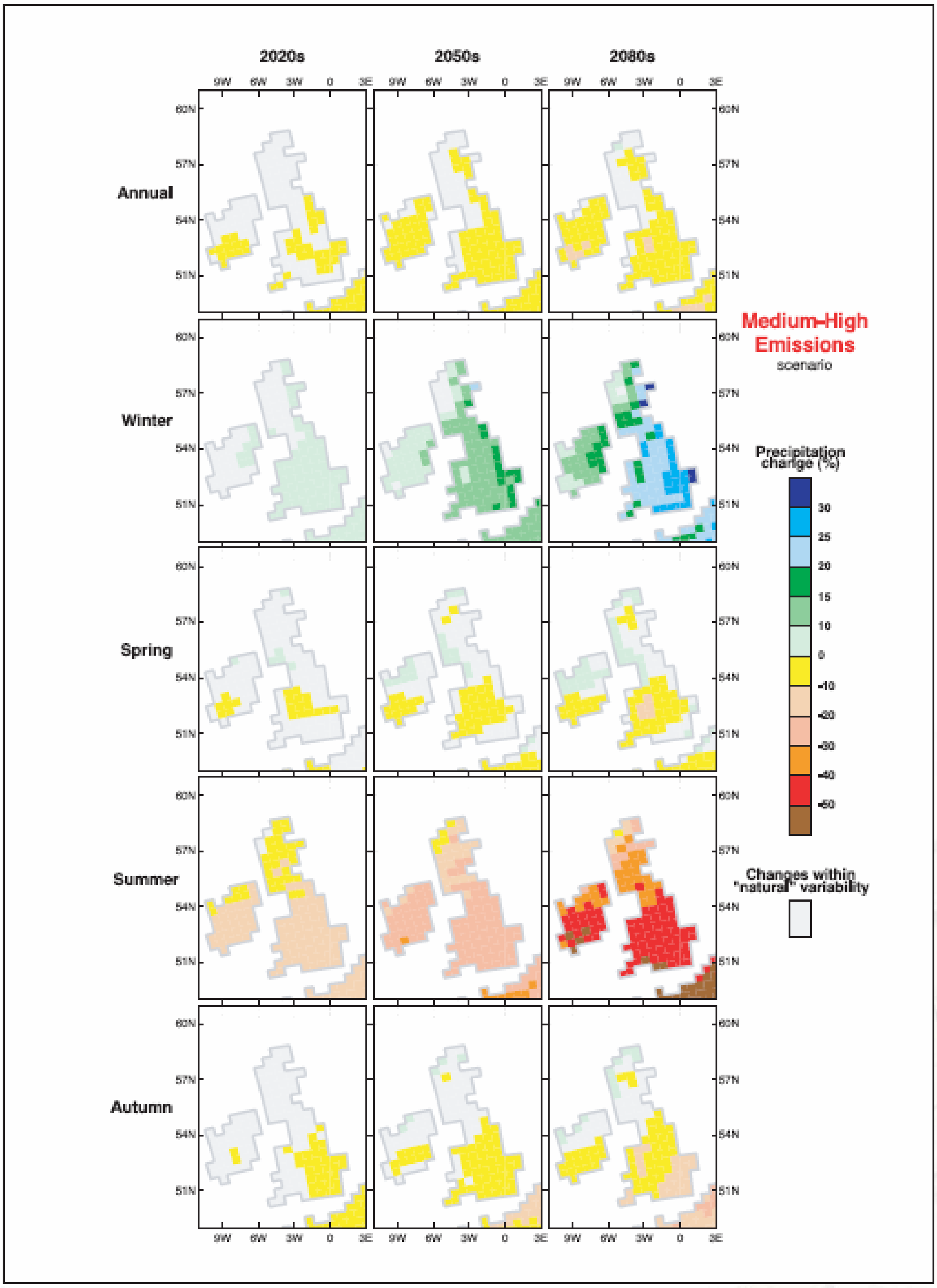



*Figure 22. Change in average seasonal precipitation under the Medium High scenario, up to the 2080s (after UKCIP, 2002)*

These changes in climate have a direct impact on the rates and nature of coastal processes, leading to changes in the nature of future coastal hazard (see Chapter 1 for a description of the links between changes in climate forcing and rate of geomorphological processes).

### 3.6.2 *Approach*

The hazard map identifies three types of hazard, namely: flooding, coastal erosion and reactivation of coastal landslide complexes. In each case, the hazard is identified as being ‘current’ where no defences are present or ‘potential where the hazard is conditional on defence failure (Figure 23).

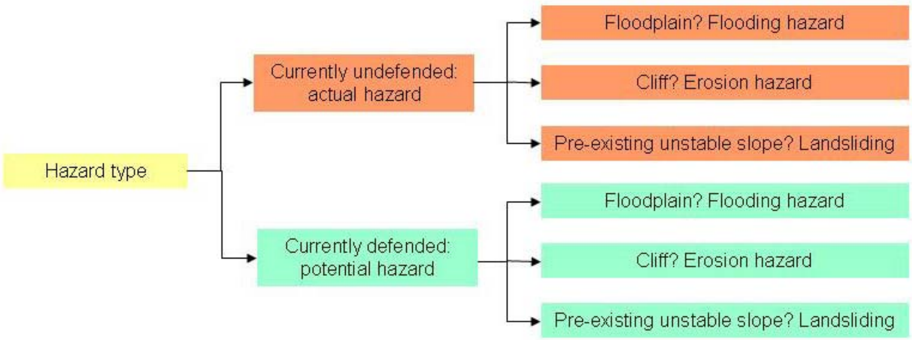



*Figure 23. Hazard classification, based on CBS and defences*

Future hazard classifications are made using maps of coastal behaviour systems, coastal defences and past and present hazard events. Coastal erosion hazard is classified according to the expected average recession rate over the next 100 years from either progressive or episodic failure. The coastal erosion hazard classes are <0.5m/yr, 0.5 to 1m/yr and >1m/yr, and reflect the possible areas of coastal hinterland that could be lost over the next 100 years. For the South Central England coastline, it has been possible to assign each distinct cliff unit a recession rate derived from the Futurecoast database. If similar data is unavailable in other EU countries, qualitative assessments of cliff behaviour can be made using expert judgement.

Coastal landslide complexes, such as the Ventnor undercliff and Lyme Regis, which have episodic behaviour over many thousands of years, are separately identified. These features are identified on Map 3 of current and historical hazards.

Areas at risk from flooding are identified by the intersection of mapped flood plains with the coastline, which have also been identified on Map 3.

In areas that are not floodplains, cliffs or landslides, no hazards are considered to be present.

## 3.7 Map 7. Potential coastal risk (2100)

### *3.7.1 Risk matrix*

There is no baseline quantitative measure of risk against which changes can be compared (such as present value of properties), therefore a descriptive approach using a matrix of relative risk ratings has been developed.

This approach assessed risk by comparing the economic consequences of flooding, coastal erosion or reactivation of coastal landslides with the likelihood of different magnitude events.

Economic consequences are measured using the population density for each section of the coastline. This approach is based on DEFRA's PAG3 documentation, and identifies four classes of population density as follows:

- High density urban (>1 person/sq metre;
- Medium density urban (0.5 to 1 person/sq metre);
- Low density urban/rural (0.1 to 0.5 people/sq metre); and
- Agricultural land with isolated communities (<0.1 person/sq metre).

The breakpoints for definition of these four groups have been selected to approximately define the four quartiles of the data set. They are appropriate for use in the relatively densely populated South Central England coastline, but should be adjusted to suit other coastline regions of Europe.

Likelihoods of hazard events are measured differently, according to the hazard type, as follows:

- Coastal erosion is quantified by expected average recession rate over the next 100 years (i.e. accounting for both episodic and progressive losses). Classes are >1m/yr; 0.5 to 1m/yr; <0.5m/yr and no erosion (due to coastal defences);
- Flood risk is quantified by the expected return interval of flood events. Unprotected floodplains are expected to flood every 10 yrs; areas defended against flooding are expected to be protected against the 1:100 year event; and other areas adjacent to floodplains between 5 and 10m OD are expected to be flooded every 1000 yrs; and
- Coastal instability risk is measured by the return interval of ground movement events, as follows: 1:10; 1:100; 1:500 and 1:1000 year events. This information is sourced from the Futurecoast cliffs database.

Using these two criteria in a matrix it is possible to assign each 'cell' a relative risk rating. This study uses a four-point classification from 1 (Low Risk) to 4 (Very High Risk), but additional classes can be added if required.

Each cell is assigned a risk rating based on expert judgement. Errors and bias can be minimised if the task is undertaken by a number experts. Such an approach has recently been used in the Tyndall Centre for Climate Change's 'Coastal Simulator' where the different possible responses of landforms to climate change are assessed by a number of experts to derive a collective opinion. The risk matrices produced for erosion, flooding and coastal instability are shown in Figure 24.

It must be stressed that potential levels of risk from different hazards (coastal erosion, flooding and coastal instability) are subjective and cannot be directly compared, i.e. E1, F1 and C1 are not equivalent risks. This is because quantitative data on hazard and consequence are unknown. It is possible that the differences in risk between E1, F1 and C1 may be order(s) of magnitude greater.

### 3.7.2 *Scenarios and assessment of risk*

The methodology allows for any number of scenarios to be tested, but in the current methodology, the impact on the coastline of two scenarios is assessed:

- 'business as usual', with limited coastal response to climate change and no change in coastal management practices over the next 100 years;
- 'worst case', with climate change having a direct and negative impact on coastal processes and dramatic changes in coastal management practices, with all defences being lost over the next 100 years.

(a) Business as usual scenario

In the business as usual scenario, the population density and degree of hazard for each segment of the coastline (i.e. the current and future hazards shown on Map 6) is visually assessed and a risk score is added in the GIS.

For erosion risk, the degree of erosion hazard (i.e. >1m/yr, 0.5 to 1m/yr or <0.5m/yr) is derived from Map 6, with all potentially eroding coasts, which are currently protected by defences, being classed as 'no erosion'. The highest risk score can only be achieved at locations of greatest population density and greatest erosion hazard, and conversely, the lowest risk scores are achieved where erosion is very slow or non-existent in locations of medium to very low population density.

**Matrices of relative risk for erosion, flooding and coastal instability**

**Relative risk classes and definition:**

| | |
|---|---|
| 4 | Very high risk |
| 3 | High risk |
| 2 | Medium risk |
| 1 | Low risk |

**Erosion risk**

| Consequences (land use class) | Degree of hazard (progressive and episodic erosion) | | | |
|---|---|---|---|---|
| | >1m erosion/yr | 0.5 - 1 m erosion/yr | <0.5m erosion/yr | Protected (no toe erosion)* |
| High density urban | 4 | 3 | 3 | 1 |
| Medium density urban | 3 | 3 | 2 | 1 |
| Low density urban / rural | 3 | 2 | 2 | 1 |
| Agricultural land / isolated communities | 2 | 2 | 1 | 1 |

**Flood risk**

| Consequences (land use class) | Likelihood of flooding | | |
|---|---|---|---|
| | 1:10 yr flood | 1:100 to 1:200 yr flood | ca.1:1000 yr flood (5 to 10m OD) |
| High density urban | 4 | 3 | 2 |
| Medium density urban | 3 | 2 | 2 |
| Low density urban / rural | 2 | 2 | 1 |
| Agricultural land / isolated communities | 2 | 1 | 1 |

**Coastal instability risk**

| Consequences (land use class) | Likelihood of significant ground movement (landslide reactivation) | | | |
|---|---|---|---|---|
| | 1:10 yr event | 1:100 yr event | 1:500 yr event | 1:1000 yr event |
| High density urban | 4 | 4 | 3 | 2 |
| Medium density urban | 4 | 3 | 2 | 2 |
| Low density urban / rural | 3 | 2 | 1 | 1 |
| Agricultural land / isolated communities | 2 | 1 | 1 | 1 |

* No toe erosion due to defences

*Figure 24. Risk matrices used for the South Central England coastline.*

Flood risk is determined by the presence or absence of flood defences and the population density of floodplain areas. The highest risk score is applied to urban areas situated on undefended floodplains. Lower risk scores are applied if defences are present, and if population density is lower. Coastal instability risk is assessed is assessed in a similar way, using the likelihood of significant ground movement as the measure of hazard. High risk scores are therefore applied to locations where population density is highest and significant ground movement is expected as a 1:10 yr event, while lower scores are applied where the likelihood of reactivation or population density is lower.

The risk of the different hazards cannot be directly compared because risks are assessed relatively. Therefore the mapping shows the relative risk scores for erosion, flooding and coastal instability separately identified with the prefix E, F or C. This means that very high risks of flooding (F4) and erosion (E4) are not the same and cannot be considered to be comparable.

(b) Worst case

To assess the impact on coastal risk of the worst case scenario, the same series of relative risk matrices can be used. To account of the impact of climate change at each coastal segment the degree of hazard (i.e. average erosion rate, likelihood of flooding or likelihood of significant ground movement) is increased. Using the matrix, this is achieved by moving once cell towards the right along the same Consequence (land use class) row. Depending on the structure of the matrix, this may lead to an increase in risk.

The impact of removal of coastal defences on erosion rate and coastal instability is assessed by choosing a likely recession rate/reactivation return period for the unprotected cliffs/landslides, and then moving one cell to the right to account for the impact of climate change. Data on unprotected cliff/landslide behaviour is available in the Futurecoast cliffs database, but expert judgement can also be applied. The impact of defence removal on flood risk is achieved by assuming all floodplain areas will be inundated on a 1:10 year basis.

### *3.8 Map 8. Hazard summary*

To demonstrate potential additional applications of the RESPONSE datasets, two non-technical summary maps have been produced which included addition information and guidance.

It should be noted that maps 8 and 9 are appropriate for use only in the UK, where planning regulations place the onus of responsibility on the developer, meaning that Local Authorities only need general guidance. Planning regulations may be different in other EU member states and therefore the nature of any additional non-technical maps should be revised as necessary.

Map 8 is a summary geohazard map and is intended to highlight 'hotspots' along the South Central England coastline for use by non-experts. The information can be used to give an overview of the processes operating in the study area and can be used to focus further study along certain stretches of the coast.

The map is a development of the current and future hazards map, but only the most significant hazards are displayed. Therefore, areas of moderate or low rates of erosion are not displayed, to give prominence to more rapidly eroding stretches of coast, unstable coastal slopes and floodplains.

### *3.9 Map 9. Planning guidance for the South Central England coastline*

The information on Map 9 is derived from the risk mapping and provides guidance on constrains to development at hot spots along the coastline. The map also highlights those stretches of coastline where levels of relative risk have risen due to the impact of climate change and/or progressive loss of defences i.e. the level of risk has changed when comparing the 'business as usual' and 'worst case' scenarios (Maps 7).

Risk could also increase if the consequence of the hazard increased, which would be caused by the population density increasing in the RESPONSE methodology. Trends in population over the next 100 years are unknown and this analysis is beyond the scope of the current RESPONSE methodology.

# 4 Sources of data

### 4.1 *Datasets*

The information presented in maps 1 to 9 comprises three main types of data: factual geomorphological information, interpretive geomorphological information and base mapping.

Base mapping includes Ordnance Survey 1:250,000 raster mapping, ESRI UK coastal outlines, and local authority boundaries from the online government geographical data website, MAGIC (Multi-Agency Geographic Information for the Countryside), which can be found at www.magic.gov.uk. Geomorphological datasets include data from the Environment Agency (EA) and existing geomorphological coastal assessments from Halcrow records. Flood data from the EA is based on current floodplain areas. Additional geomorphological data contained in maps 1 to 5 such as sediment cell boundaries, littoral drift directions and hinterland geology are from existing data sources originally commissioned for coastal mapping studies on behalf of SCOPAC and DEFRA. The geomorphological interpretation data on hazard and risk maps has been mapped from a combination of the datasets previously presented (refer to methodology for further details). Data source details and copyright information are stated in Table 13.

### 4.2 *Geographical Information Systems (GIS)*

The RESPONSE maps have been produced using ESRI ArcView 9 GIS software. Analysis and presentation of spatial data with GIS allows multiple datasets to be compared and combined to highlight and interpret spatial patterns.

*Table 13 Data Sources and copyright information*

| Dataset | RESPONSE Map | Source | Ownership | Details | Copyright |
|---|---|---|---|---|---|
| OS base mapping (1:250,000) | All | OS | OS | SCOPAC licence | Internal business use only |
| UK area, coast outline and rivers | All | ESRI | ESRI | | Internal business use only |
| Regional boundaries and responsible authorities (counties and unitary authorities) | All | www.magic.gov.uk | DEFRA | | Internal business use only |
| Backshore systems, hinterland geology, beach composition, sand dunes, saltmarsh, intertidal mudflats, net drift direction, coastal erosion input, sediment sinks and stores, coastal wave energy | 1a and 1b | SCOPAC | SCOPAC | Details provided from Halcrow's report for SCOPAC (2001) | Internal business use only |
| Cell boundaries | 1b and 5 | SCOPAC | SCOPAC | Details provided from Halcrow's report for SCOPAC (2001) | Internal business use only |
| Defence type<br>Shore management type | 2 | SCOPAC | SCOPAC | Details provided from Halcrow's report for SCOPAC (2001) | Internal business use only |
| EA published flood maps | 3 + inset maps | EA | EA | SCOPAC licence<br>Uses published data project to 2080 for 1:100 year fluvial flooding and 1:200 year tidal flooding | Internal business use only |
| Historical flooding and landslide events<br>Active processes | 3 | SCOPAC and DEFRA | SCOPAC and DEFRA | Details provided from Halcrow's report for SCOPAC (2001) and Halcrow's DEFRA FutureCoast database (1999) | Internal business use only |
| Population figures (2001 census) | 4 | www.magic.gov.uk | ODPM and ONS | The Office of the Deputy Prime Minister (ODPM) for Urban Areas, Office for National Statistics (ONS) | Internal business use only |

| Dataset | RESPONSE Map | Source | Ownership | Details | Copyright |
|---|---|---|---|---|---|
| | | | | for population data | |
| Agricultural land classifications | 4 | www.magic.gov.uk | DEFRA | | Internal business use only |
| Important industry | 4 | www.magic.gov.uk | DEFRA | | Internal business use only |
| Amenity/Tourism beaches and access | 4 | www.blueflag.org | Blue flag organisation | | Internal business use only |
| Coastal Behaviour Systems | 5 | SCOPAC | SCOPAC | Details provided from Halcrow's report for SCOPAC (2001) | Internal business use only |

# 5 References

Australian Geomechanics Society (2000) Landslide risk management concepts and guidelines. *Australian Geomechanics* **35**, 49-52.

Cowell P, Thom B (1994) Morphodynamics of coastal evolution. In: Carter RGW and Woodroffe CD *Coastal Evolution: Late Quaternary Shoreline Morphodynamics*. Cambridge University Press, Cambridge. 33-87.

UKCIP (2002) *Climate Change Scenarios for the United Kingdom: The UKCIP02 Scientific Repor*t. Tyndall Centre for Climate Change Research, School of Environmental Sciences, University of East Anglia, Norwich, UK

UKCIP (2005) *Updates to regional net sea-level change estimates for the UK*. UKCIP, November 2005.

Orford JD, Carter RGW, McKenna J, Jennings SC (1995) The relationship between the rate of meso-scale sea-level rise and the retreat rate of swash-aligned gravel-dominated coastal barriers. *Journal of Coastal Research* **12**, 589-605.

Gazzetta Ufficiale della Repubblica Italiana (1998) Misure urgenti per la prevenzione del rischio idrogeologico ad a favore delle zone col-pite da disastri franosi nella regione Campania. *Serie Generale*, Anno 139, 7 Sept 1998, 53-74. (In Italian – see Mark Lee for translation)

Gazzetta Ufficiale della Repubblica Italiana (1999) Atto di indirizzo e co-ordinamento per l'individuazione dei criteri relativi agli adempi-menti di cui all'art. 1, commi 1 e 2, del decreto-legge 11 giuno 1998, n. 180. *Serie Generale*, Anno 140, n 3, 5 January 1999.