.

Service contract B4-3301/2001/329175/MAR/B3
“Coastal erosion – Evaluation of the need for action”
Directorate General Environment
European Commission

Living with coastal erosion in Europe: Sand and Space for Sustainability

Guidance document for quick hazard assessment of coastal erosion and associated flooding

22 May 2004

National Institute for Coastal and Marine Management of the Netherlands (RIKZ)
EUCC – The Coastal Union
IGN France International
Autonomous University of Barcelona (UAB)
French Geological Survey (BRGM)
French Institute of Environment (IFEN)
EADS Systems & Defence Electronics

CONTENTS

1. INTRODUCTION

This document was intended to provide some insight in existing basic methodologies for coastal hazard assessment in Europe, such as flooding as a result of acute coastal erosion and the general threat of land loss due to long-term coastline retreat associated with sea level rise.

Preventing all floods is not possible, but they can be managed to reduce the hazard to lives and property by the most cost-effective measures (Williams, 1994). Management must be long-term, and take into account all factors that affect flood risk. An integrated approach is required to make best use of all available data, for which geographic information systems are ideal.

Amongst others, flood hazard maps are used by land use planners and the insurance industry to delineate areas of land which are at risk from flooding up to some extreme limit (Association of British Insurers, 2000). Most hazard maps used by the insurance industry show a flood boundary based on incomplete and old records of historical events. They do not include flood depth, velocity or duration that need to be taken into account when assessing the vulnerability of an area to flooding. Flood inundation modelling is able to provide this information based on a range of flood events

A variety of analytical methodologies may be used to establish Base (1-percent-annual-chance) Flood Elevations (BFEs) and floodplains throughout coastal areas of the world. These methodologies are too voluminous to be included in this guidance document. This document provides general guidance for a simple coastal flood hazard analysis for dune systems with or without coastal protection structures. Additionally, an approach is made to give guidance for assessing the threat of long term net coastal erosion for dunes, wetlands and cliffs, with the focus on hazard mapping.

Hazard assessment is a vital part in the whole risk assessment that also comprises a vulnerability assessment. Risk assessment is carried out in a series of related activities that build up a picture of the hazards and vulnerabilities that explain disaster events:

Risk = [probability of hazard] x [estimation of social/economical loss as a result of hazard]

Information is first collected on the specific location, severity, duration and frequency of threats that are faced by a society. This is followed by an assessment of potential hazard impacts on the society's livelihoods, economy, infrastructure and key facilities, etc. Those processes that either increase or decrease vulnerability, which may be economic, social, political or environmental, will always condition the scale of these impacts.

Risk assessment therefore has three central elements:

1. Collection of relevant data and information
2. Hazard analysis, understanding the scale, nature and characteristics of a hazard
3. Vulnerability analysis, the measuring of the extent to which people or buildings are likely to suffer from a hazard occurrence.

The dynamic nature of the shoreline makes it difficult to accurately assess a community's risk and vulnerability. Extreme storm events can cause rapid, episodic erosion that can move the shoreline hundreds of feet inland, followed by an extended period in which the beach accretes back, but not completely, to its former position. These episodic events can greatly increase a community's risk of damage. Further, future projections of shoreline position reflect past sea level rise, but do not reflect future rates of sea level rise, which may accelerate because of global climate change. Conversely, communities respond to the erosion hazard by constructing shoreline protection projects (e.g., beach nourishment, seawalls, dune restoration), thus lowering their vulnerability.

Within the scope of the project EUROSION, several functional aspects of information needs on local level are addressed (see figure 1). For assessing risks in the coastal zone it is necessary to combine the concept of risk and cost benefit analyses. The entanglement of vulnerability (including social / economical value) and risk (vulnerability x hazard) require such an approach.

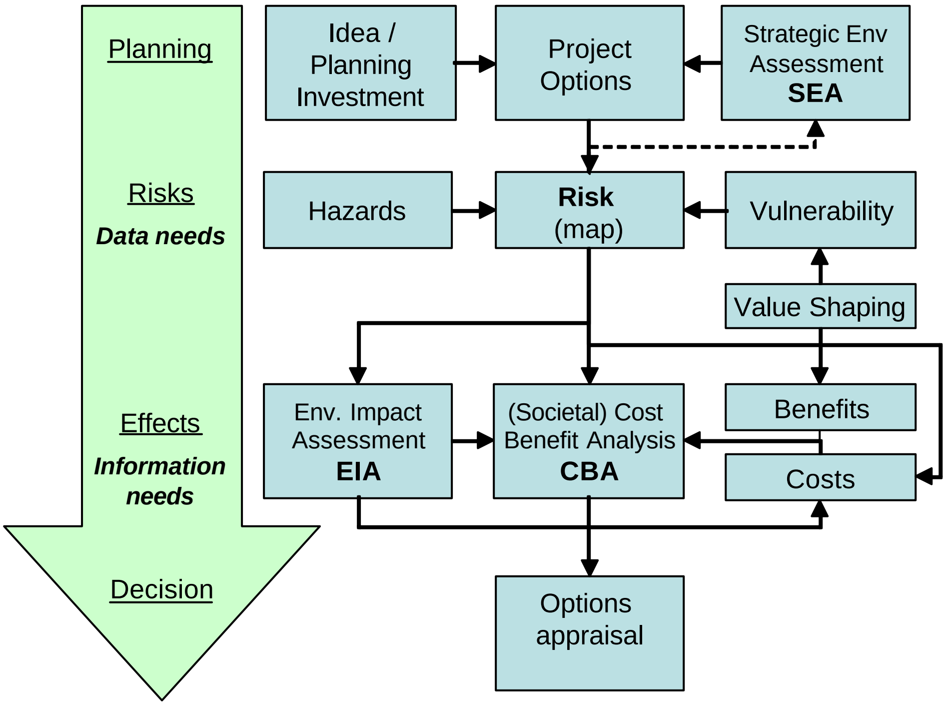

Figure 1: The EUROSION approach for functional information requirements on coastal erosion management.

In this document, the first two elements with respect to coastal hazard assessment will be discussed. For guidance on vulnerability and (combining with hazard assessment) risk assessment, see the report on cost / benefits in coastal erosion management.

2. COASTAL HAZARD ASSESSMENT

Coastal hazards in Europe are both episodic as structural. In low lying areas below mean sea level, there is a direct threat of flooding during storms. These areas are mostly associated with natural coastal defences such as beaches and dunes or artificial coastal defence structures. Another, less life threatening type of hazard is related to long term coastal dynamics and (accelerated) sea level rise. Here, coastlines (cliffs or dunes) are retreating over time, resulting in permanent land loss. Also associated with sea level rise is the increasing loss of (intertidal) wetlands where natural sedimentation may not compensate for the rising water level. Figure 2 gives an overview of processes, impacts and potential assessment tools that will briefly be discussed hereafter. In the case of acute or more structural hazard of dune areas there is a strong tendency to base models on their cross-shore profile characteristics. With respect to coastal hazard mapping, it is needed to repeat the assessment for more cross-shore transects. However, for flood modelling combination with a digital elevation model (DEM) of the flood prone area is necessary.
This geographic conversion is less needed for the traditional hazard assessment of long term cliff retreat and the loss of wetlands. Here the approach is mostly based on geographical data acquisition and processing.

In the following chapters, the five above mentioned coastal hazards will be discussed: From data collection and quick assessment tools towards coastal hazard mapping (figure 2).

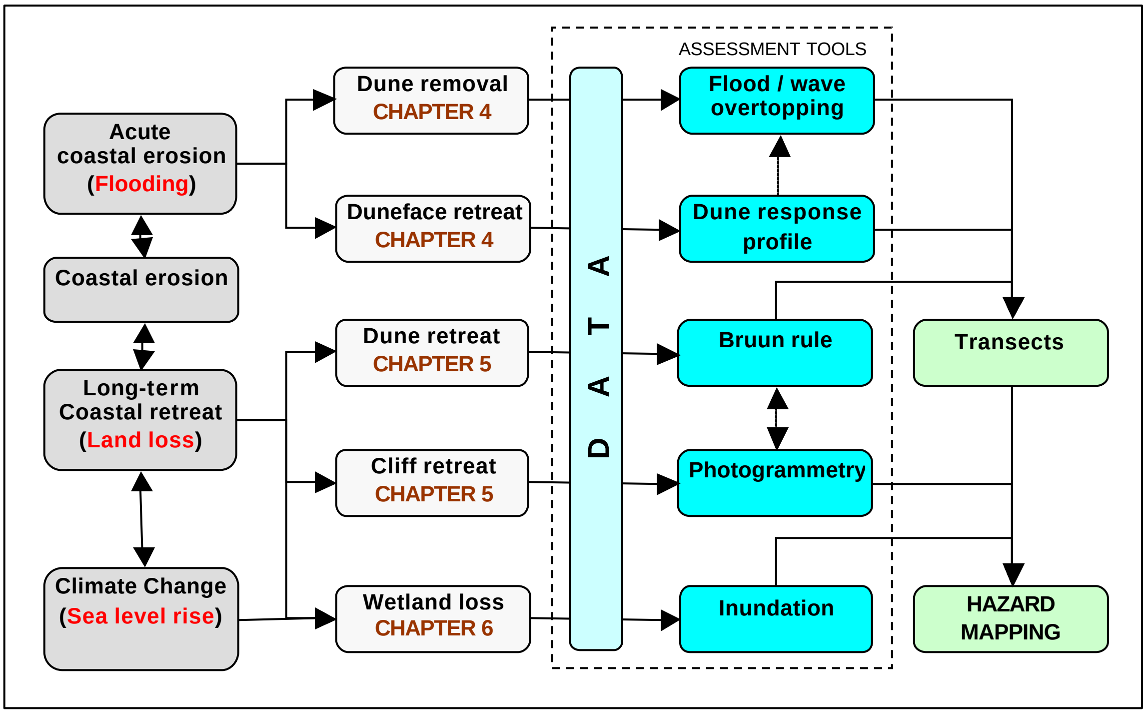

Figure 2: Impacts of coastal erosion, sea level rise and some hazard assessment approaches to come to coastal hazard mapping

3. COLLECTION OF DATA AND INFORMATION

The most relevant data needed to assess both the probability of flooding and the extent to which land loss occurs has been categorized below.

Reference topic group 1 – Administrative boundaries
- Reference topic 1.1 - terrestrial boundaries
- Reference topic 1.2 - maritime boundaries

Reference topic group 2 - Topography
- Reference topic 2.1 – Aerial photographs / orthophotographs
- Reference topic 2.2 –Satellite images
- Reference topic 2.3 - Current and historic coastline
- Reference topic 2.4 - Infrastructure
- Reference topic 2.5 - Hydrography
- Reference topic 2.6 - Terrestrial elevation
- Reference topic 2.7 - Near-shore bathymetry
- Reference topic 2.8 - Offshore bathymetry
- Reference topic 2.9 - Cross-shore profiles

Reference topic group 3 –Geomorphology, geology and sedimentology
- Reference topic 3.1 - Coastline geomorphology
- Reference topic 3.2 - Coastline geology
- Reference topic 3.3 - Seafloor sedimentology
- Reference topic 3.4 - Sediment transport
- Reference topic 3.5 - Sediment-dwelling (benthic) infauna

Reference topic group 4 - Hydrodynamics
- Reference topic 4.1 - Near-shore wave regime
- Reference topic 4.2 - Offshore wave and wind regime
- Reference topic 4.3 - Near-shore currents
- Reference topic 4.4 - Astronomic tide
- Reference topic 4.5 - Still water level

Reference topic group 5 - Land cover
- Reference topic 5.1 - Land cover
- Reference topic 5.2 - Land cover changes

Reference topic group 6 – Demography
- Reference topic 6.1 - Demography

Reference topic group 7 - Heritage
- Reference topic 7.1 - Areas of high ecological value
- Reference topic 7.2 - cultural heritage

Reference topic group 8 – Economic assets

Reference topic 8.1 - Land market value
- Reference topic 8.2 - Economic registered activities
- Reference topic 8.3 - fishery and aquaculture concession
- Reference topic 8.3 - mineral extraction concessions

Reference topic group 9 – Coastal defence
- Reference topic 9.1 - coastal defence works

4 DUNE REMOVAL AND DUNEFACE RETREAT

4.1 Introduction

The primary factor controlling the basic type of dune erosion is the pre-storm cross section lying above the 1-percent-annual-chance SWEL (frontal dune reservoir, SWEL is stillwater elevation plus wave set-up). If the elevated dune cross-sectional area is very large, erosion will result in retreat of the seaward duneface with the dune remnant remaining as a surge and wave barrier. On the other hand, if the dune cross-sectional area is relatively small, erosion will remove the pre-storm dune leaving a low, gently sloping profile. Different treatments for erosion are required for these two distinct situations because no available model of dune erosion suffices for the entire range of coastal situations.

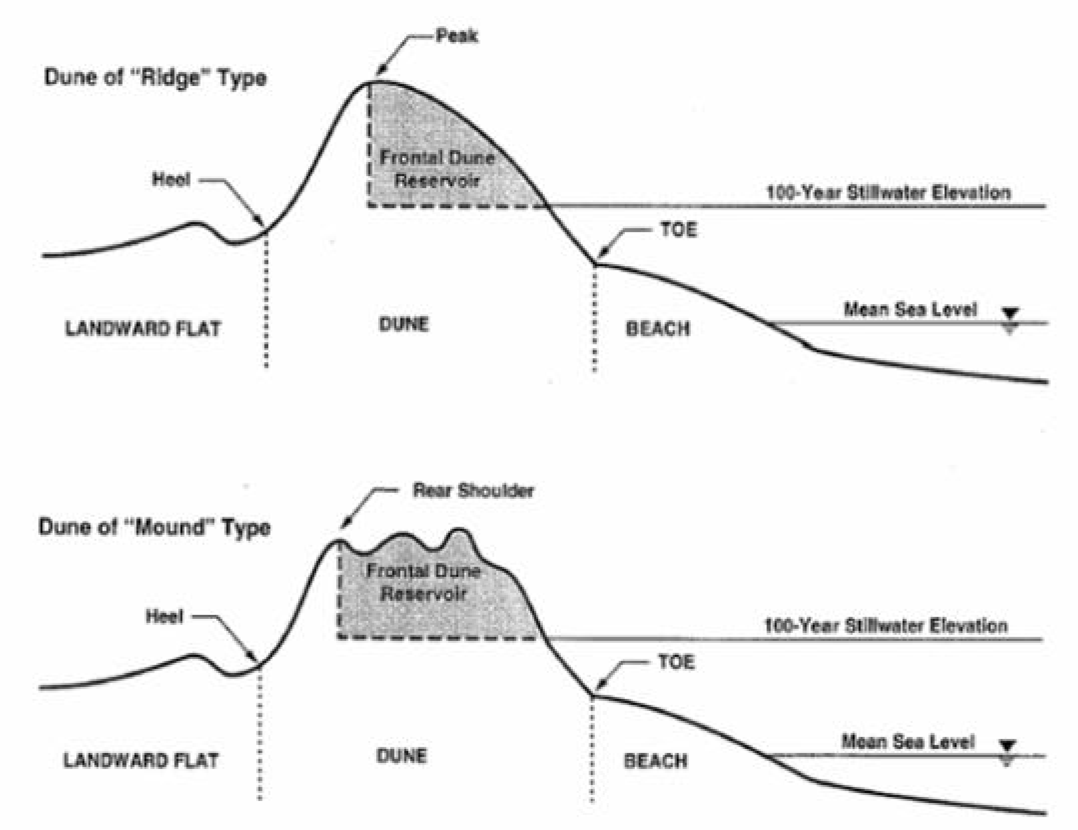

Figure 3: Different type of dunes: ridge and mound, where the peak and rear shoulder are important for hazard assessment

Figure 3 introduces terminology for two representative dune types. A frontal dune is a ridge or mound of unconsolidated sandy soil, extending continuously alongshore landward of the sand beach. The dune is defined by relatively steep slopes abutting markedly flatter and lower regions on each side. For example, a barrier island dune has inland flats on the landward side, and the beach or back beach berm on the seaward side. The dune toe is a crucial feature and can be located as the junction between gentle slope seaward and a slope of 1:10 or steeper marking the front duneface. The rear shoulder, as shown on the mound-type dune in Figure 4, is defined by the upper limit of the steep slope on the dune's landward side.

The rear shoulder of mound-type dunes corresponds to the peak of ridge-type dunes. Once erosion reaches those points, the remainder of the dune offers greatly lessened resistance and is highly susceptible to rapid and complete removal during a storm. Figure 4 shows the location of the "frontal dune reservoir," above 1-percent-annual-chance flood and seaward of the dune peak or rear shoulder. The amount of frontal dune reservoir determines dune integrity under storm-induced erosion.

4.2 Compiling relevant data

Data needed for delineating the area potentially affected by erosion-related event are:

- cross-shore profiles / transects (see *cross-shore profiles*)
- near-shore bathymetry (see *near-shore bathymetry*)
- probability of exceedance of extreme water levels (see *probability of exceedance of extreme water levels*)
- 100 yr. still water level
- Near-shore wave regime (see *nearshore wave regime*)
- Wave run-up and overtopping statistics (see *nearshore wave regime*)
- Terrestrial elevation (see *terrestrial elevation*)
- seafloor sedimentology (see *seafloor sedimentology*)
- Type of coastal defence (see infrastructure)

4.3 Dune removal and duneface retreat

To prevent dune removal during the 1-percent-annual-chance storm, the frontal dune reservoir (see figure 3) must typically have a cross-sectional area of at least 160 square meters (FEMA, November 1988). For more massive dunes, erosion will result in duneface retreat, with an escarpment formed on the seaward side of the remaining dune (see figure 4). To compute the eroded profile in such cases a simplified treatment of duneface retreat is described below.

If a dune has a frontal dune reservoir less than 160 square meters, storm-induced erosion can be expected to obliterate the existing dune with sand transported both landward and seaward. Those procedures provide a realistic eroded profile across the original dune, but do not determine detailed sand redistribution by dune erosion, overwash, and breaching.

Quantitative treatment of overwash processes is not feasible at present so the frontal dune is simply removed. The initial decision in treating erosion as duneface retreat or as dune removal is based entirely on the size of the frontal dune reservoir. For coastal profiles more complicated than those in Figure 3, it may be assumed to separate the sand reservoir expected to be effective in resisting dune removal from the landward portion of the pre-storm dune.

Figure 4 provides schematic sketches of the different geometries of dune erosion arising in coastal flood hazard assessments and the difference between dune removal and dune retreat.

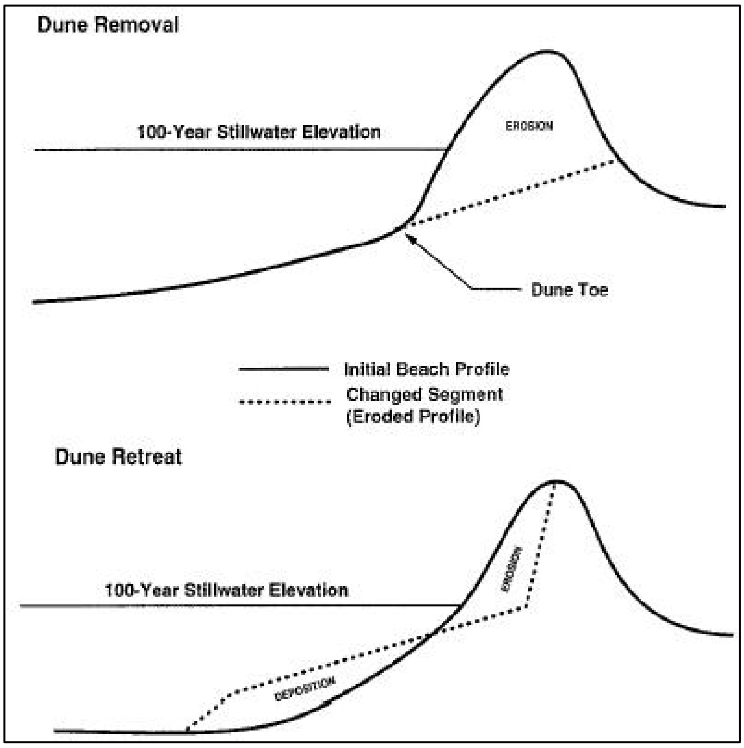

Figure 4: schematic cases of eroded dune geometries

Figure 5 presents a complete flowchart of necessary erosion considerations, outlining the major alternatives of duneface retreat and dune removal.

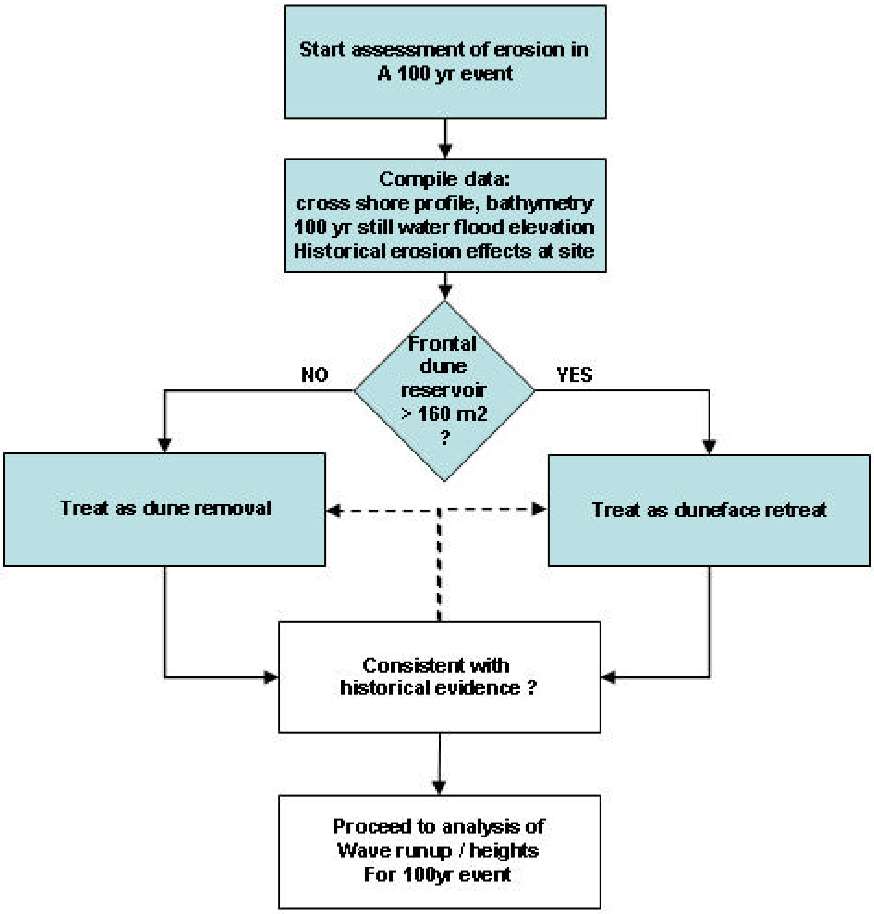

Figure 5: Flowchart of necessary erosion considerations for duneface retreat and dune removal

<u>Evaluation of Coastal structures</u>

The purpose of the evaluation is to determine whether each individual coastal structure appears properly designed and maintained in order to provide protection from the 1-percent-annual-chance flood. If a particular structure can be expected to be stable through the 1-percent-annual-chance flood, the structure geometry may figure in all ensuing analyses of wave effects accompanying the flood: coastal erosion, runup and overtopping, and wave crest elevations. Otherwise, the coastal structure is considered to be destroyed during the 1-percent-annual-chance flood and removed from the transect representation before proceeding with analyses of wave effects.

Flood protection structures can have a significant effect on the flood hazard information shown on a flood hazard map, perhaps directly justifying the removal of sizable areas from the coastal high hazard area. In contrast to flood protection, a breakwater primarily may act to limit wave action and a revetment primarily may control shore erosion, but any stable coastal structure can notably affect results of various hazard analyses for the 1-percent-annual-chance flood. Evaluation is necessary for accurate hazard assessments, because a structure might decrease flood effects in one area while increasing erosion and wave hazards at adjacent sites. Of course, the greater the potential effects of a coastal structure, the more detailed should be the evaluation process.

Documentation on the coastal structure should at least include the following:

- Type and basic layout of structure;
- Dominant site particulars,(e.g., local water depth, structure crest elevation, ice climate);
- Construction materials and present integrity;
- Historical record for structure, including construction date, maintenance plan, responsible party, repairs after storm episodes; and.
- Clear indications of effectiveness or ineffectiveness.

Treatment of dune removal

Determining the dune reservoir requires assessing the profile area located above the 1-percent-annual-chance flood level and seaward of the crest of the primary dune (see Figure 4). Where the frontal dune reservoir is less than 160 square meters, construction of the eroded profile is extremely simple: dune removal is effected by means of a seaward-dipping slope of 1:50 running through the dune toe. The eroded profile is taken to be that slope across the pre-storm dune, simply spliced onto the flanking segments of a given transect. This gives a gentle ramp across the extended storm surf zone adequate as a first approximation to the profile existing at the storm's peak. This treatment simply removes the major vertical projection of the frontal dune from the transect.
Construction of an eroded profile focuses on the usually distinct feature termed the dune toe. The dune toe is taken to be the junction between the relatively steep slope of the front duneface and the notably flatter seaward region of the beach or the backbeach berm (including any minor foredunes). If a clear slope break is not apparent on a given coastal transect, its location should be taken at the typical elevation of definite dune toes on nearby transects within the study region. The alternative is to set the dune toe at the 10-percent-annual-chance flood water level in the vicinity: that appears to be a generally adequate approximation along the Atlantic coasts. In every case, the dune toe must be taken at an elevation above that of any beach berms on local shores.

Treatment of dune face retreat

The procedure described here yields an eroded profile for duneface retreat in the 1-percent-annual-chance flood, for cases where the frontal dune reservoir is at least 160 square meters. During such retreat, the frontal dune barrier remains basically intact and eroded sand is transported in the seaward direction. The post-storm profile provides a balance between sand eroded from the duneface and sand deposited at lower elevations seaward of the dune.
The following procedure for constructing the eroded profile constitutes a simplification of the dune retreat model developed by Delft Hydraulics Laboratory (Delft Hydraulics, 1986)

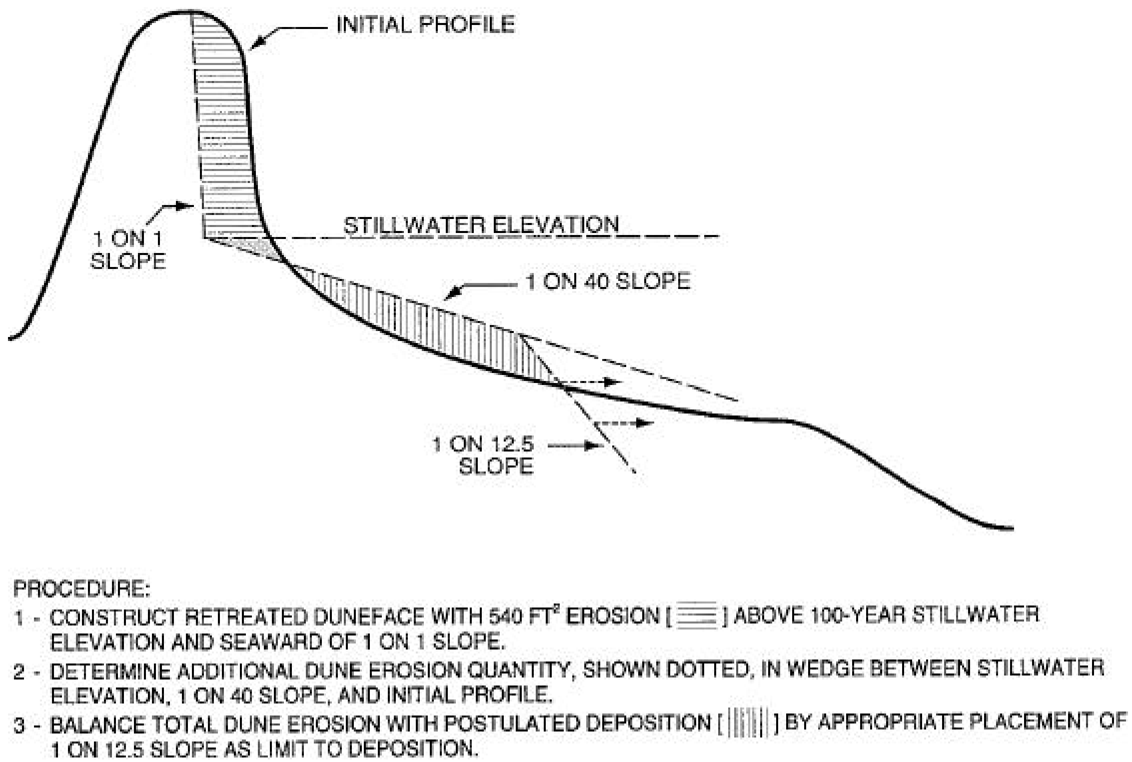

Figure 6: the procedural treatment of duneface retreat

Figure 6 summarises the simple procedure adopted to treat cases of duneface retreat. The eroded profile consists of three planar slopes: uppermost is a retreated duneface slope of 1:1, joining an extensive middle slope of 1:40, which is terminated by a brief segment with a slope of 1:12.5 at the limit to storm deposition. Upper dune erosion is specified to be 540 square meters above the 1-percent-annual-chance flood elevation and in front of the 1:1 slope. Geometrical construction balances the nearshore deposition with the total dune erosion of somewhat more than 160 square meters by an appropriate seaward extension of the 1:40 slope. The resulting eroded profile is spliced onto the unchanged landward and seaward portions of the pre-storm profile. This procedure gives a complete profile suitable for use with the Wave Runup Model in assessing an appropriate flood elevation on the dune remnant.

Wave setup, runup and overtopping for cases of dune face retreat

Wave run up is the uprush of water from wave action on a shore barrier intercepting the 100-year-return period water level. The water wedge thins and slows and reaches elevation which is higher than the 100-year-return period water level. This yields floodwaters running off or ponding landward of the dune. The mean overtopping discharge caused by waves can be predicted from the equation

Q = 0,489 EXP (0,0771 * F)

Where:
F is the maximum height of the dune remnant [m] above the 100-year return period (also called the "freeboard") and Q is expressed in cubic metres of water per second and per metre alongshore [m3/s.m].

This result was measured in Delft hydraulics tests scaled to reproduce a specific storm on the Dutch seacoast, with a significant deep-water wave height of 7,5 metre and a peak wave period of 12 seconds. Wave conditions corresponding to 100-year return period water levels along European coast may differ quite significantly from those wave conditions. However it is assumed that this formula gives a preliminary estimate of overtopping discharge.

The total quantity of water flowing into the hinterland can be estimated by integrating Q over the storm duration (taken as being 6 hours = 21600 seconds) and over the entire coastline fringed by coastal dunes. It is assumed that the variation of Q along-shore can be determined by interpolating the value of Q at profile locations.

4.4 Flood prone areas and hazard mapping

Quantity of water flowing into the hinterland as a result of wave overtopping can be converted into a flood prone area or a set of flood prone areas. This is done by first identifying the successive local minima along the cross-shore profile. A local minimum is a point cross-shore whose elevation is lower than the elevation surrounding points

a maximum water elevation inland per metre alongshore. This is done by calculating the cross-shore area delimited by the between considering the terrestrial elevation along the cross-shore profile. The cross-shore area and by iteratively estimating the cross-shore area summing the area estimating a pace of 0.1 metre

In the case of complete dune removal (see figure 4), the flood-prone area is roughly determined by the intersection of the 100-year-period water level with the terrestrial elevation.

In practice, however, water does not flow instantly in the hinterland, but propagates overland at a certain speed and encounters obstacles opposing resistance. The 100-year-return period water level is therefore reached only under exceptionally long storm duration. Some existing models make it possible to simulate the complexity of coastal flooding resulting from wave overtopping, or structural breach of the dune or dike defence. These models provide a much more reliable estimation of flood prone areas. However, they require much more important equipment and capacities. (See figure 7)

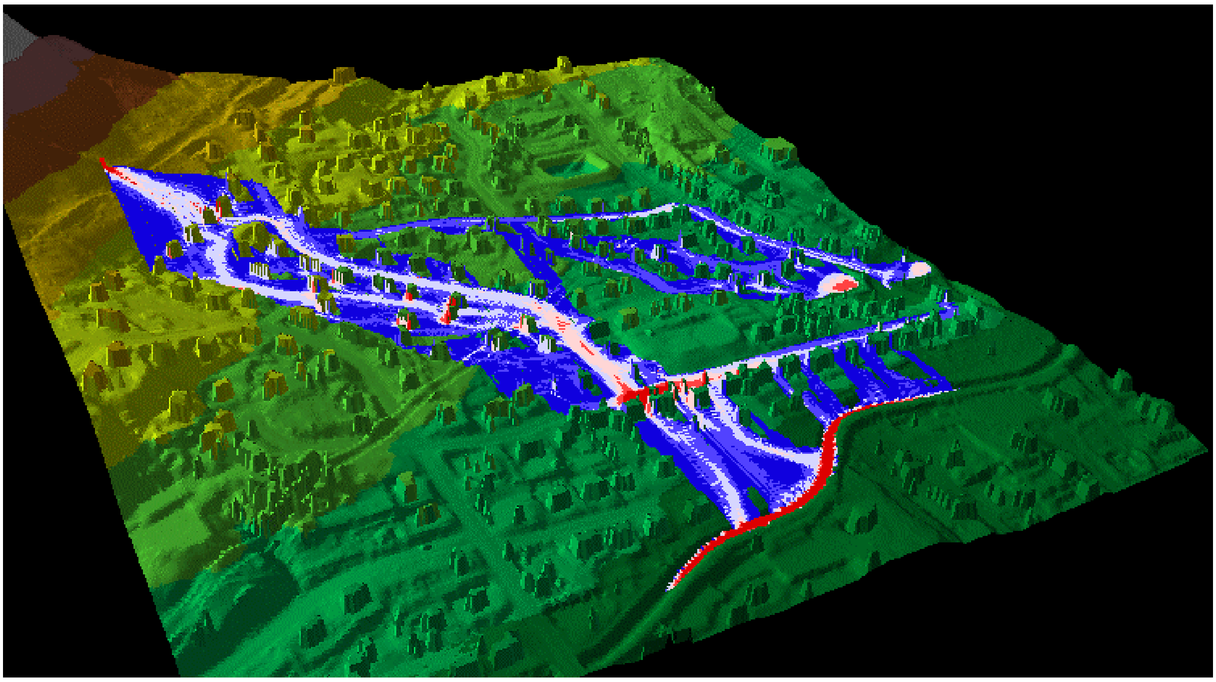

Figure 7: Illustration of an inundation process using a flood simulation model (MIKE Flood) integrated to a coastal information system. Source: Danish Hydraulics Institute (DHI)

5 LONG TERM DUNE AND CLIFF RETREAT

5.1 Introduction

For coastal management and land use planning purposes it is useful to distinguish between short term and long-term coastal erosion. Short-term coastal erosion is associated with dynamic coastline changes, which occur on all beaches (see chapter 4). Averaged over time these fluctuations do not result in permanent coastline retreat. In these situations the coastline affected by such movements is properly regarded as part of the active beach and is commonly referred to as the "dynamic envelope".

Several assessment methods exist when dealing with more or less long-term coastline recessions,

5.2 Compiling relevant data

- Reference topic 2.1 – Aerial photographs / orthophotographs
- Reference topic 2.2 –Satellite images
- Reference topic 2.3 - Current and historic coastline
- Reference topic 2.4 - Infrastructure
- Reference topic 2.5 - Hydrography
-

Reference topic group 3 –Geomorphology, geology and sedimentology
- Reference topic 3.1 - Coastline geomorphology
- Reference topic 3.2 - Coastline geology
- Reference topic 3.4 - Sediment transport
-

Reference topic group 4 - Hydrodynamics
- Reference topic 4.1 - Near-shore wave regime
- Reference topic 4.2 - Offshore wave and wind regime
- Reference topic 4.4 - Astronomic tide
- Reference topic 4.5 - Still water level

EXTRA: SEA LEVEL RISE SCENARIOS

Reference topic group 5 - Land cover
- Reference topic 5.1 - Land cover
- Reference topic 5.2 - Land cover changes

Reference topic group 9 – Coastal defence
- Reference topic 9.1 - coastal defence works

5.3 Long term dune retreat

The Bruun rule

The first and best known model relating shoreline retreat to an increase in local sea level is that proposed by Bruun [1962, see figure 8]. The analysis by Bruun assumes that with a rise in sea level, the equilibrium profile of the beach and shallow offshore moves upward and landward. Following a number of assumptions, Bruun derived the basic relationship for the extent of shoreline recession, R, due to an increase in sea level, S:

$$R = \frac{L}{B+h} S$$

Where L is the cross shore distance to the water depth h taken by Bruun as the depth to which near shore sediments exist (depth of closure), and B is the height of the dune. The analysis is two-dimensional and assumes:

1. The upper beach is eroded due to the landward translation of the profile;
2. The material eroded from the upper beach is transported immediately into the offshore and deposited, such that the volume eroded is equal to the volume deposited; and
3. The rise in the near shore bottom as a result of deposition is equal to the rise in sea level, thus maintaining a constant water depth in the offshore [SCOR, 1991].

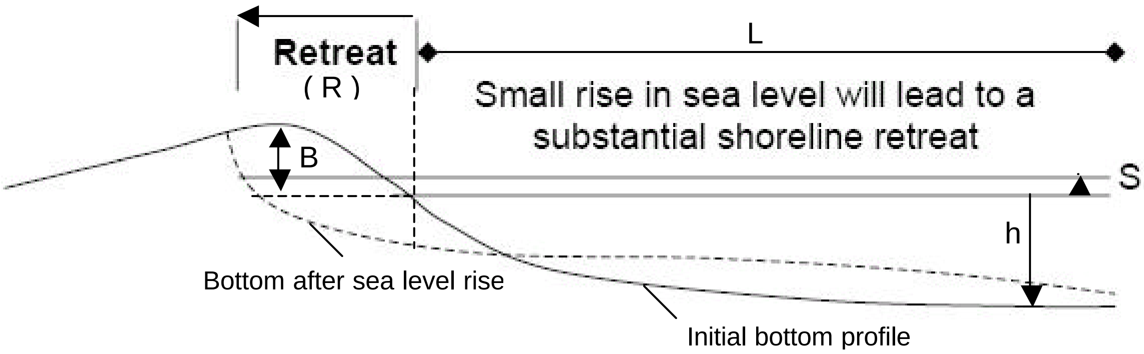

Figure 8: Main parameters of the Bruun rule

Despite its simplicity and numerous assumptions, which have in some instances led to criticism, the Bruun Rule works remarkably well in many settings

The IPCC reports that 1 cm rise in sea level erodes beaches about 1 m horizontally. This becomes a large issue for developed beaches that are less than 5 m from the ocean [IPCC, 1998]. In addition, rising sea level would create larger storm surges that would quicken the rate of beach erosion; an intense storm can erode enough shore to change its entire profile in one year [Dubois, 1990]. Dubois's research has shown that observed values of beach erosion were two to three times greater than the erosion predicted for that year. Dubois suggests that Bruun's theory and rising sea level may the primary force responsible for observed erosion rates [Dubois, 1990]. Bruun's rule states that a typical concave-upward beach profile erodes sand from the beach face and deposits it offshore to maintain constant water depth Bruun's rule can be applied to correlate sea level rise with eroding beaches. With present rates of sea level rise, 70% of the world's sandy beaches are eroding and retreating. If the rate of sea level rise continues to increase, the loss of beach to coastal erosion will increase.

5.4 Cliff retreat

Cliff recession and coastal landsliding present significant threats to land use and development, for example on the south and east coasts of England. Although individual failures often tend to cause only small amounts of cliff retreat, the cumulative effects can be dramatic. For example, the Holderness coast (UK) has retreated by around 2km over the last 1000 years, including at least 26 villages listed in the Domesday survey of 1086; 75Mm3 of land has been lost in 100 years (Valentin, 1954; Pethick 1996). On parts of the north Norfolk coast there has been over 175m of recession since 1885 (Clayton and Coventry 1986).

Cliffs are open sediment transport systems characterised by inputs, throughputs and outputs of material, i.e. they are cascading systems. The concept of a "cliff behaviour unit" (CBU) provides an important framework for cliff management (Lee 1997; Moore et al, 1998; Brunsden and Lee 2000). These units (CBUs) span the nearshore to the cliff top and are coupled to adjacent CBU's within the framework provided by littoral cells/sediment cells. A range of types of cliff system can be recognised on the basis of the throughput and storage of sediment within the system (see figure 9)

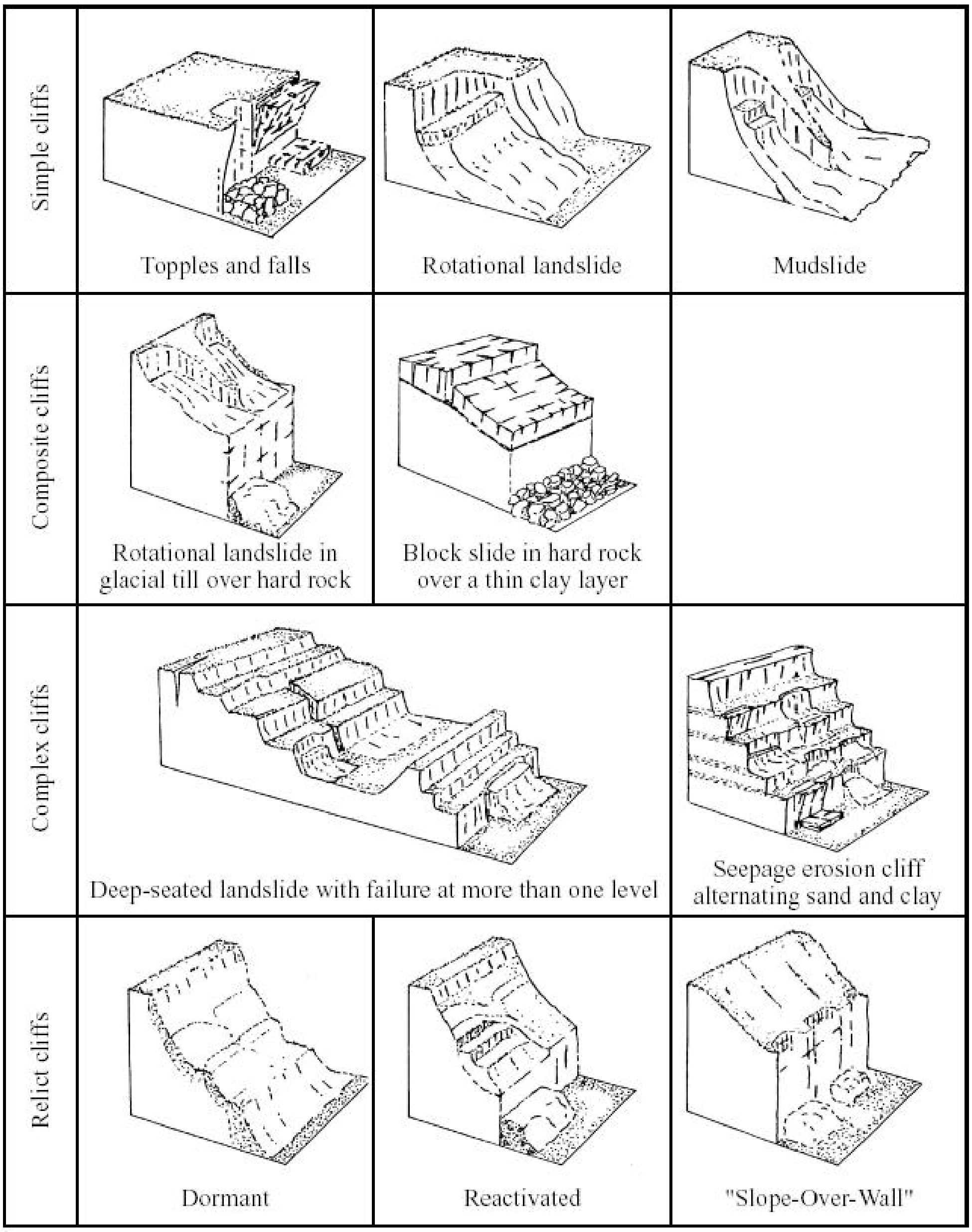

Figure 9: The main CBU Types

Over time, cliffs may demonstrate two contrasting modes of behaviour:

• a complex and uncertain sequence of recession events, often with variable time periods between events depending on the sequence of storms and the variable stability state of the cliff. Thus, storm events of a particular magnitude may be redundant (i.e. do not initiate cliff recession) until preparatory factors (e.g. weathering, strain softening etc.) lower the slope stability to a critical level at which time a smaller storm may “trigger” recession;

• the establishment and maintenance of a characteristic set of landforms within a CBU which persist through time, although individual components will be evolving and the pattern and interrelationships of these features will be continuously changing.

These two conditions highlight a fundamental problem for the prediction and measurement of cliff recession - the need to relate highly variable records or observations of recession events to the overall trend operating within a CBU. Here, it is convenient to view cliff recession over a range of relevant timescales:

1. Short term behaviour; when viewed from this perspective recession appears to be a highly variable process, with marked fluctuations in the annual recession rate around an average value. This type of behaviour is characterised by periods of no activity punctuated by short phases of recession.

2. Medium term behaviour; over this timescale the fluctuations smooth themselves out as there is a tendency for CBU's to maintain a balance between process and form through negative feedback and self-regulatory mechanisms (e.g. storage of debris). When viewed from this perspective the recession rate will be relatively constant. This medium term condition can be regarded as reflecting steady-state behaviour characterised by maintenance of CBU form, parallel retreat of the cliff profile and a balance over time in the sediment budget, i.e. the overall rate of detachment equals the overall rate of removal from the foreshore, with minimal changes in the volume of material stored within the cliff system.

3. Long term behaviour; over this timescale the characteristics of the CBU may gradually change, reflecting the progressive evolution of the cliffline in response to major environmental changes, e.g. the Holocene climate and sea level changes.

Cliff recession hazard assessment involves the assessment of the probability of a recession or coastal landslide event of particular size and type occurring over a particular time period. An important element of hazard assessment is the definition of the recession potential, in terms of the nature and size of events that could be expected in a CBU. This will require an appreciation of:

- the nature and magnitude of historical events;
- the factors influencing the pattern of recession events;
- the causes and mechanisms of possible events;
- the theoretical occurrence of triggering or initiating events.

When assessing probabilities it is often more reliable to consider the conditional probability. For example:

Annual probability of loss = Probability of Initiating Storm Event x Probability of No Beach Present (given the storm event) x Probability of a Landslide (given the preceding conditions)

The most straightforward linear regression approach to predicting cliff recession using historic data is a continuous linear model (Crowell et al., 1997, Amin and Davidson-Arnott, 1997):

$X_t = ß_0 + ß_1 t + e$

Where X_t is the recession distance at time t and e is a random variable that has a Gaussian distribution with zero mean and variance v. Hence the distribution of X_t will be Gaussian with mean $ß_0 + ß_1 t$ and variance v. If there are n historic observations of cliff position x_i at time t_i then the maximum likelihood estimators for $ß_0$ and $ß_1$ can be found from simple linear regression theory.

Although there is much uncertainty about the impact of sea level rise and climate change, it is expected to result in increased recession rates. A number of simple empirical models are available to provide an indication of the possible changes:

1. Historical projection; where future recession rates are extrapolated as follows (National Research Council 1987):

$$\text{Future recession rate} = \frac{\text{Historical recession rate}}{\text{Historical sea level rise}} \times \text{Future sea level rise}$$

The model is very simple, but assumes that sea level rise is the dominant influence on recession.

2. Geometric models; where sea level rise is assumed to result in the parallel retreat of the cliff profile (Bruun 1962), 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 i.e. the additional recession (R) above the historical rate.

$$R = S \times \frac{L}{P(B+h)}$$

Where:
S = sea level rise
h = closure depth
P = Sediment Overfill
L = Length of CBU profile
B = Cliff height

The sediment overfill function is the proportion of sediment eroded that is sufficiently coarse to remain within the equilibrium profile.

3. 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. To model reliably the three-dimensional situation, a full sediment budget needs to be calculated for the littoral cell being considered. If it is assumed, however, that the historical recession rate represents the net contribution to the sediment budget, the Bruun Rule (see above) can be modified to predict the recession increase due to sea level rise (R) as follows (Dean 1991):

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

Where:
R1 = historical recession rate
Sc = change in rate of sea level rise

The change in sea level rise is the difference between the historical and future sea level rise. This is believed to be the most realistic adaptation of the Bruun Rule for eroding cliffs (Bray and Hooke 1997).

4. Shore Platform Geometrical Model; where no beach is present to dissipate wave energy, direct relationships may be formulated to predict recession according to material strength and wave power (e.g. Sunamura 1992). Additional erosion (R) can be estimated from the amount of sea-level rise and the gradient of the shore platform, as follows:

$$R = R_1 + \frac{Sc}{h(R_1 + L)}$$

5.5 Coastline recession hazard mapping

Cliff retreat

The results need to be interpreted within the context of the contemporary and anticipated CBU behavior. Short-term predictions of cliff top recession can be misleading when the CBU evolves through episodic events occurring, on average 100 years or so. Ideally predictions should cover at least one complete recession “cycle”; the pragmatic guidance on the medium term steady-state timescales provided earlier is equally relevant here, as are the alternative approaches to expressing predicted recession rates.

Cliff recession data and predictions can be presented in a variety of ways, including:

1. Tabular form.

2. Graphical form, including:

- annual and cumulative measured recession;

- cliff profile measurements;
- plots of cliff recession simulations and predictions;
- probability density functions of the cliff position at a given time;
- probability density functions for the time required for cliff recession to reach a
- given point.

3. Map form; showing at an appropriate scale:
   - the best estimate of cliff position after a given time including confidence limits and prediction limits;
   - a zoning based on the cumulative probability distribution of cliff recession over a given time (Figure 10 and 11). For example:

Zone 1; It is certain that land within this zone will be affected by recession within a given time period.
Zone 2; There is a 50% chance that land within this zone will be affected by recession within a given time period.
Zone 3; There is a 10% chance that land within this zone will be affected by recession within a given time period.
Zone 4; There is a 1% chance that land within this zone will be affected by recession within a given time period.

Note that the probabilities that define the zone divisions are arbitrary and can be varied to suit the purpose. More detail (i.e. more zones) may be justified in areas with more assets at risk. This form of presentation does not differentiate between different locations within the same zone, although in reality properties at the landward and seaward extent of a zone will have different probabilities of being affected by recession.

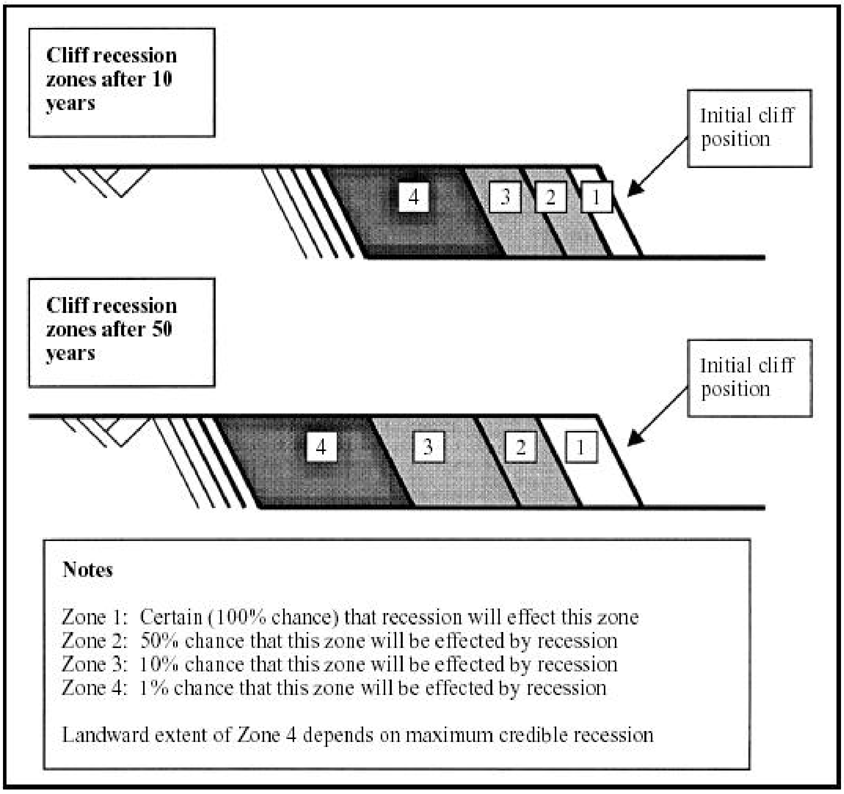

Figure 10: a zoning based on the cumulative probability distribution of cliff recession over a given time

Figure 11: Practice example of a zoning based on the cumulative probability distribution of cliff recession over a given time

Shoreline retreat

Digitally rectified aerial photographs have become an important tool in historical shoreline mapping. They are replacing the need for traditional methods such as using a zoom transfer scope to project shorelines onto a base map. Digitally rectified aerial photographs have all the elements of a photograph, but the image distortion caused by tilt of aircraft, camera lens, and relief displacement has been corrected. Also, the image is georeferenced and therefore may be combined with other forms of geographic data in a geographic information system (GIS).

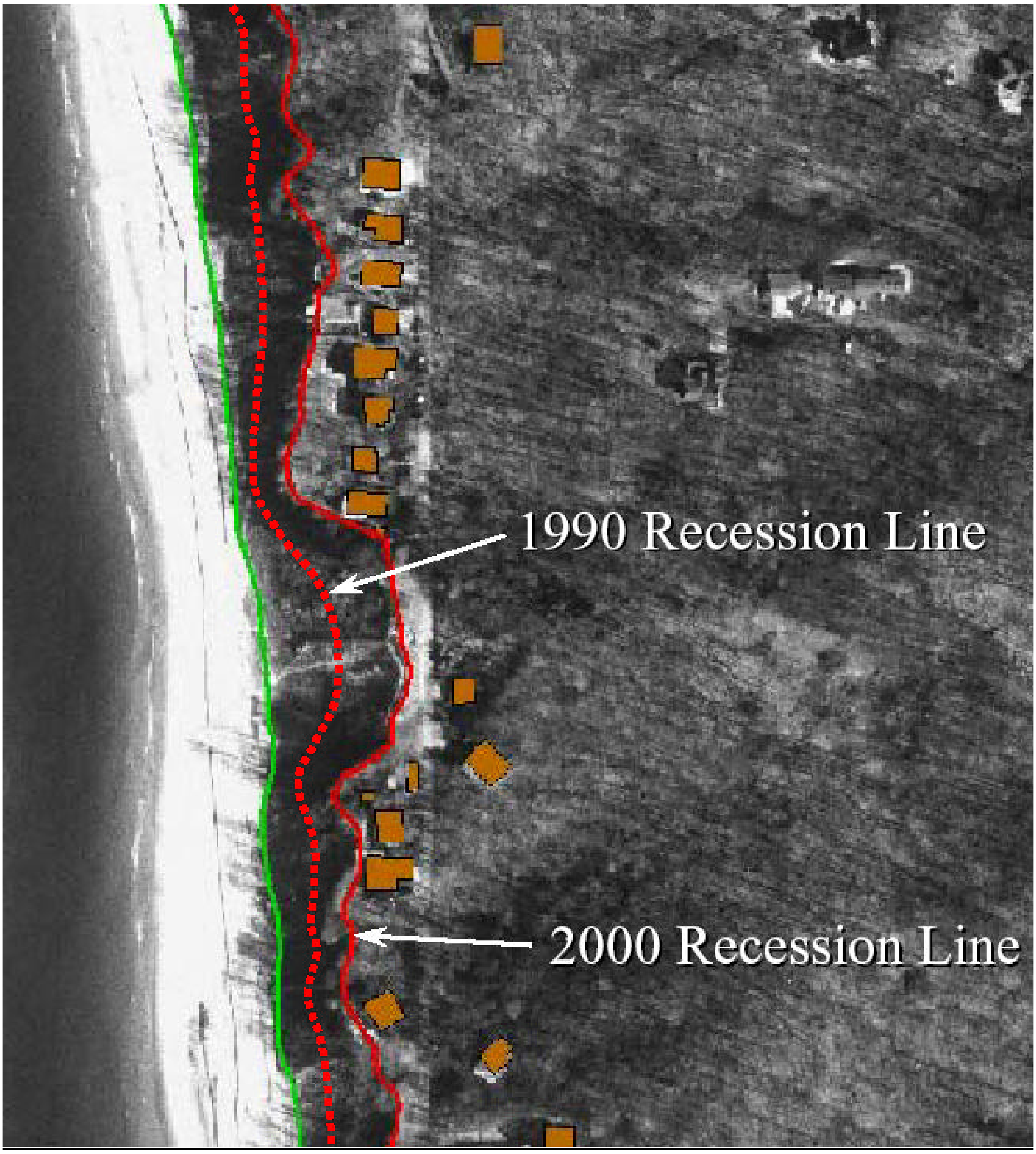

Figure 12: Practice example of recession lines for coastline retreat

Vector based shoreline change analysis and GIS application

Vector based shoreline change analysis provides a model of temporal erosion and accretion for any set of linear historic shoreline data. The vector approach to analyzing historic shoreline change data contrasts with a raster approach in its sampling flexibility and temporal scale-ability. The vector approach as illustrated in the figure below can accept any number of temporal linear representations of the shoreline and can flexibly sample those shorelines to calculate past variability and project future changes (Van Dusen, 1997).

A limited section of the shoreline change data and analysis approach are presented below. Note the shift from net overall loss (erosion) to net overall gain (accretion) as the analysis moves from left to right. Uplands are at the top of the image, offshore areas at the bottom of the image. Transects are spaced at 50 meter intervals. Scale is 1:4500

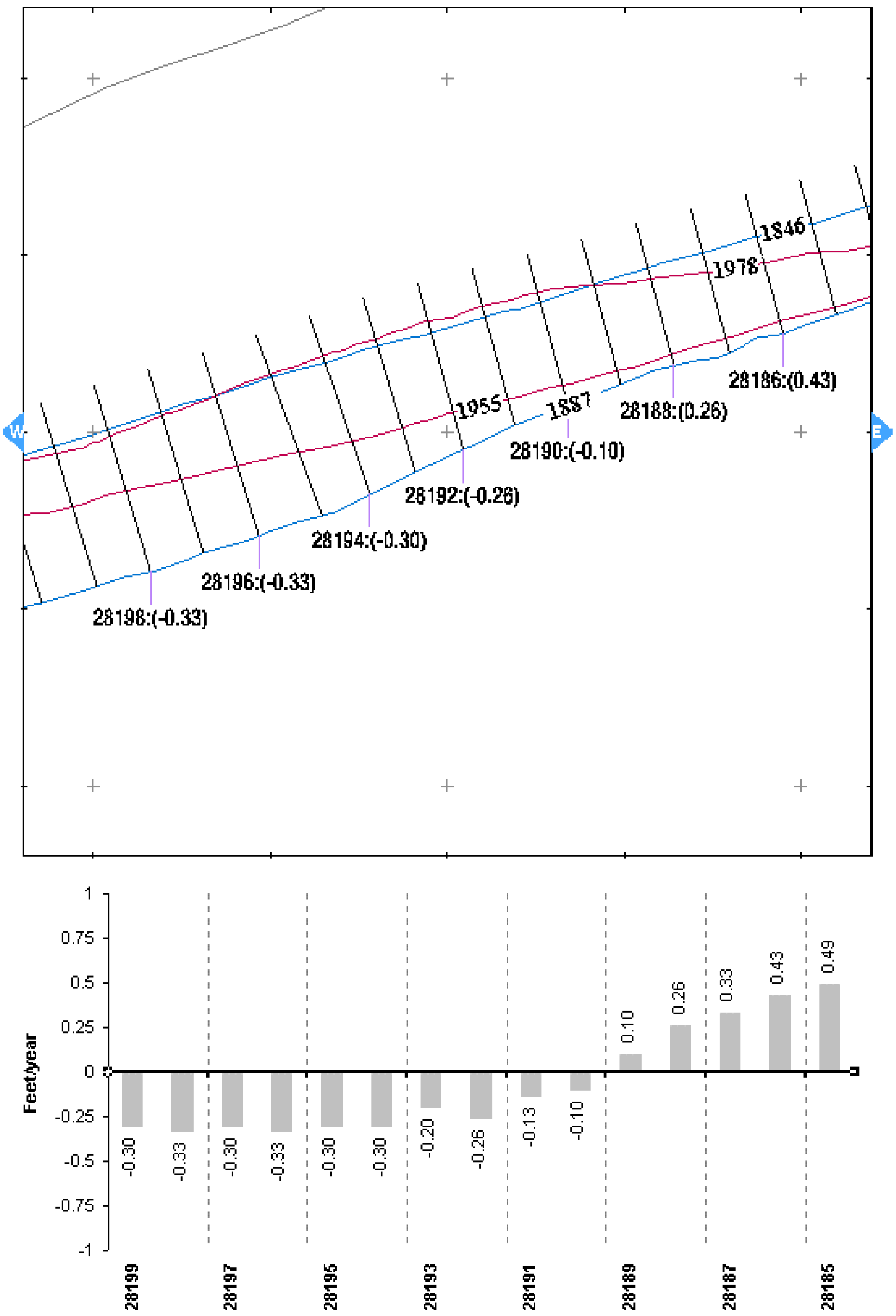

Figure 13: Practice GIS example of recession lines for coastline retreat

In the example above (figure 13), linear historic shoreline data as early as 1844 and as recent as 1982 were provided and an analysis was undertaken to define and execute a procedure for deriving the historic rate of shoreline change using a vector-based methodology.

6. SEA LEVEL RISE AND LOSS OF WETLANDS

6.1 Introduction

Wetlands are areas that are situated between land and sea. They are inundated regularly, not because of extreme situations, but simply because of the tide. Table 1 gives some European areas of coastal wetlands in km2 and as a percentage of the total area (Gilbert et al., 1990) and some other regions for comparison.

Table 1: Wetland areas (Gilbert et al., 1990)

Region	Wetlands [km2]	% of the region
North and Western Europe	31515	0.713
Baltic sea coast	2123	0.176
Northern Mediterranean	6497	0.609
North America	32330	1.639
East Asia	102074	0.999
South-east Asia	122595	3.424
Pacific ocean large islands	89500	19.385

Wetlands are of importance from an ecological point of view: they serve as nursery grounds for fish, provide food for birds and are a habitat for many other animals. Apart from that, they also provide protection from storms and flooding. Roughly, wetlands may be divided in three categories, depending on the occurring salinity levels.

1. Salt marshes
   Salt marshes occur in a higher latitude (compared with mangroves) and saline environment. Salt marshes are found on the landward side of barriers. In that position they are mainly indirectly threatened by sea level rise, in the sense that they may be buried under a barrier moving in landward direction (see also figure 15)

2. Brackish marshes
   In brackish marshes salinity levels are smaller than 30 ppt (about 17000 mg CL^-/l). They can be found in estuaries at places with calm water and abundant sediment supply. Because of this sediment supply and their own organic production, they are normally able to keep pace with a rising sea level.

3. Tidal fresh water marshes
   These marshes come across in the more elevated parts of estuaries. They are therefore less frequently inundated and have lower salinity levels (about 2750 mg CL^-/l). When sea level rises, the main hazard for freshwater marshes is saltwater intrusion; the marsh becomes brackish or saline, which results in original plant species being replaced by more salt resistant ones. Digging of access canals for navigation may also induce salinisation.

Hence, there are three major ways by which sea level rise can disrupt wetlands: inundation, erosion, and saltwater intrusion. In some cases, wetlands will be converted to bodies of open water; in other cases, the type of vegetation will change but a particular area will still be wetlands However, if sea level rises slowly enough, the ability of wetlands to grow upward-by trapping sediment or building upon the peat the sediment creates-can prevent sea level rise from disrupting the wetlands.
In explaining potential impacts of sea level rise, we focus on what the impact would be if wetlands did not grow upward, and leave it to the reader to remember that this potential "vertical accretion" can offset these impacts. The actual impact will depend on the "net substrate change," i.e., the difference between sea level rise and wetland accretion. Here, all estimates of future wetland loss are based on the assumption that current rates of vertical accretion continue.

Coastal marshes have kept pace with the slow rate of sea level rise that has characterized the last several thousand years (see figure 14). Thus, the area of marsh has expanded over time as now lands were inundated, resulting in much more wetland acreage than dry land just above the wetlands (A and

B). If in the future, sea level rises faster than the ability of the marsh to keep pace, the marsh area will contract (C). Construction of bulkheads to protect economic development may prevent now marsh from forming and result in a total loss of marsh in some areas (D).

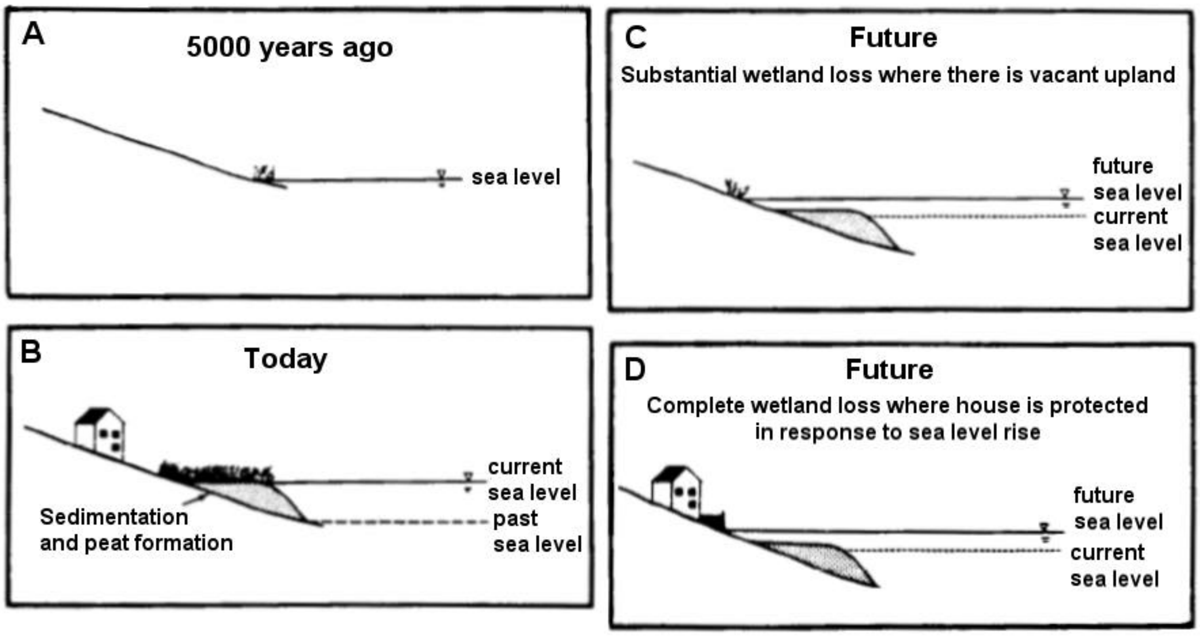

Figure 14: Partly and complete wetland loss in the future due to sea level rise and the human factor.

The direct wetland response to sea-level rise is modelled by selecting two critical values of sea-level rise, scaled by tidal range; the lower value distinguishes no wetland loss from wetland loss; while the upper value distinguishes partial loss from near-total loss. Loss is modelled linearly between the two threshold values. The potential for wetland migration on to adjacent low-lying upland is evaluated, based on coastal morphology and coastal population density. In addition to the effects of sea-level rise, direct human reclamation is likely to cause large global reductions in coastal wetlands. Based on current trends, 60% of the present wetland stock would be lost by the 2080s without consideration of sea-level rise. It is likely that the loss rate of coastal wetlands will decline with time due to both an increasing rarity, and rising living standards that give the environment a higher value. Therefore, a reference scenario of losses of 1% a year in the 1990s, declining uniformly to a constant 0.4% a year in the 2020s, was assumed. This gives a loss of 37% of the global wetland stock by the 2080s without sea-level rise (IPCC, 1995)

6.2 Compiling relevant data

Reference topic group 2 - Topography

- Reference topic 2.1 – Aerial photographs / orthophotographs
- Reference topic 2.2 –Satellite images
- Reference topic 2.3 - Current and historic coastline
- Reference topic 2.4 - Infrastructure
- Reference topic 2.5 - Hydrography
- Reference topic 2.6 - Terrestrial elevation
- Reference topic 2.7 - Near-shore bathymetry
- Reference topic 2.8 - Offshore bathymetry

Reference topic group 3 –Geomorphology, geology and sedimentology

- Reference topic 3.1 - Coastline geomorphology
- Reference topic 3.2 - Coastline geology
- Reference topic 3.3 - Seafloor sedimentology
- Reference topic 3.4 - Sediment transport

· Reference topic 3.5 - Sediment-dwelling (benthic) in fauna

Reference topic group 4 - Hydrodynamics
· Reference topic 4.3 - Near-shore currents
· Reference topic 4.4 - Astronomic tide

Reference topic group 5 - Land cover
· Reference topic 5.1 - Land cover
· Reference topic 5.2 - Land cover changes

Reference topic group 6 – Demography
· Reference topic 6.1 - Demography

Reference topic group 7 - Heritage
· Reference topic 7.1 - Areas of high ecological value
· Reference topic 7.2 - cultural heritage

Reference topic group 8 – Economic assets
· Reference topic 8.2 - Economic registered activities
· Reference topic 8.3 - fishery and aquaculture concession
· Reference topic 8.3 - mineral extraction concessions

Reference topic group 9 – Coastal defence
· Reference topic 9.1 - coastal defence works

6.3 Loss of wetlands

The potential change in salt marsh stock may be evaluated using a method described by Nicholls et al. (1999). This compares the vertical accretion potential to sea-level rise and considers the possibility of salt marsh migration due to planned or unplanned retreat of coastal defences. For vertical accretion, the rate of sea-level rise is normalised by tidal range. This is used in conjunction with a critical value of sea-level rise to determine salt marsh response to rising sea levels. Above the critical rate, increasing losses of salt marsh are assumed to occur. This critical value may be reduced as increased coastal development leads to measures that reduce the sediment supplies available for vertical accretion. There are important limitations to these methods. In particular, the loss method is difficult to validate or verify, and there is considerable uncertainty concerning the critical values that were used. In addition, the method is not specific about which part of the salt marsh is lost – only a proportional loss is determined. Therefore, the salt marsh losses are best interpreted as indicative results.

Climate change scenarios

To reduce the large number of scenario combinations, the climate change and socio-economic scenarios may be linked as shown in Table 2. The “High climate change scenario” and the “Regional Enterprise socio-economic scenario” combines the highest climate and socio-economic pressure and provides the extreme case of a society that does not respond to the threat of climate change over the next 50 years. The “Low climate change scenario” combined with the “Global Sustainability socio-economic scenario” has the lowest climate and socio-economic pressure, representing a ‘better case’ situation (Nichols et al., 1999).

Table 2. Climate change scenarios (1990 to 250s)

UKCIP98 Scenario	Relative Sea Level Rise (m)	Peak river flows
LOW	0.16	5%
HIGH	0.71	20%

Or one may it do it like this, based on IPCC assumptions (www.ipcc.ch):

- Rise of mean sea level: +55 cm (15 cm eustatic; 40 cm man made)
- Increase of tidal range: +30 cm (mthw + 15 cm; mtlw –15 cm)
- Rise of air temperature: +2.7o C

- Precipitation: +9.8 % (March-May + 22.1 %; June-August –6.0 %)
- Wind speed: +3.8 % (Sept.-Nov. +6.8 %; June-August –4.3 %)
- CO_2: +100 %

Accretion processes

The other major line of study deals with relations between sea-level variations and accretion processes on salt marshes. This is because salt marsh evolution is controlled by the changing balance between sea-level variation, tidal regime, wind-wave climate, sediment supply, and wetland vegetation (Reed, 1990; Allen and Pye, 1992). It is, consequently, suggested that acceleration of present sea-level rise due to global warming could cause substantial losses of coastal salt marshes (Orson et al., 1985; Stevenson et al., 1986; Viles and Spencer, 1995). Models of the accretion balance presented by Allen (1990) and French (1991, 1993, 1994) demonstrate, however, that no simple relationship exists between one or more of the above mentioned parameters and the growth or decay of salt marshes. This may explain why different accretion rates are recorded in salt marshes developed under apparently similar conditions. Another reason for this apparent lack of relationship is that net sediment accumulation may vary greatly within a single salt marsh area as a consequence of the morphology

A number of methods have been used to evaluate sedimentation rates on salt marshes. Many sediment budget studies have been based on the use of marker horizons (e.g. Nielsen, 1935; Letzsch, 1983), or marker piles (Harrison and Bloom, 1977). Radioisotope dating techniques have been used by e.g. Bartholdy and Madsen (1985). In recent years a number of authors have used various kinds of traps to elaborate on the direct connection between dynamics and sedimentation on short time scales. A shortcoming of all these methods is that they may provide only little spatial information. Repeated levelling may be used in order to obtain information on a wider scale

Example: Study Area of Skallingen (DK)

The Skallingen (Denmark) salt marsh is one of the biggest un-diked salt marsh areas in Europe. It covers an area of 31 km2 and is located in the Grådyb tidal area on the east (lagoonal) side of the Skallingen barrier spit (Figure 15). The Skallingen salt marsh is young. It started to develop in the beginning of the last century when dikes were build between dunes along the shorelines to the west in order to prevent overwash activity. The marsh surface is situated at heights of about 1 m above DNN (Danish Ordnance Datum). This means that the salt marsh is flooded 9% of the year. Systematic measurements of accretion rates were started in 1931 when 5 plots were covered by a 2 mm thick layer of sand

Long-term accretion/erosion from levelling
The development of the salt marsh from 1931 to 1973 is demonstrated in Figure 16a. Figure 16b shows in more details the development up to 1998. Generally, accumulation has occurred in three morphological units: 1) where the marsh has expanded towards the east, 2) on the marsh, mostly within the inner- and outer-marsh and less pronounced on the inner wadden and 3) in shape of levees along the creeks. Evidently no net erosion happens on the continuous marsh surfaces. Negative values (erosion) only occur as spikes on the profile. They are associated with new creek formations or deepening or sideways movement of old creeks.

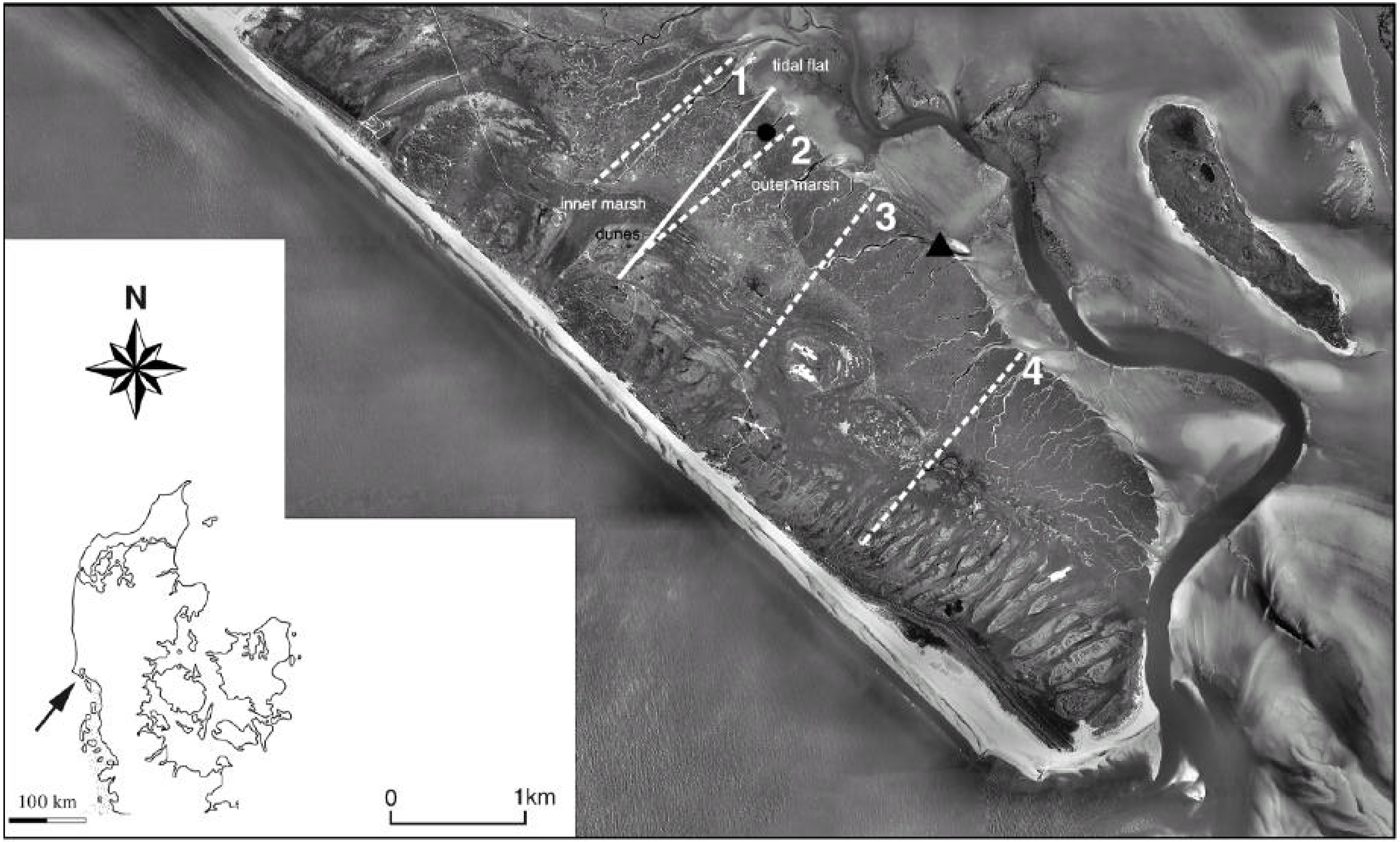

Figure 15: Example study area at Skallingen (DK) which is one of the largest un-diked salt marsh in the EU. Notice the leveling transects and location of measuring equipment.

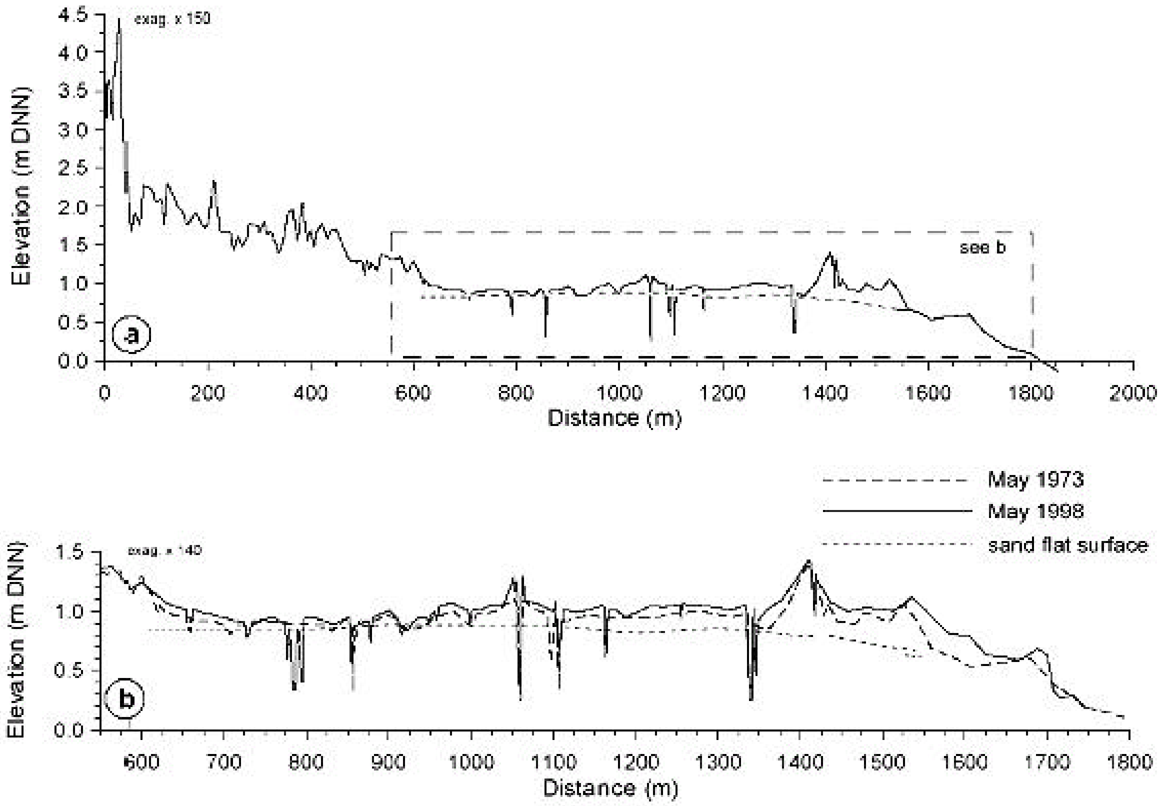

Figure 16: a) Topography of the 1973 profile and of the pre salt marsh sand surface. b) Profile of the outer part of 1998 surface compared to older surfaces (for location see Figure 16a)

6.4 wetland loss mapping

For wetland dynamics mapping one may use a common 5 km x 5 km grid based on a common geographically referenced database within an ArcView geographic information system (GIS). This can facilitate the integration of sectoral analyses, and the combination of model outputs within the same system is essential for the exchange, visualisation and presentation of the research results (Figure 17).

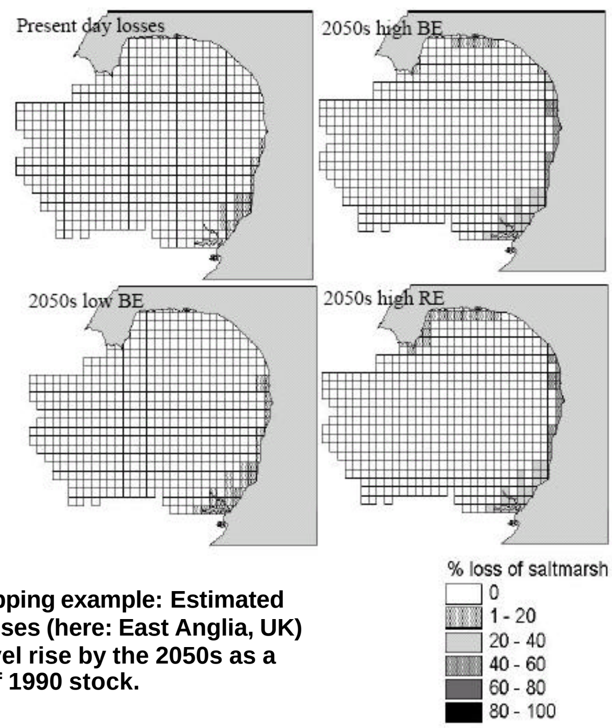

Figure 17: Mapping example: Estimated salt marsh losses (here: East Anglia, UK) due to sea-level rise by the 2050s as a percentage of 1990 stock.

7. REFERENCES

P. B. Williams, “Flood-Control vs Flood Management ,” Civil Engineering , vol. 64, pp. 51-54 , 1994.

Association of British Insurers “Inland Flooding Risk” (Sept 2000) – ABI
http://www.insurance.org.uk

Federal Emergency Management Agency (FEMA). (November 1988). Basis of Erosion Assessment Procedures for Coastal Flood Insurance Studies. Washington, D.C.

Federal Emergency Management Agency (FEMA), April 2003. Guidelines and Specifications for Flood Hazard Mapping Partners. Appendix D: Guidance for coastal flooding analyses and mapping

Delft Hydraulics Laboratory. (1986). Wave Runup and Overtopping at Dunes During Extreme Storm Surge Report M1819, Part II. (in Dutch). Delft, The Netherlands

Bruun, P. 1962, 'Sea-level rise as a cause of shore erosion', Journal Waterways and Harbours Division, vol. 88(1-3), pp. 117-130.

SCOR Working Group 89, 1991. The response of beaches to sea-level changes: A review of predictive models. Journal of Coastal Research, 7, 895-921.

Dubois, R. N., Barrier beach erosion and rising sea level, Geology, 18, 1150-1152, 1990.

Regional Impacts of Climate Change (IPCC) mdash;North America, 1998, Available: [Online][1999, January 27]

James G. Titus, ed., 1988. Sea level rise and wetland loss: an overview. Washington, D.C.: U.S. Environmental Protection Agency. 186 pp. EPA 230-05-86-013.

Gilbert, J.T.E., Vellinga, P. et al. 1990. Strategies for adaptation to Sea Level Rise. Intergovernmental Panel on Climate Change (IPCC), Response Strategies Working Group (III).

Nicholls, R.J., Hoozemans, M.J., & Marchand, M. (1999) Increasing flood risk and wetland losses due to global sea-level rise: regional and global analyses. Global Environmental Change, 9, 69-87.