Coastal cliff recession risk: a simple judgement-based model

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Abstract

To predict cliff recession rates, it is necessary to make judgements about the effects of changing environmental conditions and shoreline management practice on the recession process. A simple model is presented that allows judgements to be ordered in a systematic manner. The model can be used to generate single predicted values or a probability distribution of the possible recession rates, as illustrated by an example from the Covehithe cliffs, Suffolk. The output from the probabilistic model can also be used to support risk-based economic evaluation of the benefits of coast protection.

Keywords: *erosion, models, risk assessment, shorelines*

Recession of coastal cliffs can present significant threats to people and property (e.g. Sunamura 1992; Lee & Clark 2002). In many countries, large sums have been invested in erosion control schemes in an attempt to prevent the loss of cliff-top properties, services and infrastructure and to mitigate the risk to public safety. In England, for example, there are some 860 km of coast protection works with over £20 million spent each year on maintaining and improving these defences, and providing new schemes (e.g. Lee 2001).

Reliable predictions of future cliff recession rates are needed to support the formulation of land use planning policies that avoid locating new development in areas where erosion is likely to occur during the lifetime of the building. In those situations where coast protection works or improvements may be required to protect existing development, future recession rates are needed to evaluate options for the installation or replacement of erosion control measures. The economic justification of capital schemes for controlling cliff recession depends on modelling the risks associated with future recession both with and without the scheme in place (Hall *et al.* 2000).

Simple extrapolation of historical trends can be used to estimate the time scale over which cliff-top assets might be threatened. This approach is based on the assumption that the historical recession rate provides a reliable indication of the future rate. The limitations of extrapolating historical recession rates to yield a single value for the future recession rate can be illustrated by an example from the cliffs between Benacre and Southwold on the Suffolk coast, UK (Fig. 1); the 5–10 m high unprotected cliffs are developed in weak Pleistocene sands and gravels (Norwich Crag). Analysis of historical maps for the period 1884–1976 suggests average annual recession rates of between 3.00 and 4.74 m a^{-1} (Table 1). These rates were used to predict the cumulative recession at the different cliff sections over the period 1991–1999. The actual recession measured through repeated annual beach profile surveys over this period was significantly different from the predicted. In some cases the actual recession was nearly double the predicted (Easton Broad cliffs), whereas in other cases the actual recession was around a quarter of the predicted (Easton Woods cliffs).

Lee & Clark (2002) have pointed out that past recession rates may not provide an accurate guide to future recession rates. This is because the historical record generally consists of a limited number of measurements (in this case four topographic map dates: 1884, 1905, 1946 and 1976) and is insufficient to explain the pattern of recession events (probably of different size) that led to the cumulative land loss between the measurement dates. The pattern of past events is the result of a particular and unique set of wave, weather and environmental conditions. A different set of conditions could have generated a different recession scenario.

Predictions of cliff recession that are based on extrapolation of past trends do not reflect the potential

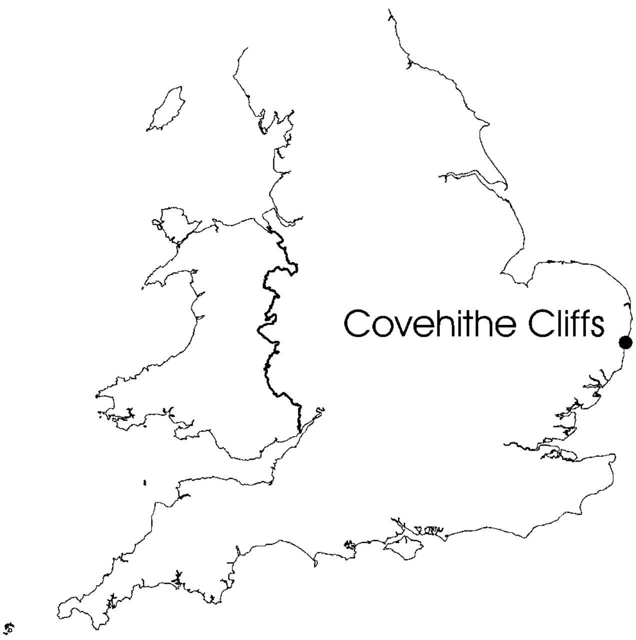

Fig. 1. Location plan for the Suffolk cliffs.

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Table 1. *Cliff recession rates for Suffolk cliffs (from Halcrow Group Ltd 2001a).*

Cliff section	Average annual recession rate[1] ($m\,a^{-1}$) (1884–1976)	Predicted recession (m) (1991–1999)	Actual recession (m)[1] (1991–1999)	Average annual recession rate ($m\,a^{-1}$) (1991–1999)	Percentage difference (actual and predicted recession 1991–1999)
Benacre cliffs	4.74	37.91	57	7.13	150
Covehithe cliffs	4.58	36.61	64	8.0	175
Easton Woods cliffs	4.24	33.91	9	1.12	27
Easton Broad cliffs	3.85	30.78	58	7.25	188
Easton Bavents cliffs	3.00	24.00	9	1.12	38

[1]Recession at cliff erosion profile along the cliff section with the largest recorded recession.

uncertainty and variability in the cliff recession process (e.g. Lee *et al.* 2001; Lee & Clark 2002; Brunsden & Lee 2004). These uncertainties include: the rate of sea-level rise; the degree of natural cliff protection provided by the beach; the response of the cliffline to higher winter rainfall and increased storminess predicted to result from climate change; the variability of the materials exposed in the cliff face at a particular time; current and future shoreline management (i.e. cliff toe protection). Uncertainty arises in cliff behaviour because of the stochastic nature of forcing events (randomness) and the fact that the cliff response can be very sensitive to the initial system state; this state is often only known in broad terms (deterministic uncertainty; i.e. even if we knew the future forcing events we could not be sure of the system response).

This paper describes a simple model that has been developed to provide a structured framework for adjusting the historical recession rate to reflect future changes in the key factors that control the recession process (Lee 2003). It can be used either deterministically (i.e. effects logically follow particular causes in a non-random manner) to generate a single recession rate or in a probabilistic manner to generate a probability distribution for the rate. The results from the probabilistic approach can form the input to risk-based economic evaluation of erosion control options (Hall *et al.* 2000).

The recession model

This model is presented as Figure 2 and involves a series of separate stages at which judgements are made about the need to adjust the historical recession rate because of changing future conditions. For example, a cliff has been retreating at an average annual recession rate of $1.0\,m\,a^{-1}$. Available knowledge suggests that in the future the rate of sea-level rise will be greater than the historical rate, there will be an increase in the effective winter rainfall (i.e. precipitation minus evapotranspiration), beach levels will decline, there will be an increase in storminess and no change in cliff toe protection. The predicted recession rate for this particular case would be

predicted recession rate =

$$\text{historical recession rate} \times S-L \times W \times B \times S \times E$$

where *S-L* is the sea-level rise factor that represents the change in average annual cliff recession rate related to change in the rate of sea-level rise (Box B in Fig. 2); *W* is the winter rainfall factor that represents the change in average annual cliff recession rate related to change in effective winter rainfall (Box C in Fig. 2); *B* is the beach level factor that represents the change in average annual cliff recession rate related to change in the degree of cliff protection provided by the beach (Box D in Fig. 2); *S* is the storminess factor that represents the change in annual cliff recession related to changes in the wave energy arriving on the shoreline as a result of changes in storminess (Box E in Fig. 2); *E* is the cliff toe protection factor that represents the change in average annual cliff recession rate related to changes in toe protection. This takes account of the influence of future shoreline management practice at the site (Box F in Fig. 2). Shoreline management elsewhere within a coastal cell can have an impact on the sediment budget and, hence, beach levels; this issue is considered as part of the beach level factor.

In this instance, modification of the historical recession rate with appropriate adjustment factors will yield a single future rate. The single route through the framework in Figure 2 might be regarded as a 'best estimate'. However, as there is uncertainty about the future conditions it is possible to develop numerous possible cases, each with different combinations of future condition changes. For example:

Case 1, rate of sea-level rise greater than the historical rate, an increase in the effective winter rainfall, a decline in beach levels and an increase in cliff toe protection;

Case 2, rate of sea-level rise the same as the historical rate, no change in the effective winter rainfall, a decline in beach levels and an increase in cliff toe protection;

Case 3, rate of sea-level rise greater than the historical rate, no change in the effective winter rainfall, no change in beach levels and no change in cliff toe protection.

Each of these cases (scenarios) will result in a different recession rate. In addition to the 'best estimate', it might be possible to define 'best case' and 'worse case'

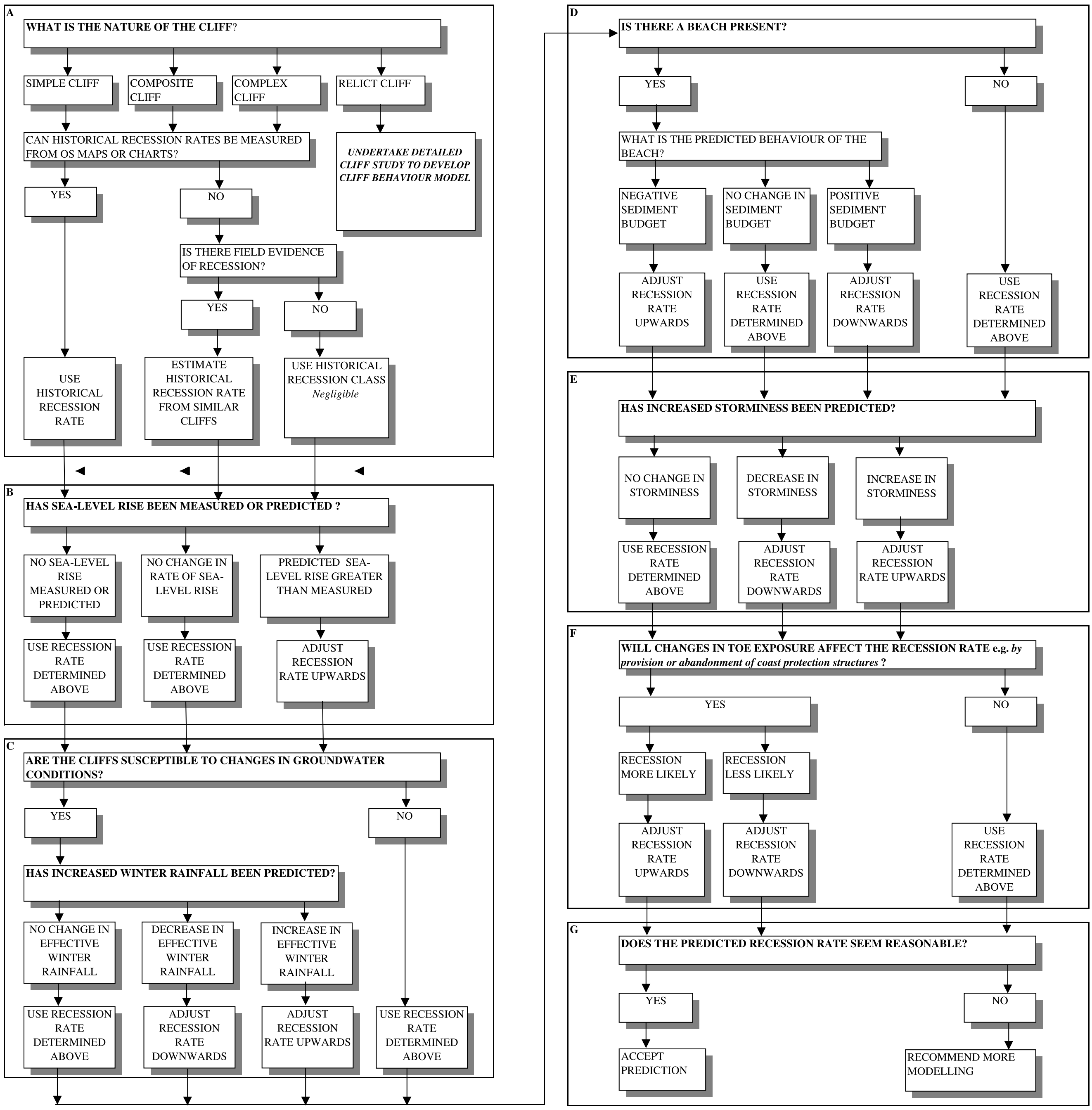

Fig. 2. Framework for the simple prediction model.

scenarios. Developing multiple cases provides the means for sensitivity testing of the predicted recession distance over a particular time period. However, this approach does not incorporate an indication of the likelihood of a particular recession rate or distance, beyond the engineer's judgement about the range within which the true value is expected to lie.

Probabilistic methods are essentially sophisticated sensitivity tests in which single or multiple data values (i.e. recession rates) are replaced by probability distributions that cover all possible values or outcomes (i.e. all possible routes through Fig. 2). A probability distribution can be developed by assigning each of the possible future conditions a probability value. The probability of a particular case occurring is the conditional probability:

$$P(\text{Case} \quad n) = P(S-L) \times P(W) \times P(B) \times P(S) \times P(E).$$

The sum of the conditional probabilities for all possible cases adds up to 1.0 and can be presented as a simple plot of average annual recession rate against its probability.

Fig. 3. The Covehithe cliffs (August 2003).

Example: Covehithe Cliffs, Suffolk

The 2 km long Covehithe cliffs, Suffolk, UK, are 10–15 m high and developed in a varied sequence of Pleistocene Norwich Crag sediments, including weak sands and gravels (Westleton Beds) and clays (the Easton Bavents Clay), overlain by later Kesgrave Formation fluvial sands and gravels (e.g. Gibbard & Zalasiewicz 1988). They have a near-vertical profile and a discontinuous talus apron of rockfall and debris slide material at the cliff foot (Fig. 3). The cliffline is fronted by a sand and shingle beach. There are no toe protection structures; the current and proposed future shoreline management policy is to 'do nothing' (Halcrow Group Ltd 2001*a*). Cliff recession rates determined at separate measurement sites along the 1.9 km long cliffline are presented in Table 2, for the periods 1884–1976 (six sites) and 1991–1999 (a single beach profile survey site).

The recession model has been used by a team of coastal engineers and geomorphologists to provide predictions of the recession rate for the cliffline that would be applicable over a 50 year time scale. Two approaches were used. The first involved the development of a 'best estimate', together with 'best case' and 'worst case' scenarios (i.e. a deterministic approach). The second approach involved generating a probability distribution of the future recession rate, based on all the possible outcomes indicated in Figure 2.

The development of the model involved establishing site-specific values for the various adjustment factors. This was achieved through group discussion, based on an understanding of the local cliff conditions and cliff–shoreline behaviour (e.g. Brunsden & Lee 2004). Specific adjustment factors were the following.

(1) *Sea-level rise factor (*S-L*)*. Although there is much uncertainty about future rate of sea-level rise, it is expected to accelerate and to result in increased recession rates (e.g. Clayton 1989; Bray & Hooke 1997). Sea-level rise can be assumed to result in the parallel retreat of the cliff profile, albeit with a corresponding rise in elevation of the cliff foot. This geometric relationship forms the basis of the Bruun Rule for deriving the shoreline response to sea-level rise (Bruun 1962).

The Bruun Rule assumes that an equilibrium profile is maintained as a landform (i.e. cliff and beach) moves inland in response to sea-level rise, by the transfer of eroded material from the upper cliff profile to the lower beach profile. The Bruun Rule can be used to estimate the rate of profile migration (R):

$$R = (LS)/H$$

where S is the rate of sea-level rise, L is the profile width (i.e. the offshore distance to the depth of closure; see below) and H is the profile depth at the depth of closure.

For example, if sea-level rise was 5 mm a^{-1}, and the depth of closure of 10 m occurs 300 m offshore, the

Table 2. *Covehithe cliffs: historical recession rates.*

Recession measurement sites	Cliff recession rates (m a^{-1})							
	1884–1905	1905–1946	1946–1976	Cumulative recession (m) 1884–1976	Long-term recession rate 1884–1976	Cumulative recession (m) 1991–1999	Short-term recession rate 1991–1999	Medium-term recession rate 1946–1976; 1991–1999[1]
A	5	3.8	5.3	419.8	4.56			5.87
B	4.09	4.09	5.59	421.28	4.58			6.10
C	4.68	3.2	5.68	399.88	4.35			6.17
D	4.59	2.3	7	400.69	4.36			7.21
E	4.4	1.4	7.68	380.2	4.13			7.75
F	4	1.2	7.4	355.2	3.86			7.53
G						64	8	

[1]Medium-term recession rate is the cumulative recession over periods 1946–1976 (30 years) and 1991–1999 (8 years) divided by the total number of years (38 years). The short-term recession for Site G was added to each of the other sites A–F to generate the medium-term rate. The recession rates at Sites A–F were determined from comparison of the cliff top positions on different Ordnance Survey map editions (see Lee & Clark 2002 for a discussion of the problems of measuring recession from historical maps). Site G is one of the Environment Agency Sea Defense Management System (SDMS) beach profile survey locations (SWD3). Each year, beach surveys are undertaken in winter and summer.

annual predicted profile migration rate would be $R = (0.005 \times 300)/10 = 0.15\ \mathrm{m\ a^{-1}}$.

The Bruun Rule is essentially two-dimensional (onshore–offshore) and assumes that longshore sediment inputs and outputs are equal and equivalent, a condition rarely achieved in reality. To model reliably the three-dimensional situation, a full sediment budget needs to be calculated for the shoreline. If it is assumed, however, that the historical recession rate represents the net contribution to the sediment budget, then the Bruun Rule can be modified to provide an adjustment factor that represents the recession increase caused by sea-level rise (R) as follows (Dean 1991):

$$R = R_1 + Sc\frac{L}{P(B + H)}$$

where R_1 is the historical recession rate ($\mathrm{m\ a^{-1}}$), Sc is the change in rate of sea-level rise (m), P is the sediment overfill (the proportion of sediment eroded that is sufficiently coarse to remain within the equilibrium beach profile), B is the cliff height (m), H is the closure depth (m) and L is the length of cliff and beach profile (to the closure depth, m). It should be noted that, in this form, the adjustment factor is an additional increment to the historical rate, not a multiplication factor.

The Bruun Rule is not without its critics (e.g. Komar *et al.* 1991), although overall validity of this approach appears to have been confirmed for the eroding cliff shores of Chesapeake Bay and the Great Lakes (Rosen 1978; Hands 1983; Dubois 1992; Zurek *et al.* 2003). Rising sea or lake levels have produced a transfer of material from the cliff to the nearshore bed resulting in recession rates that were very close to those predicted by the model.

The change in sea-level rise is the difference between the historical and future sea-level rise at the site. The historical rate on this shoreline is $1.81\ \mathrm{mm\ a^{-1}}$ (1956–1995; standard error of ± 0.48 mm; Woodworth *et al.* 1999). Although there is uncertainty about the future rate of sea-level rise over the next century, the local change in average rate is expected to be between 2 and $7.5\ \mathrm{mm\ a^{-1}}$ (Hulme *et al.* 2002).

The closure depth is the boundary of the profile beyond which there is little loss of sediment. The closure depth can be estimated as being twice the maximum wave height for a 50 year return period (Bruun 1988; 7.4 m high for this coast), that is, a closure depth of 14.8 m.

The sediment overfill function is the proportion of sediment eroded that is sufficiently coarse to remain within the equilibrium profile. This was derived from a study of cliff recession inputs carried out by the British Geological Survey (1996) and was calculated as the combined sand and gravel yield.

The length of active cliff profile was measured from the hydrographic charts by using the closure depth to indicate the seaward limits, taken here as 1500 m.

(2) *Winter rainfall factor (*W*)*. This factor takes account of the expected changes in slope instability associated with future changes in effective winter rainfall. The link between rainfall, groundwater and landslide activity is well established, and can be explained in terms of the change in porewater pressures associated with fluctuations in groundwater levels (e.g. Brunsden & Lee 2004). Halcrow Group Ltd (2001*b*) applied the UKCIP98 change scenarios (Hulme *et al.* 1998) to the Ventnor Undercliff rainfall data; the analysis suggested a 5–6% increase in mean monthly effective rainfall under the low scenario and a 12–25% increase for the high scenario. This is expected to result in an increase in the frequency or probability of landslide events in the Undercliff.

However, the link between changing rainfall patterns, landslide activity and recession rates on the Suffolk cliffline has yet to be established. The adjustment factors presented are, therefore, judgements. Three conditions were considered.

- No change in effective winter rainfall. This condition was assumed to have no net effect on the cliff recession rate (i.e. the winter rainfall adjustment factor is 1.0).
- Increase in winter rainfall. Recent climatic modelling by the Hadley Centre (Hulme *et al.* 2002) has predicted an increase in the average winter rainfall (December, January, February) of around 15–30% by the year 2080. The failure of the weak sandy Pleistocene deposits appears to be controlled by wave attack at the cliff foot rather than groundwater conditions within the cliff. As a result, this condition was assumed to have only a minor effect on the cliff recession rate (i.e. the winter rainfall adjustment factor is 1.05).
- Decrease in winter rainfall. As cliff recession appears to be controlled by wave attack, this condition was assumed to have a minor effect on the cliff recession rate (i.e. the winter rainfall factor is 0.95).

(3) *Establishing a beach level factor (*B*)*. This factor represents changes in the degree of protection provided to the base of the cliff by the beach from the waves arriving at the shoreline. Beaches control wave energy dissipation on the foreshore and, in some situations, can provide complete protection from marine erosion. In California, Everts (1991) demonstrated that a beach width (above mean sea level) of 20–30 m affords significant protection, whereas one of 60 m provides complete protection. 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 seven profile monitoring sites on the Suffolk clifflines has been defined by Lee (2004) and is shown in Figure 4. This indicates that recession rates increase exponentially as beach volumes fall (i.e. 'wedge area'). At Covehithe, the average beach wedge area between 1992 and 2003 was $7.3\ \mathrm{m^2}$.

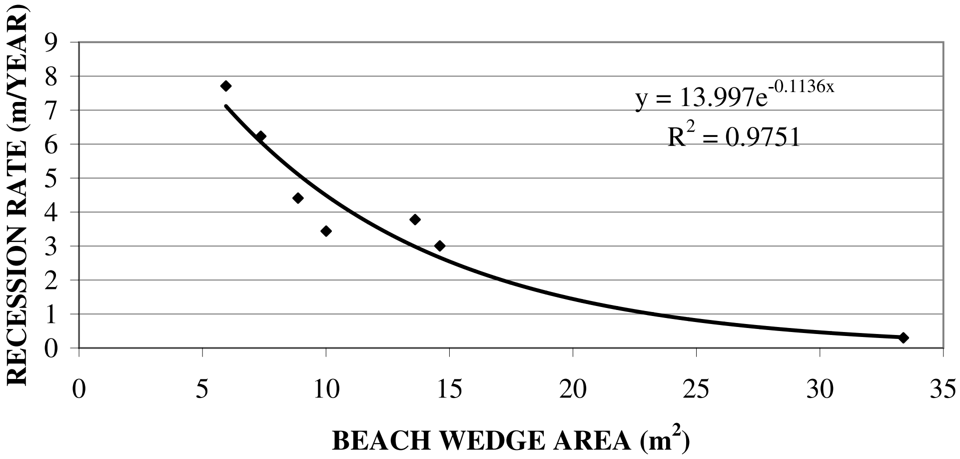

Fig. 4. The relationship between average annual cliff recession rate and beach volume (expressed as the beach profile area above high water mark (HWM) i.e. the 'beach wedge'). Each point represents a separate monitoring site (from Lee 2004).

Three beach volume conditions were considered in the model.

- No change in beach level. This condition is associated with no net change in the sediment budget of the beach; that is, any changes in the future sediment inputs from longshore drift and cliff recession would be matched by equal changes in sediment outputs from the beach to offshore or through longshore drift. This condition was assumed to have no net effect on the cliff recession rate (i.e. the beach level factor is 1.0).
- Net accretion of the beach. This condition is associated with a net increase in sediment supply to the beach, as a result of increased cliff recession elsewhere. It was considered that increased sediment delivery from cliff recession would provide only a relatively minor proportion of potential beach-building material. Therefore, it was estimated that beach accretion would be relatively minor, around 10% (i.e. from 7.3 m^2 to 8 m^2). From Figure 4, this increase in average beach volume would result in a 25% reduction in the recession rate. As a result a beach level factor of 0.75 was selected.
- Net depletion of the beach. This condition is associated with a net decrease in the sediment budget of the beach; that is, any changes in the future sediment inputs from cliff recession would be more than matched by increases in sediment outputs from the beach to offshore or through longshore drift. This condition would result in lower beach levels and increased potential for wave attack at the cliff foot. It was estimated that average beach levels might fall by 20% (i.e. from 7.3 m^2 to 5.8 m^2), resulting in a 25% increase in recession rate (see Fig. 4). As a result, a beach level factor of 1.25 was selected.

(4) *Cliff toe protection factor (*E*)*. This factor reflects the team's judgement on the expected impact of changes in shoreline management practice on this coastline and accounts for changes in wave energy arriving at the cliff toe. Three conditions were considered.

- No change in cliff toe protection. This condition is associated with no significant changes in cliff toe protection over the next 50 years (i.e. maintain the current policy of 'do nothing'). This condition was assumed to have no net effect on the cliff recession rate (i.e. the cliff toe protection factor is 1.0).
- Net reduction in cliff toe protection. This condition is associated with the instigation of a 'hold the line' shoreline management policy, such as the construction of a seawall or timber palisade. This is assumed to lead to a major reduction in recession rate. A protection factor of 0.01 was selected, based on a recent review of the effectiveness of different types of coast protection measures on the North Norfolk cliffline (Lee 2004) in terms of the reduction in recession rate between protected and unprotected cliffs with comparable beach wedge areas. In this analysis it was shown that for sites with very low beach wedge areas (<15 m^2) timber palisades have reduced recession rates by over 97% compared with the observed rates for unprotected sites with similar beach wedge areas.
- Net increase in cliff toe protection. This condition is associated with a decline in cliff toe protection (protection factor of 1.5). However, as the site is currently unprotected it was not considered to be a likely scenario.

It should be noted that the storminess factor (S) has not been included because of the difficulty in establishing a reliable measure of storminess for the Suffolk coast.

The deterministic approach

Scenarios were developed to represent the 'best estimate', 'best case' and 'worse case' situations, each involving a sequence of adjustment factors that represented different future conditions (Table 3). These factors were used to adjust a single average historical recession rate for the cliffline. This rate was established by combining the cumulative recession for each of the measurement sites over the periods 1946–1976 and 1991–1999 and dividing by the number of years in the

Table 3. *Covehithe cliffs: conditions associated with future recession scenarios.*

Scenario	Sea-level rise (mm a^{-1})	Winter rainfall	Beach level factor	Cliff toe factor
'Best case'	2	Slight decline	No change	No change
'Best estimate'	6	25–30% increase	No change	No change
'Worst case'	8	25–30% increase	Net depletion	No change

Table 4. *Covehithe cliffs: the derivation of the sea-level rise factor.*

Historical recession rate (m) $R1$	Historical rate of sea-level rise (m a^{-1}) $S1$	Future rate of sea-level rise (m a^{-1}) $S2$	Sediment overfill P%	Closure depth (m) L	Profile depth (m) H	Cliff height (m) B	$S2 - S1$	Sea-level rise factor	Future recession rate $R2$
6.77	0.00181	0.002	0.977	1500	14.8	7.5	0.00019	0.013	6.783
6.77	0.00181	0.006	0.977	1500	14.8	7.5	0.00419	0.288	7.058
6.77	0.00181	0.008	0.977	1500	14.8	7.5	0.00569	0.426	7.196

Table 5. *Covehithe cliffs: predicted future recession rates for three scenarios. (Note: Sea-level rise is an additional increment).*

Scenario	Historical recession rate (m a^{-1})	Sea-level rise factor	Winter rainfall factor	Beach level factor	Cliff toe factor	Future recession rate (m a^{-1})
'Best case'	6.77	0.013	0.95	1.0	1.0	6.4
'Best estimate'	6.77	0.288	1.05	1.0	1.0	7.4
'Worst case'	6.77	0.426	1.05	1.25	1.0	9.4

combined periods (38 years). An average value for the cliffline (6.77 m a^{-1}) was determined from the values at each of the sites. This recession rate takes account of both the recent high recession rates and the longer-term trends. It also provides a recession rate that is applicable over the period of recorded sea-level change (1956–1995; see above).

Table 4 presents the results of using the modified Bruun Rule to predict the change in the average annual recession rate associated with sea-level rise of between 2 mm ('best case') and 8 mm ('worst case') per year. The predicted recession rates for the three scenarios are presented in Table 5.

The probabilistic approach

The probabilistic assessment involved developing an event tree to represent all possible outcomes represented in Figure 2. Event trees are a specific form of branching logic diagram that allow all likely sequences of events, or combinations of scenarios, to be mapped as a branching network, with estimated probabilities at each branch (e.g. Cox & Tait 1991). Once the structure of the tree has been developed by establishing all the likely sequences of events and resultant outcomes (Fig. 5), then probability values can be assigned to each of the branches. This can be achieved through group discussion (e.g. Roberds 1990). The individual probability of achieving a certain outcome is the product of the likelihood of the initial condition (i.e. historical recession rate) and the conditional probabilities of all intervening conditions along a pathway leading to that specific outcome (i.e. an individual recession scenario). For example, let us suppose that an initial condition, that is, historical recession rate (R) has a probability $P(R)$. Given that this condition occurs, the sea-level rise factor, S, has the probability $P(S|R)$. Likewise, the winter rainfall factor (W) has a conditional probability $P(W|S)$, and so on. The probability of a particular scenario occurring is

$$\text{scenario probability} = P(R) \times P(S|R) \times P(W|S) \times P(B|W) \times P(E|B).$$

It should be noted that the notation '|' indicates 'given' in the sense that the probability $P(S|R)$ is the probability of the sea-level rise condition given that a particular recession rate has be adopted. Each fork in the branching network represents a mutually exclusive alternative (i.e. they are 'Boolean' parameters) with a cumulative probability of one, and the sum of the outcome probabilities for all the scenarios must also equal one.

The recession data presented in Table 2 illustrates that there is considerable variability between the measurement sites along the cliffline and between measurement periods. The uncertainty over which historical rate should be used in the model was taken into account

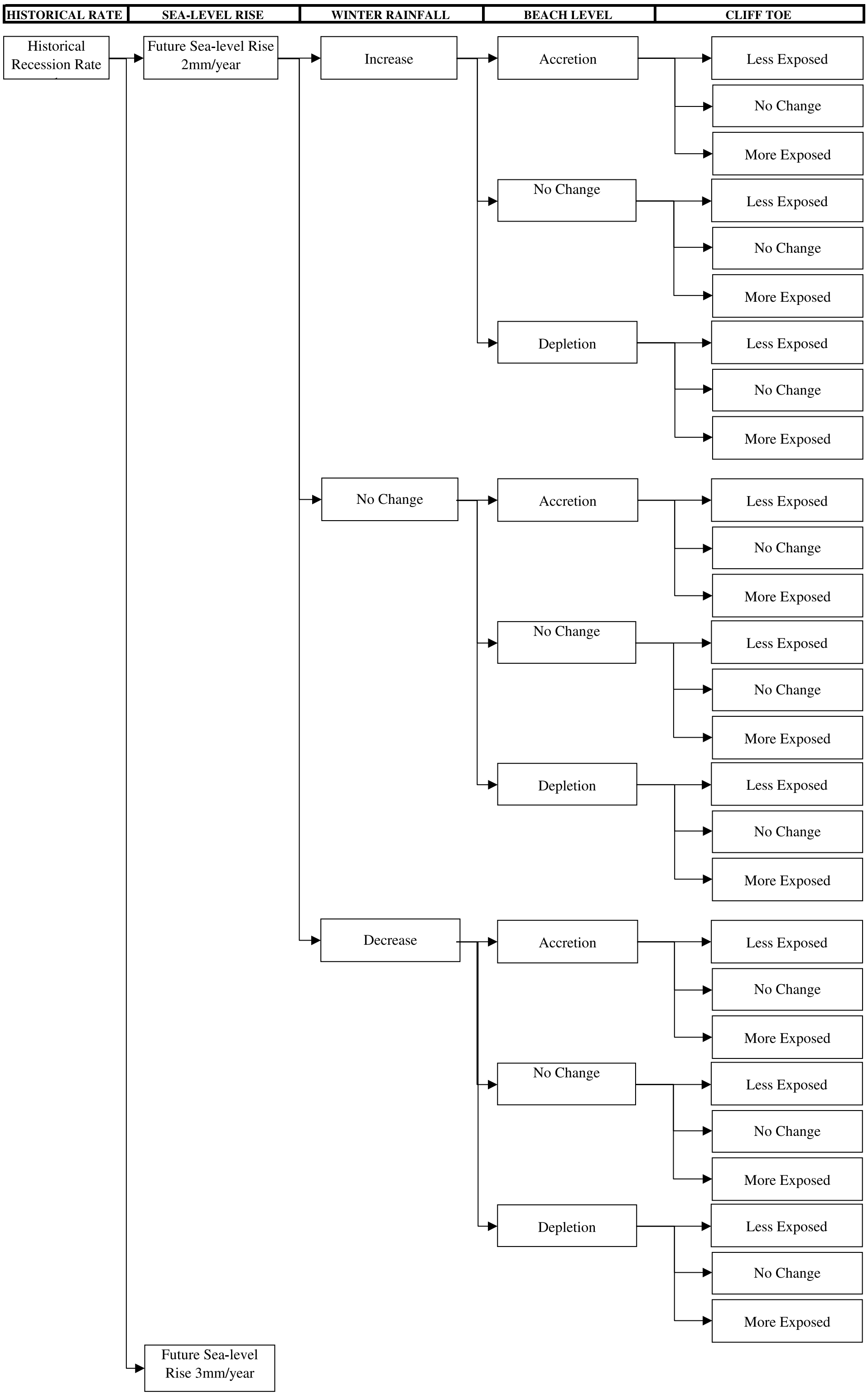

Fig. 5. Event tree representing part of the outcomes associated with the prediction model.

by assuming that each medium-term rate was equally applicable (i.e. there was a one in six chance; 0.167). Discussions were held between the coastal engineers and geomorphologists to reach consensus judgements about:

- the probability of the future rate of sea-level rise being 2, 3, 4, 5, 6, 7 or 8 mm a^{-1};
- the probability of there being an increase, decrease or no change in effective winter rainfall;
- the probability of the beach experiencing net loss, net accretion or no change;
- the probability of a change in the degree of cliff toe protection experienced along this coastline (i.e. changes in shoreline management practice).

Table 6. *Covehithe cliffs: probabilities assigned to different adjustment factors for future conditions.*

Sea-level rise factor		Winter rainfall factor		Beach level factor		Cliff toe factor	
Rate of sea-level rise ($m\,a^{-1}$)	Estimated probability	Category	Estimated probability	Category	Estimated probability	Category	Estimated probability
0.002	0.01	Increase	0.64	Accretion	0.01	Less exposed	0.01
0.003	0.04	No change	0.35	No change	0.39	No change	0.99
0.004	0.1	Decrease	0.01	Depletion	0.6	More exposed	0
0.005	0.2						
0.006	0.5						
0.007	0.1						
0.008	0.05						

Table 7. *Covehithe cliffs: sample of the results generated by the probabilistic model (note that only the 2 mm a^{-1} sea-level rise case is shown for one historical recession rate).*

		Sea-level Rise Factor				Winter Rainfall Factor					Beach Level Factor					Cliff Toe Protection Factor				
Historical Recession Rate m/year	Estimated Probability	Future Sea-level Rise m/year	Estimated Probability	Bruun Rule Adjusted Recession Rate m/year	Conditional Probability	Predicted Condition	Adjustment Factor	Estimated Probability	Adjusted Recession Rate m/year	Conditional Probability	Predicted Beach Condition	Adjustment Factor	Estimated Probability	Adjusted Recession Rate m/year	Conditional Probability	Predicted Exposure	Adjustment Factor	Estimated Probability	Adjusted Recession Rate m/year	Conditional Probability
5.87	0.167	0.002	0.01	5.88	0.002	Increase	1.05	0.64	6.18	0.0011	Accretion	0.75	0.01	4.41	0.00001	Less exposed	0.01	0.01	0.044	0.00000
																No change	1	0.99	4.412	0.00001
																More exposed	1.5	0	6.619	0.00000
											No change	1	0.39	5.88	0.0004	Less exposed	0.01	0.01	0.059	0.00000
																No change	1	0.99	5.883	0.00041
																More exposed	1.5	0	8.825	0.00000
											Depletion	1.25	0.6	7.35	0.0006	Less exposed	0.01	0.01	0.074	0.00001
																No change	1	0.99	7.354	0.00063
																More exposed	1.5	0	11.031	0.00000
5.87	0.167	0.002	0.01	5.88	0.002	No Change	1.00	0.35	5.88	0.0006	Accretion	0.75	0.01	4.41	0.0000	Less exposed	0.01	0.01	0.044	0.00000
																No change	1	0.99	4.412	0.00001
																More exposed	1.5	0	6.619	0.00000
											No change	1	0.39	5.88	0.0002	Less exposed	0.01	0.01	0.059	0.00000
																No change	1	0.99	5.883	0.00023
																More exposed	1.5	0	8.825	0.00000
											Depletion	1.25	0.6	7.35	0.0004	Less exposed	0.01	0.01	0.074	0.00000
																No change	1	0.99	7.354	0.00035
																More exposed	1.5	0	11.031	0.00000
5.87	0.167	0.002	0.01	5.88	0.002	Decrease	0.95	0.01	5.59	0.0000	Accretion	0.75	0.01	4.41	0.0000	Less exposed	0.01	0.01	0.044	0.00000
																No change	1	0.99	4.412	0.00000
																More exposed	1.5	0	6.619	0.00000
											No change	1	0.39	5.88	0.0000	Less exposed	0.01	0.01	0.059	0.00000
																No change	1	0.99	5.883	0.00001
																More exposed	1.5	0	8.825	0.00000
											Depletion	1.25	0.6	7.35	0.0000	Less exposed	0.01	0.01	0.074	0.00000
																No change	1	0.99	7.354	0.00001
																More exposed	1.5	0	11.031	0.00000

Table 6 presents the estimated probabilities that were used in this example.

Table 7 presents a sample of the model results for the cliffline. The results provide a probability distribution for the average annual recession rate that would be applicable over the 50 year time period (Fig. 6). Projecting these average annual rates over the relevant time period (i.e. 50 years) yields a probability distribution of the cliff-top position at the end of that time period (Fig. 7).

Model results: conclusions

The predicted mean recession rate of around 7 m a^{-1} generated through use of the probabilistic model is consistent with the 'best estimate' case for the deterministic model (7.4 m a^{-1}) and the recently observed values. However, the maximum predicted value of 15.34 m from the probabilistic model is significantly higher than the 'worst case' estimate (9.4 m a^{-1}). This is because the deterministic model ignores the more extreme

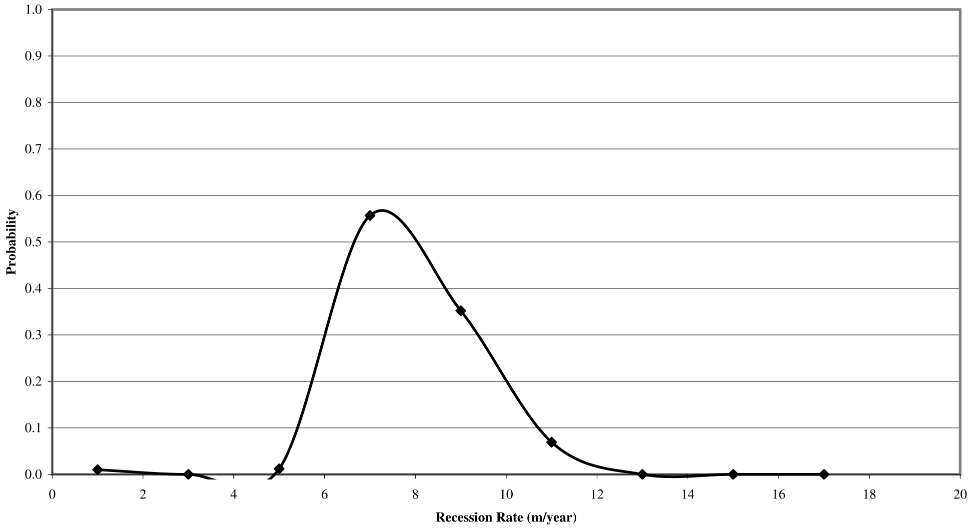

Fig. 6. Covehithe cliffs: annual recession rate probability.

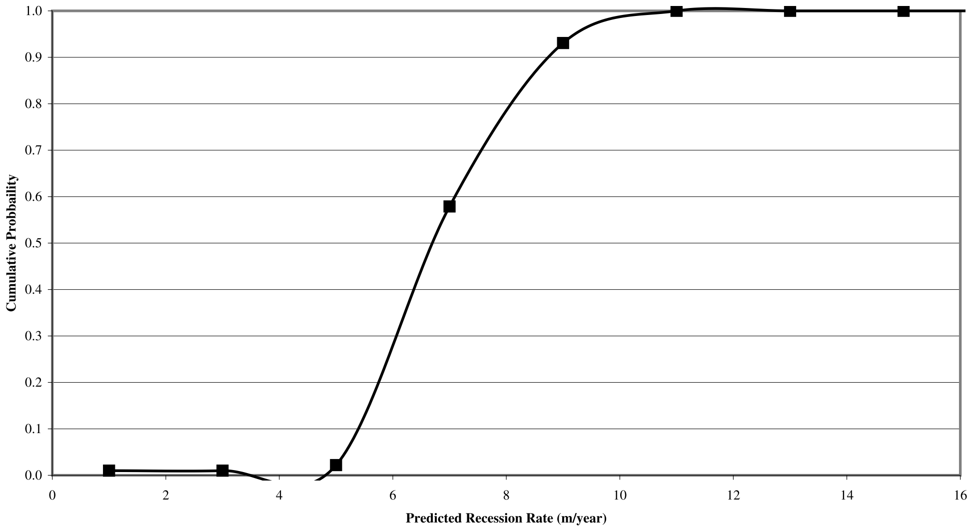

Fig. 7. Covehithe cliffs: cumulative probability of annual recession rates (m a^{-1}).

combinations of future conditions and past recession rates (a single average historical rate was used, rather than the range of rates used in the probabilistic model). The results from the probabilistic model highlight the possibility of a doubling in the rate under certain future conditions. Although this maximum value might appear extreme, it is broadly consistent with previous speculations about the impact of rising sea levels on coastal cliffs (e.g. Clayton 1989).

Risk assessment

Where assets are threatened by retreating clifflines, losses are inevitable at some point in the future because of the continuing recession. Decision-makers will tend to view the severity of the recession problem in terms of when the assets are likely to be lost and the value of the expected losses. Risk, therefore, needs to be expressed in terms of which year the losses will occur or the chance of loss in a particular year in the future.

The results of the probabilistic model were used to evaluate the risks to a hypothetical series of buildings set back at varying distances from the cliff edge. The analysis involved estimating both the levels of damages or losses that could result from a particular event (i.e. the loss of cliff-top land) and the probability that such an event occurs in a particular year. The potential losses were calculated for each 10 m wide strip of cliff-top land between the present cliff edge and 650 m further inland. The probability of loss of a particular 10 m wide strip in a given year was extracted from the probability distribution. As soon as the cliff edge encroaches within a strip containing part of an asset, the asset is assumed to be completely lost.

For example, considering the strip of land between the cliff edge and 10 m inland (Strip 1), the present value (PV; see Appendix) of the losses associated with recession in a particular year (year T) was calculated as follows:

$$PV \text{ losses (Strip 1; year } T) = P \text{ (loss Strip 1; year } T) \times \text{asset value (within Strip 1)} \times \text{discount factor (year } T).$$

As Strip 1 could be lost (or not) in any year over a 50 year period, the PV of losses associated with the event (i.e. loss of Strip 1) is the sum of the annual losses (Year 0–49) for Strip 1.

For another 10 m wide strip of land, located 90–100 m from the present cliff edge (i.e. Strip 10):

$$PV \text{ losses (Strip 10; year } T) = P\text{(loss Strip 10; year } T) \times \text{asset value (within Strip 10)} \times \text{discount factor (year } T).$$

The overall risk is the sum of the PV losses for each 1 m wide strip of cliff-top land over a 50 year period. The results are presented in Table 8 (note that for ease of reproduction the time scale has been reduced to 25 years and the recession distance limited to 150 m). The sum of the risk for that part of the example presented in Table 8 is £812 900.

Discussion

Traditional methods of hazard assessment cannot provide the context for expressing the uncertainty inherent in the cliff recession processes. Such methods are, in essence, based on extrapolation of past trends. Indeed, Varnes (1984) saw the principle of uniformitarianism (‘the past is the key to the future’) as a key tenet of landslide hazard assessment. However, the inherent randomness in the main causal factors (e.g. wave height, rainstorms, etc.) along with secular changes (e.g. sea-level rise and climate change) and deterministic uncertainty (i.e. ‘sensitive dependence upon initial conditions’; see Gleick 1988) dictate that future cliff recession cannot be expected to be an accurate match with the historical records. However, sequences of recession events are not independent of each other, but are influenced by the existing system state (e.g. beach levels, materials exposed in the cliff face), along with the size and location of previous events (i.e. state dependence). In other words, cliff recession is a process with a ‘memory’ insofar as the current and future behaviour is influenced by the effects of past events on the system (i.e. Markovian inheritance; Cowell & Thom 1994). An alternative principle for hazard assessment might be ‘an uncertain future constrained by past behaviour’.

The principle of using a series of judgement-based factors to adjust a historical pattern has been used elsewhere. For example, Finlay & Fell (1995; see also Fell *et al.* 1996) used this approach to develop a procedure for assessing the probability of failure of individual cut slopes in Hong Kong. During the 10 year period 1984–1993 a total of 2177 cut slope failures were reported. The average historical frequency of failure of 217.7 events per year was used to provide an estimate of the average annual probability of failure for every one of the entire population of cut slopes:

$$\text{probability of failure (Hong Kong} - \text{wide)} = \frac{\text{number of historical events}}{\text{total number of cut slopes}} = \frac{217.7}{20500} = 0.0106.$$

This Hong Kong-wide estimate does not differentiate between cut slopes that are more or less likely to fail. However, by using a combination of site-related factors it was possible to adjust the estimate for a particular cut, as follows:

$$\text{probability of failure (Cut } c) = \text{probability of failure (Hong Kong} - \text{wide)} \times \text{adjustment factor } (F).$$

The site-specific adjustment factor was derived from consideration of slope age, geology, geomorphology, geometry and groundwater, plus evidence of past instability. If the slope is considered less likely than average to fail, then the adjustment factor (F) will be less than 1.0, whereas the factor would be over 1.0 if the slope is considered more likely than average to fail.

The general approach is of wider value for those situations where the historical record cannot be viewed as a stationary series (e.g. there may be an increasing frequency of landslide events). This is a common problem for many sites, where future conditions are not expected to resemble past conditions, as a result of significant natural or man-induced changes such as climate change or the spread of development. In such circumstances, historical records alone cannot be used for prediction. Under changing conditions it will be necessary to take account of the uncertainty in future trends, either through the use of simple judgement-based models, as described here, or through more detailed statistical or process-based analysis (e.g. Hall *et al.* 2002; Lee *et al.* 2002).

The limited availability of information on the impact of future conditions on cliff recession dictates that many assessments will rely on expert judgement in assigning values to the adjustment factors. Indeed, Fookes (1997) noted that the art of geological or geotechnical assessment is ‘the ability to make rational decisions in the face of imperfect knowledge’. Such judgements are inevitably subjective. Reliable estimates can be developed by:

- proposing a range of possible scenarios;
- systematic testing of these scenarios through additional investigation and group discussion;
- elimination of non-credible scenarios;
- establishing agreement between team members.

Table 8. *Covehithe cliffs: risk-based economic evaluation (note cliff-top assets are hypothetical).*

		Asset values at given distance (£k)															
	A	0	0	0	0	250	0	400	0	0	0	250	0	200	0	350	140
		Sum of annual probabilities times discount rate:															
	B	0.943	0.9	0.839	0.786	0.728	0.681	0.635	0.589	0.553	0.518	0.485	0.448	0.415	0.39	0.361	0.33
	C	Risk at given distances (£k) i.e. A*B:															
		0	0	0	0	182	0	254	0	0	0	121.4	0	83.06	0	126.4	46.22
		Recession distance (m):															
Year	Discount	0	10	20	30	40	50	60	70	80	90	100	110	120	130	140	150
	factor	Simulated probability of receding given distance in given year (m):															
1	0.9434	1.00	0.21	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	0.8900	0.00	0.77	0.21	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3	0.8396	0.00	0.02	0.59	0.19	0.06	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
4	0.7921	0.00	0.00	0.18	0.51	0.15	0.06	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	0.7473	0.00	0.00	0.02	0.21	0.29	0.15	0.07	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6	0.7050	0.00	0.00	0.00	0.04	0.30	0.20	0.12	0.09	0.06	0.01	0.00	0.00	0.00	0.00	0.00	0.00
7	0.6651	0.00	0.00	0.00	0.02	0.18	0.37	0.20	0.07	0.08	0.05	0.04	0.00	0.00	0.00	0.00	0.00
8	0.6274	0.00	0.00	0.00	0.00	0.00	0.15	0.31	0.20	0.07	0.10	0.02	0.06	0.01	0.00	0.00	0.00
9	0.5919	0.00	0.00	0.00	0.00	0.02	0.04	0.08	0.09	0.20	0.05	0.10	0.03	0.05	0.04	0.00	0.00
10	0.5584	0.00	0.00	0.00	0.00	0.00	0.00	0.14	0.29	0.09	0.20	0.05	0.07	0.03	0.02	0.05	0.01
11	0.5268	0.00	0.00	0.00	0.00	0.00	0.02	0.04	0.01	0.22	0.09	0.20	0.05	0.07	0.03	0.01	0.05
12	0.4970	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.14	0.08	0.22	0.00	0.20	0.05	0.07	0.08	0.00
13	0.4688	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.04	0.14	0.06	0.31	0.00	0.20	0.05	0.02	0.08
14	0.4423	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.04	0.01	0.06	0.09	0.00	0.11	0.05	0.02
15	0.4173	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.14	0.01	0.22	0.09	0.09	0.11	0.05
16	0.3936	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.04	0.14	0.06	0.22	0.09	0.09	0.11
17	0.3714	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.00	0.01	0.06	0.22	0.09	0.09
18	0.3503	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.04	0.14	0.01	0.06	0.00	0.00
19	0.3305	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.22	0.09
20	0.3118	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.04	0.14	0.01	0.06	0.22
21	0.2942	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.04	0.14	0.01	0.06
22	0.2775	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.00
23	0.2618	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.04	0.14	0.01
24	0.2470	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.14
25	0.2330	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.04	0.00
Overall Prob.		1	1	1	1	1	1	1	1	1	1	1	0.999	0.98	0.98	0.98	0.93
Sum of risk (£k)		812.98															
Discount Factor		0.06															

Row A: This contains the market value of properties within each of the 10m-wide strips of cliff top land
Row B: This row contains values for the product of the probability of loss x discount rate for each year from 1-25
Row C: This row contains risk values calculated as: Risk (Strip 10m) = Row A (Strip 10m) x Row B (Strip 10m)
The sum of the risk is the sum of Row C i.e. £812.98K

Because of the reliance on judgement it is important that effort is directed towards ensuring that the judgements can be justified through adequate documentation, allowing any reviewer to be able to trace the reasoning behind particular judgements. Ideally, the assessment process should involve an open-minded but sceptical group of experts from a range of backgrounds, rather than single individuals; this facilitates the pooling of knowledge and experience, as well as limiting bias. A useful strategy for developing judgements is the use of an open forum (Roberds 1990; Lee *et al.* 2000). This relies on the open discussion between team members to identify and resolve the key issues related to the recession problem. Open forum discussions should question the available data and the understanding of cliff behaviour: What do we really know? How much have we assumed? Are the assumptions reasonable? Have we ignored or dismissed particular evidence? How confident are we in

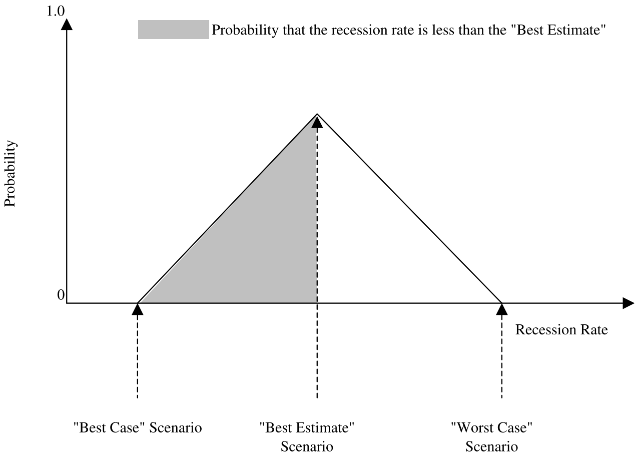

Fig. 8. A triangular distribution representing the probability of three scenarios.

our understanding of the relationships between different environmental controls and the recession process?

Appropriate factors need to be used that reflect the sensitivity of the site to changes in the environmental controls. The factors should, therefore, be site specific. This is true for both the deterministic and probabilistic approaches. The clear difference between the two approaches is assignment of probability values for each of the future conditions. This is known as 'subjective' probability assessment and relies on the practitioner's 'degree of belief' about the likelihood of a particular outcome. There are undoubted problems associated with the use of the subjective probability approach, especially where it is undertaken by single individuals. However, a range of techniques are available for eliminating or reducing the effects of these potential problems, involving more rigorous individual assessments or group consensus (e.g. Roberds 1990; Vick 2002). Sensitivity testing can be undertaken by varying the level of the adjustment factors and the estimated probabilities, to reveal the relative significance of particular judgements in generating the overall results. Identifying the more critical judgements will allow further investigations to concentrate on reducing the uncertainties in these key areas.

It is important to appreciate that the process for defining the 'best estimate', 'best case' and 'worse case' scenarios is similar in form to a subjective probability assessment. The 'best estimate' will generally coincide with the most likely situation, whereas the other two scenarios represent the upper and lower boundaries of the range of expected situations. This can be represented by a triangular distribution (Fig. 8) in which:

- the probability of the recession rate being lower than the 'best case' scenario equals zero;
- the probability of the recession rate being higher than the 'worst case' scenario equals zero;
- the probability of the recession rate being higher or lower than the 'best estimate' scenario equals one minus the chance of the scenario occurring; if the 'best estimate' value is assumed to have a 50% chance of occurring, then the chance of the future recession being under- or over-estimated is 50%.

The prediction of future recession rates generated by both the deterministic and probabilistic approaches can only be regarded as estimates. The increased complexity of the probabilistic approach should not be mistaken for increased precision. Indeed, the use of probabilities can conceal the fact that the potential for error is great because of the assumptions, judgements and uncertainties. Estimates should be 'fit for purpose'. These prediction methods should be seen as a decision-making tool, not a design tool. The level of precision and sophistication required merely needs to be sufficient for a particular problem or context so as to allow an adequately informed decision to be made; that is, both deterministic and probabilistic methods will be appropriate, depending on the circumstances. It may not be appropriate to commit resources towards developing sophisticated models.

Uncertainty is an inevitable part of the assessment process because of incomplete knowledge of the future conditions and the impact on the cliffline. These uncertainties prevent accurate prediction of the future recession rate. Probabilistic methods can acknowledge and take account of these sources of uncertainty, through providing an indication to decision-makers of the likelihood that particular distances might be affected over the 50 year time period. For example, in Figure 9 the results of the probabilistic approach are presented in terms of the percentage confidence that the 50 year recession would be less than a particular 'upper bound' value. The model indicates that there is a 95% chance that the cumulative recession over the next 50 years would be less than 650 m (i.e. a 5% chance it would be greater than this value) and a 50% chance that the cumulative recession would be less than 350 m. Clearly, a decision needs to be made as to whether the extreme, low-probability, situations are tolerable, or if they need to be taken into account in future planning and management (e.g. through the positioning of 'set-back' lines).

Decisions will have to be made despite uncertainty, provided due acknowledgement is made of the limitations (Lee & Jones 2004). In many instances, this may mean ensuring that the estimated level of risk is in the right order of magnitude. With reference to Figure 10, it may be more important to know which of the range of risk levels a cliff-top site falls within than the precise risk value. To illustrate this point, the assessed risk levels at a number of sites have been plotted in Figure 10; Site A clearly falls within risk range of one, suggesting that the most appropriate management strategy might be to do nothing. Site B has a higher estimated risk level, indicating that an appropriate strategy might be to commission a feasibility and options study to determine

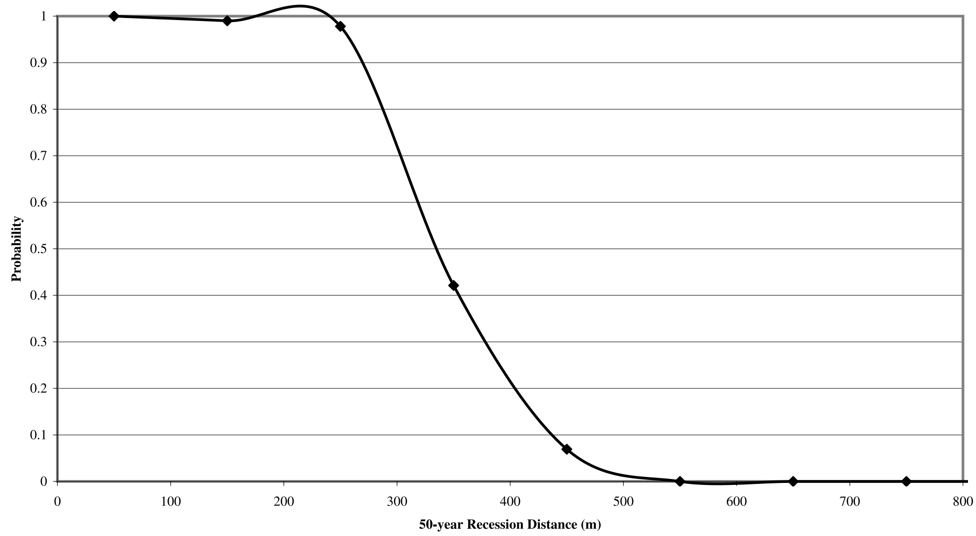

Fig. 9. Covehithe cliffs: recession zoning.

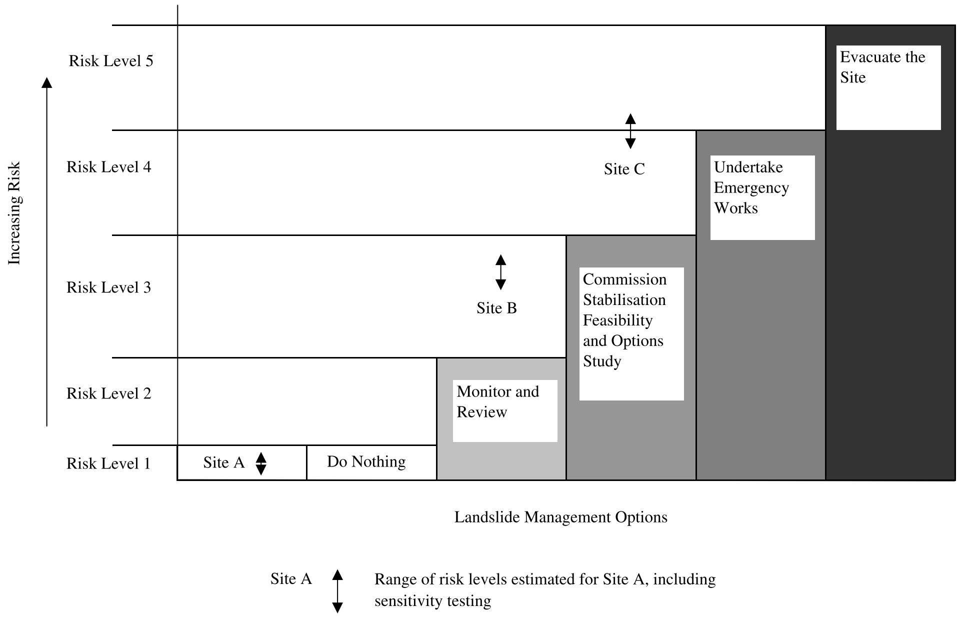

Fig. 10. A schematic illustration of the link between risk levels and decision-making (from Lee & Jones 2004).

the best ways of reducing the risk (e.g. erosion control measures). The management decision at Site C may be more problematic, as the estimated risk level appears to be close to the boundary of two risk levels. The decision-maker may choose to be cautious and evacuate the site or seek more detailed evaluation of the risks before having to make a very difficult and politically sensitive decision.

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Appendix: Present value and discounting

The economic value of any asset does not remain constant for the time scale over which the risk is being considered. If an asset is lost in Year 1 it will normally have a higher economic value than if it were to be lost in Year 10. One reason for this is that people discount the future, preferring their benefits now rather than sometime in the future; a phenomenon known as time preference. The second reason is the productivity of capital. If landslide management were not undertaken, then the resources could be diverted elsewhere and, over time, would show a return. For example, if the return from investing the resources in industry were 5% in real terms, then £100 invested now would yield the equivalent of £105 in 1 year's time. Therefore, having £100 now and £105 in 1 year are equivalent. For an asset that gives no return, £100 now is worth less than £100 in 1 year; in other words, it has depreciated.

To achieve this modification of future asset values, it is necessary to express all future losses in terms of their present value (PV) by discounting. The discount factor applicable to a particular year n can be calculated as follows:

$$D_n = (1 + r)^{-n} \quad \text{or} \quad D_n = \frac{1}{(1 + r)^n}$$

where r is the discount rate, expressed as a decimal, and Dn is the discount factor applicable for year n. The sum of the discounted flows (i.e. PV) is expressed at the mid-point of year 0. Further details have been given by Penning-Rowsell *et al*. (1992) and Ministry of Agriculture, Fisheries and Food (1999).

References

Bray, M.J. & Hooke, J.M. 1996. Prediction of soft-cliff retreat with accelerating sea-level rise. *Journal of Coastal Research,* **13** (2), 453–467.

British Geological Survey *Sediment input from coastal cliff erosion.* British Geological Survey Technical Report, **577/4/A**.

Brunsden, D. & Lee, E.M. 2004. Behaviour of coastal landslide systems: an inter-disciplinary view. *Zeitschrift für Geomorphologie,* **134**, 1–112.

Bruun, P. 1962. Sea-level rise as a cause of shore erosion. *Journal of the Waterways and Harbours Division, American Society of Civil Engineers,* **88**, 117–130.

Bruun, P. 1988. The Bruun Rule of erosion by sea level rise: a discussion on large scale two- and three-dimensional usages. *Coastal Research,* **4** (4), 627–648.

Clayton, K.M. 1989. Implications of climatic change. *In:* Editor, A. (ed.) *Coastal Management.* Thomas Telford, London, 165–176.

Cowell, P.J. & Thom, B.G. 1994. Morphodynamics of coastal evolution. *In:* Carter, R.W.G. & Woodroffe, C.D. (eds) *Coastal Evolution: Late Quaternary Shoreline Morphodynamics.* Cambridge University Press, Cambridge, 33–86.

Cox, S.J. & Tait, N.R.S. 1991. *Reliability, Safety and Risk Management: an Integrated Approach.* Butterworth–Heinemann, Oxford.

Dean, R.G. 1991. Equilibrium beach profiles: characteristics and applications. *Journal of Coastal Research,* **7**, 53–84.

Dubois, R.N. 1992. A re-evaluation of Bruun's Rule and supporting evidence. *Journal of Coastal Research,* **8** (3), 618–628.

Everts, C.H. 1991. Seacliff retreat and coarse sediment yields in southern California. *Coastal Sediments '91 (American Society of Civil Engineers),* **2**, 1586–1598.

Fell, R., Finlay, P. & Mostyn, G. 1996. Framework for assessing the probability of sliding of cut slopes. *In:* Senneset, K. (ed.) *Landslides,* **1**. Balkema, Rotterdam, 201–208.

Finlay, P. & Fell, R., 1995. *A study of landslide risk assessment in Hong Kong*. Report for the Geotechnical Engineering Office, Hong Kong.

Fookes, P.G. 1997. Geology for engineers: the geological model, prediction and performance. *Quarterly Journal of Engineering Geology,* **30**, 290–424.

Gibbard, P.L. & Zalasiewicz, J.A. (eds) 1988. *Pliocene–Middle Pleistocene of East Anglia. Quaternary Research Association Field Guide.* Quaternary Research Association, Cambridge.

Gleick, J. 1988. *Chaos: Making a New Science.* Cardinal, London.

Halcrow Group Ltd 2001a. Lowestoft to Thorpeness Coastal Process and Strategy Study Volume 2: Coastal Processes. Report to Waveney District Council, EA Anglian Region and Suffolk Coastal District Council.

Halcrow Group Ltd 2001b. *Preparing for the Impacts of Climate Change*. Report to SCOPAC.

Hall, J.W., Lee, E.M. & Meadowcroft, I.C. 2000. Risk-based benefit assessment of coastal cliff recession. *Proceedings of the Institution of Civil Engineers: Water and Maritime Engineering,* **142**, 127–139.

Hall, J.W., Meadowcroft, I.C., Lee, E.M. & van Gelder, P.H.A.J.M. 2002. Stochastic simulation of episodic soft coastal cliff recession. *Coastal Engineering,* **46**, 159–174.

Hands, E.B. 1983. The Great Lakes as a test model for profile responses to sea-level changes. *In:* Komar, P.D. (ed.) *Handbook of Coastal Processes and Erosion.* CRC Press, Boca Raton, FL, 176–189.

Hulme, M., Barrow, E.M., Jenkins, G.J., New, M., Osborn, T.J. & Viner, D. 1998. *Climate change scenarios for the UK Climate Impacts programme.* UKCIP Technical Report. Climatic Research Unit, Norwich.

Hulme, M., Jenkins, G.J., Lu, X. *et al.* 2002. *Climate Change Scenarios for the United Kingdom: The UKCIP02 Scientific Report.* Tyndall Centre for Climate Change Research, School of Environmental Sciences, University of East Anglia, Norwich.

Komar, P.D., Lanfredi, N., Baba, M. *et al.* 1991. The response of beaches to sea-level changes: a review of predictive models. *Journal of Coastal Research,* **7** (3), 895–921.

Lee, E.M. 2001. Living with natural hazards: the costs and management framework. *In:* Higgett, D. & Lee, E.M. (eds) *Geomorphological Processes and Landscape Change: Britain in the Last 1000 Years.* Blackwell, Oxford, 237–268.

Lee, E.M. 2003. *Coastal change and cliff instability: development of a framework for risk assessment and management*. PhD thesis, University of Newcastle upon Tyne.

Lee, E.M. 2004. Cliff recession and beach volumes. *Island Geoscience,* **2**, 2–3.

Lee, E.M. & Clark, A.R. 2002. *Investigation and Management of Soft Rock Cliffs.* Thomas Telford, London.

Lee, E.M. & Jones, D.K.C. 2004. *Landslide Risk Assessment.* Thomas Telford, London.

Lee, E.M., Brunsden, D. & Sellwood, M. 2000. Quantitative risk assessment of coastal landslide problems, Lyme Regis, UK. *In:* Bromhead, E.N., Dixon, N. & Ibsen, M.-L. (eds) *Landslides: in Research, Theory and Practice.* Thomas Telford, London, 899–904.

Lee, E.M., Hall, J.W. & Meadowcroft, I.C. 2001. Coastal cliff recession: the use of probabilistic prediction methods. *Geomorphology,* **40**, 253–269.

Lee, E.M., Meadowcroft, I.C., Hall, J.W. & Walkden, M.J. 2002. Coastal landslide activity: a probabilistic simu-

lation model. *Bulletin of Engineering Geology and the Environment,* **61**, 347–355.
Ministry of Agriculture, Fisheries and Food *FCDPAG3 Flood and Coastal Defence Project Appraisal Guidance: Economic Appraisal.* MAFF Publications, London.
Penning-Rowsell, E.C., Green, C.H., Thompson, P.M., Coker, A.M., Tunstall, S.M., Richards, C. & Parker, D.J. 1992. *The Economics of Coastal Management: a Manual of Benefits Assessment Techniques.* Belhaven Press, London.
Roberds, W.L. 1990. Methods for developing defensible subjective probability assessments. *Transportation Research Record,* **1288**, 183–190.
Rosen, P.S. 1978. A regional test of the Bruun Rule on shoreline erosion. *Marine Geology,* **26**, M7–M16.
Sunamura, T. 1992. *Geomorphology of Rock Coasts.* Wiley, Chichester.
Varnes, D.J. 1984. *Landslide hazard zonation: a review of principles and practice. Engineering Geology Commission on Landslides and other Mass Movements on Slopes.* Engineering Geology Commission on Landslides and other Mass Movements on Slopes. UNESCO. UNESCO, Paris.
Vick, S.G. 2002. *Degrees of Belief: Subjective Probability and Engineering Judgement.* American Society of Civil Engineers, New York.
Woodworth, P.L., Tsimplis, M.N., Flather, R.A. & Shennan, I. 1999. A review of the trends observed in British Isles mean sea level data measured by tide gauges. *Geophysics Journal International,* **136**, 651–670.
Zurek, P.J., Nairn, R.B. & Theime, S.J. 2003. Spatial and temporal considerations for calculating shoreline change rates in the Great Lakes Basin. *Journal of Coastal Research,* **38**, 125–146.

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