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Prediction of Soft-cliff Retreat with Accelerating Sea-level Rise

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ABSTRACT

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Reliable estimates of future cliff recession are needed to assess coastal vulnerability and evaluate management policies with regard to the widespread sea-level rise thought likely to result from global warming. A research gap is identified in providing appropriate predictive methods. This paper reviews the possible effects of sea-level rise upon soft-rock cliffs over a 50–100 year planning timescale. It evaluates different methods of analysing historical recession and highlights the main assumptions and rules governing future extrapolation of retreat rates. Simple predictive models including a modification of the Bruun Rule are developed and applied to estimate cliff sensitivity to sea-level rise in southern England.

The complexity of factors interacting over variable spatial and temporal scales is identified as a major problem. Irrespective of sea-level rise, recession assessments need to accommodate episodic cliff failures occurring within regular erosion cycles and differentiate instances of runaway systems change. Predictions must rely upon methods of extrapolating historical retreat. Different methods are applicable according to the presence or absence of shoreface sediments. The modified Bruun Rule appears the most appropriate for situations where cliff sediments accumulate on the shore profile. Results obtained using this model indicated that recession could increase by between 22% and 133% by 2050 according to site. Cliffs on exposed coasts and those containing high proportions of clay appear the most sensitive to change. Attention is drawn to some of the inherent uncertainties including those caused by different landslide types, lags in response and the effect of protective beaches.

ADDITIONAL INDEX WORDS: *Coastal, bluff, landslide, erosion, model, recession, Bruun Rule, sea-level rise.*

INTRODUCTION

An estimated 80% of the Earth's ocean coast is backed by sea-cliffs (EMERY and KUHN, 1982). Wherever these forms are cut in strata containing weakly resistant sedimentary units and are exposed to wave action, these "soft-rock cliffs" have a tendency towards instability and rapid change. Especially important is the possibility that retreat might increase in the future due to a widespread accelerating sea-level rise that is thought likely to result from global warming produced by an enhanced greenhouse effect (NATIONAL RESEARCH COUNCIL, 1987; BIRD, 1992). Recent best estimates obtained by modeling of global climates, the oceans and ice masses suggest a rise of 0.48m by 2100, equivalent to $4mma^{-1}$ (WIGLEY and RAPER, 1992). Although uncertain, these rates are significantly in excess of those recorded recently around many of the world's coasts (EMERY and AUBREY, 1991) and have potentially serious implications in all regions barring those few undergoing active uplift. This paper evaluates the possible impacts of sea-level rise alongside the other factors that influence cliff retreat over a 50–100 year planning timescale. It highlights deficiencies in current methods of analysing recession and assesses the capabilities of available predictive models. Simple but effective methods are identified and employed to estimate cliff sensitivity to sea-level within a specific region.

Demands for this type of information are great. Residential developments and infrastructure occupy potentially hazardous locations adjacent to many eroding cliffs. Continued human occupation and land use are frequently dependent upon erosion control measures, or the more environmentally sustainable option of adjusting activities to facilitate set-back or gradual withdrawal from hazardous zones (NATIONAL RESEARCH COUNCIL, 1990). Recent, serious coastal landslides at Scarborough, Yorkshire (CLEMENTS, 1994; CLARK and GUEST, 1994) and Blackgang, Isle of Wight (BRAY, 1994) have served to focus attention on these issues in the UK. Increasingly, it is becoming necessary to decide which types of action are appropriate at different locations. Effective evaluations of options clearly demand reliable predictions of future rates of change upon which to found realistic assessments of their relative costs and benefits.

Numerous studies have investigated the historical development (BRUNSDEN and JONES, 1976; PITTS and BRUNSDEN, 1987), process mechanisms (HUTCHINSON, 1973; BRUNSDEN, 1974; ALLISON and BRUNSDEN, 1990; forms (EMERY and KUHN, 1982; VALLEJO and DEGROOT, 1988), geotechnical properties (BARTON, 1973; JONES *et al.*, 1993) and rates of change (VALENTIN, 1954; MAY, 1966; CAMBERS, 1976; BARTON and COLES, 1984; MAY and HEEPS, 1985; and many oth-

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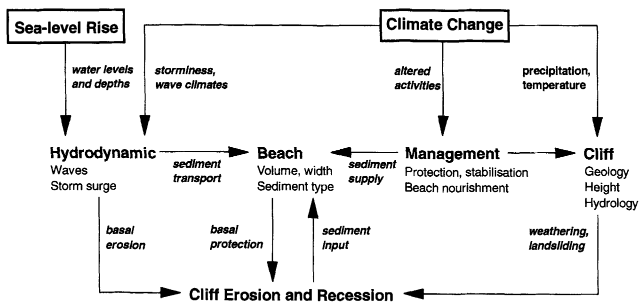

Figure 1. Summary of factors influencing cliff erosion.

ers) associated with eroding soft-rock cliffs. However, surprisingly little progress has been achieved in developing and applying methods of predicting future recession for planning purposes. These problems have been highlighted by some recent studies of cliff erosion hazards (KOMAR and SHIH, 1993; MOON and HEALY, 1994). Even less attention has been directed towards developing estimates of future change that include adjustments for sea-level rise.

Greater progress has been achieved in developing methods of measurement and analysis within the wider field of shoreline change (STAFFORD and LANGFELDER, 1971; LEATHERMAN, 1983; MORTON, 1991; FENSTER *et al.,* 1993; THIELER and DANFORTH, 1994). Several models are available to assess quantitatively shore responses to sea-level rise (LEATHERMAN, 1990, KOMAR *et al.,* 1991; HEALEY, 1991), but these are almost exclusively developed for and applied to barrier islands and low sandy coasts (*e.g.,* LEATHERMAN, 1984; 1985; WILCOXEN, 1986; GERMIAT and SHARP, 1990; LONDON and VOLONTE, 1991). Few studies have yet treated the cliff, beach and shoreface as an integrated process system. This paper investigates the possibilities of adapting such methods to the more specialised tasks of predicting cliff retreat. The main assumptions and rules for use of alternative options are highlighted. Suitable models are applied at key sites in central southern England, a coast characterised by a wide variety of eroding soft-rock cliffs (MAY, 1966; 1977) that are important beach sediment sources (BRAY *et al.,* 1995). The sensitivity of this coast to change is demonstrated by a survey of damage inflicted by the severe winter storms of 1989–1990 which revealed that cliffs were more greatly affected than any other coastal type (MARITIME ENGINEERING BOARD, 1990).

FACTORS AFFECTING CLIFF EROSION

Changes on cliffed coasts are not easily predicted because recession is the cumulative result of numerous interacting variables. Regional, overriding "first order" factors such as relative sea-level change and climate (KOMAR and SHIH, 1993) interact at more local scales with "second order" or site-specific factors to produce the spatial and temporal variability in processes and forms that characterise eroding cliffs. Thus, it is necessary to identify the critical second order factors and to assess how they might be affected by changes in first order factors as outlined in Figure 1. Marine erosion at the toe of the coastal slope erodes bedrock, removes fallen debris, steepens the coastal slope and produces instability that results in persistent recession. This process is regulated by the balance achieved between hydrodynamic forcing agents (waves and tides) and the protection afforded to the toe by the beach and shore profile. Cliff factors (geology, hydrology and profile geometry) govern the sensitivity of the cliff to the perturbations at its toe. Self-regulation by negative feedback is possible because recession may yield sediments that support, protect or load the toe.

Cliff Factors

Major variation in cliff response occurs according to material strength. Hard rock coasts erode very slowly due to the constraining factors of material strength and rock mechanics (ALLISON, 1989). They should remain essentially stable as sea-level rises (NATIONAL RESEARCH COUNCIL, 1987; FORBES *et al.,* 1989). By contrast, soft-rock cliffs are subject to additional weakening by weathering and degradation by mass movements; these processes are likely to operate more rapidly in the wetter, warmer climate predicted for regions such as southern England due to global warming (DEPARTMENT OF THE ENVIRONMENT, 1991). The types of mass movement are especially important because they affect the nature and rates of recession. Comprehensive study of landsliding in Great Britain revealed four broad coastal types identifiable on the basis of ground-forming materials (including geological structure and stratigraphy) and style of landslide activity (JONES and LEE, 1994). The classification distinguishes between landslides in: weak superficial deposits, stiff clay, stiff clay with a hard cap-rock and hard rock. The presence of cap-rocks facilitates multiple rotational failures (BROMHEAD, 1979) that characteristically produce high magnitude, but low frequency recession events (BRUNSDEN and JONES, 1980). Groundwater reservoirs confined within permeable strata that overlie or are interbedded with impermeable units produce seepage erosion at the cliff face (HUTCHINSON *et al.,* 1981) and also facilitate major mass movements (DENNESS, 1971). Climate change that affects groundwater recharge thus has the capacity to affect significantly cliff instability and retreat. The presence of clayey strata outcropping at beach level make the whole slope susceptible to rapid retreat (HUTCHINSON, 1983). Where cliffs are composed of a high proportion of clay, mudslides are a major slope degradation process and recession is related to their seasonal and episodic surging activity (PRIOR and RENWICK, 1980; BRUNSDEN, 1984). Monitoring of a site in east Devon, England has shown that some mudslide surges are related to tidal state (GRAINGER and KALAUGHER, 1987). Thus, it is hypothesised that higher sea-levels may increase inundation of mudslide toes on the beach, raising local groundwater elevations and facilitating surging movements. Dormant mudslides could therefore become reactivated causing instability of previously stable cliff-tops. On more resistant lithologies, rockfalls and topples are predominant (DAVIES *et al.,* 1991). In complex systems, several mechanisms operate simultaneously so that recession is the combined result of the different event magnitudes and frequencies. Different landslide types have different activity modes and therefore differing sensitivities to changes in first order factors.

Recent geological history should influence future cliff responses at locations where recession could intersect ancient landslides associated with earlier episodes of Pleistocene river incision (BRUNSDEN and JONES, 1976), solifluction (CONWAY, 1979), or marine erosion (HUTCHINSON *et al.*, 1980; HUTCHINSON, 1991). Reactivation of these forms results in greater instability and retreat than would otherwise be anticipated. Among soft-rock cliffs, less resistant materials should be universally more susceptible to erosion, but relationships are confounded by other interacting factors. Studies in low energy lake (JIBSON and STRAUDE, 1992; JIBSON *et al.*, 1994) and harbour (JONES *et al.*, 1993) environments demonstrate the expected inverse relation between material strength and recession. However, results from higher energy oceanic environments suggest that the degree of basal protection is of overriding importance (EVERTS, 1991; JONES and WILLIAMS, 1991). Ground forming materials therefore govern the possible range, modes and rates of recession, but the incidence of basal erosion determines the resulting cliff behaviour.

Higher cliffs should retreat more rapidly because they generate higher shear stresses and suffer larger landslides (RICHARDS and LORRIMAN, 1987). However, they also yield more sediment per unit of recession, so they should also be better able to maintain protective basal debris stores (DALRYMPLE *et al.*, 1986). The particle size distribution of the cliff erosion products and their durability in the littoral environment are important. These qualities determine the proportion of cliff input retained on the beach and active shore profile compared with that rapidly lost offshore (CARTER *et al.*, 1987; BRAY, 1992). Evaluation of this relation is facilitated by an overfill ratio which estimates the quantity of cliff material required to yield $1m^3$ of stable beach material (DALRYMPLE *et al.*, 1986). Cliffs with high proportions of clay and silt will need to retreat further to yield a given quantity of shore-stable sediment and should therefore be more sensitive to sea-level rise.

Shoreface and Beach Factors

Basal erosion by wave action is the critical factor in maintaining cliff instability so that bedrock shore platforms and their sediment cover ultimately control retreat by dissipating wave energy (MCGREAL, 1979; KAMPHUIS, 1987; RICHARDS and LORRIMAN, 1987). Two contrasting situations are identified. First are bare bedrock platforms of various types that regulate cliff toe erosion according to their solid geometry (TRENHAILE, 1987; SUNAMURA, 1992). Typically, they erode and widen as sea-level rises (TRENHAILE and BRYNE, 1986). Second are bedrock profiles covered by protective sediments that can accumulate to form beaches at the cliff toe. The critical difference is that these types can also build up to preserve profile morphology with rising sea-level. Often, the necessary sediments are supplied from erosion of adjoining cliffs, thereby permitting self-regulation of retreat.

Several platform types are recognised globally, but gently sloping forms are normally produced by recession of soft-rock, especially under macro-tidal conditions (TRENHAILE, 1987; SUNAMURA, 1992). As retreat proceeds, the platform widens so that wave dissipation increases unless the platform is eroded down at a corresponding rate, or water depths increase due to a rising sea-level. Several studies have suggested that equilibrium forms are maintained as erosion proceeds (TRENHAILE, 1974; 1980; KAMPHUIS, 1987). Relations between platform geometry and water depth have therefore been applied as a basis for modeling of long term adjustments to rising or oscillating sea-levels (TRENHAILE and BRYNE, 1986; TRENHAILE, 1989). Results indicated that rising sea-level should offset the dissipative effect of a widening shore platform so that rapid retreat rates can be maintained in the absence of protective sediments.

The presence of beach and shoreface sediments controls wave dissipation, sometimes completely protecting cliffs and shore platforms from marine erosion. Research from California suggests that a beach width (above mean sea-level) of 20–30m affords significant protection and one of 60m provides complete protection to the toe (EVERTS, 1991). However, the relation is site-specific and dependent upon local oceanographic factors and shore profile configuration. Conversely, thin sediment layers may enhance the erosion of lithified cliffs and their platforms by acting as "tools" for mechanical abrasion (SUNAMURA, 1976; ROBINSON, 1977). All variables that influence beach width and volume affect toe erosion or debris excavation and thus recession of the cliff. Especially important are longshore and cross-shore variations in sediment transport. A notable example of littoral drift reversal, beach erosion and exposure of the cliff toe is provided by KOMAR and SHIH, (1993) for the Oregon coast. Similar beach depletion and cliff stability problems can be produced downdrift of shore protection structures that intercept littoral drift (HUTCHINSON *et al.*, 1980). Cross-shore transport driven by elevated sea-levels and heavy wave action may also cause significant beach erosion, periodically during seasonal storms (KRIEBEL and DEAN, 1985) and permanently in the case of sea-level rise (BRUUN, 1988). Other, more localised zones of toe erosion may develop in association with rip current embayments (PRINGLE, 1985; KOMAR and SHIH, 1993). These examples of sediment depletion temporarily expose shore platforms to lowering, thus permanently reducing the protection afforded to the cliff when sediments are returned to the inshore profile.

Beach material character, especially its particle size influences the degree of protection that a given beach width will provide. Coarse durable materials are more likely be retained on the upper shoreface and provide natural armouring with a relatively narrow width (CARTER and ORFORD, 1984; CARTER *et al.*, 1990). Sands are more susceptible to cross-shore transport induced by seasonal storms or sea-level rise, so that a wider beach is necessary for comparable cliff toe protection. Silts and clays are liable to winnowing and removal in suspension so they are unable to contribute to the active shore profile in open coast environments. Cliffs yielding a high proportion of coarse durable products are therefore likely to be less sensitive to sea-level rise.

Hydrodynamic Factors

In the presence of a beach and dissipative shore profile, wave attack at the cliff toe is generally infrequent and related to combined incidences of high tidal levels and strong wave action. Monitoring in south east Ireland indicated a site-specific frequency of approximately 20 erosive events per year (McGREAL, 1979). Especially important are storm surges that can produce sea-levels significantly in excess of predicted tidal levels (PUGH, 1987). These phenomena exhibit significant regional variability and are most severe in shallow, partly enclosed seas and embayments (FLATHER, 1987). Catastrophic landsliding following a major storm surge in the Baltic Sea in c1900 is reported to be the major component of cliff retreat along the coast of Poland (SUBTOWICZ, 1994). Wave exposure (beach orientation relative to fetch and prevailing wind direction) also produces spatial variations in erosive potential. A good index of the overall erosive potential is provided by the joint probabilities of waves and storm surges calculated from long term wave and tidal data (HAGUE, 1992).

Unless countered by enhanced sedimentation, sea-level rise should produce increasing nearshore water depths that allow waves to break further inshore (MANSARD, 1990; TOWNEND, 1990; 1994). This is especially important over "bare" platforms and significant increases in the retreat of soft volcanic ash cliffs have been predicted for an island site in the Pacific Ocean (SUNAMURA, 1988). Higher sea-levels will reduce the return periods of extreme sea-levels produced by storm surges (GRAFF, 1981; DEPARTMENT OF THE ENVIRONMENT, 1991). Erosive events at the cliff toe should become more frequent unless the protective beach can accrete accordingly. Climate change may alter storm tracks, their frequency and severity so that the energy of wave climates and their directional distribution might vary. Although such regional changes cannot yet be modeled reliably (HOUGHTON *et al.*, 1992), some observational evidence supports the possibility of phases of increased storminess (HAYDEN, 1975; LAMB, 1991) and more energetic wave climates in the north east Atlantic (NEU, 1984; CARTER and DRAPER, 1988; BACON and CARTER, 1991). Changes in the directional distribution of wave energy can cause littoral drift reversals that result in changing patterns of beach accretion and erosion (PETHICK, 1993), thus altering the protection afforded to cliffs.

MEASUREMENT OF HISTORICAL RECESSION

Calculation of reliable historical recession rates is fundamental to the prediction of future trends even without sea-level rise. Measurements must be appropriate to the magnitude and frequency of the processes being studied and should be accompanied by analysis of the possible errors and uncertainties. Recession is measured from a series of easily identified, common, or analogous cliff features sequentially plotted over the longest possible time periods to control for variations in process rates. Data sources have been reviewed extensively elsewhere and include various historical sources, large scale topographic maps, aerial photographs and repeated field measurements (*e.g.*, HOOKE and KAIN, 1982; TRENHAILE, 1987; SUNAMURA, 1992; LANE *et al.*, 1993). The backscar or main cliff-top is the most appropriate feature, because on eroding cliffs, it forms a sharp discontinuity in terms of slope, vegetation and colour contrast on photos. Even on slopes that are thought to have been relatively stable for over 5000 years, the main backscars remain easily discernible (BRUNSDEN and JONES, 1972; 1976). This is especially important where historic topographic maps are being used because features are plotted according to the perceptions of the surveyor. Sequential cliff comparisons are therefore susceptible to interpretative error (operator variance) unless a distinct feature such as the top of the backscar is traced. The backscar is also the most relevant datum for management purposes as it delineates the hazardous and potentially unstable cliff zone (seaward) from the contemporary intact cliff-top (landward). For these reasons, it is probably the one reliable reference feature for historical studies of eroding cliffs.

The backscar should not be used as the sole datum without checking that its recession is typical of the cliff as a whole. Different failure modes having different magnitudes and frequencies operate at the cliff top and toe. Retreat of the two cliff lines is often coupled in erosion cycles of variable period governed by the intensity of basal erosion and consequent mass transfers through the system. Typically, phases of relatively continuous toe erosion gradually steepen the slope eventually leading to relatively major, but episodic failures of the backscar that reduce the mean slope angle and provide new protective debris at the toe (BRUNSDEN and JONES, 1976; VALLEJO and DEGROOT, 1988). Although the overall effect is of parallel cliff profile retreat, the width of the cliff zone is variable. Short term assessments of backscar recession may therefore be biased by an atypical interval in the cycle. Ideally, erosion assessment should cover at least one complete cycle; this assumes a knowledge of its period. The few studies that have investigated this problem suggest that the cycle period might be related to the height, width and complexity of the cliff zone, although the intensity of basal erosion is also important. Low simple cliffs cut in soft glacial sediments may complete a cycle in 5–10 years (VALLEJO and DEGROOT, 1988). A period of 30–40 years is estimated for 40 m high London Clay cliffs along the Isle of Sheppey, UK (HUTCHINSON, 1973). Along the 10–100 m high raised coastal terraces of the Oceanside littoral cell in southern California, a typical cycle is completed in between 30 and 50 years (EVERTS, 1991). High compound cliffs (100–200 m) of interbedded clays, sands and limestones require at least 100–150 years to complete their erosion cycles along the west Dorset (BRUNSDEN, 1974; BRUNSDEN and JONES, 1980) and south western Isle of Wight (HUTCHINSON *et al.*, 1981) coasts of central southern England.

Cyclic behaviour can be detected by comparison of backscar recession with the retreat of features from within the cliff zone such as the crests of benches, the crests and toes of the most seaward cliffline and the toes of basal debris stores. Major dissimilarities that are not attributable to human interference could indicate that the retreat calculated is biased towards part of an erosion cycle. Use of data from as long a period as possible is clearly the best means of controlling for cyclic erosion of uncertain period. On high, complex cliffs a 100 year period is reasonable. However, this is only generally practical for the backscar because other features in the cliff zone are subject to interpretative error on maps so limiting reliable data to that covering the past 50 years obtainable from air photographs and field survey.

It is necessary to evaluate the accuracy of the comparisons undertaken between epochs. Assuming that interpretative errors have been minimised, overall estimates of plotting or measurement errors (CROWELL *et al.,* 1991) can be produced for each epoch as follows:

$$E = (eT_1 + eT_2)/T \qquad (1)$$

where: E is the error estimate associated with the given epoch (ma^{-1}).
eT_1 is the plotting error of the backscar at the beginning of the epoch (m).
eT_2 is the plotting error of the backscar at the end of the epoch (m).
T is the duration of the epoch (years).

E indicates the minimum retreat rate that can be resolved. When E is equal to or greater than the epoch retreat rate, no significant recession is discernible. Greater precision is possible for longer epochs because plotting errors become proportionately less as the retreat distance increases. The implication is that accurate data are needed to resolve retreat over short epochs, especially when rates are slow.

Extrapolation of Trends

Historical trends may be extrapolated to produce estimates of future retreat by assuming that typical behaviour is contained within the record of backscar position. However, recession rates frequently vary from epoch to epoch making it difficult to separate long term trends from short term variability (NATIONAL RESEARCH COUNCIL, 1990). The critical analytic process is to determine which part of the historical record is most relevant for estimation of future trends. FENSTER *et al.,* (1993) found that linear extrapolations that assume a constant trend were generally preferable due to their simplicity. Despite being more realistic, non-linear models tend to produce serious errors when based on small, or short period data sets typical of those presently available for cliffs. End-point rates based on the earliest and latest positions are the most commonly applied, but they fail to indicate the variability of retreat and are subject to error when the end points are not typical. Alternatives include linear regression, or averaging of the retreat rates calculated for each epoch that records a significant trend (see Equation 1). Although these methods take into account data that are intermediate between the end points, they require relatively large numbers of recorded cliff-top positions.

In shoreline analysis, it is important to identify critical points, marked by major changes in rate of change that could indicate system change (FENSTER *et al.,* 1993). Extrapolations should then be exclusively based on, or strongly weighted towards post-change data. This method is not easily transferable to cliffs because data limitations forestall attempts to differentiate long period repetitive cycles from system change. Only where the historical data are known to cover several erosion cycles (fast-evolving, relatively low, simple cliffs), or where change is very clear is the method feasible. Extrapolations of cliff recession should therefore be based on all reliable data covering the longest possible period. Exceptions must be founded on process knowledge that demonstrates that new system equilibria have been established. An example is provided by the Black Ven landslide on the west coast of Dorset, England. Here, following at least 100 years of relative quiescence, a major new phase of instability was established in the late 1950s (BRUNSDEN and GOUDIE, 1981). Using digital terrain modeling based on analytical photogrammetry covering four epochs between 1946 and 1988, a post-1958 process balance, or dynamic equilibrium is indicated by relatively constant overall form and system budget in spite of rapid retreat (LANE *et al.,* 1993; CHANDLER and BRUNSDEN, 1995). At this location, post-1958 data should form the basis for future extrapolation.

MODELS OF SHORELINE CHANGE INCORPORATING SEA-LEVEL RISE

Simple extrapolation of historical trends assumes that all influencing factors will remain constant. It yields inaccurate results where there are major changes in cliff, beach, or hydraulic factors, as might be caused by sea-level rise. Shoreline change studies have tackled many of these issues and some methods can be adapted for use in studying eroding cliffs.

Sea-level rise causes direct submergence coupled with erosion and transport of mobile sediments, on average away from the upper, landward part of the shore profile (ORFORD, 1987, NATIONAL RESEARCH COUNCIL, 1987). A diminishing degree of protection is afforded to the cliff toe and increased rates of recession are likely. Available predictive methods include empirical historical projections, geometric models, mass conservation (sediment budget) models, and numerical dynamic equilibrium models (LEATHERMAN, 1990, KOMAR *et al.,* 1991; HEALEY, 1991). Each is constrained by assumptions and limitations which critically affect their application to cliffs as follows.

Historical Trend Analysis

This technique is based upon extrapolating historical recession with respect to sea-level rise over a given historical period (NATIONAL RESEARCH COUNCIL, 1987; LEATHERMAN, 1990). It is most effective if the shoreline is divided into relatively homogenous segments according to rate of retreat and each is analysed separately. Rates of sea-level rise are obtained from analyses of the records of nearby tide gauge stations. Future retreat (R_2) is extrapolated as follows:

$$R_2 = (R_1/S_1)S_2 \qquad (2)$$

Where: S_1 = historical sea-level rise
S_2 = future sea-level rise
R_1 = historical retreat rate

It is assumed that sea-level rise is the dominant influence on recession and all other parameters remain constant. This may be valid where rates of relative sea-level rise are rapid, but where other factors are important, it is a major limitation. Furthermore, if local conditions change with respect to the historical monitoring period, the predicted retreat will be inaccurate. Its advantage is that it is site-specific and utilises relatively easily acquired data.

The Bruun Model

It is proposed that the Bruun Model is applicable in situations where shore platforms are sediment covered. In its initial form, the Bruun Model provided a two-dimensional geometric description of the changes to shore profile geometry resulting from rising sea-level (BRUUN, 1962). It postulated that sea-level rise should result in a shift in the position and elevation of an equilibrium profile which otherwise remains constant. The initial profile is translated upward by future sea-level rise, but must also extend further onshore due to erosion and inundation. Erosion of the upper profile continues until the nearshore bed level is elevated by offshore moving sediment by an amount equivalent to the sea-level rise so as to maintain a constant profile and water depth.

The geometric relationships of the Bruun Model have been utilised to create a predictive rule (The Bruun Rule) for deriving the shoreline response to sea-level rise (BRUUN, 1962). The original prediction equation was improved by adding cliff or dune height (B) and sediment (P) parameters (WEGGEL, 1979; HANDS, 1983). These are especially important modifications that make the model sensitive to negative feedback effects caused by the products of cliff erosion which contribute to the shore profile.

$$R = S\frac{L_*}{P(B + h_*)} \quad (3)$$

Where: R = predicted shoreline recession.
S = sea-level rise.
h_* = closure depth.
L_* = length of active profile.
B = height of eroding beach berm, dune or cliff.
P = proportion of sediment eroded that is sufficiently coarse to remain within the equilibrium shore profile.

Testing has partly confirmed the overall validity of this general model in a variety of laboratory (SCHWARTZ 1965, 1967) and field environments (DUBOIS, 1975; 1976; 1977; 1992; ROSEN, 1978; HANDS, 1979; 1980; 1983; and WEISHAR and WOOD, 1983). It is especially significant that some of the strongest supporting evidence is from the eroding cliff shores of the Great Lakes (HANDS, 1983). Rising lake levels 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. Indeed, it has been argued that the accuracy of the model depends upon the availability of a readily erodible sediment store such as provided by soft rock cliffs (DUBOIS, 1992). The Bruun model therefore appears applicable to such coasts, but with several important assumptions.

Equilibrium Profile

A constant equilibrium profile is assumed as sea-level rises. In reality, the shore profile may vary in the short term due to storms (HEALY, 1991) and over longer periods according to sediment supply or deficit (DEAN, 1990). These inconsistencies have led some authors to question the whole concept of an equilibrium profile (PILKEY *et al.*, 1993). However, variability can be accommodated provided there is a geometric equilibrium over the modeling period itself. An equilibrium profile should also be valid for the cliff if the model is to be applicable here. Landscapes formed by landsliding typically adopt characteristic, regular and repetitive geometry as they evolve (BRUNSDEN and THORNES, 1979). Indeed, many cliff profiles show persistent forms as they retreat (EMERY and KUHN, 1982) and strong evidence for a condition of dynamic equilibrium has been presented for an especially complex coastal mass movement site (CHANDLER and BRUNSDEN, 1995).

Closure Depth

A seaward extremity is assumed for the equilibrium profile beyond which there is little "leakage" (export) of sediment or change in bed level. This boundary is difficult to define or measure precisely, yet it has significant effect on the amount of shore erosion needed to maintain the equilibrium profile (BRUUN, 1988; HEALY, 1991). It is widely reported that closure depth varies from site to site and values of 4–8m (HALLERMEIER, 1981a; 1981b) 6m (HEALY, 1991) and 13–18m (BRUUN, 1988) have been quoted. Theoretically, it should limit the zone of wave induced sediment transport so it might be estimated empirically from a local knowledge of sea bed sediments and extreme wave values. It has been suggested that 90% of profile change occurs within a limiting depth of twice the maximum breaking wave height for a five year return period (HALLERMEIER, 1981a; 1981b; 1981c; BRUUN and SCHWARTZ, 1985; BRUUN, 1988). Further testing of this assumption is required to remove these uncertainties. The landward boundary is easier to define and in the case of cliffs is the backscar top.

Response Time

The Bruun Model assumes an instantaneous profile response to any sea-level rise. In fact, field tests show that shore profile responses lag several years behind net changes in water level (HANDS, 1983; SCHOFIELD, 1985; WOOD *et al.*, 1994). Additional lags should be anticipated as the cliff responds to debris removal and toe erosion following shore profile changes. Profile adaptation to sea-level rise appears strongly related to the magnitude and frequency of extreme events, so response times are likely to vary according to storm surges and extreme wave climate at the shore (ORFORD, 1987; HEALY, 1991) and landslide activity on the cliff. Thus, the occurrence of episodic or cyclic recession over short and medium timescales (BRUNSDEN and JONES, 1980; VALLEJO and DEGROOT, 1988) does not invalidate the model but means that full predicted cliff responses could be delayed. Profile adjustment and hence beach and cliff recession should occur intermittently while sea-level rises continuously. Recent trends for increased storminess and wetter, warmer winters over the UK could trigger latent beach and cliff profile adjustments due to associated extreme rainfall, storm-surges and wave run-up. Such changes should be most significant for locations where relative sea-level rise is presently most rapid.

Sediment Budget Methods

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 (ORFORD, 1987; DEAN, 1990; HEALY, 1991; KOMAR *et al.,* 1991). To model reliably the three-dimensional situation, a full sediment budget needs to be calculated for the coastal segment being considered. This involves estimation of all inputs/outputs by littoral drift, onshore-offshore transport, losses to inlets etc. (EVERTS, 1985; KOMAR *et al.,* 1991). These additions are expressed by the following relationship (DEAN, 1991):

$$P(B+h_*)\,R = L_*S + G_B \tag{4}$$

Where: G_B is the net sediment budget

The left side of the equation evaluates littoral sediment yield for a given shoreline recession (R), whilst the right side is the quantity required to maintain the equilibrium profile relative to a sea-level rise (S). This is more realistic, because when sea-level rise is slow, the prevailing sediment budget is the dominant factor controlling recession. However, inclusion of the G_B term requires high quality coastal information that is often not available. Hence, an alternative approach is to assume that the historical erosion rate represents the net contribution of G_B and then to estimate the additional erosion resulting from acceleration of sea-level rise. If it is further assumed that any changes in G_B are small with time, the following equation can be utilised (DEAN, 1991):

$$R_2 = R_1 + (S_2 - S_1)\frac{L_*}{P(B + h_*)} \tag{5}$$

where:

R_1 historical recession
R_2 future recession
S_1 historic sea-level rise
S_2 future sea-level rise

This is the most easily applied and realistic adaptation of the Bruun rule for eroding cliffs. It is sensitive to variations in historical recession, coastal slope, closure depth, and the height and sediment composition of cliffs. Reliable local estimates of these parameters are therefore essential for successful application.

Shore Platform Geometrical Model

With no dissipative beach or shoreface sediment layer, direct relationships may be formulated to predict recession according to material strength and wave power (*e.g.,* SUNAMURA 1992). Additional erosion is estimated from the amount of sea-level rise and the gradient of the shore platform after SUNAMURA (1988):

$$R_2 = R_1 + \frac{S_2 - S_1}{h_*/(R_1 + L_*)} \tag{6}$$

An important simplification is the substitution of R_1 to represent the relationship between wave energy and material strength. It produces very slight overestimation of recession (SUNAMURA, 1988), as it ignores the dissipative effect of a widening shore platform as erosion proceeds. This is justified for projections over 50–100 years where platforms are already quite wide and obviates the need for geotechnical and wave climate data. The model assumes constant material strength and wave climate, that debris is evacuated rapidly from the cliff toe and that the platform retreats as a linear equilibrium profile. As with the other models, an instantaneous cliff response to increased toe erosion is assumed.

Numerical Modeling

Reliable models based on functional relationships between the dominant physical processes covering the shoreface, beach and cliff are not yet available. The approach should involve numerical modeling of cross-shore and longshore sediment transport to provide time dependent estimates of beach response based on oceanographic data. Additional models are needed to simulate basal erosion and the resultant effects transmitted by landsliding up the cliff to the backscar. This latter part is presently the major research gap, although progress might be possible by adapting geotechnical stability analyses. Potential advantages are that responses can be estimated to changes in key factors such as sea-level, wave climate, beach sediment supply, rainfall etc. Results are not constrained by having to assume constant conditions, or negligible management interference as with other methods. The stochastic nature of key variables can be accommodated through repetitive Monte Carlo simulations to obtain a time dependent probability distribution of cliff top positions (NATIONAL RESEARCH COUNCIL, 1990). When available, these methods will require high quality information and are thus unsuitable for furnishing predictions over long and variable coastal segments. They should therefore be best suited to evaluation of specific problems in high risk locations and are not further considered here.

APPLICATION OF MODELS TO THE CENTRAL SOUTHERN COAST OF ENGLAND

Historical trend analysis (Equation 2), the modified Bruun Rule (Equation 5) and the shore platform model (Equation 6) are applied to examine the possible impacts of sea-level rise on eroding cliffs at 8 locations along the south coast of England (Figure 2). Sites were selected to encompass a wide variety of cliff types with respect to geological materials, stratigraphy, landslide type, height, wave exposure, and historical recession rate (Table 1). All profiles are sediment covered, although partial bedrock exposures occur at Sites 1 (Black Ven) and 6 (Bouldnor), thus permitting application of the shore platform model. All cliffs were completely free to erode, but experienced different levels of interference due to the protection of adjacent coastal segments. Situated within a relatively small area, the sites include some of the most diverse,

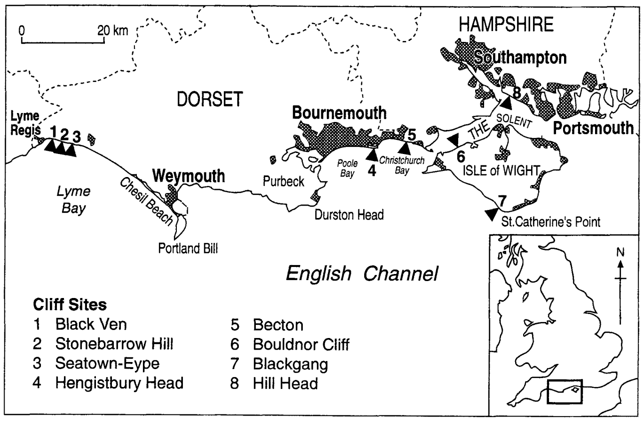

Figure 2. The study area and locations of the eroding cliff sites.

active, well-studied and intensively managed soft-rock cliff environments to be found anywhere.

Successful application of the models is dependent upon the availability of reliable local information covering the important cliff and oceanographic factors. Relevant parameters (Table 2) were obtained by reference to previous work accessed through a regional database (CARTER *et al.*, 1989) and literature review (BRAY *et al.*, 1991), produced by local coast protection authorities (BRAY *et al.*, 1995). Historical recession rates (R_1) were calculated from long records covering at least 50 years (Table 1), except where significant variations were recorded, as at Black Ven (major system change without obvious cause), Hengistbury and Becton (both affected by improved coast protection structures immediately updrift). Here, recession was calculated exclusively from post-change data. Contemporary relative sea-level (RSL) rise (S_1) was estimated from mean sea-level analyses of tide gauge records from Newlyn, Cornwall (1916–82), Portsmouth (1962–82) and Sheerness, Kent (1916–82) (WOODWORTH, 1987; PUGH, 1990), together with an examination of late Holocene geological and archaeological evidence (BRAY *et al.*, in press). Slow RSL rise was indicated for southern England ($2mma^{-1}$) but more rapid rates were recorded at Portsmouth ($5mma^{-1}$). Appropriate allowances were made for sites located close to Portsmouth and the Solent, but elsewhere the lower regional value was used. Future sea-level rise (S_2) is the sum of the contemporary RSL trend and best guess estimate of greenhouse-induced rise, modeled to 2050 (0.22m) for medium population and economic growth scenarios (WIGLEY and RAPER, 1992). Uncertainties in extrapolating historical recession data meant that 2050 rather than 2100 was a more appropriate point for prediction of cliff responses.

The overfill factor (P) was estimated from the geological literature (*e.g.*, WILSON *et al.*, 1958; BRISTOW *et al.*, 1991; MELVILLE and FRESHNEY, 1982), together with cliff sediment sampling programmes at some sites (WHEELER, 1979; LACEY, 1985; BRAY, 1986; BRAY, 1993a). Offshore sediment sampling in the vicinity of most sites suggested that materials finer than fine sand could not generally contribute to the active profile (DYER, 1970; 1971; LANGHORNE *et al.*, 1982; VELEGRAKIS, 1991). The closure depth (h_*) was estimated as being twice the maximum wave height for a fifty year return period (BRUUN, 1988). Extreme wave statistics were readily available for most sites from consultants' studies for nearby coast protection schemes. The length of the active profiles (L_*) were measured from hydrographic charts by using the closure depths to indicate their seaward extremities.

Comparison of model results against the baseline conditions extrapolated without additional sea-level rise suggests that retreat is likely to accelerate significantly at all sites (Table 2 and Figure 3). Estimated rates of change differed between models. Historical trend analysis consistently predicted more rapid recession because of its sensitivity to contemporary RSL rise. Its presumption that sea-level is the dominant force causing recession is questionable at rapidly eroding sites where rates of rise are low, thus confining its use to areas known to suffer rapid RSL rise, *e.g.*, Hill Head. Even so, its validity is governed by the accuracy of available contemporary sea-level data, causing problems in regions of variable crustal deformation. The shore platform model and the Bruun Rule both calculate a recession increment (Figure 3) for a given sea-level rise that is unaffected by either the contemporary sea-level rise or rate of recession. Greater retreat was predicted by the shore platform model as it assumes that all erosion products are rapidly removed. Where such materials have the capacity to contribute to the profile, the Bruun Rule models the negative feedback effect and predicts less rapid retreat. It therefore appears a more reliable technique on the sediment covered profiles of the study area, and the following discussion is based on results obtained using this method.

A sea-level rise of 0.22m was estimated to produce increased retreat of between 12m and 52m above baseline values according to site. These are significant changes amounting to accelerations of between 22% and 133% (Figure 3). At sites where system change has been identified, the increments resulting from accelerating sea-level rise are proportionately the smallest, as at Black Ven (22%) and Becton (43%). Similar results are calculated (Figure 4) using low (0.17m) and high (0.30m) sea-level values that represent the uncertainties in future estimates of this parameter (WIGLEY and RAPER, 1992). The clear implication is that reliable extrapolations of historic recession are the most important elements in predicting cliff retreat at such sites irrespective of rising sea-level. A disturbing possibility is that sea-level rise itself might produce system change. The models applied here assume that other factors remain constant and they therefore cannot predict such behaviour.

The greatest sea-level impacts are likely to be at Hengistbury and Becton where large quantities of sediment need to be eroded to facilitate adjustment of the long, active shore profiles. Cliff height is modest so limiting sediment yields. On high relief coasts, the proportion of cliff sediment that remains stable on the shore profile is the critical factor because total material supply is large. Hence, the sandy Seatown-Eype and Blackgang cliff segments are likely to adjust to sea-level rise more effectively than Black Ven and Stonebarrow where clay is the major ground forming type. Prevailing erosion at the latter sites is likely to be exacerbated

Table 1. *The cliff study sites.*

Location	Geology	Height (m)	Landslide Type	Wave Exposure H_{max} (m)	Historical Backscar Recession		
					Methods	Period	ma^{-1}
Black Ven	Weak Jurassic clays and marls with sandy Cretaceous cap-rock	160	Multiple rotational backscar slides feeding major mudslides that move over a series of lower terraces and surge seaward over the foreshore (BRUNSDEN and GOUDIE, 1981; BRAY, 1986; CHANDLER and BRUNSDEN, 1995).	Moderate (9.0–offshore)	Historic maps. Analytic photogrammetry.	1901–1960 1958–1988	0.38 2.24
Stonebarrow	Weak Jurassic clays and marls with sandy Cretaceous cap-rock	140	Infrequent major rotational backscar slides feeding mudslides on a lower platform. High sea-cliffs retreat by rockfall (BRUNSDEN and JONES, 1976).	Moderate/high (9.0–offshore)	Historic maps, air photos, ground survey.	1887–1987	0.40
Seatown/Eype	Weak Jurassic sandstones with some interbedded clays	88	Rockfall and occasional major slides, basal debris apron (BRAY, 1986).	Moderate/high (9.0–offshore)	Historic maps, air photos, ground survey.	1901–1987	0.30
Hengistbury Head	Tertiary sands and clays	30	Rockfall, gullying, debris flows (BRAY, 1993a).	Moderate (6.0–inshore)	Air photos, ground survey.	1987–1994	0.80
Becton	Tertiary sands and clays	25	Small, frequent rotational backscar slides feeding mudslides on a lower bench and the foreshore (BARTON, 1973).	Moderate (6.0–inshore)	Historic maps, analytic photogrammetry.	1869–1958 1958–1993	0.85 2.14
Bouldnor	Weak Tertiary clay	60	Mudslides (MAY, 1966; HUTCHINSON, 1983)	Low (<1.5)	Historic maps.	1868–1963	0.61
Blackgang	Interbedded Cretaceous sandstones and clays	130	Seepage erosion, major rotational backscar slides feeding mudslides on a lower platform. High sea-cliffs retreat by rockfall (HUTCHINSON *et al.*, 1981).	Moderate/high (no wave data, but similar exposure to Seatown/Eype).	Historic maps, air photos, ground survey.	1861–1980	0.41
Hill Head	Tertiary sands	9	Small, frequent rockfalls (BRAY 1993b).	Low (<1.5)	Historic maps.	1870–1964	0.20

H_{max} is the extreme wave height (50 year return period) obtained by statistical extrapolation from wave records (BRAY *et al.*, 1991)

Table 2. *Parameters and results from the recession models.*

Location	R_1 (ma^{-1})	S_1 (ma^{-1})	S_2 (ma^{-1})	P %	L_* (m)	h_* (m)	B (m)	R_{Base} (m)	Historical Trend R_2	Historical Trend R_{2050}	Bruun Rule R_2	Bruun Rule R_{2050}	Shore Platform R_2	Shore Platform R_{2050}
1. Black Ven 1901–1960	0.38	0.002	0.006	18	4,000	18	160	21	1.14	64	0.88	49	1.27	71
1958–1988	2.24							125	6.72	376	2.74	153	3.13	175
2. Stonebarrow	0.40	0.002	0.006	19	3,000	18	140	22	1.20	67	0.80	45	—	—
3. Seatown/Eype	0.30	0.002	0.006	50	3,000	18	88	17	0.90	50	0.53	29	—	—
4. Hengistbury Head	0.80	0.002	0.006	52	4,000	13	30	45	2.40	134	1.52	85	—	—
5. Becton 1869–1968	0.85	0.002	0.006	45	4,000	13	25	48	2.55	143	1.79	100	—	—
1958–1993	2.14							120	6.42	360	3.08	172	—	—
6. Bouldnor	0.61	0.003	0.007	15	800	10	60	34	1.42	80	0.91	51	0.94	53
7. Blackgang	0.41	0.002	0.006	40	4,000	18	130	23	1.23	69	0.68	38	—	—
8. Hill Head	0.20	0.005	0.009	83	1,000	10	9	11	0.36	20	0.45	25	—	—

R_1 = historical backscar recession
S_1 = rate of contemporary sea-level rise
S_2 = estimate of mean rate of future sea-level rise to 2050
P = % of cliff sediments stable on the active shore profile
L_* = length of active profile
h_* = closure depth
R_{Base} = baseline historical retreat projected from 1994 to 2050
R_2 = future retreat for additional sea-level rise of 0.22 m by 2050 (ma^{-1})
R_{2050} = total retreat estimated by 2050 (m)
B = cliff height

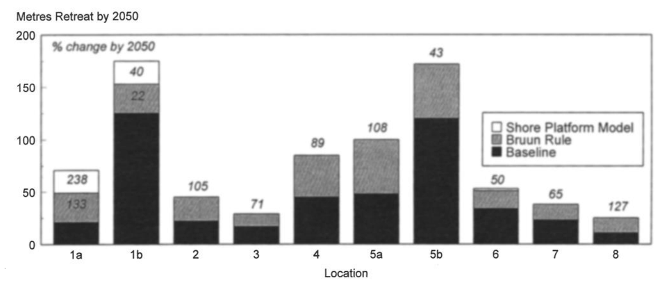

Figure 3. Extrapolations of cliff recession indicating the potential effects of sea-level rise superimposed upon baseline conditions. Note the lower predictions of the modified Bruun Rule which models the capacity of cliff sediments to build up the shore profile.

by sea-level rise, because few of the products of any accelerated cliff erosion can contribute to the shore profile. In spite of limited sediment yield due to low cliff height (Hill Head) or a predominantly clay geology (Bouldnor), only modest increases in recession are likely in the low wave energy environments of the Solent (Figure 2), because the active profiles are short. Sea-level rise therefore has the most serious implications for low clay cliffs situated on open exposed coasts where fine grained erosion products are likely to be transported offshore or become distributed across a wide active shore profile. The Holderness coast of north east England is an obvious example (MASON and HANSOM, 1988).

DISCUSSION

The models discussed in this paper are adapted specifically for gently sloping shore platform coasts composed of or containing soft-rock units. Alternative models are applicable according to the presence or absence of shoreface sediments. Cliff recession estimates produced using these methods are intended for planning purposes and not for detailed site-specific assessments. Hence, they are suitable for use in regional and national studies of vulnerability to sea-level rise (IPCC,1992; 1994; NICHOLLS and LEATHERMAN, 1995). They

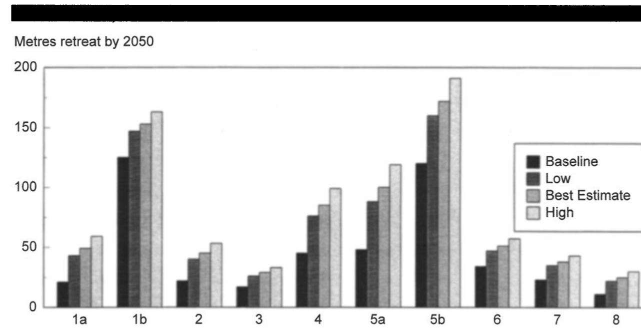

Figure 4. Cliff recession modelled for the differing sea level scenarios of WIGLEY and RAPER (1992). Note that variations resulting from system change at sites 1a, 1b, 5a and 5b are more significant than those resulting from imprecision of future sea-level rise estimates.

should also be especially valuable for defining cliff top hazard zones and in assessing the viability of setback policies (KAY, 1990). Care should be taken to incorporate additional information relating to the nature of landsliding and the magnitude and frequency of recession events if predictions are to be applied to individual high risk sites. Further testing is necessary to establish the reliability of the models in different situations. The major uncertainties are identified as follows

Response Timescales

Cliffs will not adjust instantaneously to changes in first order factors such as sea-level. There will almost certainly be lags in their responses. Projections of recession therefore should be treated as maxima and should not occur in full until after 2050 when lags have worked through the system. Estimation of delays is difficult because both the beach and cliff systems need to be considered together. Where there is no beach, responses depend upon the shore platform and cliff factors (debris removal, slope angle, material strength etc.). Elsewhere, a time lag is required for adjustment of the shore profile to higher sea-levels according to the Bruun Model. The full effects of rising sea-level cannot be experienced at the cliff-base until such adjustments are completed.

Cliff response to sea-level rise is therefore likely to lag behind that of the shore profile causing steepening (Bruun Effect), before sufficient sediment can be supplied from cliffs to restore the coastal slope. This response has been recorded in the analogous situation produced by cyclic water level fluctuation of the Great Lakes, USA (VELLEJO and DEGROOT, 1988). Here, enhanced cliff recession has been recorded as soon as 5 years following increases in lake level. It depends upon transmission of enhanced basal erosion up through the cliff system to the coastal backscar and should vary elsewhere according to cliff height, morphology, landslide history and contemporary activity. In simple low cliffs as studied on the Great Lakes, the profile should steepen rapidly and failures of the whole slope may ensue soon after basal undercutting. However, in high compound cliffs typical of the south west Isle of Wight and West Dorset coasts, wide degradation zones have partly decoupled the backscar from perturbations at the cliff toe. Changes are regulated by cyclic activity so that backscar response times might be estimated from a knowledge of erosion cycle periods. Here, 40–140 years may be required for the backscar to be affected (BRUNSDEN and JONES, 1980; BRAY, 1986).

Unfortunately, erosion cycles will not necessarily remain stable under conditions of enhanced basal erosion and debris removal. HUTCHINSON (1973) has shown that differing activity modes are possible within a single material type according to rates of toe erosion. The implication is that accurate recession prediction for individual sites will entail an appraisal of possible activity modes coupled with an understanding of their relative thresholds. Different materials or geological sequences could react differently so the research frontier is to identify common factors. For example, simple low cliffs may maintain their present form, but retreat more rapidly. Alternatively, higher, more complex cliffs have been shown to switch their forms to new steeper slope profiles characterised by higher magnitude erosion events (HUTCHINSON, 1973; CHANDLER and BRUNSDEN, 1995). Improved understanding of the governing threshold conditions is possible through the study of analogues. Diminishing levels of beach protection can be substituted for sea-level rise because they have an equivalent effect in terms of enhanced toe erosion. Such situations exist where littoral transport is intercepted by protection structures that have been located updrift of eroding cliffs. Research into the patterns of adjustment is currently in progress at those few locations in central southern England that have appropriate historical monitoring records covering the cliff, beach and shore profile.

Application of Methods and Models

In applying the models to central southern England, the availability of a wide range of cliff, beach and oceanographic information compiled in a regional database and review (BRAY *et al.*, 1995) was valuable in providing site-specific estimates of key parameters. Nevertheless, important uncertainties remain in calculating historical recession rates that might be used for extrapolation irrespective of sea-level rise. It is important to recognise instances of intermittent retreat produced by erosion cycles within cliff landslide complexes. Recession data should cover at least one cycle, to ensure that results are representative. Extrapolations assume constant conditions into the future, so where cliff systems have been disturbed or significantly altered, only post-change data are valid. Differentiation of such behaviour requires process understanding founded on appropriate monitoring records. Valid data must satisfy minimum criteria for significant change (see Equation 1). However, high accuracy is needed to resolve slow retreat rates and more rapid rates are not easily discernible over short epochs. Quantitative information is only generally available from historic maps (revised at 20–40 year intervals) and conventional air photo analyses, limiting the number of recorded cliff top positions for any site. Statistical analyses of the types proposed for shorelines by FENSTER *et al.*, (1993) are not possible on cliffs until more data are collected. Two responses are appropriate. First, available historical sources need to be utilised more fully. This should involve compilation of documentary information, *e.g.*, local newspaper and other eyewitness accounts of cliff movements, together with geomorphological mapping and assessments of form (PITTS, 1981; LEE *et al.*, 1991). The objective must be to identify the full range of possible cliff behaviour types including details of their magnitudes, frequencies, recurrent patterns and cycles of activity. Accurate quantitative data are now obtainable from historical oblique ground photographs as well as from air photos by using analytical photogrammetry (LANE *et al.*, 1993). Second, regular monitoring programmes should be established. Improved measurement speeds and accuracies using analytical photogrammetry and digital data processing mean that it should be feasible to resolve retreat by annual or biannual surveys on many cliffs using aerial photography.

Attention is drawn to some of the factors that were not included in the models applied. These include landslide type, wave conditions, shore platform variations and the influence of protective beaches, especially those composed of gravel or aprons of boulders. In spite of these omissions, the models should remain valid so long as their projections are regarded as potential long-term maxima that will not necessarily be achieved until after 2050 according to lags in response. Alteration in management practice, *e.g.,* abandonment or reinforcement of defences and possible future climate changes are additional uncertainties that could have major impacts upon future cliff recession. Improved process-based models are needed to incorporate such factors into cliff prediction estimates and to evaluate response times.

CONCLUSIONS

Many uncertainties are highlighted in this review as serious obstacles to reliable prediction of future cliff recession. Not least, are the complexity of cliff, beach and hydraulic processes that interact over variable timescales to produce recession. These complexities have so far forestalled the development of process-based models. This paper identifies a clear need for inter-disciplinary research to address these issues. In the meantime, predictions must rely upon various methods of historical extrapolation that cannot easily accommodate changing environmental conditions as produced by climate change and sea-level rise. The challenge is to develop ways of using process knowledge to improve the results obtained from such models. Examples outlined in this paper demonstrate that progress is possible by adapting available models in combination with appropriate site-specific information. In particular, an adaptation of the Bruun Rule appears to be especially suitable for cliffs, although further testing of its reliability is advocated. Its application permits sensitivity analyses of different sites to future changes.

Results obtained from the sea-level models strongly suggest that correct estimation of historical recession and selection of appropriate data subsets for extrapolation are the most important factors in predicting future trends at sites subject to cyclic erosion or system change. Therefore, it should become a priority to improve the current poor knowledge of threshold conditions governing coastal cliff system change. Uncertainties caused by imprecision of future sea-level estimates to 2050 are less important by comparison. Natural system variability or that resulting from management interference is potentially so great as to exceed the likely effects of sea-level rise over the period studied. Nevertheless, the models indicate that cliff recession could increase by between 22% and 133% along the south coast of England in response to rising sea-levels up to 2050. Results are highly site-specific due to local factors that govern cliff sensitivity. Slightly less erosion is predicted for cliffs that contribute sediments that can build up their shoreface profiles. Cliffs in energetic open coast environments with longer active profiles are shown to be more sensitive than those in more sheltered locations. Higher cliffs are more resilient against sea-level rise providing that their sediments are sufficiently coarse to remain stable on the active profile. Future research should assess the influences of different beach, shoreface and platform configurations operating in combination with different types of landslide activity to produce more definitive models.

These results are extremely valuable to managers interested in assessing the future vulnerability of coastal assets and the viability of different policy options. Reliable estimates of cliff recession are needed to indicate the likely risks to cliff-top development and permit set-back zones to be defined with greater confidence. These estimates can also be used to provide a quantitative indication of the potential benefits to neighbouring beaches in terms of increased sediment yields (BRAY, 1992). In central southern England, littoral sediment is a scarce commodity that must be managed as a valuable resource (BRAY *et al.,* 1995). Appraisal of the relative importance of cliff inputs and their likely future status within the appropriate littoral cell is therefore a necessity for effective shoreline management.

LITERATURE CITED

ALLISON, R.J., 1989. Rates and mechanisms of change on hard rock coastal cliffs. *Z. Geomorphologie N.F. Supplement Band,* 73, 125–138.

ALLISON, R.J. and BRUNSDEN, D., 1990. Some mudslide movement patterns. *Earth Surface Processes Landforms,* 15(3), 297–311.

BACON, S. and CARTER, D.J.T., 1991. Wave climate changes in the North Atlantic and North Sea. *International Journal of Climatology,* 11, 545–558.

BARTON, M.E., 1973. The degradation of the Barton clay cliffs of Hampshire. *Quartenary Journal Engineering Geology,* 6, 423–440.

BARTON, M.E. and COLES, B.J. 1984. The characteristics and rates of the various slope degradation processes in the Barton clay cliffs of Hampshire. *Quarterly Journal Engineering Geology,* 17, 117–136.

BIRD, E.C.F., 1992. *Submerging Coasts.* Chichester: Wiley, 169p.

BRAY, M.J., 1986. *A Geomorphological Investigation of the South-west Dorset Coast. Volume 1—Patterns of Sediment Supply.* Report to Dorset County Council and West Dorset District Council. Department of Geography, London School of Economics, 144p.

BRAY, M. J., 1992. The contribution of cliff instability to the coastal sediment budget. *In: Papers and Proceedings SCOPAC Conference: Coastal Instability and Development Planning (Portsmouth October 1991),* pp. 52–61.

BRAY, M.J., 1993a. *Hengistbury Head Coast Protection Works: Impacts and Implications.* Department of Geography, University of Portsmouth. Report to the Borough Council of Bournemouth. 42p.

BRAY, M.J., 1993b. *A History of Shoreline Changes and Coast Protection: Impacts and Implications for the Lee-on-the-Solent Coast.* Department of Geography, University of Portsmouth. Consultant's Report to Sir William Halcrow and Partners. 39p.

BRAY, M.J., 1994. On the edge: the Blackgang landslide of 12 January 1994. *Geographical Magazine,* 66(4), 48–49.

BRAY, M.J.; CARTER, D.J., and HOOKE, J.M., 1991. *Coastal Sediment Transport Study* (5 Vols). Report to SCOPAC, Department of Geography, Portsmouth Polytechnic, 498p. plus 32 maps.

BRAY, M.J.; CARTER, D.J., and HOOKE, J.M., 1995. Littoral cell definition and budgets for central southern England. *Journal of Coastal Research,* 11(2), 381–400.

BRAY, M.J.; HOOKE, J.M., and CARTER, D.J., in press. Planning for sea-level rise on the South Coast of England: informing and advising the decision makers. *In:* RICHARDS, K., (ed.) *Managing the Earth's Surface: Science and Policy.* Chichester: Wiley.

BRISTOW, C.R.; FRESHNEY, E.C., and PENN, I.E., 1991. *Geology of the country around Bournemouth: Memoir for 1:50,000 Geological Sheet 329.* British Geological Survey, London, HMSO, 116p.

BROMHEAD, E.N., 1979. Factors affecting the transition between the various types of mass movement in coastal cliffs consisting largely of over-consolidated clay, with special reference to southern England. *Quarterly Journal Engineering Geology,* 12(4), 291–300.

BRUNSDEN, D., 1974. The degradation of a coastal slope, Dorset, England. *In:* BROWN, E.H. and WATERS, R.S. (eds.), *Progress in Geomorphology. Institute of British Geography Special Publication no. 7,* 79–98.

BRUNSDEN, D., 1984. Mudslides, *In:* BRUNSDEN, D. and PRIOR, D.B. (eds), *Slope Instability.* Chichester: Wiley, pp. 363–418.

BRUNSDEN, D. and GOUDIE, A., 1981. *Classic Coastal Landforms of Dorset.* Landform Guides No.1. Sheffield, The Geographical Association, 39p.

BRUNSDEN, D. and JONES, D.K.C., 1972. The morphology of degraded landslide slopes in southwest Dorset. *Quarterly Journal Engineering Geology,* 5(3), 205–222.

BRUNSDEN, D. and JONES, D.K.C., 1976. The evolution of landslide slopes in Dorset. *Philosophical Transactions of the Royal Society of London,* A283, 605–631.

BRUNSDEN, D. and JONES, D.K.C., 1980. Relative time scales and formative events in coastal landslide systems. *Zeitschrift Geomorph. N.F. Supplement Band,* 34, 1–19.

BRUNSDEN, D. and THORNES, J.B., 1979. Landscape sensitivity and change. *Transactions of the Institute of British Geographers,* 4, 463–484.

BRUUN, P., 1962. Sea-level rise as a cause of shore erosion. *Journal of Waterways and Harbours Division ACSE,* 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. *Journal of Coastal Research,* 4(4), 627–648.

BRUUN, P. and SCHWARTZ, M.L., 1985. Analytical predictions of beach profile change in response to a sea-level rise. *Zeitschrift Geomorph. N.F. Supplement Band,* 57, 33–50.

CAMBERS, G., 1976. Temporal scales in coastal erosion systems. *Transactions of the Institute of British Geographers,* New Series, 1, 246–256.

CARTER, D.J.; HOOKE, J.M., and REDMOND, C.E., 1989. *SCOPAC Bibliographic Information Database.* Report to SCOPAC, Portsmouth Polytechnic, Geography Department, 61p.

CARTER, D.J.T. and DRAPER, L., 1988. Has the North-East Atlantic become rougher? *Nature,* 332, 494.

CARTER, R.W.G. and ORFORD, J.D., 1984. Coarse clastic barrier beaches: a discussion of the distinctive dynamic and morphosedimentary characteristics. *Marine Geology,* 60, 377–389.

CARTER, R.W.G.; JENNINGS, S.C., and ORFORD, J.C., 1990. Headland erosion by waves. *Journal of Coastal Research,* 6(3), 517–529.

CARTER, R.W.G.; JOHNSTON, T.W.; MCKENNA, J., and ORFORD, J.D., 1987. Sea-level, sediment supply and coastal changes: examples from the coast of Ireland. *Progress in Oceanography,* 18, 79–101.

CHANDLER, J. and BRUNSDEN, D., 1995. Steady state behaviour of the Black Ven mudslide: the application of archival analytical photogrammetry to studies of landform change. *Earth Surface Processes and Landforms,* 20, 255–275.

CLARK, A. and GUEST, S., 1994. The design and construction of the Holbeck Hall coast protection and cliff stabilisation emergency works. *In: Proceedings of the 29th MAFF Conference of River and Coastal Engineers.* Ministry of Agriculture Fisheries and Food, London. pp. 3.3.1–3.3.13.

CLEMENTS, M., 1994. The Scarborough experience—Holbeck landslide, 3/4 June 1993. *Proceedings Institution Civil Engineers Municipal Engineering,* 103, June, 63–70.

CONWAY, B.W., 1979. The contribution made to cliff instability by head deposits in the west Dorset coastal area. *Quarterly Journal of Engineering Geology,* 12, 267–279.

CROWELL, M.; LEATHERMAN, S.P., and BUCKLEY, M.K., 1991. Historical shoreline change: error analysis and mapping accuracy. *Journal of Coastal Research,* 7(3), 839–852.

DALRYMPLE, R.A.; BIGGS, R.B.; DEAN, R.G., and WANG, H., 1986. Bluff recession rates in Chesapeake Bay. *Journal of Waterway, Port, Coastal and Ocean Engineering,* 112(1), 164–169.

DAVIES, P.; WILLIAMS, A.T., and BROMBOE, P., 1991. Numerical modelling of Lower Lias rock failures in the coastal cliffs of South Wales. *Costal Sediments '91,* American Society Civil Engineers, pp. 1599–1612.

DEPARTMENT OF THE ENVIRONMENT, 1991. *The Potential Effects of Climate Change in the UK.* HMSO, London, 122pp.

DEAN, R.G., 1990. Beach response to sea-level change. *In: Ocean Engineering Science: The Sea* Volume 9 part B, Chichester: Wiley–Interscience, pp. 869–887.

DEAN, R.G., 1991. Equilibrium beach profiles: characteristics and applications. *Journal of Coastal Research,* 7(1), 53–84.

DENNESS, B., 1971. *The Reservoir Principle of Mass Movement,* Report Institute Geological Sciences, No. 72/7, 13p.

DUBOIS, R.N., 1975. Support and refinement of the Bruun Rule on beach erosion. *Journal of Geology,* 83, 651–657.

DUBOIS, R.N., 1976. Nearshore evidence in support of the Bruun Rule on shore erosion. *Journal of Geology,* 84, 485–491.

DUBOIS, R.N., 1977. Predicting beach erosion as a function of rising water level. *Journal of Geology,* 85, 470–476.

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

DYER, K.R., 1970. Sediment distribution in Christchurch Bay, southern England, *Journal Marine Biological Association of the United Kingdom,* 50, 673–682.

DYER, K.R., 1971. The distribution and movement of sediment in the Solent, southern England, *Marine Geology,* 11, 175–187.

EMERY, K.O. and KUHN, G.G., 1982. Sea cliffs: their processes, profiles, and classification. *Geological Society of America Bulletin,* 93, 644–654.

EMERY, K.O. and AUBREY, D.G., 1991. *Sea-level, Land Levels and Tide Guages.* New York: Springer Verlag, 177 p.

EVERTS, C.H., 1985. Sea level rise effects on shoreline position. *Journal of Waterways, Port, Coastal and Ocean Engineering,* 111(6), 985–999.

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

FENSTER, M.S.; DOLAN, R., and ELDER, J.F., 1993. A new method for predicting shoreline positions from historical data. *Journal of Coastal Research,* 9(1), 147–171.

FLATHER, R.A., 1987. Estimates of extreme conditions of tide and surge using a numerical model of the North-west European continental shelf. *Estuarine, Coastal and Shelf Science,* 24, 69–93.

FORBES, D.L.; TAYLOR, R.B., and SHAW, J., 1989. Shorelines and rising sea levels in Eastern Canada. *Episodes,* 12(1), 23–28.

GERMIAT, S.J. and SHARP, J.M., 1990. Assessment of future coast land loss along the upper Texas Gulf Coast to the year 2050. *Bulletin of the Association of Engineering Geologists,* 27(3), 263–280.

GRAFF, J., 1981. An investigation of the frequency distributions of annual sea level maxima at ports around Great Britain. *Estuarine, Coastal and Shelf Science,* 12, 389–449.

GRAINGER, P. and KALAUGHER, P.G., 1987. Intermittent surging movements of a coastal landslide. *Earth Surface Processes Landforms,* 12, 597–603.

HAGUE, R.C., 1992. *UK South Coast Shingle Study: Joint Probability Assessment.* HR Wallingford Ltd. Report No. SR 315. 14p. plus Tables, Figures and Appendicies.

HALLERMEIER, R.J., 1981a. Seaward limit of significant sand transport by waves. *Coastal Engineering Techincal Aid No. 81-2,* CERC, 23p.

HALLERMEIER, R.J., 1981b. Critical wave conditions for sand motion initiation. *Coastal Engineering Technical; Aid No. 81-10,* CERC, 23p.

HALLERMEIER, R.J., 1981c. A profile zonation for seasonal sand beaches from wave climate. *Coastal Engineering,* 4, 253–277.

HANDS, E.B., 1979. Changes in the rates of shore retreat, Lake Michigan 1967–1976. *CERC Technical Memorandum No. 79 -4,* 71p.

HANDS, E.B., 1980. Prediction of shore retreat and nearshore profile adjustments to rising water levels on the Great Lakes. *CERC Technical Memorandum No. 80-7,* 119p.

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.* Boca Raton, Florida: CRC Press, pp. 176–189.

HAYDEN, B.P., 1975. Storm wave climates at Cape Hatteras: recent secular variations. *Science,* 190, 981–982.

HEALY, T., 1991., Coastal erosion and sea level rise. *Zeitschrift Geomorph. N. F. Supplement-Band,* 81, 15–29.

HOOKE, J.M. and KAIN, R.J.P., 1982. *Historical Change in the Physical Environment: A Guide to Sources and Techniques.* Sevenoaks: Butterworth.

HOUGHTON, J.; CHALLANDER, B.A., and VARNEY, S.K., 1992. *Climate Change 1992: the Supplementary Report to the IPCC Scientific Assessment.* Cambridge, Mass: Cambridge University Press, 224p.

HUTCHINSON, J.N., 1973. The response of London Clay cliffs to different rates of toe erosion. *Geol. Appl. Idrogeol.,* 8, 221–239.

HUTCHINSON, J.N., 1983. A pattern in the incidence of major coastal mudslides. *Earth Surface Processes Landforms,* 8, 391–397.

HUTCHINSON, J.N., 1991. The landslides forming the South Wight Undercliff. *In:* CHANDLER, R.J., (ed.), *Slope Stability Engineering.* London: Thomas Telford, pp. 157–168.

HUTCHINSON, J.N.; BROMHEAD, E.N., and LUPINI, J.F., 1980. Additional observations on the Folkestone Warren landslides. *Quarterly Journal Engineering Geology,* 13, 1–31.

HUTCHINSON, J.N.; CHANDLER, M.P., and BROMHEAD, E.N., 1981. Cliff recession on the Isle of Wight, SW coast. *Proceedings of the 10th International Conference of the Soil Mechanics and Foundation Engineering, Stockholm,* Vol. 1, pp. 429–434.

IPCC, 1992. *Global Climate Change and the Rising Challenge of the Sea.* Intergovernmental Panel on Climate Change, Response Strategies Working Group, Coastal Zone Management Subgroup. Ministry of Transport, Rijkswaterstaat, The Netherlands. 123p.

IPCC, 1994. *Preparing to Meet the Coastal Challenges of the 21st Century.* Report World Coast Conference 1993, Ministry of Transport, Coastal Zone Management Centre, The Hague, The Netherlands. 103p.

JIBSON, R.W. and STRAUDE, J.M., 1992. Bluff recession rates along the Lake Michigan shoreline in Illinois. *Bulletin of the Association of Engineering geologists,* 29(2), 105–117.

JIBSON, R.W.; ODUM, J.K. and STRAUDE, J.M., 1994. Rates and processes of bluff recession along the Lake Michigan shoreline in Illinois. *Journal of Great Lakes Research,* 20(1), 135–152.

JONES, D.G. and WILLIAMS, A.T., 1991. Statistical analysis of factors influencing cliff erosion along a section of the West Wales coast, UK. *Earth Surface Processes Landforms,* 16, 95–111.

JONES, R.J.; CAMERON, B., and FISHER, J.J., 1993. Analysis of cliff retreat and shoreline erosion: Thompson Island, Massachusetts, U.S.A. *Journal of Coastal Research,* 9(1), 87–96.

JONES, D.K.C. and LEE, E.M., 1994. *Landsliding in Great Britain.* London: Department of Environment, HMSO.

KAMPHUIS, J.W., 1987. Recession rate of glacial till bluffs. *Journal of Waterway, Port, Coastal and Ocean Engineering,* 113 (1), 60–73.

KAY, R., 1990. Development controls on eroding coastlines: reducing the future impact of greenhouse-induced sea-level rise. *Land Use Policy,* 7(2), 169–172.

KOMAR, P.D.; LANFREDI, N.; BABA, M.; DEAN, R.G.; DYER, K.; HEALY, T.; IBE, A.; TERWINDT, J., and THOM, B., 1991. The response of beaches to sea-level changes: a review of predictive models. SCOR Working Group 89. *Journal of Coastal Research,* 7(3), 985–921.

KOMAR, P.D. and SHIH, S.M., 1993. Cliff erosion along the Oregon coast: a tectonic sea level imprint plus local controls by beach processes. *Journal of Coastal Research,* 9(3), 747–765.

KRIEBEL, D.L. and DEAN, R.G., 1985. Numerical simulation of time dependant beach and dune erosion. *Coastal Engineering,* 9, 221–245.

LACEY, S., 1985. Coastal Sediment Processes in Poole and Christchurch Bays, and the Effects of Coast Protection Works. Unpublished Ph.D. dissertation, Department of Civil Engineering, University of Southampton, 372p.

LAMB, H., 1991. *Historic Storms of The North Sea, British Isles and Northwest Europe.* Cambridge: Cambridge University Press, 248p.

LANE, S.N.; RICHARDS, K.S., and CHANDLER, J.H., 1993. Developments in photogrammetry; the geomorphological potential. *Progress in Physical Geography* 17(3), 306–328.

LANGHORNE, D.N.; HEATHERSHAW, A.D., and READ, A.A., 1982. The Mobility of Seabed Gravel in the West Solent: A Report on Site Selection, Seabed Morphology and Sediment Characteristics. *Institute of Oceanographic Sciences, Report No.* 140, 65p.

LEATHERMAN, S. P., 1983. Historical and projected shoreline mapping. *In:* MAGOON, O.T. (ed.), *Coastal Zone '83,* Vol 3, pp. 2902–2911.

LEATHERMAN, S. P., 1984. Coastal Geomorphic Responses to Sea-Level Rise: Galveston Bay, Texas. *In:* BARTH, M.C. and TITUS, J.G., (ed.) *Greenhouse Effect and Sea-Level Rise.* New York: Van Nostrand Reinhold, 151–178.

LEATHERMAN, S.P., 1985. *Geomorphic Effects of Accelerated Sea-level Rise on Ocean City, Maryland.* Washington DC.: US Environmental Protection Agency.

LEATHERMAN, S.P., 1990. Modeling shore response to sea-level rise on sedimentary coasts. *Progress in Physical Geography,* 14, 447–464.

LEE, E.M.; MOORE, R.; SIDDLE, H.J., and BRUNSDEN, D., 1991. The assessment of ground behaviour at Ventnor, Isle of Wight. *In:* CHANDLER, R.J., (ed.), *Slope Stability and Engineering; Developments and Applications.* London: Thomas Telford, 207–212.

LONDON, J.B. and VOLONTE, R., 1991. Land use implications of sea level rise: a case study at Myrtle Beach, South Carolina. *Coastal Management,* 19, 205–218.

MANSARD, E.P.D., 1990. A discussion on the impact of sea level rise on the nearshore wave climate. *Journal of Coastal Research,* Special Issue 9(2), 736–737.

MARITIME ENGINEERING BOARD, 1990. *A Statistical Survey of Storm Damage to Coastal Defences.* CERAC Report, London, The Institution of Civil Engineers. 7p. plus figures & tables.

MASON, S.J. and HANSOM, J.B., 1988. Cliff erosion contribution to a sediment budget for part of the Holderness coast, England. *Shore and Beach,* 56 (4), 30–38.

MAY, V.J., 1966. A preliminary study of recent coastal changes and sea defences in South-east England, *Southampton Research Series in Geography,* 3, 3–24.

MAY, V.J., 1977. Earth cliffs. *In:* BARNES, R.S.K., (ed.), *The Coastline.* Chichester: Wiley, pp. 215–235.

MAY, V.J. and HEEPS, C., 1985. The nature and rates of change on Chalk coastlines, *Zeitschrift Geomorphologie NF Supplement Band,* 57, 81–94.

MCGREAL, W.S., 1979. Marine erosion of glacial sediments from a low-energy cliffline environment near Kilkeel, Northern Ireland. *Marine Geology,* 32, 89–103.

MELVILLE, R.V. and FRESHNEY, E.C., 1982. *British Regional Geology: The Hampshire Basin.* Institute of Geological Sciences. London, HMSO, 146p.

MOON, V.G. and HEALY, T., 1994. Mechanisms of coastal cliff retreat and hazard zone delineation in soft flysch deposits. *Journal of Coastal Research,* 10(3), 663–680.

MORTON, R. A., 1991. Accurate shoreline mapping: past, present, and future. *Coastal Sediments '91* (American Society Civil Engineers), 1, pp. 997–1010.

NATIONAL RESEARCH COUNCIL, 1987. *Responding to Changes in Sea-Level—Engineering Implications.* Marine Board National Research Council. Washington DC: National Academy Press, 135p.

NATIONAL RESEARCH COUNCIL, 1990. *Managing Coastal Erosion.* Washington DC: National Academy Press, 163p.

NEU, H.J.A., 1984. Interannual variations and longer-term changes in the sea state of the North Atlantic from 1970 to 1982. *Journal of Geophysical Research,* 89(C4), 6397–6402.

NICHOLLS, R.J. and LEATHERMAN, S.P., (eds.), 1995. The potential impacts of accelerated sea-level rise on developing countries. *Journal of Coastal Research,* Special Issue No. 14.

ORFORD, J., 1987. Coastal processes: The coastal response to sea-level variation. *In:* DEVOY, R.J., (ed) *Sea Surface Studies: A Global View.* London: Croom Helm, pp. 415–463.

PETHICK, J., 1993. Shoreline adjustments and coastal management: physical and biological processes under accelerated sea-level rise. *Geographical Journal,* 159, (2), 162–168.

PILKEY, O.H.; YOUNG, R.S.; RIGGS, S.R.; SMITH, A.W.S.; WU, H., and PILKEY, W.D., 1993. The concept of shoreface profile of equilibrium: a critical review. *Journal of Coastal Research,* 9(1), 255–278.

PITTS, J., 1981. The landslides of the Axmouth-Lyme Regis Undercliff NNR, Devon, Unpublished PhD dissertation, University of London.

PITTS, J. and BRUNSDEN, D., 1987. A reconsideration of the Bindon landslide of 1839. *Proceedings of the Geologists' Association,* 98, 1–18.

PRINGLE, A.W., 1985. Holderness coast erosion and the significance of ords. *Earth Surface Processes Landforms,* 10, 107–24.

PRIOR, D.B. and RENWICK, W.H., 1980. Landslide morphology and processes on some coastal slopes in Denmark and France. *Zeitschrift Geomorph. N.F. Supplement Band,* 34, 63–86.

PUGH, D.T., 1987. *Tides, Surges and Mean Sea-level: A Handbook for Engineers.* Chichester: John Wiley and Sons. 472 p.

PUGH, D.T., 1990. Is there a sea-level problem? *Proceedings of the Institution Civil Engineers, Part 1,* 88, 347-366.

RICHARDS, K.S. and LORRIMAN, N.R., 1987. Basal erosion and mass movement. *In:* ANDERSON, M.G. and RICHARDS, K.S., (eds.), *Slope Stability.* New York: Wiley, pp. 331–357.

ROBINSON, L.A., 1977. Marine erosive processes at the cliff foot. *Marine Geology,* 23, 257–271.

ROSEN, P.S., 1978. A regional test of the Bruun Rule on shoreline erosion. *Marine Geology,* 26, M7–M16.

SCHOFIELD, J.C., 1985. Coastal change at Omaha and Great Barrier Island. *New Zealand Journal of Geology and Geophysics,* 28, 313–322.

SCHWARTZ, M.L., 1965. Laboratory study of sea-level rise as a cause of shore erosion. *Journal of Geology,* 73(3), 528–534.

SCHWARTZ, M.L., 1967. The Bruun theory of sea-level rise as a cause of shore erosion. *Journal of Geology,* 75(1), 76–92.

STAFFORD, D.B. and LANGFELDER, J., 1971. Air photo survey of coastal erosion. *Photogrammetric Engineering,* 37, 565–575.

SUBOTOWICZ, W., 1994. Catastrophical transformation of cliff coast in Poland. *In:* CARVALHO, S., (ed.) *Littoral 94 Proceedings,* Eurocoast, Portugal, Lisbon, 1, pp. 281–287.

SUNAMURA, T., 1976. Feedback relationship in wave erosion of laboratory rocky coast. *Journal of Geology,* 84, 427–437.

SUNAMURA, T., 1988. Projection of future coastal cliff recession under sea-level rise induced by the greenhouse effect: Nii-jima Island, Japan. *Transactions, Japanese Geomorphological Union,* 9(1), 17–33.

SUNAMURA, T., 1992. *Geomorphology of Rocky Coasts,* Chichester: Wiley, 302p.

THIELER, E.R. and DANFORTH, W.W., 1994. Historical shoreline mapping (I): Improving techniques and reducing positioning errors. *Journal of Coastal Research,* 10(3), 549–563.

TOWNEND, I.H., 1990. Effects of sea-level rise on the coastal zone. *In:* DOORNKAMP, J.C., (ed.) *Greenhouse Effect and Rising Sea-Levels in the UK.* Nottingham: M1 Press, pp. 63–83.

TOWNEND, I.H., 1994. Variation in design conditions in response to sea-level rise. *Proceedings of the Institution Civil Engineers Water Maritime & Energy,* 106, Sept., 205–213.

TRENHAILE, A.S., 1974. The geometry of shore platforms in England and Wales. *Transactions of the Institute of British Geographers,* 62, 129–142.

TRENHAILE, A.S., 1980. Shore platforms: a neglected coastal feature. *Progress Physical Geography,* 4, 1–23.

TRENHAILE, A.S., 1987. *The Geomorphology of Rock Coasts.* Oxford: Oxford University Press, 384p.

TRENHAILE, A.S., 1989. Sea-level oscillations and the development of rock coasts. *In:* LAKHAN, V.C. and TRENHAILE, A.S., (eds.) Applications in coastal modeling. *Elsevier Oceanography Series 49,* Elsevier: Amsterdam, pp. 271–295.

TRENHAILE, A.S. and BRYNE, M.L., 1986. A theorecical investigation of the Holocene development of rock coasts with particular reference to shore platforms. *Geografiska Annals,* 68A, 1–14.

VALENTIN, H., 1954. Der landverlust in Holderness, Ostengland Von 1852–1952. *Erde,* 6, 296–315.

VALLEJO, L.E. and DEGROOT, R., 1988. Bluff response to wave action. *Engineering Geology,* 26, 1–16.

VELEGRAKIS, A.L., 1991. *Coarse-grained Sediment Deposits within Christchurch Bay (The Shingles Bank).* Report to New Forest District Council by the Department of Oceanography, University of Southampton.

WEGGEL, R.J., 1979. A method for estimating long-term erosion rates from a long-term rise in water level. *Coastal Engineering Technical Aid No. 79-2,* CERC.

WEISHAR, L.L. and WOOD, W.L., 1983. An evaluation of offshore and beach changes on a tideless coast. *Journal of Sedimentary Petrology,* 54, 847–858.

WHEELER, R.G., 1979. *A Study of the Coastal Engineering Problems at Hook, Warsash.* Unpublished third year project report, Department of Civil Engineering, University of Southampton, 173p.

WIGLEY, T.M.L. and RAPER, S.C.B., 1992. Implications for climate and sea-level of revised IPCC emissions scenario. *Nature,* 357, 293–300.

WILCOXEN, P.J., 1986. Coastal erosion and sea-level rise: implications for Ocean Beach and San Francisco's Westside Transport Project. *Coastal Zone Management Journal,* 14(3), 173–191.

WILSON, V.; WELCH, F.B.A., and ROBBIE, and GREEN, G.W., 1958. The geology of the country around Bridport and Yeovil. *Memoir of the British Geological Survey, Sheets 327 and 312.* London: HMSO, 239p.

WOOD, W.L.; STOCKBERGER, M.T., and MADALON, L.J., 1994. Modeling beach and nearshore profile response to lake-level change. *Journal of Great Lakes Research,* 20(1) 206–214.

WOODWORTH, P.L., 1987. Trends in UK mean sea level. *Marine Geodesy,* 11, 57–87.