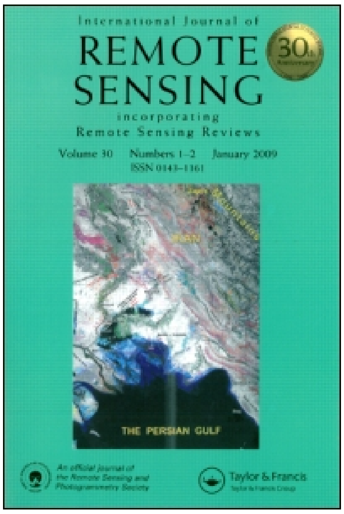


International Journal of Remote Sensing
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713722504

Using geomorphological rules to classify photogrammetrically-derived digital elevation models

A. B. Moore [a]; K. P. Morris [b]; G. K. Blackwell [c]; A. R. Jones [d];P. C. Sims [d]
[a] Spatial Information Research Centre, Department of Information Science, University of Otago, PO Box 56, Dunedin, New Zealand; e-mail: amoore@infoscience.otago.ac.nz. [b] Discovery Software, 36 Elm Park, Paignton, Devon TQ3 3QQ, UK. [c] Uphill, Lustleigh, Newton Abbot, Devon TQ13 9SE, UK. [d] Department of Geographical Sciences, University of Plymouth, Drake Circus, Plymouth, Devon PL4 8AA, UK.

To cite this Article Moore, A. B. , Morris, K. P. , Blackwell, G. K. , Jones, A. R. andSims, P. C.(2003) 'Using geomorphological rules to classify photogrammetrically-derived digital elevation models', International Journal of Remote Sensing, 24: 13, 2613 — 2626

To link to this Article: DOI: 10.1080/0143116031000066891

URL: http://dx.doi.org/10.1080/0143116031000066891

INT. J. REMOTE SENSING, 2003, VOL. 24, NO. 13, 2613–2626

Taylor & Francis
Taylor & Francis Group

Using geomorphological rules to classify photogrammetrically-derived digital elevation models

A. B. MOORE*, K. P. MORRIS†, G. K. BLACKWELL‡,
A. R. JONES§ and P. C. SIMS§

*Spatial Information Research Centre, Department of Information Science, University of Otago, PO Box 56, Dunedin, New Zealand; e-mail: amoore@infoscience.otago.ac.nz
†Discovery Software, 36 Elm Park, Paignton, Devon TQ3 3QQ, UK
‡Uphill, Lustleigh, Newton Abbot, Devon TQ13 9SE, UK
§Department of Geographical Sciences, University of Plymouth, Drake Circus, Plymouth, Devon PL4 8AA, UK

Abstract. An object-orientated expert system is used to identify beach and cliff landforms from Digital Elevation Models (DEMs) on the basis of topological and morphometric rules. The ord landform of the Holderness coast, north-east England, is interpreted as an indicator of enhanced cliff erosion and consists of various beach, till shore platform and associated steep/stable cliff constituents. Each of these are characterised by expert rules through their topological relationship with other constituents and typical values of height, slope, aspect and convexity. Two DEMs (1996 and 1997) are derived from the application of digital photogrammetry to stereo aerial photography provided from the LOIS (Land–Ocean Interaction Study) project. A rule-based classification of landforms is performed using COAMES (COAstal Management Expert System), producing results that conform to historical ground estimations and which identify zones of intense erosion and their commensurate movement with the ord landform over time. The result is achieved through the intelligent storage and operation of classification techniques, which should facilitate non-specialist usage.

1. Introduction

Coastal managers need an informed perspective in order to make effective and sustainable decisions about the land–sea interface (Sims 1998). Geohazard problems, such as cliff erosion, have benefited from the application of 'specialist' sub-branches of science, for example geomorphology (Carter 1988). This is evident from the content of UK Shoreline Management Plans (Ministry of Agriculture, Fisheries and Food (MAFF) 1995, Swash *et al.* 1995, Potts 1999). Of course the monitoring of such geomorphological processes and 'natural' coastal change required by modern shoreline management generates data as exemplified by Sims and Ternan's (1988) proposed geomorphological database and the work on sediment budgets for the coastline of central Southern England by Bray *et al.* (1995). However, what is of interest here are the tools used to get the most out of

---

Presented at the Remote Sensing of the Marine Littoral Environment Meeting, Linnean Society, London, 15–16 December 1999.

International Journal of Remote Sensing
ISSN 0143-1161 print/ISSN 1366-5901 online © 2003 Taylor & Francis Ltd
http://www.tandf.co.uk/journals
DOI: 10.1080/0143116031000066891

those data. Some geomorphological examples include classification of rocky coasts using airborne multi-spectral scanning (Wadge and Quarmby 1988), use of Geographical Information Systems (GIS) to estimate coastline change from digitized maps and photographs (Sims *et al.* 1995) and the detection of shoreline changes using satellite images and tidal data (Chen and Rau 1998).

This paper reports on the use of another kind of tool (expert systems) on photogrammetrically-derived Digital Elevation Models (DEMs) to monitor the ord landform (Pringle 1985) of the Holderness coast, north-east England (figure 1). There is a sparsity of expert systems with a coastal application (but see Scheerer 1993, McGlade 1997, Houhoulis and Michener 2000). This is surprising since such systems, along with other types of coastal zone management information system (CZMIS), are seen as the solution to integrating the range of formats, qualities, sources and disciplines invariably found in coastal data and information (Ripple and Ulshoefer 1987, Miller 1994). The dearth of marine and coastal expert systems indicates that a strong potential niche exists in ocean or coastal science.

A specific illustration of geomorphological effect on coastal zone management lies in the close relationship between beach morphology, cliff erosion and land loss at Holderness (Pringle 1985). In the short term, relative erosion of the cliff is more rapid in places where the upper beach becomes lower and narrower, exposing a till platform at the foot of the cliff (figure 1). This is the centre of the ord landform, serving as an indicative feature of increased cliff erosion. Independent volumetric calculations have backed up this perceived effect of upper beach absence, showing that cliff erosion is approximately five times greater without the protection of the upper beach (Pringle 1985, Richards 1997).

It follows that if the movement of an ord can be extrapolated into the future, then the locations and times where the greatest erosion will take place can be predicted, using past ord studies to indicate likely erosion rates. Prediction would be valuable in the short term and on a local scale. This is especially true since long-term evidence points to an overall constant rate of erosion (the uniform coastline is

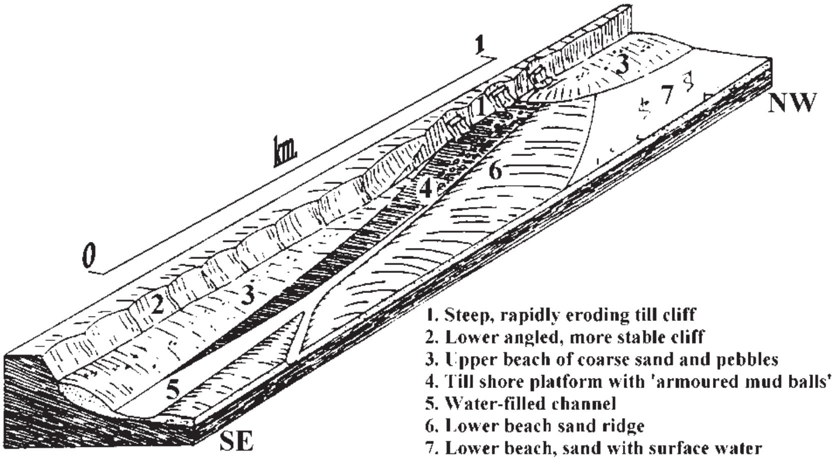


Figure 1. The characteristic features of a Holderness ord (from Pringle 1985). Increased erosion occurs where the upper beach is absent from the foot of the cliff, exposing the underlying till platform.

evidence of this), despite the short-term and local-scale variability (Balson *et al.* 1996). This ability to predict has implications for the management of the natural and human coastal environment with the loss of valuable agricultural, residential and industrial land and the construction of sea defences on dynamic beach topography. These changes in turn call for a coastal zone management response. The intended role of the COAstal Management Expert System (COAMES — Moore *et al.* 1996, 1998), the subject of this paper, is to provide decision support to help formulate this response.

2. Expert systems

2.1. *Basics*

By definition, 'expert systems are computer systems that advise on or help solve real-world problems requiring an expert's interpretation and solve real-world problems using a computer model of expert human reasoning reaching the same conclusion the human expert would reach if faced with a comparable problem' (Weiss and Kulikowski 1984). They have been around since the mid-1960s (Durkin 1996), and the recent increase in the scale of high performance computing has benefitted expert systems, along with other artificial intelligence applications, such as neural networks and genetic algorithms (Openshaw and Abrahart 1996).

The core of an expert system commonly consists of two parts: a domain-independent inference engine and a domain-specific knowledge base. The inference engine is at the heart of the expert system, processing user input, controlling the use of stored knowledge and data and, finally, defining the system output. The knowledge base is a repository of expert knowledge covering both facts and rules (Robinson *et al.* 1986). 'Facts' describe single values such as basic information or events. Expert 'rules' model behaviour of, and functions relating to, a theme. Laurini and Thompson (1992) add two other expert system constituents: a module for knowledge acquisition (through which knowledge is elicited from the expert) and a module for interfacing with the user. The latter is the means through which (a) the user can engage in dialogue with the system, and (b) the system can present output and the explanation of how that output was derived.

COAMES is an object-orientated expert system, consisting of the core elements as defined above (the object-orientated knowledge base incorporates both the expert's factual knowledge and the process knowledge embodied in models), a user interface and a database (Moore *et al.* 1996). Most expert systems have the same basic form, though the arrangement may change in terms of conceptual form and nomenclature.

2.2. *Object-orientation*

COAMES is underlain by an object-orientated knowledge structure, where modelling is performed through the functions and attributes belonging to objects in reality (called classification — Worboys 1995). For example, objects may contain geomorphological rules and are classified within the prototype domain. Figure 2 shows the form of the class structure for the geomorphological prototype. The morphometry subclasses (the classes below 'morphometry' in the hierarchy) slope, aspect and convexity are defined by their attributes and functions; these are contained or encapsulated within the class definition. In addition, they inherit all the elements of the morphometry superclass (the class above in the hierarchy). The

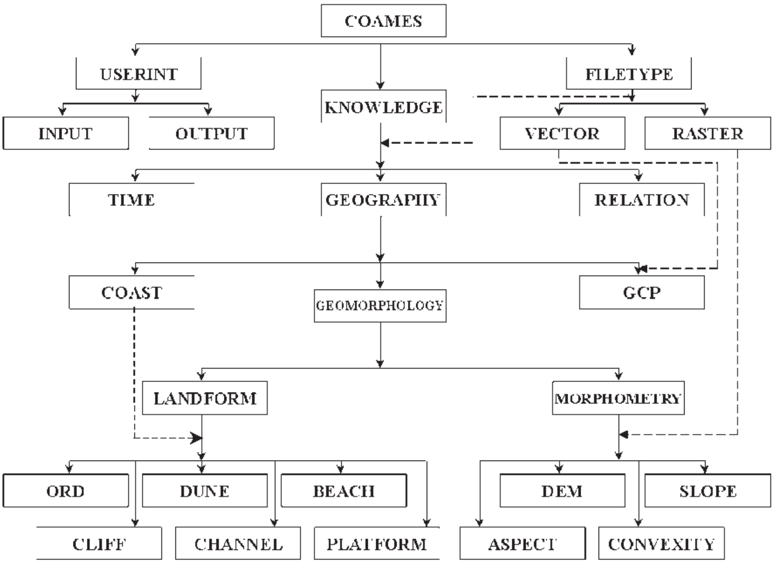


Figure 2. The object-orientated hierarchical structure of knowledge and data in the prototype (multiple inheritance links are dashed).

broken line links in another class, the raster class, from which inheritance is derived. This is multiple inheritance (Tello 1989), where a class inherits from more than one superclass. This inheritance reflects a property that is common to slope, aspect and convexity in the case study — the 2D raster data structure. Each instance of a given class is termed an object. Therefore, for other geomorphological features, new objects may be created, such as upper beach or till platform.

The rules contained within the object define their interrelationships with other constituents of the ord and their morphometric properties. For instance, the upper beach has rules to describe both its adjacency to a stable cliff (interrelationship between constituent elements), and characteristic upper and lower limits of slope (morphometric properties).

The object-orientated design of COAMES has been established above. The interface and main workings of the expert system are programmed in C++, an object-orientated language (the interface is also Java based). While COAMES is not presently linked to an object-orientated database, it is conceptually and functionally a true object-orientated expert system.

3. Procedure

The COAMES prototype has been developed to characterise beach morphology on a rapidly eroding coast, captured by multi-temporal stereo aerial photography.

3.1. *The study area*

The shoreline sector, which forms the area of study (figure 3) consists in part of glacial till cliffs which are subject to a long-term and rapid recession rate estimated at about 2 m a^{-1} (Valentin 1954, Pringle 1985, Mason and Hansom 1988, Hoad 1991). In front of the cliffs is the ord landform, which is typically 1 to 2 km in

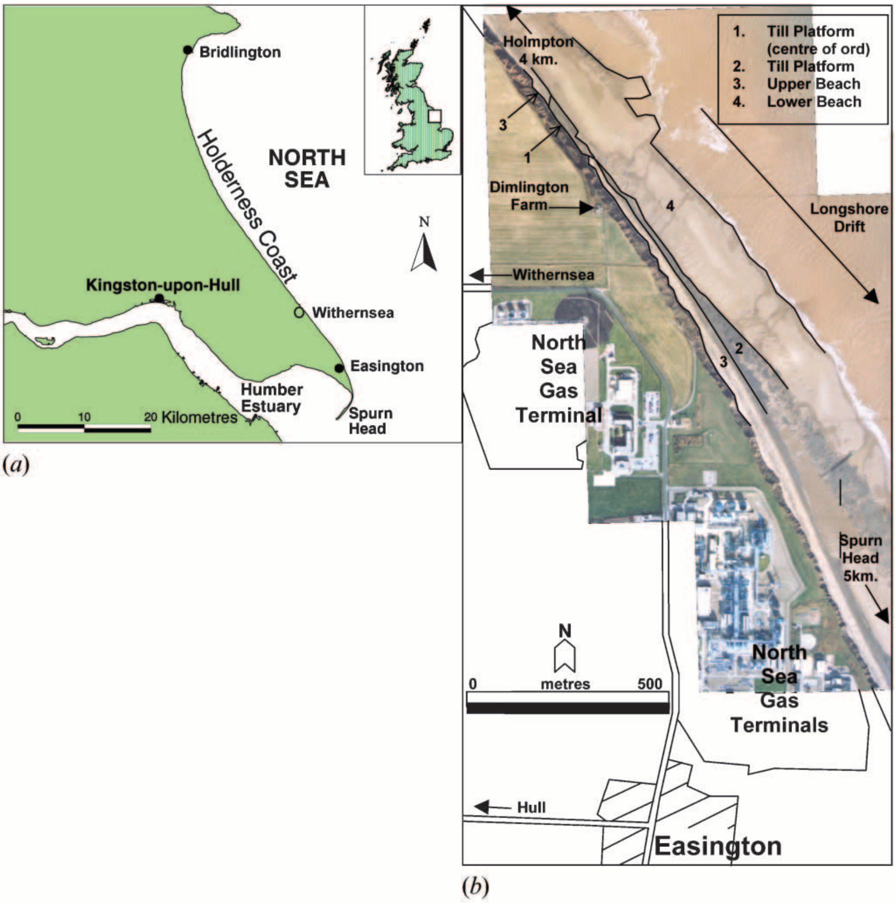


Figure 3. Location map of (*a*) the Holderness Coast; (*b*) the study area, based on an orthographic photograph derived from the 26 October 1996 sortie.

length (Scott 1976). The ord migrates in the direction of longshore drift (south-east) at an average rate of approximately 500 m a^{-1} (Pringle 1985), during which the overall form of the composite feature retains its integrity (Pringle 1981). This average figure masks much forward and backward variation of movement throughout the year. A more recent study (Richards 1997) has recorded movement southward of between 130 and 800 m a^{-1}. The ord currently adjacent to the Dimlington–Easington stretch of the Holderness coast was chosen for this study (figure 3(*b*)). Recent studies have revealed this ord to be that most resembling the archetypal ord (which is outlined in the introduction and in figure 1), in terms of both form and behaviour (A. W. Pringle, personal communication, 1999).

The beach (ord) morphometry can be summarized as follows.

- Upper beach: usually convex in profile (Pringle 1981), and slopes relatively steeply seaward from 3.6° minimum to 4.9° maximum (Scott 1976)—the figures are from measurements of ords in the Holmpton–Easington area.
- Lower beach: an even and gentle overall gradient, with an asymmetric sand

ridge having a seaward-facing slope of 0.4° minimum to 3.6° maximum and a landward-facing slope of 4.0° minimum to 4.5° maximum (Pringle 1985).
- Till platform: the slope was estimated at 5° minimum to 9° maximum in a 40 m wide strip parallel and adjacent to the cliff foot, and 1° minimum to 1.5° maximum further seaward (Pringle 1985).

The Holderness coast was chosen for study for the following reasons:

- *The dynamicism of the coast locally*. The scale of erosion here is such that it is measurable over time periods as short as one month. This means that even the most recent part of the historical record (in the form of maps and aerial photography) may show huge change.
- *The abundance of data and knowledge*. There is a large collection of recent aerial photography (since 1994) of this coast, flown in support of the Natural Environment Research Council (NERC)-funded project, the Land–Ocean Interaction Study (LOIS). Therefore, it forms a wealth of potential data for the expert system, providing an ideal test. Existing geomorphological knowledge is not in short supply—this coast has been the subject of much research in the past, fulfilling a knowledge base test.
- *The complexity of the landform in question*. The ord is a complex, composite landform, setting a challenge for its representation in the expert system.

The beach and cliff adjacent to Easington and the North Sea Gas Terminals is the specific area of study.

3.2. *Digital photogrammetry*

The stereo aerial photographs flown for LOIS were taken by a Wild RC-10 camera from a NERC Piper Chieftain Aircraft at 1000 m. Photographs for two specific dates (26 October 1996 and 8 April 1997) were chosen for the following reasons:

- the interval covers winter, the time of year when most erosion is expected to take place (Pringle 1985);
- the photography on these dates covered the area of interest at spring low tide (exposing an optimal area of beach) without cliff shadow, clouds or haze;
- the chosen photography allowed for a good spread of ground control points (GCPs).

The GCPs to be used in photogrammetric processing were collected through a Differential GPS survey (using two Ashtech Z-12 geodetic receivers) undertaken in late October 1996 in conjunction with the aerial photography sorties. The GCPs were accompanied by topological (relative position) descriptions of the constituent features of the ord. Examples of descriptions include 'upper beach next to cliff' or 'junction of till platform and lower beach'. These descriptions are used by the expert system to locate landforms on the DEM.

The photography was scanned and photogrammetrically processed (using Erdas Imagine Orthomax) to derive DEMs (regularly spaced grids of elevations) as input into the expert system. A predefined sampling interval of one metre was used. For the purposes of geomorphological feature identification, this sampling interval was considered adequate as the landforms to be identified were significantly larger than this spatial resolution. There may be instances, such as when measuring cliff erosion, where denser sampling strategies may be required. Finally, DEMs are accessed as data in the expert system.

3.3. *Use of the expert system*

The constituents of the expert system will be discussed in turn: (1) user interface; (2) models; (3) data; (4) knowledge base and inference engine.

3.3.1. *User interface*

This is the program front-end through which the user can pose a scenario or query. An initial user input is processed through an elementary natural language procedure (i.e. a system that allows processing of typed English) that identifies words based on comparison with lists of terms contained within classes such as 'Coast' (coast-specific terms such as 'shingle', 'beach' etc.) and 'Relation' (context-specific terms such as 'next to', 'in' etc.). Such a query could be 'track the movement of upper beach within an ord from time 26/10/96 to 04/04/97 at Easington'. Certain words from this (e.g. 'ord') are used to trigger or invoke a set of knowledge rules, in this case based on the topology between beach features shown in figure 1. This interaction will develop into the envisaged dialogue between the coastal zone manager and the system. At the end of the expert system run, the user is informed through the interface how the expert system reached a conclusion.

3.3.2. *Models*

Within the expert system, geographical algorithms such as definition of regions and raster processes (deriving slope, aspect and convexity from a DEM) are embedded as models in the knowledge structure as a property of the relevant class. The rationale for this is that as the algorithms simulate geographical constructs, they themselves should be regarded as models.

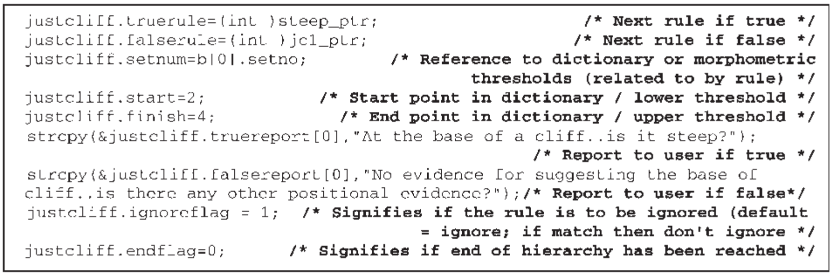
3.3.3. *Data*

Datasets will be stored in flat files, for example, the DEMs and GPS positional data used in the case study. Surveyed points may locate the junction of upper beach and till platform. This descriptive information is included with the data.

3.3.4. *Knowledge base and inference engine*

The inference engine is the heart of the expert system, assimilating user queries, and associated knowledge and data to provide meaningful output to the user. Knowledge processing is enabled through the knowledge structure via deduction, or forward chaining. It is used for 'What if ?' scenarios. Therefore, if a condition A is true and the rule A→B can be found in the rule base, then we can deduce that B is also true (Fisher *et al.* 1988). Figure 4 contains the structure for the rule 'justcliff' (enquires whether or not the object in question is a cliff in general).

All the knowledge relating to 'justcliff' is encapsulated in this structure. The inference engine decides whether 'justcliff' is true by comparison to the set of dictionary terms under 'setnum' (b(0).setno refers to the terms) and between 'start'



```
justcliff.truerule=(int )steep_ptr;                        /* Next rule if true */
justcliff.falserule=(int )jc1_ptr;                        /* Next rule if false */
justcliff.setnum=b|0|.setno;        /* Reference to dictionary or morphometric
                                               thresholds (related to by rule) */
justcliff.start=2;             /* Start point in dictionary / lower threshold */
justcliff.finish=4;             /* End point in dictionary / upper threshold */
strcpy(&justcliff.truereport[0],"At the base of a cliff..is it steep?");
                                                    /* Report to user if true */
strcpy(&justcliff.falsereport[0],"No evidence for suggesting the base of
cliff..is there any other positional evidence?");/* Report to user if false*/
justcliff.ignoreflag = 1;  /* Signifies if the rule is to be ignored (default
                                      = ignore; if match then don't ignore */
justcliff.endflag=0;       /* Signifies if end of hierarchy has been reached */
```

Figure 4. The structure for the rule 'justcliff' within the knowledge base.

and 'finish' (these are references to specific terms). If it is true then it will try whether or not it is a steep cliff by using 'truerule' to point to the next structure. If false, then 'falserule' is used in the same way. At the same time the relevant report is printed out to the user ('truereport' and 'falsereport'). By default, 'ignoreflag' is set to 1. Upon the rule being true, it is set to 0, instructing the inference engine on future forays through the structure hierarchy to regard this rule. This is in effect a way of teaching the inference engine to recognize only those rules that are relevant. This is the first stage in what Fisher *et al.* (1988) call a 'recognize–act cycle'. The 'endflag' is a way of telling the inference engine not to go any further down this hierarchy, either stopping or shifting attention to other groups of knowledge. This process is repeated until the hierarchy has been fully descended (figure 5).

As an example of the above, if the query is not concerned with cliffs, as in the case above, then the hierarchy is descended to make the same inferences on the basis of 'beach', where the rule would find a match. If the query was concerned with cliffs, then the hierarchy is descended to ascertain whether a 'steep' or 'stable' cliff is the object of interest. This process carries on until the 'end' rule is reached. The configuration of the ord rule hierarchy is derived from the archetypal ord schematic in figure 1. It represents one interpretation of the schematic, though it can be seen how more detail can be added or more links implemented. For example, continuing the 'cliff' branch of the hierarchy to subsequently follow up whether the cliff is contiguous to an upper beach or till platform, or enabling two or more rules in combination to define a feature.

The trained hierarchy is subsequently descended again (the second part of the 'recognize–act cycle') with the GCP topological description replacing the user query as the source of comparison. Movement through the knowledge tree is restricted to the flagged areas (i.e. those marked 'true' — ignoreflag = 0). If the GCP in some way defines the feature to be isolated in agreement with the original query, then the associated three-dimensional coordinates are recorded and used to define a region. This is facilitated through a function encapsulated in the geography class as a model. This use of the associated topological information gives the GCPs intelligence. The format of one such GCP entry may be:

ID	**Topological Description**	**X**	**Y**	**Z**
101,	upper beach next to cliff,	539350.81,	421345.59,	3.56

All the while, the inference engine (IE) works separately from the knowledge

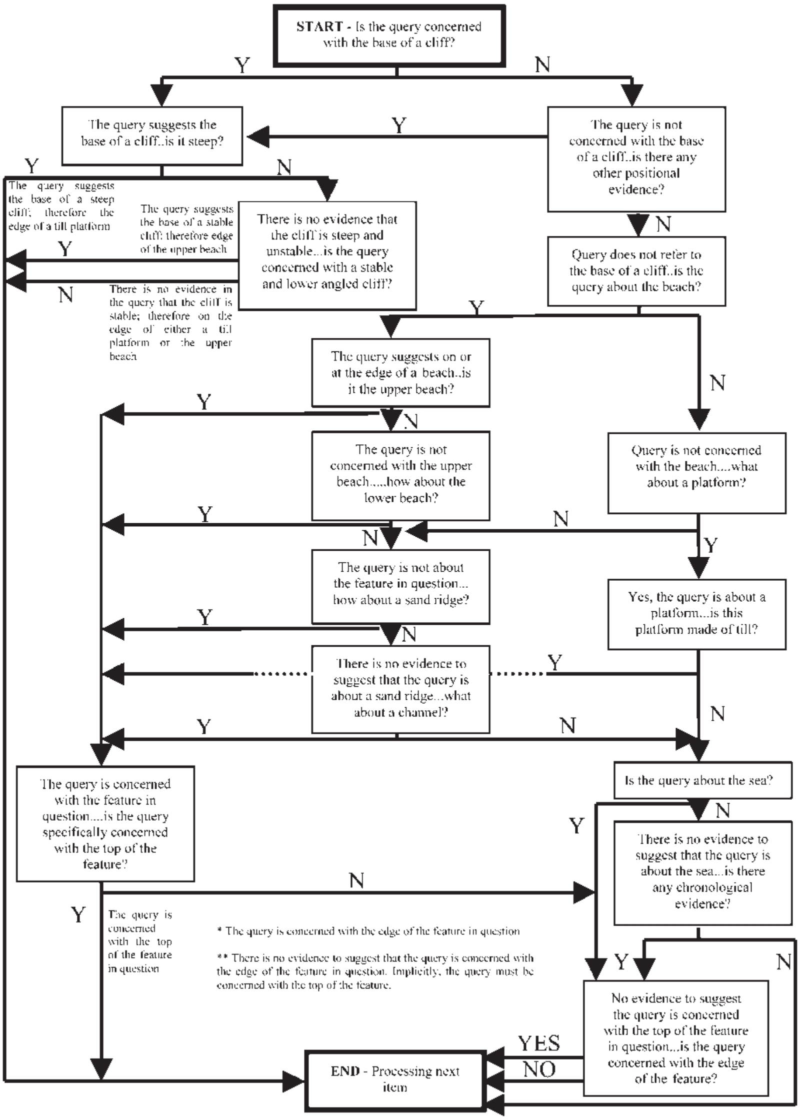


Figure 5. The hierarchy of rules used to process the user query and ascertain which portions of knowledge to use. The configuration is derived from the archetypal ord schematic in figure 1. Each of these rules have attributes that link with the relevant dictionary terms. The extracted terms are compared with the user query.

and database. This is important from the point of view of modification, a task that would be hard to do if the IE was hard-wired to the other components.

The derived region acts as the focus for morphometric measures (Evans 1972) such as altitude, slope, aspect and convexity (stored as models under the morphometry class) to delineate the feature to a greater degree. Representative thresholds of these for each ord constituent are encapsulated in the geomorphology class. These thresholds are stored as unique morphometric rule hierarchies (figure 6), which were descended in turn. For each of height, slope, aspect and

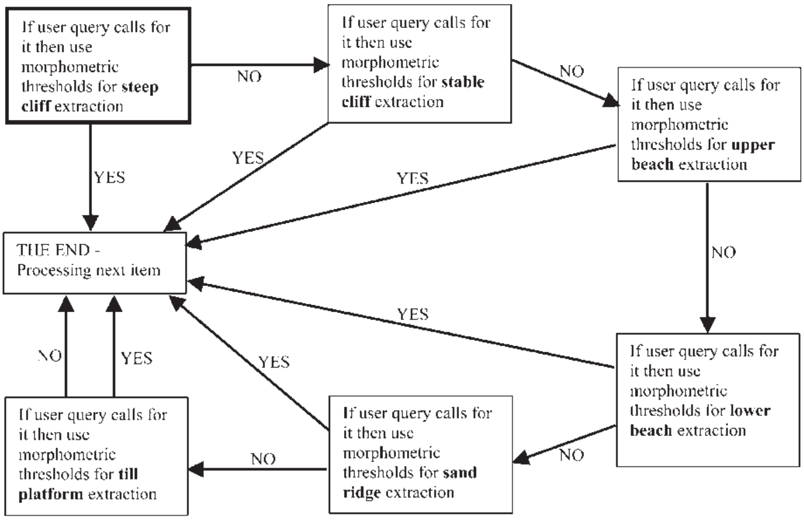


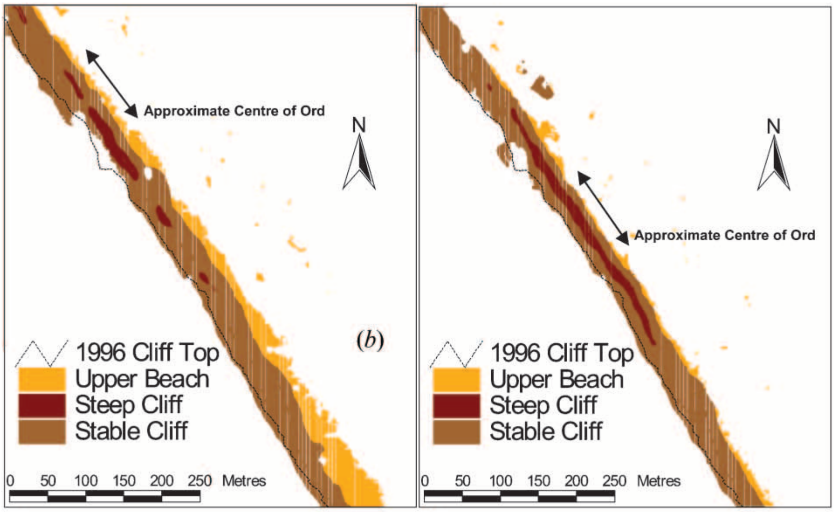
Figure 6. The hierarchy of rules used to set parameters for morphometric extraction. There is a set of these rules for each basis of extraction: height, slope, aspect and convexity. Each of these rules have attributes that link with the relevant morphometric thresholds. The extracted thresholds are passed to the relevant morphometric function.

convexity, the ignoreflags set in the ord rule hierarchy were used to stop at the rule corresponding to the feature of interest (having started at the initial steep cliff rule). Each rule has attributes that link with the relevant morphometric thresholds. The procedure for manipulating with numbers (as opposed to words) is very similar. The above structure is preserved, though 'setnum' is given a special number to make the inference engine recognize that numbers are being dealt with in this case. For instance, in the case of the structure 'justcliffslope', cliffs can broadly be said to be between 20° and 90° in terms of slope; these limits are represented in 'start' and 'finish', to be processed by the expert system. (The maximum and minimum feature threshold values that were stored as knowledge in the expert system were originally estimated by conventional ground survey — a summary can be found in section 3.1). The identified thresholds were stored and passed to the relevant morphometric function, which was used, along with the region, to classify the DEM for a particular feature on the basis of either height, slope, aspect and convexity.

4. Results

Figures 7(*a*) and 7(*b*) are decision support output maps intelligently derived from DEMs on the basis of queries requesting the location of steep cliffs, stable cliffs and the upper beach at the two acquisition dates. Using the figures as decision support output, the centre of the ord, if present, can be deduced from the relative geographical configuration of these three features. The cliff top line for 1996 was digitized from the orthophotograph of 26 October 1996 and is provided here as a point of reference. Regardless of slope, the edge of the grassed area was accepted as the top of the cliff, so there may be disparities between this line and the identified landforms.

There is evidence for ord presence and associated movement in the direction of



(*a*) (*b*)

Figure 7. The identification of steep cliff, stable cliff and upper beach at Easington from DEMs of the study area at two dates, using topological and morphometric rules accessed by the COAMES expert system (Ordnance Survey National Grid): (*a*) 26 October 1996; (*b*) 8 April 1997.

longshore drift. In the time period from October 1996 to April 1997, the southern end of the steep cliff zone (about 100 m long at first) had been extended by approximately 250 m southward in the direction of longshore drift, while the northern end migrated some 75–100 m southward. In the past, movement of the ord centre has been estimated at approximately 500 $\mathrm{m\,a^{-1}}$ in the direction of longshore drift (Pringle 1985)—these results support that figure.

Thin sections of upper beach can be seen to migrate at the same rate and in the same direction, reinforcing the observed correlation between steep cliff and upper beach absence that is typical of the ord landform. The correlation of stable (lower gradient) cliff areas and the more extensive upper beach zones (Pringle 1981) can also be identified from the results.

This is notably not the case to the extreme north of the April 1997 map. The supposed presence of stable cliff on the beach indicates a misrepresentation in the stereomatching process, probably caused by surface water on the beach. There are also instances where upper beach areas have been erroneously classified where the lower beach should be (on comparison with figure 3(*b*)).

5. Conclusion

In this paper, a geomorphological case study has demonstrated the capabilities of a rich yet accessible structure in capturing a limited environment (i.e. the domain of a beach landform) and in modelling the objects and processes operating within. The case study has successfully shown the identification of landforms from photogrammetrically-derived DEMs through use of this expert knowledge and data. Analysis of the decision support output has identified the centre of the ord landform and shown its movement over a six-month period to be in accordance with theory. Given the association of the centre of the ord with enhanced cliff erosion, such areas can be identified prognostically in the short term. This, in turn, will have a direct effect on social and economic activities.

However, there is room for improvement with the expert system method as implemented here. The results exhibit considerable 'noise' (e.g. gaps in the upper beach/stable cliff; erroneous classification of upper beach). This occurrence of noise is bound to happen where morphometric thresholds are defined as explicitly as they are here. With logical modelling, there is an inherent uncertainty through the use of terms like 'steep cliff' (i.e. what exactly is steep in mathematical terms?). This difference would be reflected in a comparison with output derived from mathematical modelling, with the logically derived result increasingly likely to be accompanied by a measure of uncertainty. In such cases, non-definitive reasoning, such as fuzzy logic or Bayesian analysis, is used. For instance, the morphometric thresholds could be fuzzified. Another solution is the use of more knowledge (i.e. derived from other data sources), such as a spectral image of the beach to indicate patterns of heterogeneous sediment distribution. Fuzzification is part of an overall treatment of error handling required by the system (another use of which is the translation of descriptive terms into quantities). Incorporation of a cliff erosion model into the system is another further step.

The expert system is accessible in that it encourages non-specialist usage. The same results could have been replicated with guidance from an expert to manually apply the morphometric thresholds and zoom in to the correct area with a series of repetitive operations. Using COAMES, this guidance is stored in the system, so that the coastal manager does not need to know what computational processes were run to arrive at the decision support output (though the information is there if needed). Therefore, COAMES is more flexible than the manual process, being able to use whatever the scope of the user input, knowledge base and database allows.

From their beginnings, expert systems have proven useful in situations that do not lend themselves to unaided user analysis. For example, there is the case of the PROSPECTOR expert system in geological prospecting, a domain where knowledge is inherently incomplete or uncertain (Alty and Coombs 1984). With COAMES, knowledge of the coastal zone can be equally fragmented and ambiguous. On top of cliff and beach erosion prediction, we know that a huge amount of coastal data and information exist—it needs the analytical capabilities of the expert system to handle these challenges effectively.

Acknowledgments

This research was aided by financial and infrastructure support from Plymouth Marine Laboratory (as part of the Land–Ocean Interaction Study) and latterly a research grant from the University of Plymouth, which is gratefully acknowledged. The authors would like to thank Dr Ada Pringle for her advice on Holderness geomorphology and, along with Karla Youngs and George Pringle, for help with the surveying. We are grateful to the NERC Geophysical Equipment Pool/Ashtech Europe for loan of the GPS equipment and technical support, British Geological Survey for the pre-surveyed GPS points and the NERC Airborne Remote Sensing Facility for the acquisition of aerial photography.

References

ALTY, J. L., and COOMBS, M. J., 1984, *Expert Systems – Concepts and Examples* (Manchester: NCC Publications).

BALSON, P. S., TRAGHEIM, D. G., DENNISS, A. M., WALDRAM, D., and SMITH, M. J., 1996, A photogrammetric technique to determine the potential sediment yield from recession of the Holderness coast, UK. In *Partnership in Coastal Zone Management*, edited by J. Taussik and J. Mitchell (Cardigan: Samara Publishing Ltd.), pp. 507–514.

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

CARTER, R. W. G., 1988, *Coastal environments – An introduction to the physical, ecological and cultural systems of coastlines* (London: Academic Press).

CHEN, L. C., and RAU, J. Y., 1998, Detection of shoreline changes for tideland areas using multi-temporal satellite images. *International Journal of Remote Sensing*, **19**, 3383–3397.

DURKIN, J., 1996, Expert systems: A view of the field. *IEEE Expert*, **11**, 56–63.

EVANS, I. S., 1972, General geomorphometry, derivatives of altitude and descriptive statistics. In *Spatial analysis in geomorphology*, edited by R. J. Chorley (London: Methuen), pp. 17–90.

FISHER, P. F., MACKANESS, W. A., PEACEGOOD, G., and WILKINSON, G. G., 1988, Artificial intelligence and expert systems in geodata processing. *Progress in Physical Geography*, **12**, 371–388.

HOAD, J., 1991, Monitoring of the inter-tidal beach profile to tidal and wave forcing. *Proceedings of the Coastal Sediments '91 Conference, Seattle* (Seattle, USA: American Society of Civil Engineers), pp. 385–395.

HOUHOULIS, P. F., and MICHENER, W. K., 2000, Detecting wetland change: A rule-based approach using NWI and SPOT-XS data. *Photogrammetric Engineering and Remote Sensing*, **66**, 205–211.

LAURINI, R., and THOMPSON, D., 1992, *Fundamentals of spatial information systems* (London: Academic Press).

MCGLADE, J. M., 1997, SimCoast™ — an expert system for integrated coastal zone management and decision-making. NOAA–NMFS workshop on biological and physical changes within the north-east shelf ecosystem of the USA. Workshop Background Paper, University of Warwick.

MINISTRY OF AGRICULTURE, FISHERIES AND FOOD (MAFF) 1995, *Shoreline Management Plans – a guide for coastal defence authorities* (London: MAFF), PB 2197, pp. 24.

MASON, S. J., and HANSOM, J. B., 1988, Cliff erosion and its contribution to a sediment budget for part of the Holderness coast, England. *Shore and Beach*, **65**, 30–38.

MILLER, D., 1994, Coupling of process-based vegetation models to GIS and knowledge-based systems for analysis of vegetation change. In *Environmental information management and analysis*, edited by W. K. Michener, J. W. Brunt and S. G. Stafford (London: Taylor and Francis), pp. 497–509.

MOORE, A. B., MORRIS, K. P., and BLACKWELL, G. K., 1996, COAMES — Towards a coastal management expert system. *Proceedings 1st International Conference on GeoComputation* (Leeds, UK: University of Leeds), 2, pp. 629–646.

MOORE, A. B., MORRIS, K. P., BLACKWELL, G., GIBSON, S. E., and STEBBING, A., 1998, An expert system for coastal zone management: A geomorphological case study. *Marine Pollution Bulletin*, **37**, 361–370.

OPENSHAW, S., and ABRAHART, R. J., 1996, *Geocomputation. Proceedings 1st International Conference on GeoComputation* (Leeds, UK: University of Leeds), **2**, pp. 665–666.

POTTS, J. S., 1999, The non-statutory approach to coastal defence in England and Wales: Coastal defence groups and Shoreline Management Plans. *Marine Policy*, **23**, 479–500.

PRINGLE, A. W., 1981, Beach development and coastal erosion in Holderness, north Humberside. In *The Quaternary in Britain*, edited by J. Neale and J. Flenley (Oxford: Pergamon), pp. 194–205.

PRINGLE, A. W., 1985, Holderness coast erosion and the significance of ords. *Earth Surface Processes and Landforms*, **10**, 107–124.

RICHARDS, J. A., 1997, Study of ords and cliff erosion at the Holderness coast using digital elevation models derived from stereo aerial photographs. MSc thesis, University of Plymouth.

RIPPLE, W. J., and ULSHOEFER, V. S., 1987, Expert systems and spatial data models for efficient geographic data handling. *Photogrammetric Engineering and Remote Sensing*, **53**, 1431–1455.

ROBINSON, V. B., FRANK, A. U., and BLAZE, M. A., 1986, Expert systems applied to problems in Geographic Information Systems: Introduction, review and prospects. *Computers, Environment and Urban Systems*, **11**, 161–173.

SCHEERER, D. J., 1993, Reasoning under uncertainty for a coastal ocean expert system. *Johns Hopkins APL Technical Digest*, **14**, 267–280.

SCOTT, P. A., 1976, Beach development along the Holderness coast, north Humberside, with special reference to ords. PhD thesis, University of Lancaster.

SIMS, P., 1998, Coastline erosion, protection and management in Devon and Cornwall. In *Environmental management and change in Plymouth and the South West*, edited by M. Blacksell, J. Matthews and P. Sims (Plymouth: University of Plymouth), pp. 73–92.

SIMS, P., and TERNAN, L., 1988, Coastal erosion: Protection and planning in relation to public policies — A case study from Downderry, south-east Cornwall. In *Geomorphology in environmental planning*, edited by J. M. Hooke (New York: Wiley and Sons), pp. 231–244.

SIMS, P. C., WEAVER, R. E., and REDFERN, H. M., 1995, Assessing coastline change: A GIS model for Dawlish Warren, Devon, UK. *Proceedings CoastGIS'95* (Cork: University of Cork), pp. 285–301.

SWASH, A. R., LEAFE, R. N., and RADLEY, G. P., 1995, Shoreline management plans and environmental considerations. In *Directions in European coastal management*, edited by M. G. Healy and J. P. Doody (Cardigan: Samara Publishing Ltd), pp. 161–167.

TELLO, E. R., 1989, *Object-oriented programming for artificial intelligence* (Reading: Addison–Wesley).

VALENTIN, H., 1954, Der Landverlust in Holderness, Ostengland, von 1852 bis 1952. *Die Erde (Berlin)*, **6**, 296–315.

WADGE, G., and QUARMBY, N., 1988, Geological remote sensing of rocky coasts. *Geological Magazine*, **125**, 495–505.

WEISS, S. M., and KULIKOWSKI, C. A., 1984, *A practical guide to designing expert systems* (Totawa NJ: Rowman and Allenheld).

WORBOYS, M. F., 1995, *GIS: A computing perspective* (London: Taylor and Francis).