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Contemporary Multidisciplinary Approaches to Coastal Classification and Environmental Risk Analysis

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ABSTRACT

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Coastal classification or typology based on multidisciplinary data and multivariate analysis has recently emerged as a tool in coastal management. In this paper, eighteen published accounts of coastal classification procedures are reviewed in order to determine the reasons for such an increase, the variability between different approaches and the utility of each approach. The increase in use of such approaches to coastal classification may be linked to technological advances and widespread use of Geographic Information Systems (GIS). The main differences identified between the indices are in terms of scale of application, variables included, mode of analysis, mode of presentation and the nature of the risks being assessed. While many authors drew attention to limitations imposed by lack of availability of data, in general it was concluded that few indices adequately considered the physical basis for interaction between variables used in the classification procedure. In particular, while most indices recognise the need for socio-economic data, few were able to adequately incorporate such information. Those indices with the highest utility in risk assessment are considered to be those in which (a) the nature of potential perturbation and (b) the issues of management concern were clearly defined. Those in which neither is adequately defined are likely to be of use mainly as databases. A potential stepwise approach to development of specific coastal classification indices is outlined in which user needs and interrelationships between variables are examined in the planning stage. We recommend development of a GIS-based hierarchy of coastal classifications on varying spatial scales in which resolution may be adapted and variables combined differently according to specific aspects of management concern at different spatial management levels.

ADDITIONAL INDEX WORDS: *Coastal classification, typology, GIS, coastal management, vulnerability/sensitivity.*

INTRODUCTION

The need for ease of understanding of complex, multidisciplinary, multivariate environmental data has given rise to development of numerous indices which seek to present information in a format that can be understood by the non-specialist. This approach is particularly favoured in the environmental sphere where access to, and understanding of, multidisciplinary data are frequently required (CULLEN, 1990; REYES *et al.,* 1993; COOPER *et al.,* 1995). The coastal zone, as the boundary of land, water and air is subject to threats from diverse sources. As an attractive location for human development, the coastline is also subject to multifarious anthropogenic impacts, which have increased markedly over the past few decades (GOLDBERG, 1994). In this context it is not surprising that besides coastal databases being developed for coastal classification, a number of indices have been developed with the intention of assessing the vulnerability or sensitivity of a coast to threats from various hydrodynamic, climatic or anthropogenic perturbations. Recognition of the need for different approaches to coastal protection in various locations (*e.g.* NORDSTROM, 1989) or of spatial variation in coastal zone management objectives (CARTER, 1988) highlights the need for identification of distinct types of coast.

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Earth scientists have long recognised variation in the distribution of coastal hydrodynamic forcing mechanisms and in the variety of coastal types (DAVIES, 1972; KELLETAT, 1989). Physical differences in coastal morphology have been attributed to variations in tidal range, wave parameters, sediment texture, storm intensity and frequency and sea-level history. Several authors have examined the spatial distribution of various coastal types and coastal dynamics on global and regional scales (DAVIES, 1972; KELLETAT, 1989; CARTER, 1990).

Recognition of coastal variability in physical, ecological and human characteristics has prompted efforts to classify coasts using multidisciplinary information (LOICZ, 1995). Such coastal classifications or typologies have frequently been associated with risk assessment and coastal management and have been greatly aided by the capability to store and examine relationships between multidiciplinary data sets in a digital format, typically using a Geographical Information System (GIS) and/or using computer-assisted multivariate analysis. In the last several years several such indices and classification proccedures have been developed for coastal areas. These typically involve multidiciplinary data sets which are combined through multivariate analysis or through procedures designed to reduce such information to a simplified (usually single) measure of coastal attributes, either in relation to a perceived threat, or purely as a classification procedure for coastal management or data retrieval. In most cases such classification procedures involve the use of secondary data sets which have previously been assembled.

The principal objective of most coastal indices is the classification and partition of the coastline into units that exhibit similar attributes or characteristics. For each of these coastal units a particular response or range of responses to future events may be assigned. Ideally, the classification procedure seeks to obviate the need for detailed studies of individual localities and attempts to extrapolate findings from well studied localities to others that are less well known to facilitate appropriate management strategies and thus minimise the potential impact of environmental perturbation in the identified vulnerable area.

The range of physical perturbations that are commonly considered by such indices include future sea level rise, episodic storms, climate change and human impact. Our discussion will centre on those indices designed to assess coastal classification and indices which classify coasts in terms of their response to hydrodynamic perturbation, either through direct or indirect human disturbance, progressive change in the plane at which wave and current action operates, and/or the effect of episodic, high magnitude events.

Recent global review of the accretionary/erosional status of coasts (BIRD, 1985) indicates that the majority of the worlds beaches are eroding. Several authors (*e.g.* BIRD, 1993; GORNITZ, 1990), have linked such coastal response to a general global rise in sea level (HOUGHTON *et al.*, 1990) and predict that in view of predicted increases in the rate of sea-level rise that '. . . the rate and extent of coastal erosion is expected to intensify' (GORNITZ, 1990). Related impacts of climate variability and changing return periods of extreme events have also received considerable attention with a general consensus on the future establishment of decreased return periods for extreme events (storm surges, abnormal tides) associated with rising sea levels. This theme has been taken up by several authors (HUGHES and BRUNDRIT, 1992; JELGERSMA *et al.*, 1993) as justification for the development of coastal vulnerability indices and risk analysis procedures to 'help coastal planners, managers, engineers and developers to realise their professional responsibility in addressing appropriate responses to future climatic change' (HUGHES and BRUNDRIT, 1992).

Coastal vulnerability indices have therefore mainly been developed as management tools for coastal areas as an aid in implementing preventative management strategies in advance of probable impacts. The ability to implement viable and effective shoreline-management plans is, however, contingent upon the extent to which the natural processes affecting the shoreline and its natural and human defences are understood (CARTER, 1988).

Aims

This study reviews eighteen published coastal vulnerability indices designed to assess and categorise coastal response to perturbations or progressive change in the associated hydrodynamic regime on a range of time scales. For each of these indices the reason for its development, the context in which it was applied and the parameters which it invoked as indicative measures of vulnerability were identified and categorised to assess the degree of consensus or variability among authors (and wherever possible, coastal managers) on what contributes to vulnerability and/or sensitivity of the coastal zone. The scale of application and utility of each index was then assessed in terms of its applicability on a variety of spatial scales. From the review (which is intended to be indicative rather than exhaustive) a number of points emerge regarding the rationale behind index development, their utilisation as management tools, and the strengths and weaknesses in the conceptual framework of previously published indices. It is hoped that such a review will provide both scientists and potential users with an impression of the range of indices currently in use and their utility. In addition, by highlighting inadequacies or shortcomings in previous approaches it is hoped that this paper may provide some perspective for the development of new indices. For the purpose of this paper oil spill sensitivity and pollution vulnerability indices (*e.g.* JENSEN *et al.*, 1990) were not incorporated, as these indices involve a different range of coastal effects (eg smothering, infiltration, poisoning).

REVIEW

Eighteen classification procedures were reviewed and a summary of each is presented below. Each index was analysed in terms of the perceived threat, measures of vulnerability, scale of application and analytical and final mode of presentation. For ease of reference the indices are summarised under three headings according to their intended or actual spatial scale of application.

Indices of International- and Inter-Regional-Level Application

[1] The CORINE 'Coastal Erosion Project,' (QUELENNEC, 1989) sponsored by the Commission of the European Community is a Europe-wide study aimed at the assessment and identification of areas of potential and current coastal erosion. Three main groups of variables were studied in each of the 11 European countries involved. These groups of variables were [1] morpho-sedimentological characteristics of the coastal zone; [2] evolutionary trend of the shoreline (erosion, stability, accretion); and [3] presence or absence of coastal defense works. In this approach the coastline is divided into segments on the basis of its morpho-sedimentological features of which 4 categories, rocky coast, beaches, tidal marshes and artificial coasts are identified. The shorelines of these coastal segments were then digitized for each country and data pertaining to the 3 remaining variables were added from a database as attributes. A 1:1,000,000 scale map is being developed to display the characteristics of the coastal segments, also some basic preliminary statistics were carried out, such as the distribution of the length of the coastline within the 11 European coastal countries. The index is GIS-based. It appears to be response-based in that erosional status is assessed as the major measure of vulnerability.

[2] JELGERSMA *et al.* (1993) were commissioned by the Food and Agriculture Organisation (FAO) of the United

Nations to study the potential effects of rising sea-level on areas of the developing world. The study focussed on 207 low lying, deltaic areas at a scale of 1: 5 million. Data on eighteen variables were collected and used as inputs to a multivariate characterisation and classification scheme (OSDA), from which four main categories of variables that contribute to vulnerability emerged. These were [1] OFFSHORE, which consisted of six marine variables; [2] SHORELINE which consisted of seven variables which describe the morphology of the shoreline itself; [3] DELTAIC PLAIN which consists of four variables which incorporate river conditions and the composition of the delta; [4] ACTIVITIES which is a measure of human influence but which consists of a single variable, population.

Cluster analysis was then used to group areas of similar characteristics. Four variables: wave energy, tidal range, lithology of deltaic plain and length of growing period on the deltaic plain, (length of the dry season), were given a double weighting in the final clustering algorithm as they showed strong influence on the grouping. The cluster analysis revealed 3 main groups of coastal types and from these one area in each cluster was described in relation to its expected reaction to an increasing sea level by using both historical information and present day trends.

[3] & [4] GORNITZ and KANCIRUK, (1989) and GORNITZ, (1991) developed a large-scale coastal hazards database to identify areas of the (U.S.) coast in danger of inundation and/or erosion due to a future rise in sea level. Data on seven variables (relief, lithology, coastal landforms, vertical land movements, horizontal shoreline movements, and tidal range) were input into separate GIS coverages within the ARC/INFO software package and each assigned a rank between 1 and 5 according their relative vulnerability, with 5 being the most vulnerable. These coverages were then overlaid and the variable scores combined into a coastal vulnerability index which consists of the product of 'inundability' (relief, subsidence) and 'erodibility' variables (lithology, landform, wave height and tidal range), divided by the total number of variables.

Indices with Regional-Scale Application

[5] GORNITZ (1990) applied a coastal vulnerability index similar to that first developed by GORNITZ and KANCIRUK (1989) to the east coast of the U.S.A. to determine areas vulnerable to sea-level rise. The index itself again includes input of several variables into a GIS system (ARC/INFO) that relate to both coastal erosion and inundation (relief, lithology, coastal landforms, vertical land movements, horizontal shoreline changes, tidal ranges and wave heights). The variables are ranked from 1–5 with 5 being the most vulnerable. Various algorithms were used to obtain different coastal vulnerability indices (CVI's) after the 7 coverages were combined in the GIS. These indices were:

- CVI1: the product of risk classes divided by the number of variables;
- CVI2: the average of geology and geomorphology and of tide range and wave heights;
- CVI3: the average of the squares of the risk classes; and
- CVI4: the square root of CVI1 which compresses the wide range of scores

These four indices showed very high correlation, however CVI4 was chosen for application. The results of the index application were divided into four even parts with the upper quartile described as the most vulnerable. These results were then displayed and queried on the GIS. The paper included suggestions for further work such as the inclusion in future indices of variables on population per shore length and on storm frequencies, intensities and surges.

[6] A study to identify areas of the U.S. southeast coast that are vulnerable to permanent inundation and episodic flooding due to rising sea-level was conducted by GORNITZ *et al.*, (1993). A coastal Risk Assessment Database was developed for the study which was then linked to a GIS. The study was carried out in the U.S. southeast and for each coastal segment (approximately 5.3 km), data on the following 13 variables were amassed (elevation, geology, landform, relative sea level change, shoreline erosion/accretion, mean tide range, maximum wave height, annual tropical storm probability, annual hurricane probability, hurricane frequency-intensity index, mean forward velocity, annual mean number of extratropical cyclones, mean hurricane surge).

All variables were ranked between 1 and 5 with 5 being the most vulnerable. Multiple regression analysis was used to correlate some of the variables after which factor analysis was used to group factors into 3 classes according to their contribution to: (1) Permanent inundation, (2) Episodic inundation and (3) Erosion potential. Each of these classes was then weighted according to its importance in determining the vulnerability of coastal areas to sea-level rise. Basic analysis consisted of the percentage of shoreline within each of the coastal risk classes being determined, followed by a more detailed analysis using a Coastal Vulnerability Index (CVI) algorithm which yielded several CVI's. The CVI that was adopted gave weights of 35:25:40 to permanent inundation, episodic inundation and erosion potential, respectively.

$$\text{CVI8a} = 3.500 \cdot \text{PI} + 0.833 \cdot \text{EI} + 2.667 \cdot \text{EP}$$

where *Permanent Inundation* = (Elevation + Local vertical movement); *Episodic Inundation* = [(0.25 Tropical storm prob + 0.75 Hurricane prob) + Hurricane intensity index + Tropical cyclone mean forward velocity + Annual mean number of extratropical cyclones + Mean hurricane surge + tidal range]; *Erosion Potential* = [(Geology + Landform)/2 + Shoreline erosion + Wave height].

The results of the CVI were divided into 4 classes according to their scores and displayed as maps using GIS. The maps were intended for use by coastal planners and managers in determining coastal plans for various areas. Possible improvements on this CVI were suggested at the end of the paper, such as the inclusion of economic, demographic and anthropogenic factors.

[7] FRICKER and FORBES (1988) developed a Coastal Information System (CSI) for coastal description and classification for use by the Geological Survey of Canada. The system was primarily designed to provide a "simplified paradigm

for organising information and data". The objectives of this approach were to:

(1) encourage consistent description within the Geological Survey;
(2) use conventional language rather than codes or symbols;
(3) enable systematic data organisation and management;
(4) provide a scale-independant coastal inventory; and
(5) enable rapid customised map production.

The CIS involved division of the coastline into areas with similar geological or geomorphological characteristics based on oblique aerial photography and groundtruthing at selected localities. These areas were divided into 37 main regions, each of which was further subdivided into 15 localities, each of which was made up of a number of segments, the mean number of which was 141 per locality. The computer database in which this information is stored is itself arranged hierarchically according to regions, localities and segments. The maximum spatial resolution of the CIS is 200 m. It is intended as a database which enables rapid data retrieval but which could also permit the selection of various data elements and their combination in user-defined sensitivity indices.

[8] FLEMMING and TOWNEND (1989) developed a system to provide a coastal-management database for East Anglia (approximately 750 km of coastline). The project was designed to (a) establish and map the alongshore variation of several variables (described below), (b) to assess the correlations among these variables and (c) to determine their contribution to coastal erosion vulnerability. The initial step in the project was to develop a database of existing data sources. This highlighted several variables for which information could not be obtained from previous sources and therefore 6 additional studies were carried out:

(1) definition of wave climate offshore at 10 km intervals;
(2) study of the residual flow regime in the southern North sea and local wind effects on nearshore current residuals;
(3) detailed analysis of beach profiles over the last 10–25 years;
(4) a description of extreme sea-level rise, tectonic movement and subsidence;
(5) a quantification of sea-level rise, tectonic movement and subsidence; and
(6) a summary of recent literature.

Nineteen variables were then used to classify the coastline. These data were entered into a coastal-management database which is based on a GIS but which can handle both single and complex data structures. The authors noted that this database can then be used for various analysis ranging from identification of certain variables at a particular point, to seeking associations between the variables to identify vulnerable areas. More detailed translation then facilitated the definition of coastal units which display similar characteristics. Various management strategies of both policy options and management/engineering options have been developed from the information stored on the database.

[9] LEE *et al.* (1991) developed a model to simulate, on a regional-scale, the main processes involved in vegetated wetland conversions and related shoreline changes due to rising sea-level. The area studied was approximately 900 km^2 in NE Florida and the model consisted of a software combination of GIS, remote sensing and a rule-based model (SLAMM3). The remote sensing element uses SPOT satellite data to classify coastal landcover and landuses at a pixel resolution of 20·20 m and this was groundtruthed, both in the field and also using photographs. The SLAMM3 simulation model operates by using a complex decision tree method and can be used at different spatial resolutions (125·125, 250·250 and 500·500 m). The SLAMM3 model consists of a database of the following variables: landcover and landuse, elevation data and site characteristics such as subsidence rate, tidal ranges, wind direction and the location of dykes. The SLAMM3 model contains both the inundation and spatial model, the inundation model contains 5 processes:

(1) relative sea-level change, including subsidence, sedimentation and accretion;
(2) conversions between classes;
(3) protected by coastal engineering structures;
(4) death and colonisation;
(5) change to tropical conditions;

The spatial model also includes 5 processes:

(1) erosion of wetlands due to increased fetch for waves:
(2) exposure to open ocean and subsequent erosion of wetlands;
(3) beach erosion;
(4) overwash;
(5) erosion of sandy lowlands.

These models are processed within the SLAMM3 and the output is viewed through pcARC/INFO or ERDAS. Further refinements that were suggested for the model are the inclusion of data on floods and storm surges.

[10] BAINBRIDGE AND RUST (1995) presented a system of coastal geological analysis for use by engineers. The study is based in an area of south and southwest England and uses a GIS along with an expert system shell to identify suitable areas for planning along the coast. The following four main classes of variables were initially identified as the main indicators of coastal vulnerability:

(1) cliff stability factors *e.g.,* rock strength, resistance to erosion;
(2) geological factors *e.g.* cliff height and steepness;
(3) oceanographic variables *e.g.* wave climate, storm-surge incidence, nearshore currents; and
(4) meterological variables *e.g.* rainfall intensity, pore pressure.

The final set of variables, however, were not used in the final database as they were considered to act through the geological and oceanographic variables. Attribute data for these variables was then entered into a GIS for a small study area. A prototype model was developed whereby all the variables were entered into the expert system along with a rule-based system of decision trees. The model, once tested, was then developed for a full-scale area in which the spatial data may be interrogated through the GIS to the expert system and the results redisplayed via the GIS.

[11] HUGHES and BRUNDRIT (1992) applied an existing vulnerability index (GORNITZ and KANCIRUK, 1989) with a new risk-analysis procedure to determine the impacts of sea-level rise on approximately 300 km of South Africa's coastline. The index attempts to locate high and low risk areas on the basis of infrastructure location. GORNITZ's (1990) index was used to select the areas most vulnerable to sea-level rise which were then subjected to a risk analysis procedure in which the economic value of infrastructure is considered in relation to a range of hazards. The 'economic value' can be calculated by either the replacement value, loss of earnings or desirability. The vulnerability index consists of a 3D risk matrix involving risk (R), location (i), infrastructure (j) and hazard (k). The total risk of each location (Ai) is given by:

$$(Ai) = \Sigma\ (jkRijk)$$

the rating of each hazard (Bj) is given by:

$$(Bj) = \Sigma\ (ikRijk)$$

and the rating of each target infrastructure (Ck)

$$(Ck) = \Sigma\ (ijRijk)$$

When summed each element may be scaled to give relative vulnerabilities to sea-level rise. The relative vulnerability of each area was then plotted against its vulnerability ranking in the form of a bar chart. Potential further refinements that were identified include a currency unit value for land to identify its economic value and also a study of the effects of population numbers and the effects of increasing coastal urbanisation on coastal vulnerability.

[12] DANIELS *et al.* (1992) developed GORNITZ's (1990) index further. A study was carried out on six areas which represent 3 different levels of economic development (selected from a previous study of the southeast coast of the U.S.). Three sea-level scenarios were simulated and for each area the amount of land that would be vulnerable to inundation was calculated, based on elevation. This process was then repeated, this time taking into account the effects that coastal defences such as sea walls would have on the inundation process.

The CVI that was used consisted of the 7 variables used in previous studies and also included 6 new climatic variables [1] annual tropical storm probability % [2] annual hurricane probability % [3] hurricane frequency-intensity index [4] mean forward velocity [5] annual mean hurricane surge. These new variables were analysed with the 7 previous ones and principal component analysis was used to group them. The results identified three classes of vulnerability:

(1) permanent inundation which incorporates elevation and local vertical movement variables both evenly weighted;
(2) episodic inundation which consists of the climatic variables and tidal range with the tropical storm probability and annual hurricane probability being averaged with weights of 0.25 and 0.75; and
(3) erosion potential which consists of geology, landform, shoreline erosion and wave height variables.

These groups are weighted 35:25:40 in their order above. The indices were tested on 8 different stations and then applied to the 6 study areas and the amount of land that would be lost under each scenario was calculated.

[13] WILLIAMS *et al.* (1993) developed an index specifically to determine the vulnerability of dune systems to multifarious impacts in order to apply correct management strategies. The index is designed to be applied to a whole dune system and it was tested on 11 sites in the SW peninsula (Devon and Cornwall) of Britain. The index involves a simple checklist approach with each dune complex assessed by 54 variables, the results of which were each scaled between 0 and 4.

The total of the first 43 variables which relate to dune morphology, beach condition etc give a value known as the site vulnerability index. The results of this are displayed on plotted diagrams with 4 axes (A, B, C and D). All the axes are measured as percentages with the A axis relating to site and dune morphology, B relating to the condition of the beach, C relates to the surface characteristics of the seaward 200 m and D relates to pressure of use. These 4 intersections on the axes are then joined to make a quadrangle.

From the remaining 11 variables an index of protective measures is derived, these recent protection measures are plotted (as a percentage) in the form of a circle around the 4 axis. If the circle covers all 4 points on the axis it is assumed that protection measures are sufficient for this area and vice versa.

[14] A study by TOWNEND and FLEMMING (1994), funded by the National Rivers Authority, aimed to develop a more detailed understanding of the processes causing erosion with a view to implementing superior coastal defences. The project was based on the Anglian coast of England and involved two assessment methods. The first approach was a manual classification whereby chainage diagrams were developed from selected data sets extracted from an existing database. These were interpreted subjectively by a coastal manager to assess how the coast was behaving in a given area.

The second approach was that of GIS-based classification, where GIS was used to provide various descriptive maps. Eighteen variables in total were entered into the GIS system, with the coastal strip being divided according to the ". . . extent of individual data attributes." Various maps were produced by the process of griding the polygon data into squares of 500 m and assigning a value to them based on the source polygon (1–7). Combinations of these gridded maps were then overlaid and the variables were entered into an undefined algorithm the results of which were displayed in the form of maps. Six interpretative maps of key processes such as tidal action, wave action, sediment potential etc. were developed, and from these maps four other evaluation maps were derived for [a] natural flood vulnerability, [b] shoreline erosion potential, [c] beach face erosion potential and [d] environmental significance.

Indices for Local Application

Several indices have been developed that were intended for application over coastal stretches of less that 100 km. In such studies the effects of macroscale climatic variability and hydrodynamic forcing are reduced or negligible and more local variations are of importance in defining spatial variability in sensitivity and vulnerability to coastal perturbations.

[15] McCue and Deakin (1995) reported on a coastal study initiated by Great Yarmouth Borough Council, U.K. with the aim of defining coastal management units for the Borough's shoreline. To determine whether the coastline was advancing or retreating, Ordnance Survey maps between 1884 to 1970 (at 1:10,000 scale) were used. Shoreline change was analysed along every 250 m of the shoreline. Measures of the net lateral movement of sediment were also recorded according to the retreat or advance of the shoreline. These values were then incorporated into a retreat model which included estimates of both eustatic and local sea-level rise rates for the area.

The movement of offshore sand bars was also included in this study and fifteen bathymetric surveys ranging from 1846–1992 were used to construct digital terrain models (DTM's) with 50 m grid spacing. These DTM's were overlaid using a GIS and the variability as a function of the amount of change relative to the depth at each grid point was recorded and then used to show the areas of stability and the more mobile areas of the sandbanks.

The coastline was then classified into management units using a combination of physical and human factors. The physical factors consisted of lithology, coastal forcing mechanisms and their intensities combined with geomorphic and open coast/estuarine classifications while the human dimension consisted of landuse. All of these factors were overlaid in the GIS and areas of coast with similar characteristics were identified.

[16] Hughes *et al.* (1992) assessed the vulnerability of Walvis Bay (Namibia) to rising sea-level using four categories of potential impact: increased coastal erosion; flooding and inundation; increased saline intrusion and raised water tables; and reduced protection from extreme events. Three different sea-level rise scenarios (20, 50 and 100 cm) were used for this study over time scales of 35, 90 and 110 yr. Three separate models were used to simulate the vulnerability of Walvis Bay to sea-level rise. First the Bruun rule was used to model coastal erosion using berm height, the maximum depth for shore normal sediment transport and the distance to this depth, with an addition to account for changes in rates of longshore transport. This was applied to 11 profiles for each of the three sea-level rise scenarios. Salt water intrusion into the local aquifer was modelled using surface slope, sea level increase and the shoreward displacement of the interface with the model, assuming that the aquifer maintains a stable wedge position.

A Joint Probabilities Method (Pugh and Vassie, 1978) was used to analyse 9 years of hourly tide gauge data to provide return period curves for sea-level. This method consists of the probability of a certain water level occurring being considered as the sum of the probability of all possible combinations of tide and surge that could make up that level. The effects of inundation are predicted by assuming that coastal areas below 0.9 m, 1.2 m and 1.7 m elevation will be flooded in relation to each of the 3 sea level scenarios at MHWS.

[17] Dal Cin and Simeoni (1989) studied a 62 km stretch of the Middle Adriatic (Italy) to identify and then assemble coastal stretches with similar physical characteristics for management purposes. The coastal stretch was divided into 22 segments, each of which was 2–3 km long. For each segment, data was collected on 18 variables which were categorised into the following groups: hydrodynamic (3 variables), shoreline evolution (4 variables), sedimentological (3 variables), morphological (6 variables) and human (2 variables). The variables were then evaluated by R-mode factor and cluster analysis to produce a dendrogram on the basis of which, the coastal segments were divided into 3 principle groups morphological groups (A, B and C) and three secondary groups (BC, AC and AB).

Each group appeared to show a common mode of shoreline behaviour. Group A beaches were eroding prior to 1950's and are now protected by seawalls. They have few bars and some are highly urbanised. Group B beaches are near river mouths and are strongly influenced by them. They are retreating and tend to have narrow, steep gravel beaches. Group C beaches occur where the coast is in equilibrium. They are wide, sandy beaches with low energy flux multiple bars and may be highly urbanised.

Several of the 15 variables were used to indicate the vulnerability of the coastal zone. Factor 1 quantifies the protection of the onshore strip behind the beach as a result of human intervention, Factor 2 quantifies the elements that generate coastal vulnerability and Factor 3 quantifies the natural protection that each single segment offers the belt behind the beach. Factors 1 and 3 tend to quantify components that provide safety both natural and by human intervention therefore total safety can be obtained by summing these. Factor 2 is related to the vulnerability of the coastal zone to erosion and therefore the total vulnerability of a segment can be calculated by the percentage of Factor 2 with respect to the sum of Factors 1 and 3. Pie charts were used to display the vulnerability of the different coastal segments.

[18] Dal Cin and Simeoni (1994) subsequently developed a system for the Southern Coastal Zone of the Marche (Italy) with the aim of providing a means for proper coastline management by classifying areas of the coast according to their vulnerability. A 70 km stretch of coastline was divided into 24 segments, wherever possible using natural boundaries *e.g.* river mouths. Fifteen variables were then used to characterise each segment. Three of these variables described the hydrodynamics and energy characteristics, four were related to the evolutionary trends of the beach, seven described the morphological and sedimentological features of the exposed beach and sea floor and one variable was related to human intervention ie. defensive structures and ports (these structures were related to a value according to their defensive capacity for example groynes = 1 and sea walls = 4).

The values of the 15 variables were collected, normalised and then subjected to factor and cluster analysis. The results of R-mode factor analysis indicated that only 3 factors explain 80% of the total variance. Therefore the coastal segments can preliminarily be divided into 3 homogeneous groups, A, B and C. Upon detailed evaluation, groups A and B were subdivided into A1 and A2 and B1 and B2.

Group A beaches consisted of both gravel and sand and indicated low vulnerability due to the presence of defensive structures and favourable natural conditions. Group B beaches tended to be located near river mouths and showed a high vulnerability due to the absence of either natural or artificial protection. Finally Group C beaches tended to represent engineered areas of coastline, in areas where wave energy flux is strongest and defensive structures have been built, which protected the sea cliff but almost eliminated the beach. These beaches tend to show a low degree of vulnerability.

The results of the study are displayed in the form of pie charts indicating the percentage of vulnerability to inundability of the coast. In general the model has a flexible arrangement, but possible modifications identified by the authors include the use of variables to define wave action and subsidence and also to investigate the possibility of weighting certain variables.

DISCUSSION

Scales of Application

Climatic and oceanographic processes operate at heterogeneous scales and magnitudes and indices which are applied over a large area will necessarily lack the detail contained in higher resolution applications since the scale of differentiation of coastal types and response must lead to generalisations. Such indices do, however, provide spatial perspective which is often sacrificed in smaller scale applications and *vice-versa*.

In some cases attempts to resolve the problem of scale were made by applying a detailed index to a larger area in the hope to cover several scales of process magnitude (BAINBRIDGE and RUST, 1995), however, in the process of enlarging the scale and still using a coarse resolution other problems can be encountered such as small peninsulas and islands being omitted (GORNITZ *et al.*, 1993). The spatial resolution of many of the indices varied from 5′ latitude and longitude (GORNITZ, 1990; HUGHES and BRUNDRIT, 1992) to 125 m·125 m (LEE *et al.*, 1991), with most involving coastal units of a few km. Coarse-resolution studies at global/international scales are useful in international policy formulation, however, they do not provide useful information for management at a local-area level. In a number of cases, coarse resolution was acknowledged (GORNITZ, 1990; GORNITZ *et al.*, 1993; GORNITZ and KANCIRUK, 1989), but this must be viewed in the context of the objectives of the study.

Most research to date has focused on large-scale vulnerability analysis, however, the coastal management hierarchy must be able to accomodate the possibility of identification of a vulnerable coastline by a small-scale index within an area that is classified as non-vulnerable on a large scale. There are examples of downscaling of global or inter-regional scale indices to regional scale (HUGHES and BRUNDRIT, 1992) through modification and addition of other means of assessment.

Motivation for Index Development

Broad interest in the development of coastal vulnerability indices is reflected in the variety of institutions that have worked on or funded research in them. Development of most of the indices considered (Table 1) was enabled by funding from regional, national and international agencies which have a direct coastal environmental management responsibility. The willingness of such organisations to support development of coastal vulnerability indices suggests an appreciation of their potential value for management. In a few cases, index development was funded by research councils which do not have a direct coastal management function, although they may perceive a potential value to bodies which do.

At an international level, the United Nations Food and Agricultural Organisation requested a study to characterise low lying coasts of the developing world in terms of the effects of a rising sea-level (JELGERSMA *et al.*, 1993) and The Commission of the European Communities funded a study of the vulnerability of European coasts (QUELLENEC, 1989). In the U.K., the National Rivers Authority funded research on index development to '. . . initiate a better understanding of the processes causing erosion, as a basis for a more strategic approach to the provision of sea defence' (TOWNEND and FLEMMING, 1994). Such a motivation is difficult to reconcile with development of a vulnerability index which perhaps assumes a prior knowledge of coastal processes. Regional-scale studies have been funded by the U.S. Department of Energy (DANIELS *et al.*, 1992; GORNITZ and KANCIRUK, 1989, GORNITZ, 1990, GORNITZ *et al.*, 1993), and local scale studies for the North Atlantic Treaty Organisation (WILLIAMS *et al.*, 1993), Borough Councils (MCCUE and DEAKIN, 1995) and research foundations (HUGHES *et al.*, 1992).

Inasmuch as the funding of a research project implies an interest in its outcome, the review indicates an apparent need for some means of coastal classification at an international level. Such a situation is unsurprising given the wide geographical variation in coastal process and response as well as the type of coastal hazard that must be considered by organisations with an international remit in coastal management. While several government departments have funded classification procedures at a regional level, the relative paucity of local-scale applications provides cause for concern. The fact that some local-scale applications were funded by research organisations rather than local-management structures suggests that lack of resources may play a role. The same observation may also imply a lack of appreciation or even rejection of the perceived value of such approaches at a local scale. Clearly indices designed for broad-scale application provide little valuable information for management at a local level unless they are modified or extended. The research required to develop new, fine resolution indices may be too expensive for local management structures who may look to higher levels in the management hierarchy to fund development of such approaches.

From this review of eighteen coastal classifications there appeared to be three overriding reasons as to why such classification procedures were developed: (a) to facilitate shoreline management under contempary conditions, (b) to categorize potential shoreline responses to future sea-level rise, and (c) for data storage and management. As a proactive management aid, an index of coastal sensitivity is potentially

Table 1.

Authors	Year	Reasons for Development	Scale of Applicability	Funding Body
Dal Cin, R., Simeoni, U.	1989	To assemble coastal stretches with similar physical characteristics for management purposes	Regional—62 km	Dipartimento di Scienze Geologiche e Paleontologiche, Universita Ferrara, Italy
Flemming, C.A., Townend, I.H.	1989	To assess correlations among variables and their input to coastal erosion and to form a series of maps of the coastline	Regional East Anglia (750 km)	Anglian Water
Fricker, A., Forbes, D.L.	1989	A simplified paradigm for organising information and data	Regional	Geological Survey of Canada
Gornitz, V., Kanciruk, P.	1989	Assessment of SLR impacts	Global	U.S. Department of Energy
Quelennec, R.E.	1989	Assessment of SLR impacts	Global	Commission of the European Community
Gornitz, V.	1991	Assessment of SLR impacts	Global	U.S. Department of Energy
Lee, J.K., Park, R., Mausel, P.W., *et al*	1991	Assessment of SLR impacts	Regional	U.S. Environmental Protection Agency
Daniels, R.C., Gornitz, V., Mehta, A.J., *et al*	1992	Assessment of SLR impacts	U.S. Southeast coast	U.S. Department of Energy
Hughes, P., Brundrit, G.B.	1992	Assessment of SLR impacts	Global but applied at regional scale here—300 km	South African Department of Environmental Affairs and the Foundation for Research Development
Hughes, P., Brundrit, G.B., Searson, S.	1992	To demonstrate the vulnerability to SLR of semi-sheltered environments and the need for accurate sediment budgeting	Regional—970 km^2	The Foundation for Research Development
Gornitz, V., Daniels, R., White, T.W., *et al*	1993	Assessment of SLR impacts	U.S. Southeast coast	U.S. Department of Energy
Jelgersma, S., Van der Zip, M., *et al*	1993	Assessment of SLR impacts	Global 1:5 million	Food and Agricultural Organisation of the U.S.
Williams, A.T., Davies, P., Curr, R., *et al*	1993	To determine vulnerability of dune systems to apply management strategies	On dune complex's Regional/Local?	The North Atlantic Treaty Organisation (Scientific and Environmental Affairs division)
Dal Cin, R., Simeoni, U.	1994	Classification of areas according to their vulnerability for management purposes	Regional—70 km	Italian National Research Council
Townend, I.H., Flemming, C.A.	1994	To develop a more detailed understanding of the processes causing erosion with a view to implementing superior coastal defenses	Regional 500 m grid squares, 750 km East Anglia	National Rivers Authority Anglian Region with grant aid from MAFF
Bainbridge, B., Rust, D.	1995	To develop a system of coastal geological analysis for use by engineers	Regional	Joint Information Sub-Committee of the Higher Education Funding Council for England and Wales
McCue, J., Deakin, R.	1995	To create a shoreline management plan for the area	Regional	Great Yarmouth Borough Council

valuable in the development of planning and management guidelines and policy. According to WILLIAMS *et al.* (1993) '. . . loss of geomorphological and ecological diversity is a prime indicator of vulnerability and any technique that can assess such variations in time and space MUST be a useful tool for dune managers'. Such a statement minimises the possibility of natural evolutionary trends in diversity, assumes a knowledge of previous conditions (comparison of diversity cannot be made effectively on a solely spatial basis), and implies limited consultation with dune managers. It also highlights the necessity for the nature of the factor that produces vulnerability or sensitivity to be defined. In the case of oil spills cited above, quite different levels of vulnerability may exist in comparison to impacts associated with storms. In relation to sea-level rise, predictive models of where and how inundation and erosion are likely to take place, how much land is going to be lost *etc.* are of great service in providing management strategies especially if they can be incorporated into an easily understood coastal classification.

Variables Included

The selection of the numbers and types of variables used in the various classifications varied greatly according to the main aims of the study. One of the macro-scale studies, (QUELENNEC, 1989) used 3 main groups of variables to identify high risk coastal areas in Europe. Studies such as that of WILLIAMS *et al.* (1993), which was developed to study coastal dune vulnerability, incorporated 54 different variables at a meso-scale level, while the majority of the other studies in-

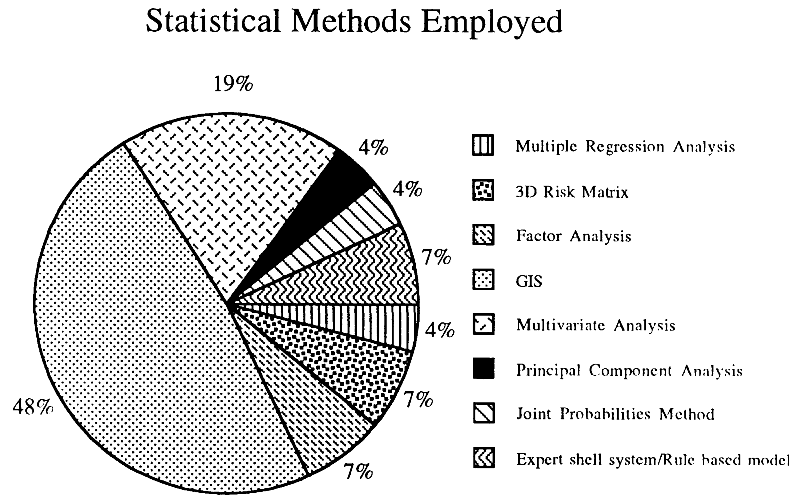

Figure 1. Statistical methods employed in the coastal classification procedures reviewed. Note the Dominance of GIS as a classification tool.

volved between 6 and 19 variables. According to DAL CIN and SIMEONI (1989) '. . . the more numerous the variables affecting the coast that are taken into consideration then the more correct will be the resulting zoning.' This assertion is highly debatable, since various parameters respond differently to different coastal perturbations. In addition, the inclusion of several variables that may have similar effects on the coast or of irrevelant variables may mask the importance of other response variables.

Multivariate statistical analye such as multivariate analysis, cluster analysis and principal component analysis can distil down a large number of variables and highlight those that are most significant in explaining variability within a given coastal stretch. They should be used with care, either after having established the importance of various response variables, or to analyse the source of variation between sites. Multivariate analysis has been used to classify the coastal zone either morphologically, *e.g.* into: offshore, shoreline, deltaic plain (JELGERSMA *et al.*, 1993), or according to coastal response to a given perturbation *e.g.* permanent inundation, episodic inundation and erosion potential (DANIELS *et al.*, 1992). These two types of coastal classification (morphological and response) may or may not coincide.

Most authors use multidiscipilary data in development classifications. The fact that many of them acknowledge the need for socio-economic variables is interesting in that it suggests an acknowledgement that the classification is being developed with human development as an important element in the classification procedure. The lack of data on socio-economic factors (JELGERSMA *et al.*, 1993), or of knowledge as to how these measures are to be incorporated into such indices, provides cause for concern and suggests that experts from the human sciences are insufficiently involved or consulted in the development of these indices.

The fact that the same authors used different variables when applying indices to different areas (*e.g.* GORNITZ *et al.* (1993) different approach to U.S. southeast coast) points to the need for consideration of different variables based on the area of application even on the same scale. It is also clear from the work of JELGERSMA *et al.* (1993) that regional scale applications mask important differences within given areas.

Mode of Analysis

Most of the statistical methods employed in the derivation of the coastal vulnerability indices were relatively simple statistical tests, mainly involved in the grouping together of variables of similar effect/weighting on the coast. Some papers (FRICKER and FORBES, 1989; WILIAMS *et al.*, 1993) appeared to be chiefly concerned with database development rather than the further refinement of data as a primary goal.

Of the 18 papers reviewed the most common statistical method of analysing the variables used in the creation of the indices is that of cluster analysis (Figure 1). Cluster analysis belongs to that group of statistical techniques in which the success of its application is the prime determinant of its value. It is therefore imperative that the variables selected can be justified in terms of their ability to differentiate on the basis of sensitivity. In this regard many of the papers which used multivariate analysis gave little consideration as to the validity of the parameters used. Few examined the interrelationships between variables and the statistical basis for their inclusion/exclusion. The subjectivity involved in this approach is not often fully understood by those unfamiliar with factor analysis or by coastal managers. The danger of such an approach is that the capacity for improper manipulation of the data (*e.g.* by weighting or excluding variables) to alter the output may not be approciated by a coastal manager.

The reliability of the results of these statistical tests depends on the accuracy at which the data was collected, the applicability of the statistical test chosen and the interpretation of the results. It is also aptly pointed out by GORNITZ (1990) that "changes in space or time will mean that simple time averaged spatial correlation's have to be treated with care," thereby indicating that for indices to still be beneficial in time, that databases need to be updated with current information. Problems also arise in that the development of a single index for vulnerability may obscure the significance of certain individual variables in relation to their spatial location. The true reliability of a vulnerability index that uses statistical methods is in the validation of the results that it produces with field measurements to ground-truth the results.

GIS is the most common form of deriving a coastal vulnerability index, with 13 out of the 18 indices reviewed using GIS methodology either as a tool in the development or in the application of the index (Figure 1). Of those authors who used GIS, the majority commended its use. For example "... the role of GIS within the system was essential for data input, storage manipulation and model preparation with an efficient linkage between the model and various operational functions" (LEE and PARK *et al.*, 1991) and "... the use of GIS to store and analyse this time series data contributes immensely to the credence of selecting appropriate management strategies based on accurate and up to date coastal process measurements" (MCCUE and DEAKIN, 1995).

GIS applications have a definite spatial dimension and the resulting accuracy of GIS indices is precisely related to the cell resolution at which the study was undertaken. In this regard a note of warning is sounded by MCCUE and DEAKIN (1995) in that "... a GIS stores, retrieves and processes data: it does not establish facts." This must clearly be considered when interpreting classification results. Some authors also highlight the difficulties of a non-specialist operating a GIS and therefore the need for future developments to be orientated more towards these non-specialist users.

Suggestions for Further Study

Thirteen of the eighteen papers studied suggested further improvements that could be made to their original classification. The most common addition of those proposed is that of including economic factors. This is clearly demonstrated in Figure 2. The need for inclusion of economic factors is followed by the need for storm surge data, derivation of classifications at a smaller scale, the need for population data, and the need to weight the variables (only 3 of the 18 approaches used weighted variables).

BAINBRIDGE and RUST (1995) proposed that their future work could include data on the land, its infrastructure and the cultural, ecological and historical significance of the area. DAL CIN and SIMEONI (1989) realised that the main advantage of their method was in its relative simplicity, however that it could be improved with the addition of some more variables and the use of more complex mathematical algorithms.

There was also a suggestion in some of the papers of the need to fill gaps in data already gathered. Some of the larger scale indices indicated that although they were able to identify vulnerable and potentially vulnerable areas, a more detailed survey of these areas would be necessary to develop plans of coastal defence *etc.* For example GORNITZ and KANCIRUK, (1989) said that from their vulnerability index, high areas of coastal vulnerability can be identified. It is then possible for coastal planners or managers to adapt this approach to produce a higher resolution study as the previous resolution is quite coarse as it is intended ultimately for global coverage. JELGERSMA *et al.* (1993) also pointed out this scale problem. They decided that the scale was too large, that although there was differentiation between disparate deltas there was none within an individual deltaic system, which can be relatively large, for example the mouth of the river Ganges. JELGERSMA *et al.* (1993) noted that they hoped that a more intricate study would identify these differences between areas within one deltaic system.

Final Presentation Format

The final format of the majority of the indices is in the form of a map or chart. DAL CIN and SIMEONI (1989) used pie charts to display the differing vulnerabilities of the coastline. WILLIAMS *et al.* (1993) incorporated the use of line graphs of 4 axis each representing the percentage scores of a different variable group, with the protection measures indicated by a circle drawn around the plot. Both approaches require experience in their interpretation and imply a period of assimilation by potential users.

Many indices were represented on hard copy maps. While these may be comparatively cheap to produce and distribute, they are inflexible in terms of data interrogation. They do not have the interactive capacity of digital maps such as those generated by GIS. TOWNEND and FLEMMING (1994), used a GIS to generate many interpretative and evaluation maps using various combinations of the database variables, as opposed to one map or chart representing one single combination of the data, which ultimately has a limited ability to display information. JELGERSMA *et al.* (1993) indicate that their maps are being entered into a GIS and will soon be available in digital form, which possibly reflects in hindsight that they should have been first entered into a GIS.

Interpretation of Results and Applicability

The interpretation of the results produced by these indices is crucial in determining their success as predictors of coastal vulnerability. Their elucidation is not always straightforward, for example "... scores need careful interpretation as low protection indices do not necessarily mean inappropriate management strategies" (WILLIAMS *et al.*, 1993) and "... the definition of coastal units is highly subjective and requires the interpreter to have an appreciation of the regional variations, be responsive to local detail and be consistent with the arguments used to define coastal units" (TOWNEND and FLEMMING, 1994). Also the applicability of an index to different areas will depend on whether it is easily reproduced and whether it has been field tested to validate the results. Given that one objective of classification is the reduction and ease of use of data, those that require further interpretation are likely to be least useful to managers.

GENERAL DISCUSSION

The widespread use of GIS in these applications is clear. Its ability to conduct spatial operations in the data, to inte-

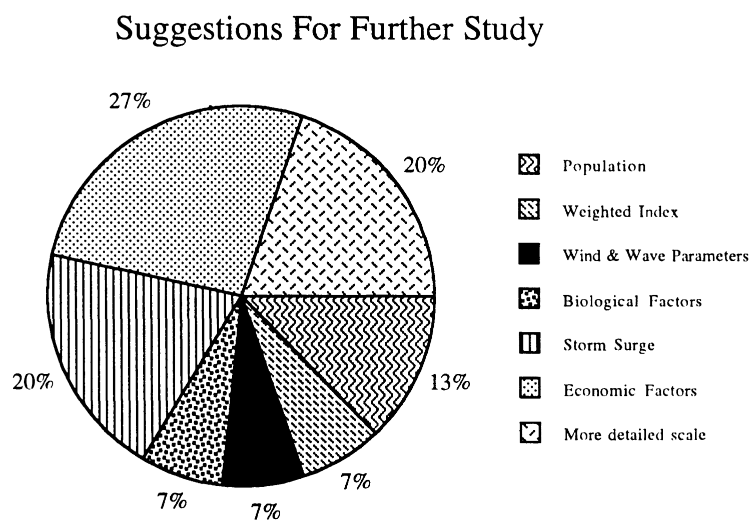

Figure 2. Recommendations for improvements to classifications suggested by original authors. Socio-economic factors are frequently identified as factors that are inadequately incorporated. The question of scale variation in the classification procedure is also widely recognised.

grate with remote sensing applications and to link different data sets all combine to make GIS a powerful analytical tool for coastal management. Such facilities, however, do not obviate the need for understanding the relationships between parameters and processes in the coastal zone. Indeed, of these 18 indices reviewed, only one (HUGHES *et al.,* 1992) used a conventional geomorphological model of shoreline response (the Bruun rule). The lack of acknowledgement by other authors of the difficulty in assessing coastal response to alterations of physical conditions is a major shortcoming of the indices reviewed. The absence of more than an 'intuitive feeling' regarding the role of the factors assessed in the prediction of physical coastline response in the indices reviewed is striking. For example, GORNITZ and KANCIRUK (1989) opine that microtidal coasts are at lower risk from sea-level rise, than macrotidal coasts. Such a generalisation is impossible to firmly substantiate at present.

Even the Bruun Rule does not have universal applicability and is strictly 2-dimensional in approach (PILKEY *et al.,* 199?). No use was made of alternative 2-dimensional shoreline response models *e.g.* barrier translation or overstepping (CARTER, 1988). Similarly, while several conceptual models exist of the 3-dimensional behaviour of coasts under sea-level change and variations in intensity of dynamic forcing factors these were neither used nor was their lack of use acknowledged as a shortcoming.

Effective management of the coastline requires its interpretation as an integrated system including both natural and human-influenced dimensions. The use of coastal classification procedures to achieve this objective is therefore commendable, however, it must be recognised that such systems are not able to adequately incorporate patterns of coastal behaviour other than those implied from existing morphology. Man's impact is recognised as a crucial element in coastal environmental management in most of the papers reviewed. JELGERSMA *et al.* (1993) put this into context thus "... these human induced changes have far greater and more immediate impacts on lowlying coastal areas (both positive and negative) than the expected effects of a gradual sea-level rise over the next half a century or so." Anthropogenic activities need to be included in classifications of coastal risk as they are (a) important controlling factors, through, for example deforestation and its resultant impacts on sedimentation and (b) vital measures of coastal vulnerability. As GORNITZ and DANIELS (1993) suggest in terms of coastal management options, "... it is the perceived social and economic worth of the resources within the region at risk that will determine which, if any, efforts are made to protect a given area ...". The lack of inclusion of direct and indirect human impacts on most of the studies was obvious and was mainly related to unavailability of data than to lack of recognition of its importance. It is noticeable that whereas 13 indices (72% of those reviewed) stressed the importance of human utilisation and the incorporation of some socio-economic measure, these rank as 3 of the least utilised factors. Availability of data was cited by 6 authors as a constraint on index development and applicability. This suggests that production of better indices may be precluded by unavailability of data.

The results presented above indicate the widespread acceptance of coastal vulnerability indices as a useful element in coastal zone management among agencies charged with a management function. In this context, the appeal of such an approach is most probably linked to the condensation of multivariate data into a single, easily inderstood value.

Each of the indices reviewed purports to assess coastal sensitivity or vulnerability for which a variety of potential indicators are used. Two main forms of variation exist among the indices reviewed: the nature of the variables used to assess vulnerability; and the nature of the stress-inducing agent to which a coast is considered vulnerable. While many authors explicitly state the risk for which the index has been developed, others do not. This is viewed as a major shortcoming, as a coastline's response to various environmental disturbances may be quite different. We contend that there is no index that can be claimed to provide an assessment of risk to all potential environmental perturbations. Therefore any vulnerability index must state explicitly the nature of the risks of which it seeks to take account. The utilisation of different parameters to assess vulnerability to the same factor is evident in the review. This, however, is not necessarily a shortcoming as the factors which are important in indicating coastal sensitivity are likely to vary from one location to another. If management input has been sought and the concerns of managers have been incorporated in the index, then such variability is acceptable.

Temporal variation in vulnerability exists as coasts adjust morphologically to change. A period of intense erosion may be associated with a change from drift to swash alignment as a result of changing sea-level and associated sediment flux. Consequently indices need to be constantly reviewed and updated.

Evidence from existing indices shows that they have been developed to assess coastal vulnerability to a wide range of environmental perturbations, some of which are clearly defined, others which are more nebulous. The range of variables that have been used to assess vulnerability is wide; in some cases they have been selected carefully and their inclusion is justified in terms of management objectives—in others apparently random selection of variables has resulted in inclusion of several parameters which measure essentially the same thing and which therefore weight the index toward that variable. We suggest that, by definition, no index exists, or can be developed, that has global applicability in terms of management objectives. The latter are inherently variable both in time and space, and the nature and intensity of risks to which shorelines are exposed varies greatly. These limitations mean that coastal vulnerability indices must be developed at a specified scale, for a specified risk and assess vulnerability for a range of management-specified vulnerability indicators. Selection and application of any existing index in a given setting must take cognisance of its developmental constraints and intended level of application.

The utility of existing measures in risk assessment can be assessed by reference to the detail at which both potential environmental perturbations and specific coastal response and/or management concerns are defined (Figure 3). Those in which both are clearly defined have the highest utility but will not have wide application since perceptions of risk and coastal morphology vary spatially and it is unlikely that two managers will have identical concerns within similar environmental frameworks. Those indices in which neither parameter is adequately defined, while they may be easily constructed at various scales and over a wide geographical area, are less likely to contribute to specific management issues. The latter group of indices may however, contain information that is of use in a coastal database, particularly if the information is stored in a digital format.

Many of the indices reviewed commented that their study could be repeated at a smaller scale to provide greater detail. Given the discussion above in which spatial variability in management issues of concern is considered likely, it may be more appropriate to contemplate a hierarchy of local, regional and global scale indices. In such an approach, common variables could be stored but compiled using different algorithms depending on the level of detail required (resolution scale) and the nature of the management concern.

COASTAL RESPONSE/MANAGEMENT CONCERNS

CAUSE OF PERTURBATION	Defined	Undefined
Defined	High utility for specific purpose	Potential utility with refinement
Undefined	Potential utility with refinement	Low initial utility - general database

Figure 3. Conceptual view of the utility of coastal classification procedures in risk assessment. Four scenarios are defined based on the degree to which the nature of potential environmental perturbation and the likely coastal response has been defined.

In view of the marked variation in scale and intended mode of application of existing approaches it is clear that there is no existing simple approach that suits all purposes. Consequently adoption of an approach or design of an alternative will require careful thought. We recommend the following, step-wise approach to coastal classification and analysis in the development or adoption of clasification procedures:

(1) What is the area to be considered? The extent of the area to be covered will determine the resolution that can be achieved and hence the scale of data acquisition and display.

(2) What is the reason for classification? The ultimate uses to which the classification will be put must be specified so as to aid in parameter selection for use in the analysis. If the classification is to be used for risk analysis, the nature of such risk must be clearly evaluated at the outset so that coastal attributes which are likely to respond to the risk identified, can be selected and included in the classification procedure.

(3) What factors contribute to variability in the region? This is aimed at identifying the main expressions of variability within the area of interest as an aid to selection of variables for use in the classification.

(4) How do these factors interact? Interactions between factors should be identified so that the same variable is not duplicated or given unduly high weighting.

(5) Can these factors be quantified? Quantification of variables depends to a large extent on past applications on the availability of existing data. This is likely to impose a constraint on the variables selected as most previous applications were not concerned with collection of primary data. In instances where variables cannot be directly quantified an ordinal scale based on qualitive assessment could act as a surogate if multivariate analyses are to be used.

(6) What classification procedure is to be used? Identification of a mode of analysis depends largely on the study objec-

tive and on the nature of the data to be used. Analysis should take account of these constraints and make use of the most appropriate means.

(7) Who is the target audience/end user? Identification of the likely user is of prime importance as the classification is unlikely to reach its desired goal (presumably as an aid in management) if the person charged with using it is unable to understand or manipulate the data as supplied. This may impose limitations on the mode of analysis and of display.

(8) What means of display should be employed? The means of display depends upon the end users intentions with regard to the data. Clearly, some types of GIS are of little use to an unskilled operator while conversly, hard copy charts do not permit easy manipulation or adoption of alternative classification procedures.

CONCLUSIONS

With the coastline coming under increasing pressure from tourism and economic development, there is a pressing need for environmentally acceptable solutions to present and both short- and long-term future shoreline problems. Coastal classifications and vulnerability indies, such as those reviewed in this paper, can usefully contribute to the development of coastal management strategies but the purpose for which they were developed must be considered. The indices reviewed were developed for various end users, by various scientists, each of whom had a specific interest in how the classification was to be used. Given the rapid increase in coastal development worldwide, and the lack of detailed information on every location, coastal classification is likely to make an important contribution to coastal management. The limitations of such classifications must, however, be borne in mind.

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