DEVELOPMENT OF A RISK-BASED APPROACH TO COASTAL SLOPE INSTABILITY ASSESSMENT IN CORNWALL

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As part of an investigation into the risks posed by coastal landsliding along the Cornish coastline an initial site reconnaissance of the coastline has been performed to identify failure mechanisms and locations. Factors that have been taken into consideration include lithology, coastal recession rates, likely instability or landslide mechanism, coastal geometry and geomorphology and coastal aspect. A scale-dependent evaluation of the coastline has been performed ranging from sectors (10-50 km), areas (5-10 km), zones (1-2 km) and local (10's m). The site reconnaissance has established an inventory of landslide mechanisms. The identified mechanisms, and occurrences of the different types of instability, have been defined within the scale-dependent framework. This has led to a greater understanding of the distribution and location of the varying mechanisms of instability along the coastline. The identified mechanisms range from small-scale rockfall to relatively large-scale translational failures.

Key sections of coastline were identified for more detailed analysis and risk quantification. The subsequent risk evaluation are based on a structured qualitative approach that includes both likelihood and consequence analysis and allows relative risks to be determined. Examples of varying risk categories are presented to highlight the variety of coastal scenarios. Further work is in progress to quantify the risks involved.

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INTRODUCTION

The coast of Cornwall stretches for a total length in excess of 500 km, with the peninsular being surrounded on three aspects by the Atlantic Ocean producing a diverse range of coastal slopes. Seventy five percent of the coastline has either been designated as an Area of Outstanding Natural Beauty (AONB) or Heritage Coast, significantly increasing the visitor appeal. The coastal slopes also provide important leisure and recreational activities, as well as housing a large proportion of the county's residents. The static population is considerably enlarged by the influx of over 3 million visitors annually.

The scale of coastal instability in England and Wales is considerable. Ten percent of the total length of English and Welsh coastlines contains a risk from either flooding or erosion. Within this length, property at risk is estimated to be worth £220 billion, with agricultural land contributing another £7 billion. In England alone there are 860 km of coastal protection, with over £20 million being spent every year on maintaining and improving these defences (McInnes, 2000), thereby mitigating the risk to public safety.

The coastal slope or coastal zone, according to the Department of the Environment (1992), in which instability could occur, was defined as '*...the geographical extent of coastal natural processes and human activity related to the coast...*'. The base of the coastal slope was delimited by the mean low water mark (MLW), and typically extends inland for a few hundred metres.

Research into coastal slope stability in Cornwall has been limited. Jones and Lee (1994) and Jones *et al*. (1988) indicate only 47 landslides, all with a coastal location. This number largely underestimates the number of true landslides in the county. The lack of research to date may be a result of the perceived stability of 'hard rock' coastlines and their conservative recession rates. Only a few of the recorded landslides have been analysed in detail, highlighted in Coard *et al.* (1987) and Shail *et al.* (1998). Instability was considered, however, in the production of the Shoreline Management Plan (SMP, 1999a, b, c), by indicating the percentage of unstable cliff faces. These percentages, where high (>60%), indicate a high probability of failure. These instability percentage figures, coupled with the predicted recession rates, indicate areas of particular concern for hazard and risk analysis.

In the SMP, coastal recession, instability percentage and landslide occurrence are indicatively linked to the geology of the surrounding area. The geology of the study area in Cornwall is dominated by interbedded slates/sandstones, the Lizard complex and granites that are overlain by a variable thickness of poorly consolidated Quaternary sediments (Figure 1). Average recession rates range from 0.01 m per year in the granites to nearly 1 m per year in poorly consolidated Quaternary sediments (SMP 1999a, b, c).

The differing lithologies contribute to a wide range of possible instability mechanisms and volumes, from individual rock falls (<1 m^3) to large translational slides (10^6 m^3). The interaction of aspect, lithology and structure has formed the basis for a scale hierarchy which has been used to evaluate the instability risks in Cornwall.

HIERARCHY OF SCALE

The scale hierarchy, depicted in Table 1, was established through an initial site reconnaissance of the coastline. This included collation of coastal conditions such as aspect, slope angle and morphology, lithology, land use, probable instability mechanism and prevailing structure. Jones and Lee (1994) and Lee (1995) highlighted the interrelationship between geology and structure in the distribution of landslides within Great Britain, with particular reference to landslide-prone lithologies. The division of the Cornish coast, based on lithology should indicate whether there are particular lithologies and structures that provide a greater probability of instability than others. Figure 1 shows the geology of Cornwall, together with landslide location data presented by Jones *et al*. (1988). Figure 1 indicates that coastal landsliding in Cornwall is predominately contained within the interbedded slates/sandstones of the Upper and Upper

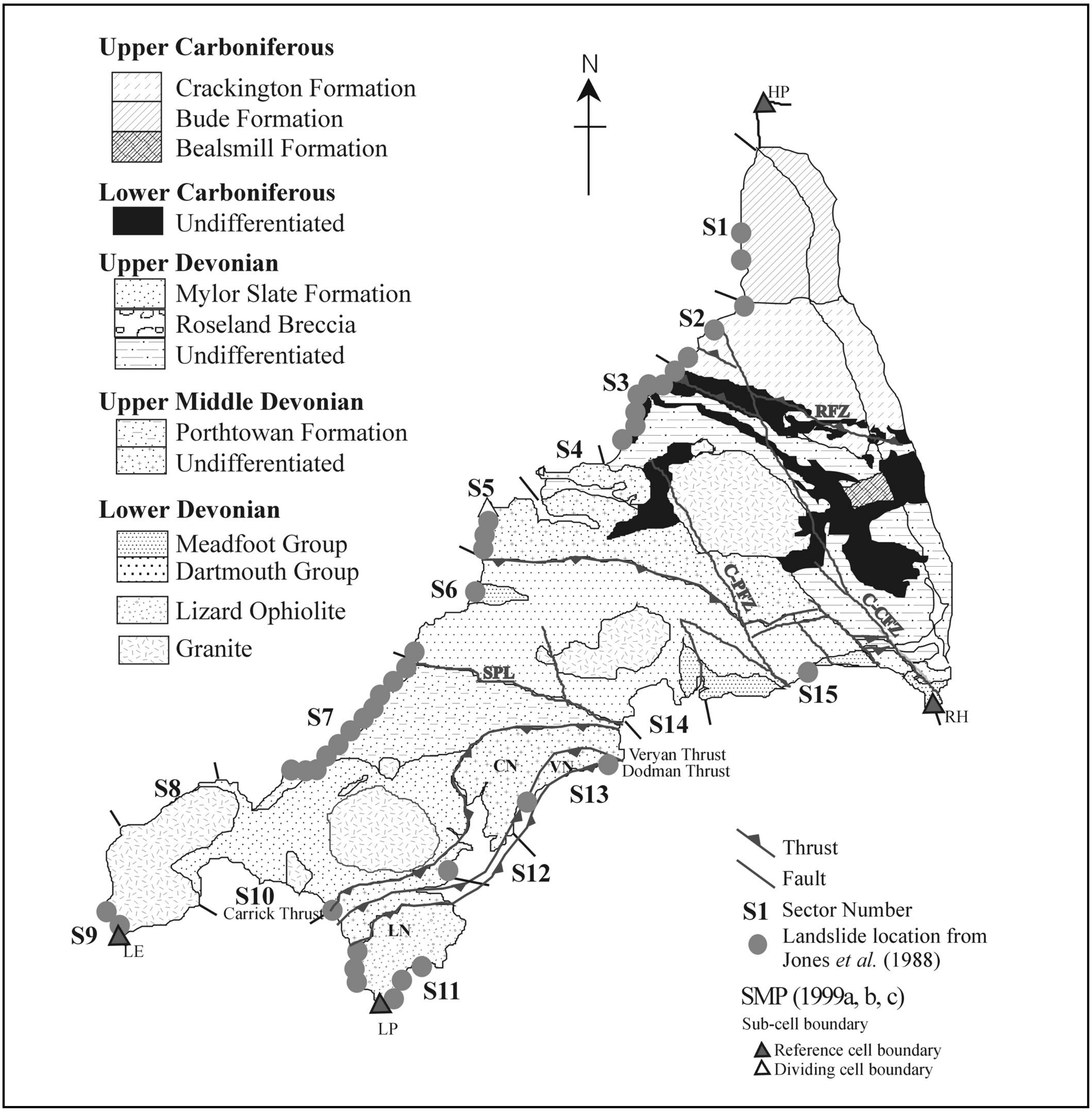

Figure 1. *Diagrammatic representation of the geology and structure of Cornwall, adapted from Selwood et al. (1998) with landslide locations from Jones et al. (1988) and SMP (1999a, b, c) major cells. CN- Carrick Nappe; LN- Lizard Nappe; VN- Veryan Nappe; C-CFZ- Cambeck-Cawsand Fault Zone; C-PFZ- Cardinham-Portandler Faults Zone; RFZ- Rusey Fault Zone; SPL- Start-Perranporth Line.*

Middle Devonian and Lower Carboniferous and to a limited extent, the Lizard complex and the granites.

In the current investigation structure and differing aspect (offshore direction from coast) were included in the scale hierarchy (Table 1), especially at a sector and area scale. Sectors, where possible, were confined to one single lithology, to avoid complication and to allow comparisons between landslide prone lithologies. The locations of sectors are included in Figure 1, with identification numbers S1-15. Sectors 9 and 11 are confined within a single lithology, however in these sectors aspect changes dramatically through almost 180°, so further subdivision to a smaller scale is required. Sectors 9 and 11 have been divided into 2 areas, one area covering each aspect, e.g. S9, area 1 (S9, A1) aspect is southwest, with area 2 (S9, A2) aspect being southeast.

Areas are further subdivided into zones with an individual instability mechanism identified, such as falls, slides and flows, using the classification scheme shown in Table 2 and the volume/magnitude of failure shown in Table 3. These subdivisions are based on a number of previous coastal studies in a variety of coastal locations in the UK. Zones have also been classified in terms of whether the instability is current, recent or ancient/relic, which indicates either active, dormant or historical conditions. Within a particular zone the instability mechanism may change dramatically, from topples on a vertical/overhanging free face to planar slides created through a change in the geological structure, cliff height or aspect. The change in geology can also be dramatic. This can result in different instability mechanisms, such as rotational/translation failures, high angle slides or falls. Where appropriate, small changes in material strength have been identified within local zones together with changes in aspect, cliff height, type of lithology, instability mechanism or groundwater.

Coastal Classification	Control	Scale
Sector (several areas)	Geology and structure	10 - 50 km
Area (several zones)	Aspect, average recession rates, cliff height, material strength, coastal use (SMP 1999a, b, c)	5 - 10 km
Zone	Instability mechanism, coastal use, aspect, recession rate, detailed cliff height	1 – 2 km
Local (individual instabilities)	Individual mechanism & analysis, hazards, consequences	10's of metres

Table 1. *Scale hierarchy for risk evaluation on coastal slopes.*

Coastal recession considerations

Landslide activity (Cruden, 1991) is an important component of cliff recession which can evolve into repeated sequences of first-times failures which involve the mobilization of peak strength of the material, characterised by large, rapid displacements particularly where there are large differences between peak and residual strengths such as the Holbeck Hall failure, Scarborough, (Anon, 1994). It can also evolve into reactivation of pre-existing landslides where part or all of a previous landslide mass is involved in new movement along a pre-existing shear surface, where materials are at a residual strength, such as Lyme Regis, Dorset; Blackgang and Castlehaven on the Isle of Wight. The problem is not one of recognition, but of predicting the rate of recession and hence the level of risk to property and infrastructure (Lee, 1995; Lee *et al.,* 2001; Lee *et al.,* in press). When evaluating the risks posed by coastal landsliding it is also important to take into consideration additional factors, such as climate change (Bromhead and Ibsen, 1997; Burroughs, 2001; Collison *et al.,* 2000).

Short-term climatic variability is a factor where increased rainfall levels and ground water storage all raise instability probability and therefore coastal recession. At Lyme Regis, for example, records show that in 6 of the last 8 years rainfall has been above the long-term average, with winter rains increasing by 20-30%. Ibsen (2002) suggests that by 2080 the climate will change to substantially drier summers (decrease in rainfall by 8-23%) and wetter winters (increase in rainfall by 6-22%), indicating the continuation of the trend. The climate variation will cause clays to dry and desiccate in summer and resaturate in winter. This cyclic process decreases material strength, additionally increasing the probability of coastal instability. The increased water in the hydrological cycle could also cause sea levels to rise by up to 0.5 m, from the present to 2100, with variations in the estimates ranging from 0.15 m to 0.95 m depending on different scenarios (Andrews and Howard, 2002). This may have a considerable influence on recession rate, frequency of severe storms and a major impact on coastal instability.

The SMP (1999a, b, c) used geological reports/memoirs, aerial photographs and field observations to subdivide the coast into different management units based on a number of factors with a view to establishing evolutionary trends and sediment inputs. Identified coastal characteristics were used to estimate the rate of cliff top and basal recession over the next 100 years, in broad categories e.g. 0, >0-1, 1-2, 2-5, >5 m. Coupled with this rate the percentage of unstable length and a total annual volume of sediment contributed over the entire length of the cliff section have been established (SMP 1999a, c). The data has also been used for decisions on coastal management. The creation of sea defences, e.g. sea-walls and rock armouring, as well as preventative measures to prohibit sediment transport and long shore drift, through the erection of groynes, have all evolved through a detailed knowledge of the coastal environment.

Qualitative risk assessment

The development of geotechnical risk assessment and risk acceptance in rock slopes has included research on the highways of the Rocky Mountains in the United States and Canada over the past 20 years by Bunce (1997), Evans (1997), Fell (1994), Finlay and Fell (1997), Finlay *et al.* (1999) and Hungr *et al.* (1999). The application of these types of analysis for geotechnical risk assessments has provided a basis for risk quantification and evaluation on coastal slopes within Cornwall.

The risk assessment framework that has been used as part of this investigation is divided into two principal components, hazard consequence and likelihood. The product of hazard consequence and likelihood equate to risk, which is defined as:

$$\underset{\text{Loss/Year}}{\text{Risk}} = \Sigma \underset{\text{Loss}}{\text{Hazard consequence}} \times \underset{\text{Year}^{-1}}{\text{Likelihood}}$$

Figure 2 provides an overview of the qualitative risk assessment framework adopted for analysis of coastal slopes. The hazard consequence analysis included consideration of parameters such as geology, aspect, rainfall, likely producing instability mechanism, instability volume (m^3) and the rate at which failure occurs (m/s). Other considerations included spatial factors, which relate to the vulnerability of the element, including slope edge-property distance, economic loss and human impact. Likelihood is based on the interaction of geology, aspect and rainfall.

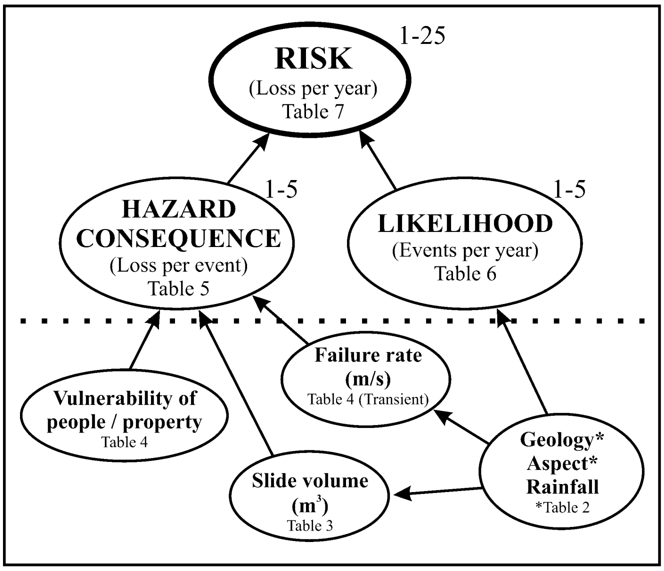

Figure 2. *Qualitative risk assessment influence diagram used in analysis of coastal slopes.*

The individual parameters included in the qualitative risk assessment, are described in the following sections, with the use of an example taken from a section of sector 7 on the North coast, presented as Figure 3 in a Geographical Information System (GIS) format (Figures 3a, b, c).

Hazard

The classification of instability events was undertaken through analysis of the failed slope morphology and a comparison of the morphology of the intact slope with morphology of slopes that have failed with similar aspect, discontinuity structures and/or lithology. Morphological identification of instability mechanisms was undertaken through Table 2 and descriptions based on Brundsen (2002), Cruden and Varnes (1996), Dikau *et al.* (1996), Hutchinson (1988, 1995, 2001) and Varnes (1978, 1984). The volume of unstable/failed material has been classified in the field with the use of Table 3. The primary and secondary

Mechanism / Hazard	Sub-mechanism quantification	Reference	Classification
Complex (prefix)		C	Large multi-stage degradation of the slope caused by a series of mechanisms.
Quaternary (prefix)		Q	Quaternary deposits. Material in a unconsolidated state, either debris or earth. Often poorly consolidated and forming the upper margins of the cliff face.
No mechanism (Dunes, sand bar)		NA	No mechanism event due to Quaternary deposits overlying. Sub categories using earth quotation.
Slump (Debris or earth)		SP (D / E)	Material fails due to loss of internal strength. Often in vertical cliff sections (Quaternary deposits).
Slide (Progressive & regressive) (Rock or debris or earth)		S (R / D / E)	Toe area may deform, producing move ment along a shear surface.
Slide (Progressive & regressive) (Rock or debris or earth)	Rotational	Sr	Rotational movement around a point (sliding), circular failure surface: single, successive, multiple.
	Non-rotational	Snr	Compound two stage movement: Non-circular: listric, bi planar; single, progressive, multistoried.
	Translational (slab / planar)	St	Different acceleration points within the mass causing thinning and separation or down a plane: planar, stepped, wedge, non-rotational.
Flow (Rock or debris or earth)		Fl (R / D / E)	Involve a complex run-out from source in a semi-liquid form: natural.
Topple (Rock or debris or earth)		T (R / D / E)	Topple mechanism influenced by rock type.
Topple (Rock or debris or earth)	Flexural	Tf	Detached from pre-existing discontinuities, onion skin failure or due to compressive forces.
	Block	Tb	Central mass moves outside the blocks fulcrum (leading edge).
	Secondary	Ts	Failure of supporting lithology by toppling causing above material to fail. Commonly described as a Fall.
Fall		Fa (R / D / E)	Mechanism involve: planar, wedge, stepped, vertical movement, through free-fall over at least part of the trajectory.
Caving		CA	Formation of a zawn with the back collapsing. Geomorphological stack sequence.
Caving	Measured	Ω_{D}^{H}	Height of zawn. Depth of zawn into cliff.

Table 2. *Coastal classification used within the scale hierarchy developed from Brundsen (2002), BS 5930 (1999), Cruden and Varnes (1996), Department of the Environment (1992), Dikau et al. (1996), Hutchinson (1988, 1995, 2001), Jones and Lee (1994) and Varnes (1978, 1984).*

instability mechanisms with failure volume have been abbreviated for ease of use in the field and within the GIS database (see Figure 3a and Tables 2 and 3).

Consequence

Essentially, the elements used in consequence analysis can be divided into two broad categories, either permanent (property) and/or transient (people) classified through Table 4 and Figure 3b. In the consequence analysis, rate of failure was only considered on a transient use, due to the ability of transient users to avoid slides with a moderate to slow failure rate (Varnes, 1978, 1984; WP/WLI, 1995). Permanent structures were assumed to be either damaged or lost, irrespective of the rate of movement. The location and proximity to an adverse event should also be considered in the analysis and this is provided through Table 5. Classification of the land above and contained within the coastal slope has been undertaken through interpretation of the SMP (1999a, b, c) and displayed in Figure 3b. The lower coastal slope, which includes beaches, is dependent on access provisions, e.g. tidal conditions and the access period between high and low watermarks.

Hazard consequence analysis has been undertaken initially at a zone level, and through more detailed analysis in local zones

	Volume of material		
Volume description	Volume	Reference	Classification
Small volume 0-10^2 m^3	Rock <1 m^3	rf	Individual rocks
	Debris <10 m^3	df	Collection of individual rocks
	Boulder fall 10-10^2 m^3	bo	Few large boulders
Moderate volume 10^2-10^4 m^3	Block fall 10^2-10^4 m^3	bl	Large block which fragments during travel
Large volume 10^4-10^6 m^3	Cliff fall 10^4-10^6 m^3	cl	Cliff section collapse
Massive volume >10^6 m^3	Bergstruz >10^6 m^3	be	Massive volumes of material, huge run-out distances

***Table 3.** Volume classification of instability on coastal slopes, modified from Department of the Environment (1992), Dikau et al. (1996) and Jones and Lee (1994).*

(Figure 3a). Incidents of coastal instability on cliff-backed beaches pose a significant threat to public safety. A coastal slope failure, highlighted in Bristow and James (2002) indicated the possibility of injury and/or loss of life that could have been caused by coastal instability, at Carlyon Bay (S14) and the high angle planar failure at Chapel Porth (S7) (West Briton, 2002); both of which had to be stabilized through controlled explosion to avoid further failure.

The potential influence on footpaths and infrastructure is emphasised by the collapse of the coastal path between Praa Sands and Rinsey Head (S10) (Western Morning News, 2003) due to a rotational failure in the Quaternary sediments, causing the footpath to be diverted. In the case of the partial collapse (2 m vertical displacement) of the coast road at Whitsands Bay (S15) (Cornish Times, 1995), the failure caused traffic to be diverted and was believed to be induced by increased ground and surface water.

A qualitative value was assigned to each potential instability, depending on hazard components (Figure 3a) such as volume, rate of failure, aspect, geology and rainfall, as well as consequence components, coastal use and land use (Table 5, Figure 3b). The interaction of these components was expressed in a qualitative description, i.e. low, medium or high. The qualitative descriptions, in turn, were converted into values, i.e. very low = 1, low = 2, medium = 3, etc. for multiplication with likelihood.

Likelihood

The predicted return period for slope instability is influenced by a number of factors including rock mass properties, strength and hardness, Rock Mass Rating (RMR) and Rock Quality Designation (RQD) ratings and the local history or frequency of previous instability. These factors were considered together in a qualitative manner to allow an estimation of possible return period of instability to be made (Table 6). Estimates of rock mass quality such as RMR and RQD, for example, were used to give an indication of likely slope stability and coastal recession. Stereographic interpretation of discontinuity orientation data was used to indicate the most likely mechanism of instability. Rock strength and hardness were used to assess the likely impact of coastal processes.

Risk

The descriptors of hazard consequence, Table 4, were multiplied with the descriptors of likelihood, Table 6, each using a range of 1-5, resulting in an evaluation of risk, Table 7, in the range 1-25. In this scheme the higher numbers represent the higher risks. The example results are shown in Figure 3c. It is planned to develop this analysis further towards quantification, as used by Coggan *et al.* (2000) for a specific cliff/beach location.

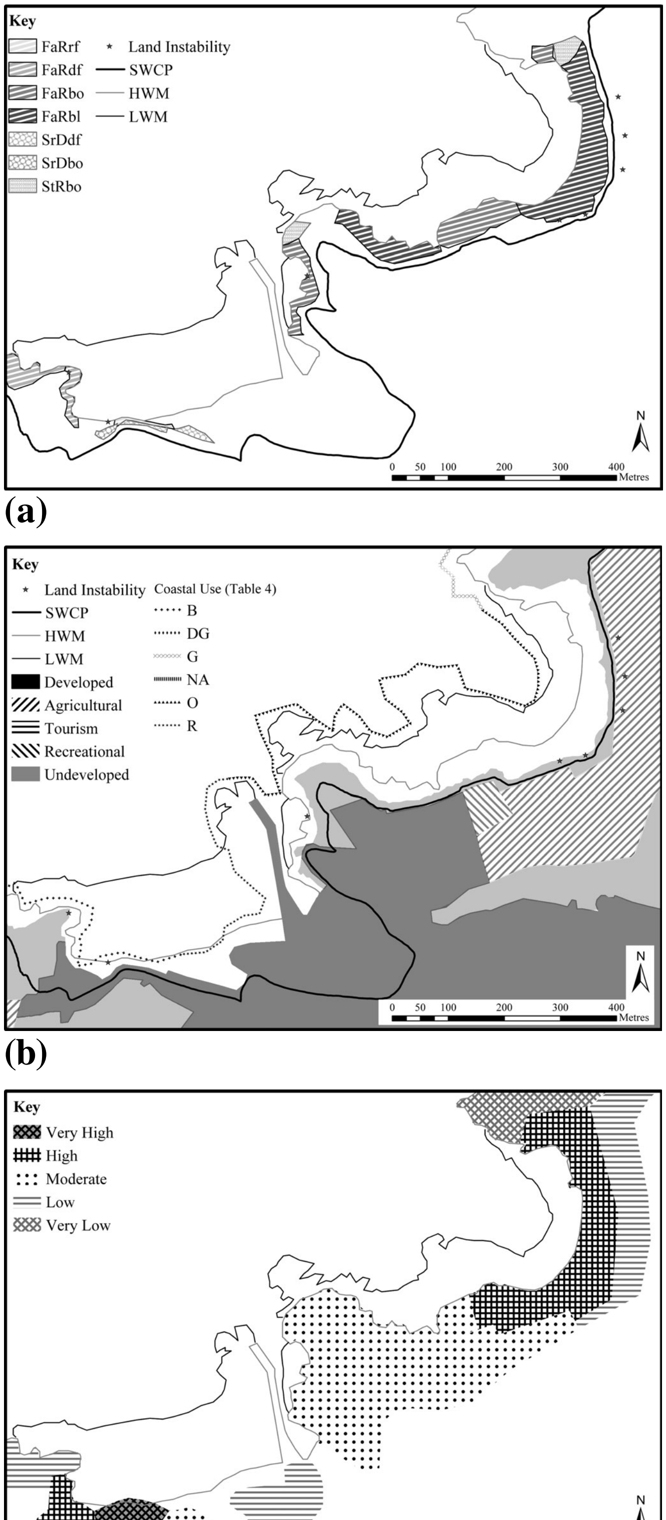

***Figure 3(a)** Instability mechanisms in local zones (Table 1) on the coast. Instability mechanism abbreviations are related to the reference column in Table 2 and volume/magnitude related to the reference column in Table 3. SWCP: South West coastal path. **(b)** Coastal land use, taken from SMP (1999a, c). Land use categories i.e. Y, O, G, LG, R, DG and B are taken from Table 4. Developed, agriculture, tourism, recreational and undeveloped modified from the SMP (1999a, c). SWCP: South West Coastal Path. **(c)** Risk evaluation of coastal instability. Coastal use, instability mechanism and coastal consequence used in the evaluation on the coastal slope. Key from Table 7.*

Primary Use		Symbol			Notes
Permanent	**Property** (Buildings, infrastructure)	**Y**	**R**	**B**	Permanent fixed in a static position, risks posed continually (24hrs; 365 days a year).
	Land (Agricultural, private)	**O**			
Transient	**Recreation** (Footpaths)	**G**	**DG**		Predominantly in daylight hours (»12hrs a day), tide and weather dependant, vastly controlled by climatic conditions and seasonal variations.
	Tourism (Beaches, cafes, hot-spots)	**LG**			

Table 4. *Coastal classification for use in consequence analysis.*

CONSEQUENCE		
Descriptor[#]		**Description**
Insignificant	1	Coastal footpath located >20 m from cliff edge; natural coastal slope; coastal footpath.
Minor	2	Coastal footpath located <20 m from cliff edge; road, infrastructure or services endangered; agricultural land.
Medium	3	Beach only used at low tide; property >30 m of coast (visual loss); agricultural buildings; constant use of footpath; minor disruption to road, infrastructure or service; public inconvenience; medium financial loss; human injury (minor).
Major	4	Beach in moderate to high use; property 20-30 m from edge; road, infrastructure or services destroyed; large financial loss (e.g. garden); human injury (major);
Catastrophic	5	Beach in high to very high level of use; property <10 m from cliff edge; possible human fatalities.

Table 5. *Consequence classification on coastal slopes developed from AGS (2000). Note: [#] Taken from AGS (2000) on the classification of landslide consequences.*

CONCLUSIONS

A qualitative approach to coastal instability risk assessment has been developed in the specific context of conditions encountered in Cornwall. The authors are aware of the inherent limitations associated with the qualitative approach adopted, but consider that the framework is comprehensive and the logic (Figure 2) allows for development into quantitative assessment. The development and presentation of the many underlying components through the use of GIS overlays provides a means to rapidly assimilate the key issues and to identify the spatial locations of the range of risks (Figure 3a-c).

Evidence of Activity	Occurrence or Reoccurrence		Indicative Return Period (years)
Current	Very high	5	0.01
Recent	High	4	0.1
Recent	Medium	3	1
Ancient	Low	2	10
Ancient	Very Low	1	100

Table 6. *Frequency of failure.*

Level of Risk	Qualitative Assessment	
21-25	**VH**	Very high
16-20	**H**	High
11-15	**M**	Moderate
6-10	**L**	Low
1-5	**VL**	Very low

Table 7. *Risk evaluation on coastal slopes within Cornwall.*

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