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THE DEVELOPMENT OF A HOLISTIC EXPERT SYSTEM FOR INTEGRATED COASTAL ZONE MANAGEMENT

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THE DEVELOPMENT OF A HOLISTIC EXPERT SYSTEM FOR INTEGRATED COASTAL ZONE MANAGEMENT

by

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ABSTRACT

Coastal data and information comprise a massive and complex resource, which is vital to the practice of Integrated Coastal Zone Management (ICZM), an increasingly important application. ICZM is just as complex, but uses the holistic paradigm to deal with the sophistication. The application domain and its resource require a tool of matching characteristics, which is facilitated by the current wide availability of high performance computing.

An object-oriented expert system, COAMES, has been constructed to prove this concept. The application of expert systems to ICZM in particular has been flagged as a viable challenge and yet very few have taken it up. COAMES uses the Dempster-Shafer theory of evidence to reason with uncertainty and importantly introduces the power of ignorance and integration to model the holistic approach. In addition, object orientation enables a modular approach, embodied in the inference engine – knowledge base separation. Two case studies have been developed to test COAMES. In both case studies, knowledge has been successfully used to drive data and actions using metadata. Thus a holism of data, information and knowledge has been achieved. Also, a technological holism has been proved through the effective classification of landforms on the rapidly eroding Holderness coast. A holism across disciplines and CZM institutions has been effected by intelligent metadata management of a Fal Estuary dataset. Finally, the differing spatial and temporal scales that the two case studies operate at implicitly demonstrate a holism of scale, though explicit means of managing scale were suggested. In all cases the same knowledge structure was used to effectively manage and disseminate coastal data, information and knowledge.

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AI	Artificial Intelligence
ALC	Atlantic Living Coastlines
BPA	Basic Probability Assignments
CA	Cellular Automata
CBR	Case Based Reasoning
CFs	Certainty Factors
CI	Computational Intelligence
COAMES	Coastal Management Expert System
cSAC	candidate Special Area of Conservation
CSDGM	Content Standards for Digital Geospatial Metadata
CSV	Comma Separated Variable
CZM	Coastal Zone Management
D-S	Dempster-Shafer
DEM	Digital Elevation Model
DGPS	Differential Global Positioning System
DLL	Dynamic Link Library
DSS	Decision Support System
ECoS	Estuarine Contaminant Simulator
EDMED	European Directory of Marine Environmental Data
EDSS	Environmental Decision Support Systems
EHI	Estuarine Health Index
ERSEM	European Regional Seas Ecosystem Model
ES	Expert Systems
FBEI	Fal Bay and Estuaries Initiative
FDS	Fuzzy Dempster-Shafer
FGDC	Federal Geographic Data Committee
FMG	Bay of Fundy / Gulf of Maine / Georges Bank
FoD	Frame of Discernment
GC	GeoComputation
GCP	Ground Control Point
GIS	Geographical Information Systems / Science
GML	Geography Markup Language
GPS	Global Positioning System
GUI	Graphical User Interface
HPC	High Performance Computing
ICOMIS	Integrated Coastal resource Management Information System
ICZM	Integrated Coastal Zone Management
IE	Inference Engine
IKBS	Intelligent Knowledge Based Systems
JNCC	Joint Nature Conservancy Committee
KAS	Knowledge Acquisition Systems
KB	Knowledge Base
LOIS	Land-Ocean Interaction Study
LTRM	Longshore Transport Rate Model
MB	Measure of Belief
MBR	Memory Based Reasoning
MBR	Minimum Bounding Rectangle
MD	Measure of Disbelief

MIQ	Machine Intelligence Quotient
NERC	Natural Environment Research Council
NOAA	National Oceanographic and Atmospheric Administration
OES	Ocean Expert System
OO	Object Orientation
OODB	Object-Oriented Database
RAMCO	Rapid Assessment Module Coastal Zone
RMSE	Root Mean Square Error
SCOPAC	Standing Conference On Problems Associated with the Coastline
SEIDAM	System of Experts for Intelligent Data Management
SES	Spatial Expert Shell
SMP	Shoreline Management Plan
SPM	Suspended Particulate Matter
SQL	Structured Query Language
WWW	World Wide Web

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AUTHOR'S DECLARATION

At no time during the registration for the degree of Doctor of Philosophy has the author been registered for any other University award.

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Signed............................

Date...30/10/2001........

"The whole island should have been longer if only the page had permitted."

- Matthew Paris, medieval cartographer, describing his 'conspicuously squarish map of England' (Tufte, 1997).

1. INTRODUCTION

1.1 Establishing a Research Gap and the Need for New Research

Management of the coastal zone is now recognised as an issue of importance due to the growing social, demographic and environmental pressures that threaten its sustainability. More than half the world's population live within 60 km of the coastline and it is anticipated that this will rise to 75% by the year 2020 (UNEP, 1995). Furthermore, the number of environmental treaties has been growing steadily since 1950, establishing an exponential growth from the 1970's onward (French, 1995). This has been accompanied by a general increase in interest in coastal zone management (CZM) (Jones, 1995). Traditionally, coastal zone managers have relied on manual and paper-based methods of information management. But with the increased pressure on coastal zone managers due to this ever-increasing surge of information the rationalization of CZM tasks is becoming more difficult. Advances in the methodologies of both coastal zone management and computing serve to significantly aid the manager in this increasingly complex environmental and economic structure. In addition, Longhorn (2000) acknowledges that coastal zone management would be very difficult without data, much of it (due to its complexity) requiring computer manipulation.

Integrated Coastal Zone Management (ICZM) is defined as sustainable management of the coast, integrating the concerns of all coastal stakeholders in relation to all coastally related goals (Clark, 1998; Scholten *et al.*, 1999). In practising ICZM, a **holistic** approach is essential (EC, 1999), where holism dictates that the whole is worth more than the sum of the parts (Simmons and Cox, 1985). There is also a requirement for high-performance computing in ICZM, in helping to identify relevant issues, in indicating expected impacts of alternative actions, and in the integration of environmental and socio-economic data and knowledge for effective coastal management (Riddell, 1992; UNEP, 1995; Laydner, 1996). This is reinforced by Agenda 21 and the European Union's Demonstration Programme (Fedra, 1996; French, 1997; EC, 1999). Recently, a marked increase in the size, speed and economics of high performance computing has taken place, creating the potential for such computationally intensive geographical and coastal analysis. Expert systems and other artificial intelligence (AI) applications are amongst those that are benefiting from this trend (Openshaw and Abrahart, 1996), and have experienced a surge in interest with the expectation that they will form an integral part of geographical analysis (Fischer, 1994b).

Moore *et al.* (1996) reported on a conceptual outline of an expert system for coastal zone management. Expert systems offer decision support or help solve real-world practical problems using a computer model of expert human reasoning, coming to the same conclusion as a human expert facing a similar problem (Weiss and Kulikowski, 1984). Extensive use within multidisciplinary environments suggests that the potential of expert systems is great (Durkin, 1996), though in a geospatial context, the complexity of problems has limited its use (Fischer, 1994b).

The range of formats, qualities and sources is seen as the major challenge in building future coastal zone management information systems (Ripple and Ulshoefer, 1987). Miller (1994b) stresses the value of multidisciplinary applications (*i.e.* coastal zone management), which provides a diversity of application and a research domain of more worth. Ricketts *et al.* (1989) state that having knowledge and enabling easy access to knowledge is essential for ICZM. Such knowledge can be provided by an expert system, which can bring a unique logical modelling capability to the coastal environment. So it was surprising to find that there was a sparsity of expert systems with a coastal application (Hendee, 1998) – this was further confirmed in a review by Moore (2000). The Ocean Expert System is one such system, reported to collect, interpret and manage sparse, uncertain and 'crisp' oceanographical information for military purposes (Dantzler and Scheerer, 1993; Scheerer, 1993). SimCoast is another example, a fuzzy logic expert system enabling the analysis of biophysical and socio-economic processes in tandem, to identify impacts and important issues for coastal zone management (McGlade, 1997). This dearth of marine expert systems indicates that there is a strong potential niche for AI in ocean and / or coastal science.

More specifically, the coastal zone is an area in which management has been historically important and will continue to have a prominent role in the future. Such a complex task will greatly benefit from the application of computer technology (see section 2.2.2), more specifically using an expert system. The conflict of interests that occur in the coastal zone is ample requisite for efficient and effective management.

COAMES (COAstal Management Expert System) is the system being developed as part of this Ph.D. study. It has evolved out of a need for enhanced management, and the desire to achieve ICZM, which employs holism at its heart, with a method that also models holism. This method is the Dempster-Shafer theory of evidence; a way of reasoning with uncertainty, which operates within COAMES and has the potential to provide that holistic capability. Conceptually, COAMES enables the manipulation of spatial and aspatial data to aid effective coastal zone management.

Figure 1.1 shows the socio-economic and natural scientific domains in which the system would be used, enabling socio-economic and environmental data, related simulation models and contextual information to be integrated. This in turn allows the manager's tasks to be performed more centrally and consistently, optionally using output from the system as a decision support tool and exploring management options and subsequent lines of query in an interactive manner (Moore *et al.*, 1997).

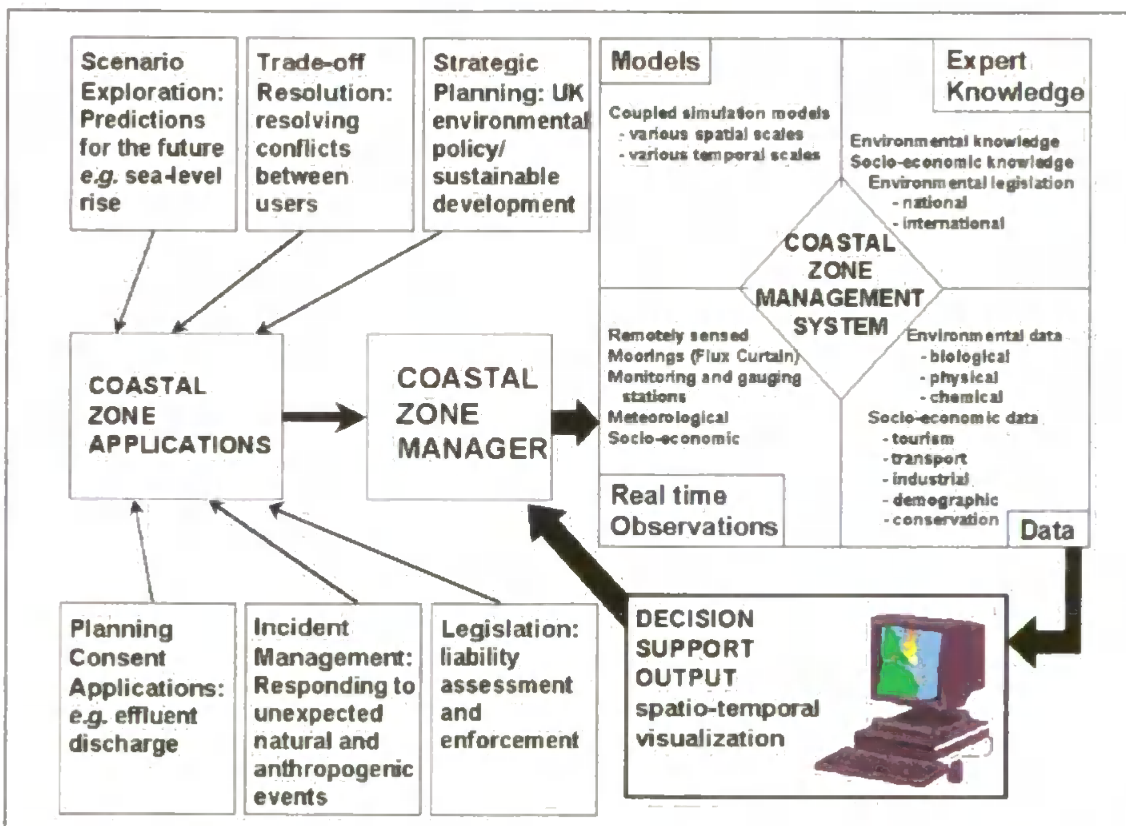


Figure 1.1: The interaction of the Coastal Zone Manager with a Coastal Zone Management System. The pressures acting on the manager at any one time are translated for the information system, which extracts data and knowledge relevant to the situation at hand, producing decision support output, based on which the manager can take action, perhaps refining the described scenario with further system dialogue if required.

Thus, COAMES is of potential value as a comprehensive platform of knowledge and data with the help of which informed and optimal decisions can be made.

A major role of COAMES is to integrate expert knowledge and data into a structure that owes much to the way that humans perceive reality – the object-oriented paradigm. Through object-orientation, disparate data, knowledge and models can be integrated, to deal with queries regarding the coastal zone that can span disciplines. For instance, a cliff can be regarded as an object (in programming parlance), with all properties and attributes associated with that cliff (*e.g.* height, slope, descriptive data) stored digitally within that object. In an expert system context, rules may be stored in the object that describes the behaviour of the cliff. Rules like this form the knowledge base, and it is important that they are stored separately from the inference engine (the reasoning machine at the heart of any expert system) to allow easy modification of either entity. Exploration of this modular approach is an integral part of the thesis.

1.2 Aims

The thesis aims to meet the need for data, information and knowledge management (natural environmental and socio-economic) in coastal zone management (CZM), necessitated by sheer volume and international policy. The key to how science (*e.g.* geomorphology) can best serve CZM lies in information dissemination (i.e. putting scientific knowledge in a form that is widely understandable) - the thesis will explore this link through the use of expert systems.

A holistic system will be developed, capable of flexibility and portability to handle different spatial and temporal scales, disciplines and institutions, data, information and knowledge, and various technologies. Out of the two categories of EDSS (Environmental Decision Support Systems - translatable to expert systems) identified by Rizzoli and Young (1997) - problem specific (corresponding to a formal ontology: Raper 1999a), and situation and problem specific (corresponding to a informal ontology: Raper 1999a), it is the aim of the expert system discussed in this thesis (COAMES) to opt for the former. A two-tier system able to handle differing complexities is proposed here, enabling simple metadata access but also geomorphological rule and model handling.

This will make optimum use of the high standard of technology available, exploring the expert system application gap in CZM (*i.e.* matching application with technology). The main form of such exploration lies with two major technological innovations facilitating the holism specified above. Firstly, there is the application of the Dempster-Shafer theory of evidence, a technique potentially capable of modelling holism, in a domain that employs holism at its centre: ICZM. Secondly, there is the separation of the inference engine and knowledge base within the expert system. An important theme in the philosophy of COAMES is the ease with which additional groups of data and knowledge can be incorporated into the framework, due to this modular approach.

Initial efforts to construct COAMES were devoted to developing a prototype covering a narrow domain in coastal expertise. Such development of a prototype is recommended where there is a high degree of uncertainty in the specification (Fedra and Jamieson, 1996). Later development of the system adopted a holistic approach, covering the whole subject domain. There will be two areas of study (with two associated domains) - the Holderness coast, North Yorkshire (geomorphology) and the Fal Estuary, Cornwall (metadata access for ICZM). These case studies were chosen as the optimum test of the system's genericity and holism, covering various scales, disciplines and institutions, formats of data, information and knowledge, and various technologies. Also the distinction is made between the specialist (using expert knowledge for a geomorphologic problem) and the mundane (using same expert system inference engine for searching the right metadata). This points the way towards levels of access - the first level is metadata and data access, and the second level is scenario exploration.

1.3 Case Study Areas

1.3.1 The Holderness Coast, North Yorkshire

The Holderness case study uses coastal geomorphology as the domain of application, to characterise beach landforms on a rapidly eroding coast (Holderness) using expert knowledge and data. The reason for choosing Holderness as a case study area is partly historical. This stretch of coast is at the centre of the Land-Ocean Interaction Study (LOIS) study area. The author was involved with LOIS from 1996 to 1999.

LOIS was a multi-disciplinary, multi-institutional initiative (Community Research Project) involving some 11 Natural Environment Research Council (NERC) institutions and 27 Higher Education establishments, running from 1992 - 1998. The diversity and complexity of the coastal environment is such that a piecemeal approach to its study is not suitable. To overcome this LOIS aimed to study the coastal zone in a holistic manner, by a thorough analysis of biological, chemical and physical processes and elements, relating to terrestrial, riverine, marine and atmospheric systems. These systems considered together fulfilled the broad aim of LOIS: to give marine environmental scientists an understanding of and ability to predict the nature of environmental change in the coastal zone of the UK, facilitating improved environmental management (NERC, 1994; Moore *et al.*, 1996). One of the main products of the LOIS as set out in its Implementation Plan is "Geographic Information Systems (GIS) incorporating databases and models to make the understanding and information accessible for the purposes of coastal zone management". The work outlined in this thesis was a response to this - an information system that aims to go further than a GIS in the provision of information (through the use of expert knowledge), or value-added data that has been modified to make it immediately usable in coastal zone decision making (NERC, 1994; Moore *et al.*, 1998).

The Holderness coast has the breadth of discipline for a good case study, as the extensive coastal erosion in the area, though operating naturally, impinges on the socio-economic environment. 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) will show huge change. In fact, there is a large collection of recent aerial photography (since 1994) of this coast, flown in support of 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 (see section 4.2), fulfilling a knowledge base test. One landform in particular, the ord, has been the subject of long-term study (Pringle, 1981, 1985). It has been linked to enhanced cliff erosion, making it particularly suitable from the coastal zone management viewpoint. It is also a complex, composite landform, setting a challenge for its representation in the expert system.

1.3.2 The Fal Estuary, Cornwall

The Fal Estuary case study has metadata provision as a domain of application, covering data, information and knowledge of both natural environmental and socio-economic themes, operating at a variety of spatial and temporal scales. The reason for choosing the Fal Estuary as a case study area is also partly historical, being one of the areas of interest for the EU Atlantic Living Coastlines project (ALC), in which the author was involved from 1998 to 2000.

ALC (1998-2000) had a main aim of developing an integrated coastal zone management strategy for the counties of Devon and Cornwall in the south-west of England. In tandem with this is an integrated coastal zone management information strategy, backed up with recommendations for a coastal zone management information system. An inventory of data and information has been compiled along with a review of existing information systems, which has contributed to the design of three system templates or examples - employing geographical, dialogue and list access to metadata. These were considered by a cross section of local coastal zone managers, planners and researchers, whose recommendations fed into the development of a metadata access demonstration system to back the overall information strategy (Moore *et al.* 2000).

It is intended that COAMES will facilitate the intelligent extraction of metadata from the Fal metadataset. At the Fal Estuary, there is again a mix of natural and anthropogenic concerns (*e.g.* the Wheal Jane incident in 1992, where tin mine waste was discharged into the estuary). Correspondingly, there is a huge amount of associated data and knowledge from research, not only on this but also on a wealth of other disciplines, and at a variety of scales. Digital access to such an abundance of metadata would provide an extensive test of the expert system. Finally, it has recently emerged (EC, 1999) that metadata provision is at the forefront of current CZM information management, so it would seem a necessary focus for this thesis.

1.4 Overview of the Thesis

The next chapter provides a literature review for the thesis, firstly establishing a philosophical basis from a holistic perspective before outlining relevant research in coastal science (with reference to coastal zone management), expert systems (including their use in conjunction with decision support systems and geographical information systems) and the role of the Internet. Chapter 3 describes the components and processes of COAMES, relating how the design meets the coastal zone manager's requirements. Chapters 4 and 5 outline the Holderness and Fal Estuary case studies, including some discussion of the results. Chapter 6 discusses and brings together the findings of the two case studies and gives a critique of the thesis, assessing how successfully the thesis, and COAMES, has fulfilled the original aims. Chapter 7 builds on the foundation provided by the thesis (and COAMES) to put forward ideas for further research, which both extrapolate thesis research themes, and explore alternative technological approaches. Finally Chapter 8 forms a short statement (derived from Chapters 6 and 7) outlining the major findings of the thesis.

1.5 Summary

Rationale for an Expert System in Coastal Zone Management

- The importance of CZM - evidenced by general increased interest (Jones, 1995).
- The overwhelming amount of data, information and knowledge in CZM (French, 1995) would suggest that there is a need for an information system.
- The importance of data, information and knowledge in CZM is recognised by the Rio Earth Summit Agenda 21 and the EU Demonstration Programme on Integrated CZM (UN, 1992; EC, 1999) - this stresses that need.
- Various technologies exists to meet the need - for the first time, high performance computing is widely available, allowing the application of artificial intelligence (expert systems) and geospatial algorithms (Openshaw and Abrahart, 1996).
- It is important that any technology matches the application. In this case the holistic and complex approach of ICZM is matched by the expert system with its use of the theory of evidence.
- The lack of expert systems in coastal zone management is surprising, since the application of such systems is seen as a major challenge in CZM (Sorenson, 1991). CZM meets the "multidisciplinary application" qualification that provides the optimum expert system test (Miller, 1994b). There is a niche for research.

- CZM operates at multiple scales and deals with multifarious data (in terms of sources, qualities and formats - Ripple and Ulshoefer, 1987). This complexity and the need for integration in CZM can be met by expert system application.
- On a technical note the close entwining of the knowledge base and inference engine, which has characterised expert systems, must be addressed.

Aims

- To meet the need for data, information and knowledge management in CZM, necessitated by sheer volume and national / international policy.
- To investigate ways in which science (*i.e.* geomorphology) can better serve CZM through expert systems, which would act as an effective disseminator of coastal data, information and knowledge.
- To make optimum use of the high standard of technology available, exploring the expert system application gap in CZM (*i.e.* matching application with technology).
    - To explore the separation of the inference engine and knowledge base within the expert system (a modular approach).
- To develop a holistic system to handle different spatial and temporal scales, disciplines and institutions, complexities, data, information and knowledge, and various technologies. A two-tier system is proposed, enabling simple metadata access but also geomorphological rule and model handling.

The two areas of study will be Holderness (geomorphology) and the Fal Estuary (metadata access for ICZM), chosen to be an optimum test for the system.

2. LITERATURE REVIEW

2.1 Philosophy

This section sets out to establish an ontological and epistemological basis for the thesis. Geography and environmental science (feeding into coastal zone management), and computer science (feeding into GIS and GeoComputation) will be explored to provide this basis. Epistemology is the study of knowledge and knowing, and is often confused with ontology (Gruber, 1993), which is the study of what exists and their nature of existence (Mayhew, 1997). Translated to IT, this is the configuration of entities and relationships that exist in some domain of knowledge (TechTarget.com, 2001). Focusing further into artificial intelligence, it is the "specialization of conceptualisations" to facilitate knowledge sharing (Gruber, 1991, 1993). An example is the object-oriented class structure integral to the thesis and described in section 3.5

From a coastal GIS viewpoint, Raper (1999a) distinguishes between an informal and formal ontology. Informal ontologies are the norm, with precise knowledge of the phenomena being represented in a narrowly defined domain, but not easily portable to other domains. A formal ontology may enforce explicit metadata descriptions on phenomena, or the phenomena may have widely understood predictions, which makes for a more portable set of entities. Both approaches can be used optimally in the correct situations. However, a formal ontology will be imposed on the thesis domain (through metadata), as it is commensurate with a holistic approach. The remainder of this section explores the philosophical setting of this thesis, with particular reference to the holistic-reductionist viewpoint.

2.1.1 Holism and Reductionism

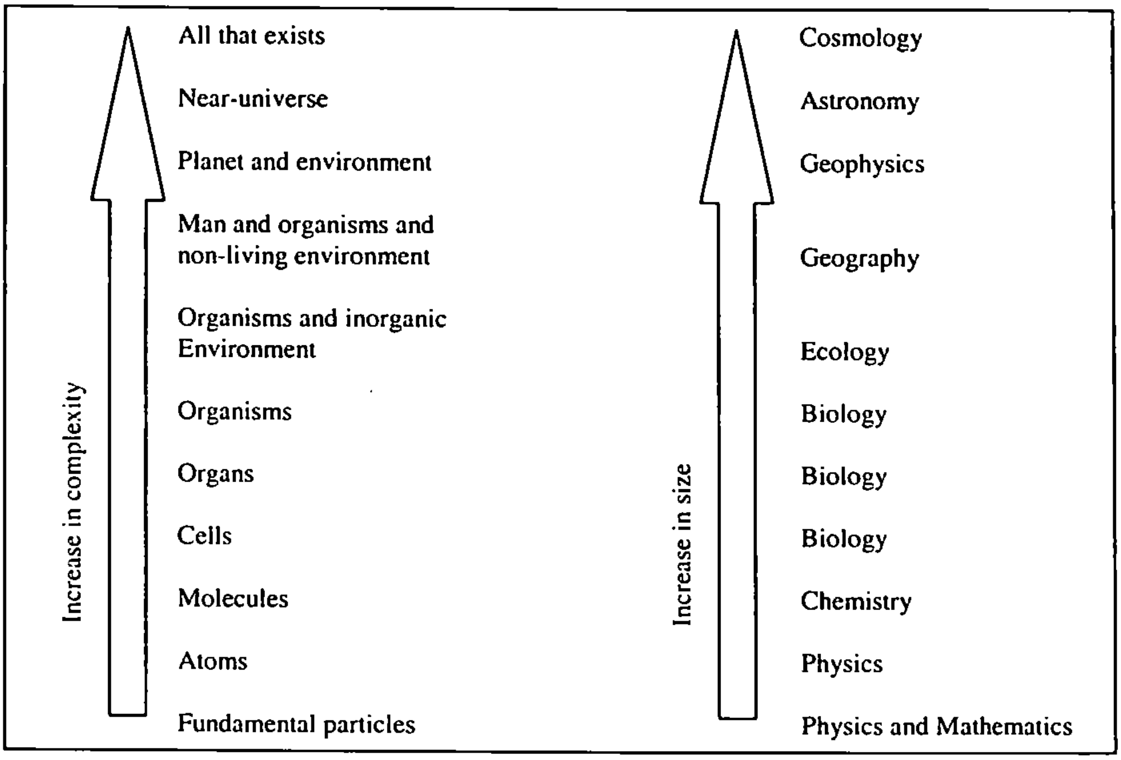


Figure 2.1: A hierarchical scheme of knowledge (adapted from Simmons and Cox, 1985).

Figure 2.1 demonstrates a scale-based hierarchy of knowledge, between the limits of cosmology (all that exists) and physics / mathematics (fundamental particles). At one time (see section 2.1.2 for a more complete historical setting), geography was depicted on a regional basis as the sum of natural and social / human facts about a given place. The overall result was a series of fragmented descriptions of disparate places. This is an example of reductionism, which occurs if geography is dealt with in terms of the tiers below in the hierarchy (*i.e.* communication is through technical terms or mathematical / symbolic logic). Holism occurs where the explanation is in terms of the same tier or above in the hierarchy. Fundamental properties of holism include the notion that the whole is more than the sum of the parts, and that the whole has properties that are not predictable from analysis of the constituents. Although there is a dichotomy between holism and reductionism, both must exist, and are complementary, so a balance between the two must be struck (Simmons and Cox, 1985).

As an example, Wilson (1981) aspires to a geography of synthesis that also formulates theories (*i.e.* a reductionist approach) for "whole-systems" of geographical interest. Latterly, this has been reflected by Chang and Terwillinger (2000), who advocate an ability to incorporate both reductionist and holistic approaches for enhanced understanding in the domain of anthropogenic influence on plant geography.

However, geography has always been a subject in need of a holistic view, as it consists of various "systematic branches" belonging to one science or another and requiring integration. Geography has accordingly been labelled a "science of synthesis" (Holt-Jensen, 1988). As will be established in section 2.2.4, one of the defining properties of Integrated Coastal Zone Management (ICZM) is a holistic approach, and therefore holism, more than reductionism, will inform the philosophical and historical basis in the next section.

2.1.2 Early Holism in Geography

Holistic thought started with the ancient Greeks, who used teleology (the notion of an overall purpose) to conceive a holism of people and place (Simmons and Cox, 1985). In the early to mid 19th century, the idealist philosopher Georg Hegel used teleology (with the "overall purpose" being that of God) to project thinking towards a comprehension of the whole (i.e. the infinite). At about the same time and in a similar fashion, the classical German geographer Carl Ritter believed that the natural and social spheres of existence cannot be treated in isolation as they both affect each other in a variety of relationships. He used the word *Ganzheit* to describe that a region had a unity and was more than the sum of its parts. By the late 19^{th} century, Ritter's disciple Elisée Réclus had shifted away from teleological thought in anarchic fashion, bringing the ideas of American George Parkins Marsh into geography – instead of the earth making man, it is man that makes the earth. Opposing this at the time were the strictly natural tenets of Darwinism. The German geographer Friedrich Ratzel advanced the idea of *Ganzheit*, describing the region as a functioning organism. Ratzel also introduced environmental determinism, that humanity is controlled by the laws of nature.

The move from the teleological was reflected in a move from inductive reasoning to hypothetico-deductive reasoning. Major advances in physical geography (variously called physiography, then geomorphology) occurred at this time (*e.g.* Penck and alpine glaciers; Cvijic and Karst landforms), so that by the end of the 19^{th} century, the balance in geography had shifted towards the natural.

The French geographer Paul Vidal de la Blache reasserted man's impact on nature, whilst keeping the two as a united whole. This 'possibilism' was a continuation of elements of Ritter's work, in that it re-established the region as a fundamental unit in geography. Such regionalization was reflected in the UK, where regional surveys were put forward as an essential prerequisite to regional planning (Sir Patrick Geddes) and there was exploration of how to divide land into regions (Charles Fawcett: Holt-Jensen, 1988). The use of natural (river catchment) boundaries postulated at this time is a precursor to current management divisions of the coast, where sediment cells are used as the geographical basis of Shoreline Management Plans (see section 2.2).

This human geography is humanistic and idiographic (*i.e.* stresses the uniqueness of places) and came under much criticism from a nomothetic (*i.e.* law-giving) viewpoint. This was the precursor of the "quantitative revolution" of the 1950's and 1960's.

2.1.3 The Quantitative Revolution and Critical Geography

The concept of the quantitative revolution in geography was strongly influenced by Thomas Kuhn's (1962) paradigmatic view of scientific progress. Moving away from the idea of science as a linear activity where new findings automatically build on previous research is the notion of "revolutions" or fundamental changes effected through choice of paradigm. Paradigms are "models or exemplars" that in this case indicate tasks and methods in doing geography. Adopting a model-based paradigm, British geographers such as Peter Haggett, Richard Chorley and David Harvey made great advances towards a unifying methodology for geography, making use of quantitative methods (Holt-Jensen, 1988). This is a form of reductionism, and such generalization in geography has been successful in part, though for every law put forward, there are numerous exceptions observed in reality (Simmons and Cox, 1985). Other symptoms included increasing specialization and therefore fragmentation (Holt-Jensen, 1988). Finally, quantitative methods were already being used in physical geography, resulting in less of a paradigm shift (Orme, 1985).

The metatheory of positivism (with empiricism) has found most overlap with the quantitative theories (this roughly corresponds with the 'empirical-analytic' world-view of Jürgen Habermas: cited in Raper, 1999b), with a critical (or radical: Bennett, 1985) geography adopting an opposing stance. Within the critical geography is a humanistic geography (the 'historical hermeneutic' world-view of Habermas: cited in Raper, 1999b) consisting of idealism, whose most notable exponent is the Canadian geographer Leonard Guelke. Idealism "is a method by which one can rethink the thoughts of those whose actions he seeks to explain" (Holt-Jensen, 1988). In this way, the method is akin to the knowledge acquisition process described in section 2.3.6 (*i.e.* getting expert knowledge from the expert and in a computer-readable form). Critiques of humanism include the structuralists (to Habermas, structuralism alone is the 'critical' world-view: cited in Raper, 1999b), who are concerned with how mechanisms within structures manifest themselves at the empiricist level (Holt-Jensen, 1988). Structural thinking took on many forms, including structuration, realism, locality studies and new regional geography, all of which were based on study at the local scale. This leaves the question of how to translate study within these modern stances to the global scale (Peet, 1998).

Latterly, poststructuralism and postmodernism have criticised structuralism, yet find themselves in even more of a fragmented state, with isolated and distributed research activity (Peet, 1998). An example is the poststructuralist philosopher Michel Foucault (Philp, 1985), who reinforces the fragmented, local and specific view by rallying against what he calls "totalising discourses" and accordingly the holistic viewpoint (a discourse is a system of possibility for knowledge). Postmodernism is a celebration of the unique and of difference (Pickles, 1995b; Macmillan, 1997). Strands of the philosophy that have found their way into geography include Jacques Derrida's intertextuality (reading between the lines – Brian Harley adapted this research to demonstrate how maps can wield power over society; latterly John Pickles has applied the same ideas to GIS [see section 2.1.5]: Schuurman, 2000) and Jean Baudrillard espousing thoughts on digital control over society through simulation (virtual reality: Pickles, 1995b).

The above represent the effects of technology on society, but there have been strong accusations that critical philosophy is not geographical enough and makes little use of technology (Openshaw, 2000). Macmillan (1998) hopes that GeoComputation (see section 2.1.4) can enable geography to "emerge from its post-modern slumbers" (though in fuzzy logic he sees a possible compatibility – in handling degrees of truth – of postmodernism and science; talk of compatibility has been echoed by Pickles (1995a) for critical geography in general). The next section balances the societal impact of GIS with such technocratic viewpoints and places GIS and GeoComputation in their philosophical context.

2.1.4 Beyond the Quantitative Revolution

Holt-Jensen (1998) stated that an essential element of the quantitative revolution back at its inception was the use of computers. This is certainly true of GIS and GeoComputation, widely thought to be of the same lineage as the quantitative methods of the 1960's (Macmillan, 1997).

Macmillan (1997) defines GeoComputation (GC) as "a set of activities, conducted in or around a computationally sophisticated environment, in which the geographical sciences are developed and applied". GC consists of four "technologies" – GIS creating the data, AI and computational intelligence (CI) providing smart tools (including expert systems), high performance computing (HPC) providing the power and science providing the philosophy. The origins of GC are holistic, the term initially being used to describe a computational human geography research agenda and finding that the ideas and methodologies were just as applicable, if not more, to physical geography (Openshaw, 2000). This is an echo of Openshaw's (1991) statement, that GIS provides a "domain within which virtually all of geography can be performed".

Longley (1998) concurs with the holistic viewpoint, seeing the role of the computer moved from a scientific tool used at specific stages in research, to a holistic agent in data exploration, collection and transformation. Fotheringham (2000) introduces a different slant on GeoComputation, stressing that no global model may exist without improvement by local models, which are used to describe anomalies and exceptions. This strikes a balance between holism and reductionism.

Openshaw (2000) described GC as a new paradigm, representing a distinct break from the quantitative revolution. GC is less constrained by computer power and the relative availability of data makes it less theoretical. The agency of the computer as a constraint has been demonstrated by Macmillan (1997), who uses the Varignon Frame (a mechanical computer built to give solutions to Weberian industrial location problems) to show that the complexity of calculation is a direct function of the computing power available at the time. Veregin (1995) sees computers (on a contemporary basis) as influencing (*i.e.* constraining) the choice of research problems and research design in geography.

2.1.5 Critics of GIS and GeoComputation

During the years of 'critical' geography supremacy in the 1970's and 1980's, Pickles asserted that positivism was still being practiced widely (supporting the quantitative revolution – GIS – GC continuum view) but this went unheeded by critical geographers until the 1990's (Macmillan, 1997; Schuurman, 2000). Schuurman (2000) identified three waves of criticism by human geographers from 1990-2000. The first wave (early 1990's) was greeted within GIS with a mixture of acceptance (that it correctly reflected shortcomings in GIS) and contempt (showing the critics' lack of understanding). The dialogue was healthy, if heated, and yet betrayed the existence of a language gulf between GIS researchers and their sociotheoretical critics. At the start of the second wave (mid 1990's), attention was brought to this schism (though there was an absence of dialogue as GIS researchers ceased to take part in the debate at this stage) – this was a measured criticism and the main output was the publication of the book "Ground Truth" (Pickles, 1995c). The third wave in the late 1990's saw critics in partnership with GIS – they had no choice, given its ubiquity within geography (Schuurman, 2000).

Around this time was a real awareness of a science of GIS, a development predicted by Goodchild (1992). Wright *et al.* (1997) stated that GIS could be practiced anywhere on a continuum from 'GIS as a tool' to 'GIS as a science' (with 'GIS as toolmaking' in-between). In response, Pickles (1997) took a critical stance, but heralded a science of GIS that involved the "scholarly investigation of its origins, logics, systems, new capacities and new uses". Couclelis (1998) tried to place GC in a similar context, finding it fragmented ontologically and epistemologically, identifying its then current status with postmodernism (contrary to Openshaw's announcement of a new paradigm). She postulated "whether the geocomputation whole will ever be more than the sum of the computational parts". In establishing an epistemology of GeoComputation, Couclelis saw the theory of computation (originally established in the 1960's) contributing in three ways – being able to control shape or object symbols or other arbitrary entities, as well as numbers; expressing qualitative change from comparison; and exploring phenomena through a full stepwise description.

Geography is currently in Schuurman's (2000) third wave, with social theorist critics and GIS researchers working together (see Pickles [1999] for initial progress in this research). Donna Haraway (cited in Schuurman, 2000) suggested this collaboration approach, in that it is better to critique from a position of involvement (within GIS) than from a remote stance. This has parallels with evolutionary prototyping (see section 2.2.3).

2.1.6 Recent Thinking on Holism in the Environmental Sciences

The previous section has established that current thinking in GIS and GeoComputation is mainly towards the holistic. Hooke (1999) sees and encourages a similar trend in geomorphology away from reductionism (in "geographical and integrative scale of analysis"). In other examples, Stern (1992) argued for a return to a holistic regional geography using synergetics, the analysis of self-organising phenomena; Pahl-Wostl (1993) used synergetics on the aquatic ecosystem; Naveh (2000) proposed a paradigm shift to a holistic landscape ecology; and finally Hill *et al.* (1995) used holistic rather than reductionist variables in building a model to forecast development and colonization of an exogenous tropical algae in the Mediterranean. In the latter example, the reason for choosing holism is down to the incomplete datasets and sampling difficulties inherent in the maritime environment. Bartlett *et al.* (1992) add the following factors in studying the coastal zone holistically: multiscaled data (data exists at different scales and is also needed at different scales), the need for a fuzzy approach to handle uncertainty, multi-dimensional data and temporal dynamics (see Kemp and Kowalczyk, 1994; Wachowicz and Healey, 1994; Raper and Livingstone, 1995 for discussion of time-space representation). Kucera (1995) adds the ability to handle data with different datums, organisations, dates and format types.

However, through the recent interest in systems analysis, the holistic approach has been prevalent for much longer than the last few years. A system (or abstraction of reality) is defined as a whole through the interdependence of its parts (Holt-Jensen, 1988). An object-oriented model of a domain (such as that demonstrated in section

3.5) shows parity with the system as defined here. Within geography, the ecosystem (system of interrelationships between plants, animals and inorganic matter, independent of scale, but within a set area) is probably the most widely known and used, demonstrating an intuitive rather than quantitative holism.

Successes of holism include raising awareness of the environment and the need to maintain a high level of environmental quality. This mostly came about through regarding the planet as a whole and the related causality of actions. This is the approach behind the Gaia concept, for example in determining that the unique gaseous composition of the Earth is a "consequence of the co-evolution of life and inorganic matter" (Simmons and Cox, 1985).

The current need for holism has been established, though back in 1985 Simmons and Cox acknowledged that true holism might be beyond our "brain power", and is probably unattainable (Martin Kent, pers. comm.). They suggest the computer as the means of tackling this obstacle. A current concern within GIS is the interoperability of systems to facilitate the exchange and linkage of resources, such as spatial data (Vckovski, 1998). Similarly, Gruber (1991) suggested a common language and ontology to enable sharable and reuseable knowledge bases; Gahegan *et al.* (2000) put forward a semantic framework to account for the gaps in knowledge which, if filled, would enable information with a set meaning and purpose to be used in other contexts; and Ramroop and Pascoe (2001) used one common ontology to process queries of metadata subject to several standards. In common with holism is a need to integrate, and an acceptance that true interoperability is a target to aim for (Vckovski, 1998).

2.2 Coastal Overview

Early progress in coastal zone management through independent sectoral policies failed to appreciate the overall complexity of the coastal zone, due to their narrow scope of operation (UNEP, 1995). In recent times, Integrated Coastal Zone Management (ICZM) has been evolving rapidly (Jordão *et al.*, 1996), being a flexible form of resource management for sustainable development in the coastal zone (UNEP, 1995). It brings together the tasks facing the coastal zone manager without being a panacea for all coasts (Clark [1998] stresses not to try to do too much in an ICZM programme). These tasks include resolving user conflicts, considering planning applications, evaluating possible scenarios, observing legislation, responses to emergencies and other tasks, in both the natural and socio-economic environments, onshore and offshore. The need for integrated coastal zone management can be seen in many processes that cross coastal regions. For example, the relationship between saline and fresh water in estuaries is strong (*e.g.* in the diffusion of pollution), requiring holistic management strategies (DoE, 1996). The evidence is that ICZM adds to the economic and social prosperity of coastal communities (Clark, 1998). In recent years, coastal zone management has become a focus of increased interest generally, due to the implications and cost of sea level rise (Jones, 1995).

It is generally accepted that the amount of data and information for coastal zone management is growing at a phenomenal rate (Jones, 1995). However, it has been little over a decade since the issue of data and information started appearing in the coastal zone management literature in its own right. From an analogue viewpoint, Hooke (1988) stressed the need for "cataloguing and inventories", bringing together the information at the base of policy implementation and design. There are direct parallels with this and the current metadata provision issue.

Data and information bases are essential tools for current ICZM, helping reduce a high level of uncertainty and providing decision makers with the means of identifying relevant coastal issues (UNEP, 1995, French, 1997). Agenda 21 of the Rio Earth Summit marked the implementation of an integrated CZM initiative, concerned with the sustainable development of coastal areas and the marine environment. Also paramount was the liaising with all interested groups to provide access to relevant information (French, 1997): "Special emphasis should be placed on the transformation of existing information into forms more useful for decision making and on targeting information at different user groups. Mechanisms should be strengthened or established for transforming scientific and socio-economic assessments into information suitable for both planning and public information." (UN,1992).

2.2.1 Science as a Major Impetus

Coastal managers need an informed perspective in order to make effective and sustainable decisions about the land-sea interface (Sims, 1998). Much activity has stemmed from recognition of the potential value of the application of science to coastal zone management problems (Carter, 1988; Möller, 1999). Geo-hazard 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 (MAFF, 1995; Swash *et al.*, 1995;

Potts, 1999). The activities of man as a geomorphological agent was recognised as early as 1864, though the realisation that this agency was often detrimental to the environment did not come until the early 20th Century. Since then, geomorphological knowledge has fed into, amongst others, coastal protection, land management and river basin control (Brunsden, 1985). Politically, scientific support for rational decision making in the public interest has been attacked from both the left and the right in the last century, only re-emerging with the fall from favour of those two ideologies (Macmillan, 1997). This ascent has more or less coincided with an increased environmental awareness brought about by the holistic viewpoint (Simmons and Cox, 1985).

The data and information component is never far away from the application of science to ICZM problems. For example, Sims and Ternan (1988) advocated construction of a geomorphologic database (containing key information on coastal processes and environmental hazards) to meet the needs of planners who may not have the appropriate information to hand. Hooke and Bray (1995) report on just such an endeavour, a bibliographic database on the sediment transport of Central Southern England, collated as part of SCOPAC (Standing Conference On Problems Associated with the Coastline) as a pre-requisite for research on that subject.

One of the benefits for ICZM of having adequate information to hand, is a move from reactive management towards proactive management. Cooper and Harlow (1998) identify the economic (seawall damage minimized) and environmental (maintain consistent beach volumes) benefits of having a high quality long-term beach monitoring record in Poole Bay. In the same way Jelliman *et al.* (1991) discuss wave, beach profile and beach replenishment data.

There is uncertainty in communicating science to coastal decision-makers. The range of scientific disciplines required as input to coastal zone management (*e.g.* oceanography, geography, marine biology) makes for a diverse information base. The decision-maker may find this hard to digest, leading to uncertainty in knowing how and when to act; this is frustrating as they are frequently under pressure to act rather than consider alternatives. The timescale and properties of natural coastline change do not coincide with human use of the coast - this forms another source of uncertainty (Sims, 1998). Cooper *et al.* (1994) propose synthesizing environmental information to effect communication with the decision-makers. Their Estuarine Health Index (EHI) is the product, taking the form of map icons or bar charts.

2.2.2 Use of Computer-Based Tools

An extra dimension to this is the use of advanced IT tools to get the most out of coastal data. Sims *et al.* (1995) report on the use of a Geographical Information System (GIS) to measure coastline change from digitised maps and photographs at Dawlish Warren spit. NOAA's (National Oceanographic and Atmospheric Administration) Ocean GIS is an example of another tool to provide regulatory and environmental spatial data and legal information for managers (Payne, 1999). Other examples include the classification of rocky coasts using airborne multispectral scanning (Wadge and Quarmby, 1988) and the detection of shoreline changes using satellite images and tidal data (Chen and Rau, 1998). There is an extensive review of tools such as expert systems in section 2.3, and their use in conjunction with GIS and decision support systems (DSS - section 2.4).

2.2.3 User Expertise and the Need for Consultation

Davos (1998) sounded a cautionary note on the issues of information generation, control and dissemination. The collections of environmental data and information and use of tools above are designed only to be accessed and understood by small groups of highly specialized experts (resulting in the "marginalisation of information"), which may have the effect of losing contact with the coastal stakeholder. What is needed is a consultation process that involves the coastal stakeholder from the beginning, making use of their perceptions and access to relevant technology. This is highlighted by a proposed distributed environmental information infrastructure fostering collaborative networks and active liaison with the custodians of data / expertise (Busby, 1999; Burrill, 1999). A way of making scientific data more accessible to the decision maker is to turn it into useful information.

The need for consultation is highlighted by the European Union Demonstration Programme (Doody *et al.*, 1998; EC, 1999) in the use of appropriate Information Management Technology. Although GIS and DSS can be visually impressive, they may be misleading through the assumption that they 'know' the answers, a typical technological fallacy. They can also be of a highly technical nature, acting as a barrier to understanding and therefore use (Ricketts, 1992; Green, 1995; Canessa and Keller, 1997). One way to get around this is by introducing levels of access. Soncini-Sessa *et al.* (1990) propose a two-level DSS, where an advanced user (environmental scientist) employs the DSS as a modelling environment to develop new models, and end users (environmental managers and stakeholders) access DSS knowledge in an easy and structured way. Buhyoff *et al.* (1994) describe an expert system for landscape visual assessment that explains the logic of results throughout, avoiding the black box scenario that often faces the user (see also section 2.3.4). These solutions mitigate the pitfalls of user-friendly technology: further information is needed so that it is not misused (Hootsmans *et al.*, 1992).

To avoid potential disillusionment on the part of the user, developers should bear in mind that simple solutions are often required by the coastal zone manager. Users should also be fully educated on getting the optimum use out of a system that meets their needs and not opt for the newest, most technically accomplished one. An effective way to make sure that developers and users are 'talking the same language' is to involve the user in the system design process (Shepherd, 1998; EC, 1999). This was also flagged in the development of the HelFal (Green, 1995) and the Canadian FMG (Bay of Fundy / Gulf of Maine / Georges Bank) InfoAtlas (Ricketts, 1992) systems. In practice, Canessa and Keller (1997) implemented the method of user involvement through questionnaires. In software development, a process of evolutionary prototyping is needed to ensure that communication between the developer and projected end user is sufficient to produce an optimal end product. Evolutionary prototyping is where the projected users of a system are actively involved in the development process (Kay, 1999); an account of evolutionary prototyping is given by Moore (2001) in the development of the Atlantic Living Coastlines Metadata Access System (see section 5.2.3).

2.2.4 A Holistic View

Coupled with this need to consult with the stakeholders is a move towards the holistic view, with wide-ranging information taken into account (Doody, 1996, EC, 1999). The typical situation is that data and information have been collected and collated for numerous individual projects of local scale. This has meant that there is a large volume of data, but it is fragmented, leaving substantial gaps. This data fragmentation may even be unique to the marine environment, a product of the large number of marine data sources (land-based data can be accessed from a relatively small number of sources) (Wright *et al.*, 1998). The data may also be largely undocumented, so it may be of uncertain quality. Other qualities unique to coastal and marine data have been specified in section 2.1.6. This puts the onus on data providers to think about possible alternative users of data. The data generators or experts have roles in processing raw data into information. An overall strategic viewpoint is called for (as with 'State of the Coast' reports or Shoreline Management Plans – EC, 1999), where these gaps can be identified and prioritised - are they worth filling? This would depend on a prior identification of relevant issues and user needs for information to address those issues (Busby, 1999). Other tasks include raising awareness, building participation, creating an appropriate context for decision-making, maintaining the knowledge base and implementing an information exchange mechanism (EC, 1999).

A call for a holistic viewpoint is also a call to physically integrate data and information. Historically, this has been difficult and expensive to do (disparate locations, incompatible formats: Kucera, 1995) and has been regarded as one of the most complex tasks in data management (Busby, 1999; Jones, 1995; UNEP, 1995). A case in point is the effort made to collate data for the LOIS (Land-Ocean Interaction Study) Overview CD-ROM (Morris *et al.*, 2000). Additionally, Jones (1995) regards the biggest technical challenge in coastal zone management as the integration of GIS with coastal process models.

2.2.5 Metadata

An overall message from the EU Demonstration Programme is to "Be issue led, not data led" – don't collect all the data that exists, just data relevant to a specific issue. But even with groundwork, there are problems: not going deep enough with searching for data (erroneously identifying data gaps where no gap exists), data overload, copyright and incompatible formats. Data producers and providers can help by wide dissemination of metadatasets and making data available on-line (EC, 1999).

The use of metadata (or "data about data") for accessing and disseminating coastal data and information has been recognised at the international level by the EU Demonstration Programme (EC, 1999) and the InfoCoast '99 conference (Bridge, 1999). The message has filtered through, judging by the amount of metadata provision sites for coastal and marine data on the Internet, for example: EDMED (BODC, 2001), "What's in Your Backyard? (EA, 2001) and the Australian Oceanographic Data Centre (AODC, 2001). The use of metadata has become a way to bring data together virtually into one base without physically integrating them. By bringing summary information to the attention of users, the metadatabase facilitates the discovery and usage of disparate datasets (in effect, acting as a catalogue or shop window). The collation of metadata is itself time-consuming and difficult. The JNCC

(Joint Nature Conservancy Committee) Coastal Directories Project is an example of collation of this sort (Doody, 1996). Another example is the scoping study information audit for the Cornish Coast (Hartland Point to Land's End; Lizard to Rame Head) Shoreline Management Plan (Sir William Halcrow & Partners, 1996).

The most widely known of metadata standards (guidelines) are those specified by the US Federal Geographic Data Committee (Content Standards for Digital Geospatial Metadata) for use with the National Geospatial Data Clearinghouse (a distributed network that allows public and private data providers to publish their spatial data) - FGDC, 2001. For a fuller explanation of the FGDC standard, see section 5.3.

Other standards looked at include those of the UK Association for Geographical Information (AGI). Many of the more common fields are covered, especially data quality (AGI, 1999). The ubiquity of the FGDC CSDGM standard may change as the ISO standard is currently in development and anticipated in early 2002 (ISO, 2001). These are known as formal standards – up until these appeared, standards were piecemeal, serving a particular organisation, discipline or user community (Medyckyj-Scott *et al.*, 1996).

The next section forms a background of expert systems. Hooke (1999) has noted that, in fluvial geomorphology, manuals are being created that guide non-specialists through geomorphological assessment: "If this can be done, then a logical step is to develop decision support systems and expert systems".

2.3 Expert Systems

Expert Systems (ES) or knowledge-based systems has its origins in Artificial Intelligence (AI), the aim of which is simply, to simulate human reasoning (Laurini and Thompson, 1992). Expert Systems are the most mature products to emerge from this field (Raggad, 1996), dating back to the mid-1960's, when researchers at Stanford University developed a program that used chemical expert knowledge to automatically deduce molecular structure (Durkin, 1996).

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). Expert systems are similar to Intelligent Knowledge-Based Systems (IKBS), except that the latter incorporates "more indirect forms of knowledge representation" (such as fuzzy logic and neurocomputing) to form hybrid systems (Openshaw and Openshaw, 1997).

A survey estimated that about 12,500 expert systems have been developed (Durkin, 1996) and the USA and European market for ES was £100 million in 1994 (Openshaw and Openshaw, 1997). Coupling this with the assertion that expert systems have received a great deal of attention in the professional literature, computing literature and government agencies (Robinson *et al.*, 1986), one begins to picture just how extensively expert systems have been embraced. Cheng *et al.*, (1995) go so far as to say that expert system research has emerged as a distinct field of study in itself.

However, despite the large number of developments, only an estimated 10% of medium to large expert systems actually fulfil expectations (Keyes, 1989; Raggad, 1996) due to reasons such as weak inference engines, hard, slow and tedious required knowledge formulation, and inadequate knowledge (Oravec and Travis, 1992). Openshaw and Openshaw (1997) give even less optimistic evidence, stating that much less than 1% of expert system prototypes survive to become full working systems.

Durkin (1996) has remarked that, on balance, progress since the birth of expert systems has not lived up to the initial successes and resultant hopes. This said, expert systems have come far, and still have enormous potential. Navinchandra (1993) observed the 1980's as the heyday of expert systems and the 1990's as a period of decline, but places this information in the context of a life cycle of phases.

Specifically, Fischer (1994b) has noted that artificial intelligence in geography (and since most coastal zone issues are inherently spatial, this can extend to coastal zone management) has received an 'explosion' of interest in the last few years. Furthermore, Fischer asserted that there was no longer any question that expert systems (and neural networks) would be integral in building the next generation of intelligent Geographical Information Systems (GIS). The reason why there is plenty of scope for use of expert systems in this subject area is that GIS without intelligence have a limited potential to effectively solve spatial decision support problems in a complex or imprecise environment. It is precisely this complexity that has hampered the application of expert systems in geography (particularly GIS). Openshaw (1995) reinforces this, comparing AI progress in geography with the rate of growth of MIQ (Machine Intelligence Quotient) of consumer products and industrial systems.

Is this reason to believe that expert system potential in geography is limited? After all, they need to be fed with up-to-date knowledge to remain viable, are "brittle" due to application in narrowly defined domains, have no facilities to dispense common sense (see also Minsky [2000] for a discussion of common sense in human-computer interaction) and are not good at recognising when they fail (Openshaw and Openshaw, 1997). Also, they cannot perform better than human experts and no human experts are good enough (Openshaw, 1995). One solution lies in developing systems at superhuman levels, though an expert system that encompasses the knowledge provided by several expert sources already goes beyond the capability of any one human (Ferrier and Wadge [1997] state that for geological expert systems "few individuals have mastery over the whole"). On a more prosaic level, expert systems applied to mundane tasks would benefit the expert, by leaving more time to work on other issues (Durkin 1996). One major academic advantage of expert systems development is the improved accessibility to, and dissemination of, subject knowledge. Preparation of a rule base provides insights into a domain and forces the protagonist to think systematically (P F Fisher, 1989). In this way, expert systems can ease the management of complex situations (*e.g.* law). Other beneficial properties of expert systems include cheaply disseminating scarce skills and expertise, preservation of knowledge indefinitely, an objective approach, speed and efficiency due to automation, and a means of commodifying a hitherto intangible resource (Openshaw and Openshaw, 1997).

2.3.1 A Brief History of Expert Systems

In the early days of expert systems during the sixties and seventies, researchers looked for better ways to represent knowledge. The number of such developments was modest, but their contribution was valuable. The noted expert systems MYCIN and PROSPECTOR (see section 2.3.2) were built in this phase. Based upon the success of these lucrative examples, the technology was plied with more money in the 1980's, leading to growth.

Development was helped when there was a shift in emphasis from overstretching technology (by purporting to develop the definitive expert system that could solve problems even the experts could not) to developing expert systems for narrow domains and mundane tasks in the mid eighties (Dantzler & Scheerer, 1993; Fischer, 1994b; Durkin, 1996).

In terms of hardware and software, the seventies heralded logic-based expert system development on powerful workstations with declarative languages such as Prolog and Lisp (Smith and Jiang, 1991). Because of this hardware / software exclusivity, only a select few scientists were involved in ES creation. Later, in the eighties, there was a move towards PCs with users mainly building on existing expert system shells. This accessibility meant that expert system development was more widespread (Durkin, 1996).

The shell or 'skeleton' allows the specialist to focus on the knowledge base rather than the workings, which it already provides. e.g. EMYCIN & KAS (Knowledge Acquisition Systems) are the shells for MYCIN and PROSPECTOR respectively (see section 2.3.2), but with all domain-specific knowledge removed. Shells provide the builder with a number of tools for effective use of the inference engine. Key tools include editing, debugging, consult-the-user and explanation (help) functions (Robinson *et al.*, 1986).

2.3.2 Early Geospatial Expert Systems

One of the most noted earth science expert systems is PROSPECTOR, which was developed to assist field geologists (Alty and Coombs 1984). The original system was designed to assess sites for the existence of certain deposits, to evaluate geological resources in a region and to identify the most favourable drilling sites. Despite initial success in discovering a mineral deposit, none have been found since using PROSPECTOR (Katz, 1991).

Geological expert knowledge is incomplete and uncertain due to the knowledge underlying problem solving and the available evidence upon which a conclusion is to be reached. This uncertainty is dealt with in the systems through forms of non-definitive reasoning, such as the use of conditional probabilities and Bayes' Theorem (section 2.3.8).

The arrangement of the PROSPECTOR model can be described as spaces connected by rules to form a network. A space may be some observable evidence or a hypothesis; each space has a probability value indicating how true it is. Rules have the role of specifying how a change in the probability of one space can be propagated to another (Robinson *et al.*, 1986).

GEOMYCIN (Davis and Nanninga 1985) has been developed from EMYCIN, which is itself an 'empty' (*i.e.* devoid of context-specific rules) version of MYCIN, an expert system used for the diagnosis of infectious blood diseases (Buchanan and Shortliffe, 1984 – see section 2.3.8 for details on certainty factors, the inference method used). GEOMYCIN incorporates geographically equivalenced parameters, geographic data files, and rules that are geospatially specific. These capabilities have been utilised to build a realistic demonstration expert system for fire behaviour in a major Australian national park.

Table 2.1 contains a list of expert system applications.

General
Frank (1984) - LOBSTER - logic-programming paradigm.
Lilburne *et al.* (1996) - Spatial Expert Shell - Object-Oriented GIS / ES System coupling
Robinson *et al.* (1987) - survey of 20 expert systems.
Smith *et al.* (1987) - KBGIS-II - handles complex spatial objects
Zhu & Band (1994) - multi-source data integration.
Cartography
Cress & Diester (1990) - production of Geological Engineering Maps (GEM)
Freeman & Ahn (1984) - AUTONAP - cartographic name placement.
Robinson & Jackson (1985) - MAP-AID for map design.
Yue *et al.* (1991) A Statistical Cartographic Expert System for China.
Engineering
Evans *et al.* (1993) - investigation of expert systems and GIS in civil engineering.
Spring & Hummer (1995) - engineering knowledge for accident causation to show hazard locations.
Environmental
Folse *et al.* (1990) - simulating mountain lion movement (!)
Pearson *et al.* (1992) - Landslide Hazard Assessment.
Robinson *et al.* (1986) - ORBI - DSS for resource planning / environmental classification
Ecological
Lam (1993) - ecological modelling, GIS and ES: a case study of regional fish species richness model.
Loh & Hsieh (1995) ES to spatially model secondary succession on a savanna woodland site.
Mackay *et al.* (1994) - ES / GIS for simulation of forested ecosystems
Miller (1994b) coupling knowledge-based systems and GIS, model of vegetation change.
Miller & Morrice (1991); Miller (1994a) Predicting upland vegetation changes using ES and GIS.
Hydrological
Gumbricht & Thunvik (1997) - 3D hydrogeological modelling with ES / GIS
Merchant (1994) - DRASTIC model for groundwater capability.
Smith *et al.* (1990) - Extracting channel networks from noisy DEM data.
Tim (1996) - hydrological / water quality expert systems.
Wang (1997) - choosing appropriate groundwater model / provide future data collection guidance
Soil mapping
Skidmore *et al.* (1991) - use of expert systems and ancillary data to map forest soils.
Skidmore *et al.* (1996) - LCMES (Land Classification and Mapping Expert System) to map forest soils
Zhu *et al.* (1996a) - infer and represent information on the spatial distribution of soil.
Land Use
Navinchandra & Goran (1986) - GEODEX - evaluating site suitability for specific land use activities.
Goldberg *et al.* (1984) - FES - Forestry Expert System - landcover change.
Mackay *et al.* (1992) - KBLIMS (Knowledge Based Land Information Manager and Simulator).
Tanic (1986) - urban planning
Wei *et al.* (1992) - land use suitability.
Zhu *et al.* (1996b) - Islay Land Use DSS (ES / GIS) - assessing potential for development
Remote Sensing
Goodenough *et al.* (1995a) - an intelligent system (SEIDAM - System of Experts for Intelligent Data Management) for calibrating AVIRIS spectrometer data.
Goodenough *et al.* (1995b) - Methodology for creating sequence of intelligent expert systems
Kartikeyan *et al.* (1995) - automated analysis of human expert's interaction in remote sensing classification
Kontoes *et al.* (1993) - classification using geographical context data
Morris (1991) - extraction of 3D structural parameters from remotely sensed imagery and DEMs.
Srinivasan & Richards (1993) - Analysis of mixed data types for photo-interpretation.
Socio-economic
Cowen & Ehler (1994) - SDSS (ES / GIS) for economic development
Heikkila (1990) - Modelling Fiscal Impacts Using Expert GIS: Theory and Strategy.
Sarasua & Jia (1995) - Integration of a GIS and KBES for pavement management.
Varghese & O'Connor (1995) - expert GIS for route planning

Table 2.1: A list of selected expert systems, arranged by application.

2.3.3 Coastal and Ocean Expert Systems

A detailed literature review of expert systems managed to draw out only three projects with a marine application sufficiently advanced enough for report (Moore, 2000). Since the review was carried out (1997), the initial findings of this thesis have been published (Moore *et al.*, 1998, 2001). The content of these papers is covered in Chapters 4 and 5.

The Ocean Expert System (OES) is a means to optimally exploit sparse data and incomplete coastal environmental information in tactical oceanography support. Tactical oceanography employs the military use of archival or contemporaneous oceanographic information to gain tactical advantage. Therefore, tactical oceanographic support is a problem of information acquisition, interpretation and management. To meet these ends, expert system technology has been explored for suitability analysis. There is an iterative analytical approach - as new knowledge is gained, it is fed back into the system, updating estimate of the local scene description. It has an ability to provide an explanation of the decision making process, since the user of the OES system is not necessarily an oceanographic expert (Dantzler and Scheerer 1993).

SimCoast™ is a fuzzy logic rule-based expert system shell, enabling coastal zone practitioners to create and evaluate different policy scenarios for coastal zone management. It has a multi-disciplinary and multi-sector approach, assimilating specialist and indigenous coastal zone knowledge through the use of reasoning tools.

Rule generation (for policy formulation and decision-making) is effected through workshops and consensus discussions.

A two-dimensional multi-zoned transect lies at the heart of SimCoast™ (Figure 2.2); this can be populated by zone-specific features (*e.g.* ports, mangroves) and activities (*e.g.* shipping, aquaculture). The effects of activities on the features are evaluated in relation to defined policy targets (*e.g.* water quality, ecosystem integrity) measured in particular units (*e.g.* *E.coli* ppm, number of fish species). This evaluation is the result of consensual expert rules, which are defined during workshops. The workshops themselves are designed with specific foci (*e.g.* fisheries, ballast water discharge) and aims (*e.g.* policy development) in mind (Bottrell, 1999).

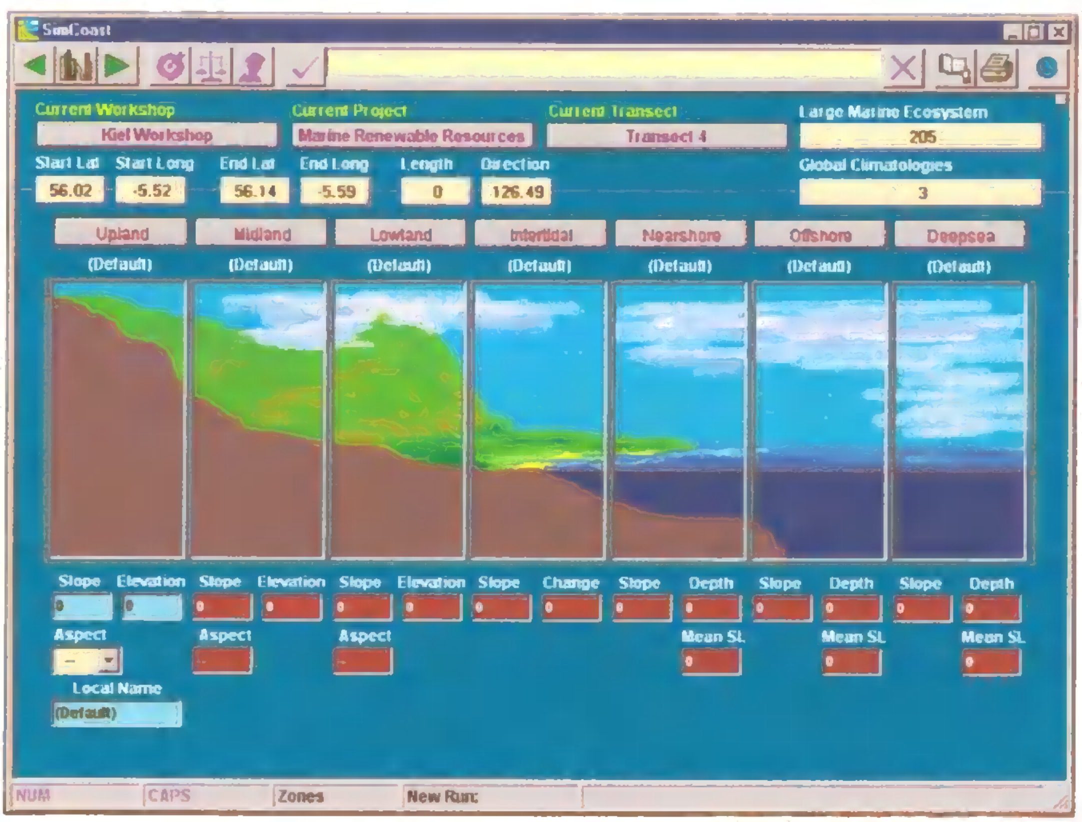


Figure 2.2: A SimCoast™ screen - a transect is divided into zones, into which coastal features and activities can be placed (from Bottrell 1999).

Finally, the DSS ICOMIS (Integrated COastal resource Management Information System) has been applied to the Thai coast for the conflicting land uses of mangrove forest conservation and development of shrimp culture in mangroves (Looijen *et al.*, 1995). The system consists of remote sensing, GIS and modelling on one hand, and a multi-objective DSS on the other. The structure follows the decision-making process, from problem definition, through the search for alternatives and selection criteria, through the evaluation of alternatives to the selection of alternatives.

2.3.4 Elements and Processes of an Expert System

Elements

It has been noted that ordinary computer programs organise knowledge on two levels: data and program. Most expert systems organise knowledge on three levels: facts, rules and inferences (Robinson and Frank, 1987). These three levels correspond to two independent core parts of the expert system according to Robinson *et al.* (1986); these are a domain independent inference engine and a domain specific knowledge base (covering both facts and rules).

Expert 'rules' model behaviour of, and functions relating to, a theme. 'Facts' describe single values such as basic information or events. Other than the core elements of the expert system there are two other basic parts, a module for knowledge acquisition and a module for interfacing with the user (Laurini and Thompson, 1992). The role of the user interface in expert systems has come to the fore recently, with the emphasis on interaction instead of the expert system working in its own state space and giving out an answer at the end of the program run (Avouris and Finotti, 1993). Interaction has been flagged since the 1970's, with Shortliffe (1976) stressing that an expert system should be useful (implicit in this is the role of the user interface, which should be the means by which the "ease of communication" property of Davis *et al.* [1989] should be effected), be able to explain its advice (or give adequate explanation of the expert system process: Davis *et al.*, 1989; Fischer, 1994a; Zhu *et al.*, 1998). Once a problem has been defined, the first step in developing a knowledge base is the construction of a conceptual model of the problem domain (Hayes-Roth *et al.*, 1983).

Processes

Figure 2.3 shows the configuration of a typical rule-based expert system, displaying the interactions between the elements introduced earlier. From application to application this arrangement may change in terms of conceptual form and nomenclature, though essentially the workings are the same.

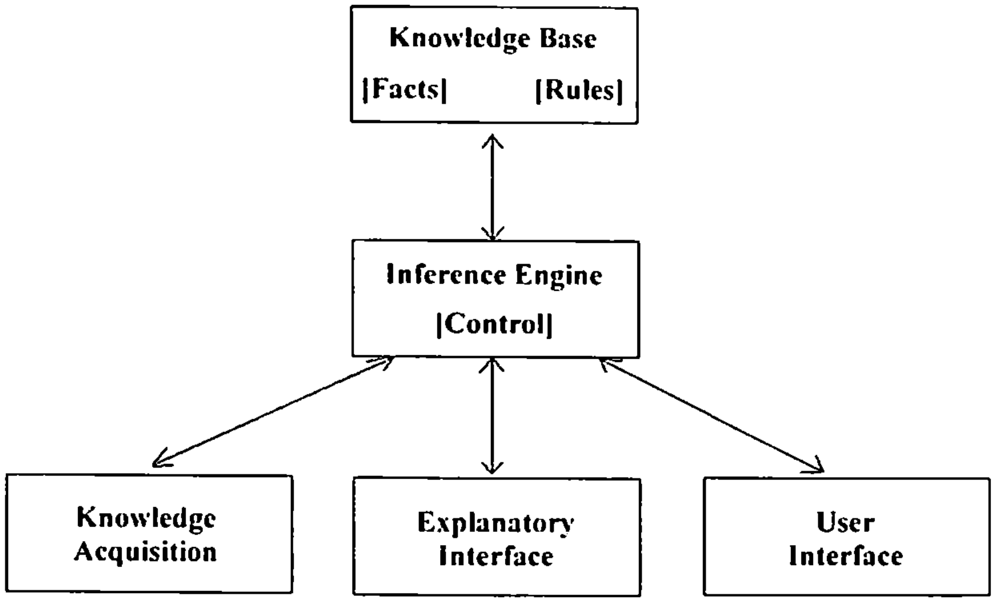


Figure 2.3: The configuration of a typical rule-based expert system (from Robinson *et al.*, 1986).

Fisher *et al.* (1988) describe the processes within an expert system as a 'recognise-act cycle'. Firstly, the inference engine checks the situation parts of each production rule (section 2.3.5) to see if the input facts and embedded facts will allow evaluation of the rule. If so then the rule is selected. After this process, the selected rules form a 'conflict set' of rules. Then the inference engine takes the first production rule in the 'conflict set' and implements it. This is called forward chaining, and is one of a few inference processes to be explored in further detail in this section. Finally, the cycle is repeated until all of the possible information has been extracted from known facts and rules. The explanation module will then tell the user how the expert system reached a conclusion.

The process of forward chaining is also known as deduction. 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. There is a reverse process to forward chaining, predictably called backward chaining or abduction (reasonable explanation). It is mostly used for discovering the reasons behind a situation. In short, if B is true and the rule A -> B applies, then by abduction A is also true (Laurini and Thompson, 1992). There are two other less advertised processes. Induction occurs when two facts are always concomitant and it would be reasonable to assume that there is a rule expressing a relationship between them. In formal terms, if A is true and B is also true then the rule A -> B applies. Finally, transitivity involves the interplay of two rules. If A -> B and B -> C we conclude that A -> C is true (Laurini and Thompson, 1992).

Control and search

The terms forward and backward chaining are also used in connection with search strategies used to traverse the rule base, or state-space. In state-space search, operators can search in a forward direction from a given initial state to a goal state (also called data-driven search) (Robinson *et al.*, 1986). This implies that there is no knowledge of the goal in the system (Fisher, 1990). Searching in a backward direction from a given goal to initial state (also called goal-driven search - Robinson *et al.*, 1986) implies that there is some knowledge about the goal in the system (Fisher, 1990).

Searches in state-space are conducted with the root node (at the top of the hierarchy) as the starting point, from which progress to child nodes (further down the hierarchy) is the next stage. One of the child nodes will be the goal. There are several types of search; depth-first search, breadth-first search and any number of heuristic ('rule-of-thumb') search methods. The latter is the most popular method of search used, as an applicable heuristic can be chosen for the specific problem addressed. As an example, two best first algorithms (the simplest of heuristic search methods) are outlined here. In 'costed search', the lowest cost child node is removed, then the children of that investigated, and so on, until the goal is reached, or there are no more child nodes to investigate. In 'branch-and-bound search', the lowest cost child node is expanded; this continues until all links are exhausted and the cheapest path to the goal chosen (Fisher, 1990).

2.3.5 Knowledge Representation

According to Kartikeyan *et al.*, (1995) there are three conceptual models to represent knowledge - rule-based (Wharton, 1987), frame-based (McKeown, 1987) and blackboard architecture (Hayes-Roth *et al.*, 1983). The choice of these methods is dictated by the nature of the problem concerned.

Rule-Based

The rule base contains procedural knowledge and therefore can be programmed using conventional languages. There are several ways in which domain-dependent knowledge can be encoded, which incorporates searching of many paths in the knowledge base, not all of which lead to solutions. Several languages allow for triggering of rules by patterns, of which Prolog has historically been the most popular. Here, first order predicate logic is used to represent knowledge in terms of formulae.
e.g. Jack gave Anne a book = GIVE(Jack, Anne, book)

Production rules have been extensively used to encode knowledge. They comprise a series of IF-THEN statements, which performs an action if a certain condition is met. Alternatively, logical representation can be used, as in the following example:

A1 & A2 &......& An -> B

This notation means that B is true when A1, A2,......A(n) are true (Robinson *et al.*, 1986).

Frame-Based (Object Orientation)

Another group of knowledge encoding methods are semantic networks and frames. A specialised form of semantic network is the decision tree, a hierarchical network bound by a series of rules, coupling search strategies with knowledge relationships (Turban, 1995). Frames can be traced as part of the heritage of object orientation (Smith and Jiang, 1991). The object-oriented way of thinking and programming is conceptually closer to the real world than procedural programming methodologies or record-based relational databases. For this reason it is closer to the way humans think, making it the ideal structure for artificial intelligence techniques (Laurini and Thompson, 1992). Ferrier and Wadge (1997) concur, identifying object-orientation as a means of structuring more complicated types of knowledge base than rule-based systems.

Regarding the paradigm differently, it makes considerable progress towards letting the application domain uniquely define the form of the computer model (Raper and Livingstone 1995). This contrasts with the convention (for example in environmental modelling), where the representational basis of a GIS is often allowed to drive the form and nature of the model.

Object-oriented models break down an information space into objects. The required properties of an object is that they are identifiable, of interest and describable. Figure 2.4 shows an example of an object, with associated attributes (Worboys, 1995).

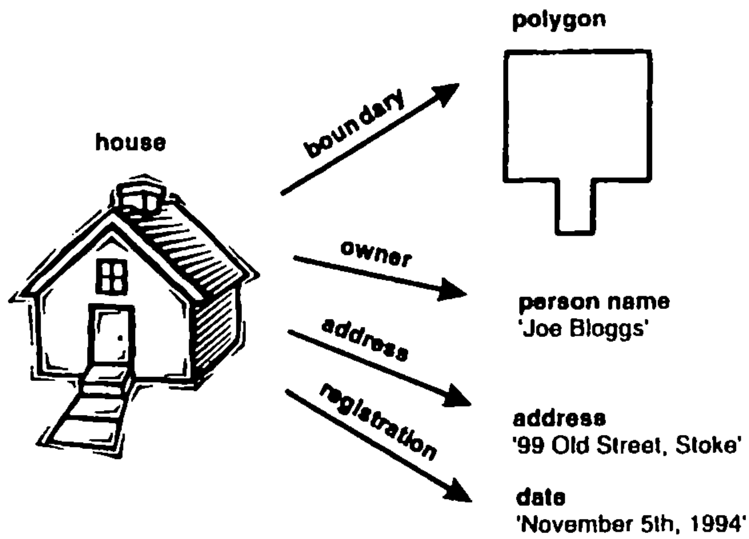


Figure 2.4: An example of an object, with associated attributes (from Worboys, 1995).

Perhaps the major conceptualisation in object-oriented programming is that of the class. Classification involves the assignment of individual occurrences defined on the basis of selected attributes or functions. All classes will have specific attributes unique to themselves - *i.e.* the difference between public and private.

For instance, there can be a class, raster, with subclasses slope, aspect and convexity, which are defined by their attributes and functions; these are said to be encapsulated within the class definition. In addition, they inherit all the elements of the raster class (as the next tier up in the class hierarchy), such as a 2D-array data structure. It is also possible for a class to inherit from more than one superclass, in what is known as multiple inheritance (Tello, 1989). Systematic methods exist to define classes for any given application (*e.g.* Booch's method [1994] – see section 3.5).

Lilburne *et al.* (1996) report the development of the Spatial Expert Shell (SES) involved the combining of a GIS and an enhanced expert system shell (Smart Elements, which consists of Nexpert Object combined with a GUI developers kit). A client-server set-up was initiated (with Smart Elements the client and Arc/Info the server). SES consists of a group of spatial classes with predefined state and behaviour (*e.g.* GIS elements - display, vector, raster - are all grouped under a top level class called gisObject).

Blackboard Architecture

The conceptual basis is that a tentative plan may be made by the co-operative decision of many specialists. These are all arranged on the "blackboard", which is a global data structure for the retention of problem solving information. There is a hierarchical arrangement of information on the blackboard.

In the case of a geographical planner program (Geoplanner) reported by Leroux and Li (1990), there are three levels, each requiring a planner - conceptually, from top to bottom; task level, concept level and route level. It was found to be powerful enough to address complex issues such as geographical planning, and flexible enough to accommodate additional planning techniques as required.

2.3.6 Knowledge Engineering

Knowledge engineering is one of the greatest challenges in building expert systems (Scott *et al.*, 1991) - indeed Fisher *et al.* (1988) go as far as to say ".... perhaps the major effort in developing an expert system."

The predominant process in knowledge engineering is knowledge acquisition, which is defined as the transfer and transformation of problem solving expertise from some knowledge source to a computer program (Buchanan *et al.*, 1983). Sources for such problem solving expertise include human experts, textbooks and scientific journals (Robinson *et al.*, 1986).

Knowledge engineering in general involves the codifying of human knowledge, a method by which the expert's knowledge and ways of reasoning can be understood (Laurini and Thompson, 1992). The knowledge engineer chooses a specific paradigm, within which facts and rules can be elicited. For example, SimCoast conceptualises in terms of elements such as activities and features (Bottrell, 1999). There is a parallel between this operation and software development but for expert systems the choice of paradigm to use is not obvious, and varies with the application (Robinson *et al.*, 1986). When new knowledge becomes available, it has to be verified with existing knowledge for consistency (Laurini and Thompson, 1992).

Methods have been suggested to ease knowledge acquisition by having direct interaction between the domain expert and the program, thus bypassing the knowledge engineer. This is facilitated by having the program 'taught' by the expert by feeding it problems and seeing how it reacts, making amendments and adding knowledge as appropriate (Davis and Lenat, 1982).

Knowledge acquisition can be observed as a "bottleneck" in developing knowledge-based systems. The manual approach to this suffers from experts unable to articulate their reasoning rules. On the other hand the automated approach (which induces rules from a set of training cases) suffers from a lack of training cases. Jeng *et al.*, (1996) have put forward an integrated approach that uses the strengths of both, in having human experts responsible for solving problems, and utilising an inductive learning algorithm for reasoning and consistency checking.

Huang and Jensen (1997) offer an alternative method of automated knowledge-base construction for image analysis expert systems with GIS data. An inductive machine-learning technique is used for the image classification of wetlands, bypassing knowledge elicitation but dependant on appropriate training data.

2.3.7 Error Modelling in Expert Systems

For an expert system being used in any commercial or academic environment the user will want to know how much significance the output has, to assess its validity. Therefore some measure of the quality of results is essential for the following practical reasons. Firstly, there will be assurance that any investments for development will be potentially safe. Without such a measure, the comparison of different analyses would be difficult (Burrough, 1992). The knowledge of the accuracy of any information required for decision-making is important where there is a range of data types and reliabilities (Miller and Morrice, 1991). Next, future data collection and sampling strategies would benefit from such information. Finally analysis would be 'anarchical' without quality control (Burrough, 1992). It is therefore important to understand the statistical meaning of each data set for final investigation (Moon and So, 1995). For a good overview of the nature and sources of error in geospatial data in particular, Burrough (1986) gives a comprehensive grounding. These were discussed with reference to COAMES in Moore *et al.* (1996).

Duckham *et al.* (2001) put forward ontology of imperfection, a hierarchy that includes "error" (or inaccuracy) along with "imprecision" forming the second tier ("imperfection" is the top tier). It is proposed that this treatment of imperfection could feed into geographical information integration.

2.3.8 Dealing with Uncertainty

Expert systems, by their very nature, deal with a lot of uncertain data, information and knowledge. However, the treatment of uncertainty in expert systems has mainly been neglected, as some have found no significant difference between using uncertainty and an assumed certainty (Turban, 1995), though Davis *et al.* (1989) rate an ability to incorporate uncertainty in an expert system. Tversky and Kahneman (1974) quote empirical evidence that people are poor estimators of probability, and probabilities derived from published data were also found to be wide of the mark (Ben-Bassat *et al.*, 1980). Even so, such deviation results in only small changes to a value derived from, for instance, Bayes theorem.

Despite this, several methods have been used to combine or integrate uncertain information for inference - these include Bayes Theorem, the Dempster-Shafer theory of evidence, certainty factors and fuzzy sets. In remote sensing terms, these are all methods of data fusion. Fusion can be distributed (multiple sources are classified individually, then combined) or effected centrally (combining all data at once). Recent expert system research (and COAMES) is of the distributed type (Petrou and Stassopoulou, 1999). Kanal and Lemmer (1986) have appended a pre-process (representation of uncertainty through, for example, probability or hedges) and a post process to this integration (extracting inferences from the combined information) to make a 3-stage process. The methods of integration will be tackled in turn.

Bayes' Theorem

This is the most common method of evidence combination for interdependent probabilities (each of which represents a piece of evidence), calculating uncertainty about the likelihood of a particular event occurring, given a piece of evidence (Shortliffe, 1976; Srinivasan and Richards, 1993; Moon and So, 1995; Skidmore *et al.*, 1996). The examples of Wu *et al.* (1988) and Schenk and Zilberstein (1990) apply Bayes to the classification of Landsat data and interpreting linear map features respectively. Finally, Middelkoop and Janssen (1991) use Bayesian maximum likelihood classification to combine spectral image information, GIS and knowledge of temporal relationships.

Wright and Buehler (1993) give a good in-depth account of the Bayes calculation process applied to land suitability analysis. The Bayes formula is:

$$P(H_i|E_j) = \frac{P(E_j|H_i)P(H_i)}{\sum_i P(E_j|H_i)P(H_i)}$$

where $P(H_i|E_j)$ is the posterior probability that hypothesis H_i occurs given the evidence E_j (where i is any number from 0 to the total number of hypotheses being considered, and j is any number from 0 to the total number of pieces of evidence being considered);

$P(E_j|H_i)$ is the conditional probability;

$P(H_i)$ is the prior probability (the probability that hypothesis H_i is true);

The denominator $\sum_i P(E_j|H_i)P(H_i)$ is also called the classical marginal probability (Skidmore *et al.*, 1996), the probability that any item of evidence exists.

The calculated posterior probability becomes the prior probability H_i for the next evidence-driven calculation (Skidmore *et al.*, 1996, Naylor, 1983).

Variations on Bayes include the Bayesian (or belief or causal) network (Pearl, 1986), a hierarchy that supports the efficient calculation of probabilities using a reduced number of initial values (Scheerer, 1993). It allows bi-directional inference, with messages being sent from causes to effects, and, diagnostically, from effects to possible causes (Pearl, 1986). Stassopoulou *et al.* (1998) used this method in the Mediterranean region to assess the risk of desertification after a forest fire.

In the end, the formula only produces a single value, which gives no indication of precision or the breakdown of support for hypotheses and support from evidence (Spiegelhalter, 1985; Turban, 1995). Scheerer (1993) adds more points of criticism, that all evidence and hypotheses have to be expressed as propositions, and therefore have to be anticipated in advance (also Shortliffe, 1976), even where there is likely to be a quantitative lack of knowledge (Spiegelhalter, 1985). Further points include the exponential "explosion" that occurs in the number of values required to calculate Bayes; also, the introduction of new evidence requires the updating of all conditional probabilities. Finally, Bayes and other probabilistic measures do not allow for ignorance (Spiegelhalter, 1985). This is covered by the next combination mechanism, the Dempster-Shafer theory of evidence.

Dempster-Shafer theory of evidence

The Dempster-Shafer (D-S) theory of evidence (Dempster, 1967; Shafer, 1976) is an extension of Bayes theorem. It waives the need for exhaustive prior or conditional probabilities before calculation can take place and thus can be used where evidence is lacking or where evidence is based on vague perceptions. Most importantly, it introduces the representation of ignorance.

Normally, where probabilities are not known, maximum entropy means that equal prior probabilities are unrealistically assigned to each competing piece of evidence, and the sum of all assigned probabilities must equal one. With Dempster-Shafer theory, an ignorance value (ignorance = 1 represents complete ignorance) can be used to represent the lack of information, rectifying what would be erroneous with probability (Gordon and Shortliffe, 1984; Scheerer, 1993; Turban, 1995). Related to this is the fact that when belief is assigned to a particular hypothesis ($P(H)$), the remaining belief does not necessarily then support that the hypothesis' negation (i.e. $P(-H)$, or probability of 'not H', does not necessarily equal $(1 - P(H))$.

Other advantages of using D-S include the ability to use evidence supporting more than one hypothesis (a subset of the total number of hypotheses). Finally, D-S models the narrowing of the hypothesis set with the accumulation of evidence, which is exactly how experts reason (Gordon and Shortliffe, 1984).

However, singletons (single hypotheses) are assumed to be mutually exclusive and exhaustive. Likewise, evidence needs to be independent (Gordon and Shortliffe, 1984; Scheerer, 1993). Ling and Rudd (1989) offer methods to combine the dependent opinions of experts, which is a realistic option. Another drawback is the computational complexity of D-S (Gordon and Shortliffe, 1984). Barnett (1981) offers a routine that reduces the computations to linear time. Peddle (1995) found the methods of generating evidence subjective and inconsistent, a by-product of its general (or holistic) nature.

Gordon and Shortliffe (1985) developed an approximation method to D-S theory, this time tackling hierarchical evidence, advancing from their 1984 idea of using small groups of hypotheses (or members) when dealing with large overall memberships. Soon after, Shafer and Logan (1987) adapted D-S theory for hierarchies, producing a more robust method (outlined in Appendix A). This mirrored Pearl's (1986) efforts with Bayes' theorem and also reduced computational complexity.

Other examples of Dempster-Shafer use include Ferrier and Wadge (1987 - geological analysis of sedimentary basins), Srinivasan and Richards (1990 - remote sensing classification), Kontoes *et al.* (1993 - classifying remotely sensed images for agriculture) and le Hégarat-Mascle *et al.* (1998 - fusing optical and radar images for forest area detection). Section 3.9.1 has more details about the formulae used in D-S.

Certainty Factors

The Shortliffe method of combining error measures uses certainty factors (CFs), the belief in an item of evidence. Its origins are in the MYCIN project (Shortliffe, 1976; Buchanan and Shortliffe, 1984), developed as an alternative to Bayes' theorem. CF values range from -1 to 1 (Forsyth, 1984) and are derived from subtracting the measure of disbelief (MD) in a piece of evidence from the measure of belief (MB) in the same evidence (Turban, 1995). For the combination of two pieces of evidence, the following equation is used:

$$CF[H|E1,E2] = CF[H|E1] + CF[H|E2] \times (1 - CF[H|E1])$$

where $CF[H|E1,E2]$ is the combined certainty factor attributed to the pieces of evidence $E1$ and $E2$ with reference to a hypothesis H. For combination of different MBs and MDs, the equation is the same; just substitute in for CF.

Although this method has had appreciable success with MYCIN, it has a less than rigorous mathematical basis (Gordon and Shortliffe, 1984; Forsyth, 1984). Having said that, it is symmetric in that the order in which successive pieces of evidence are processed does not matter. Finally, this method moves towards certainty in an asymptotic manner as evidence builds up, conforming to intuition (Forsyth, 1984; Graham and Jones, 1988).

For applications of certainty factors, see Morris (1995), who describes the use of weighted CFs to extract geological structures from remotely sensed images. Loh and Hsieh (1995) give an account of the application of CFs to modelling succession in a savannah landscape.

Fuzzy Logic

The fuzzy set, which is the basic construct of fuzzy logic, was introduced by Zadeh (1965). It is defined as "a class of objects with a continuum of grades of membership". It has been used extensively for the processing of non-crisp terms such as 'good', 'fair' and 'poor' (see Brimicombe, 1996). It is a way by which imprecise or uncertain data can be modelled, where instead of absolutes such as 'no' and 'yes' (crisp or Boolean logic), there is a gradual scale from 0 denoting 'no' to 1 denoting 'yes'. Leung and Leung (1993) have found these properties particularly suitable to overcome the Boolean logic that pervades current GIS, especially in the areas of databasing, explanation, interfacing and natural language.

Taking an example from Turban (1995), the notion of tallness is one that is hard to quantify. A person who is six feet in height may have a 0.75 probability of being reckoned as 'tall'. In fuzzy logic terms, the degree of membership within the set of 'tall' people for that person is equal to 0.75.

There has been no shortage of successful fuzzy expert systems applications. By way of example, Zhu *et al.* (1996a) use fuzzy logic for soil inference and Borri *et al.* (1998) use a fuzzy approach to evaluate environmental systems. Kovalevsky and Kharchenko (1992) constructed an engineering geological expert system able to handle fuzzy information. Finally, Binaghi *et al.* (1998) use a fuzzy Dempster-Shafer (FDS) approach to evaluate slope instability and produce instability maps.

2.4 Decision Support Systems and Geographical Information Systems

2.4.1 DSS

Decision Support Systems (DSS) are explicitly designed to support a decision research process for complex problems. As such, DSS would appear to be an ideal tool for the complex domain of coastal zone management. It provides a framework for integrating database management systems with analytical models; graphical display and tabular reporting capabilities; and the expert knowledge of decision makers (Densham, 1991).

The following are distinguishing characteristics of a DSS (Geoffrion, 1983):

- it is designed to solve ill-structured problems (when the objectives of the decision-maker and the problem are ambiguous)
- it has a powerful, easy-to-use interface
- enables the flexible combination of analytical models and data
- enables exploration through feasible alternative model outputs

- it is flexible enough to accommodate many decision-making styles, and when additional capabilities are needed
- it allows problem solving to be both interactive and recursive

A difference between DSS and ES, according to Kirkby *et al.* (1996), is that the user of a DSS provides the methodology and experience to direct the system, rather than having it internally programmed as in an ES.

As an example of use of expert systems within a decision support environment, WaterWare (Fedra and Jamieson 1996) is a decision support system for river basin planning. It has been designed to integrate the capabilities of GIS, database management systems, modelling techniques, optimisation procedures and expert systems (in the context of handling some of the more complex queries in a problem-specific manner). Furthermore, it is a completely open, modular system with different degrees and mechanisms of coupling at various levels of integration, presenting the user with a common logical structure for hands-on analysis and information retrieval.

Davis *et al.* (1991) describe a DSS to organise and display coastal vegetation information. The system can retrieve current GIS graphics database files. The embedded expert system enhances the value of mapping data for planning through an integrated classification process applied to the vegetation data. Through this a botanical importance hierarchy was established (*e.g.* primary community types are of high botanical conservation importance; alien plant communities are insignificant). The DSS employs a transparent information approach for non-computer literates.

RamCo (Rapid Assessment Module Coastal Zone) is a tool to construct a decision support system. It is termed a decision support generator. It has been used to characterise shrimp farming in south west Sulawesi as a case study. A schematic of the system is shown in Figure 2.5.

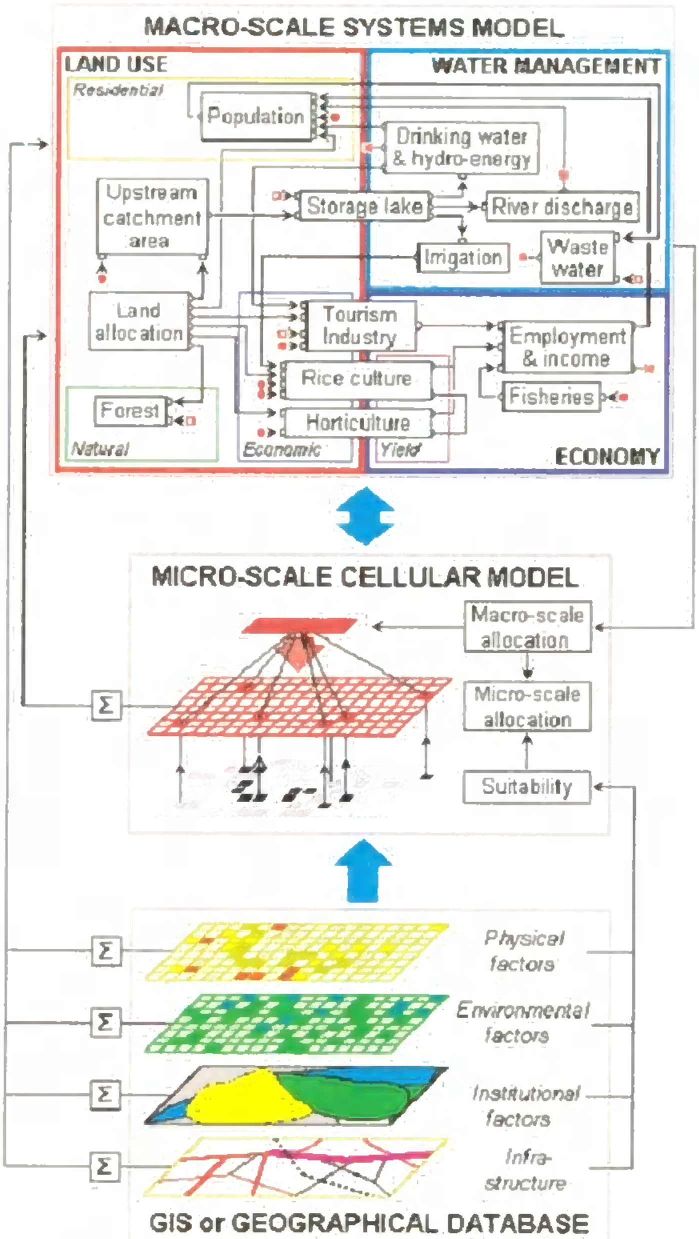


Figure 2.5: The organisation of RamCo (CZMC, 2001).

At the top, the user can configure the coastal zone system uniquely to wherever it is, with elements such as land use, water management and economy. There is also a GIS database here at the bottom with themes such as infrastructure and environmental factors. Both interact with a cellular model that iteratively allocates cells to a particular land use. The rationale for RamCo is one of reducing costs and effort involved in constructing a decision support system, normally a complex, costly and time-consuming process (CZMC, 2001).

Other applications include comparing the requirements of economic sectors and social factors (Barath and Futo, 1984), fauna (red deer - Aspinall, 1992) and coastal flora (Raal *et al.*, 1995).

2.4.2 GIS

The application of expert systems in GIS is well established. Historically, the key problem domains for expert systems in GIS have been automated map design and generalisation; terrain and feature extraction; geographical digital databases / user interfaces; and geographic decision support (Robinson *et al.*, 1986).

This section deals with the methods by which expert systems and GIS can be linked or coupled. It should be noted that those striving to integrate expert systems and GIS (for the benefits that they would both give each other) have not done as well as hoped due to exaggerated claims on the part of the creators when such initiatives were first mooted (Lilburne *et al.*, 1996).

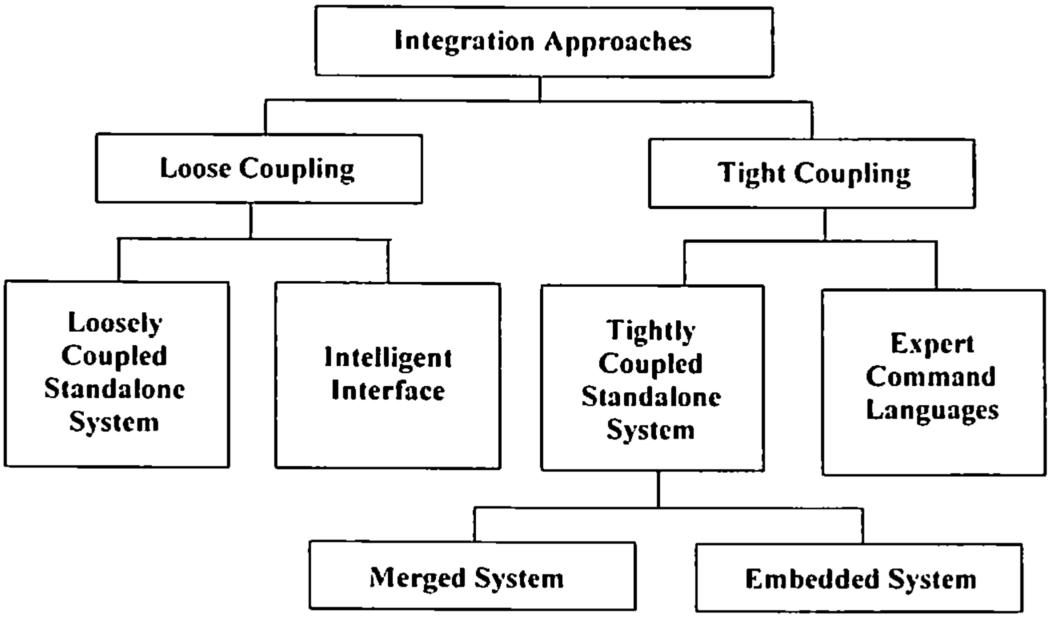


Figure 2.6: A classification of GIS and expert system integration methods (from Zhu and Healey, 1992).

Referring to Figure 2.6, the first of the linking methods is loose coupling, where expert systems and GIS are 'loosely' integrated by communication links, in other words a channel that transfers data from GIS to the expert systems. This is called a 'loosely coupled standalone system'. It is also possible to build an 'intelligent interface' to a GIS. For example the expert knowledge about spatial modelling procedures can be incorporated. Loose coupling does not provide expert systems with the spatial data handling capabilities of GIS.

A more effective means of linking is tight coupling, which integrates expert systems and GIS with communication links in such a way that GIS appears to be an extension of expert system facilities, and vice versa. One appears as a shell around the other. A 'tightly coupled standalone system' can be as a merged system, with expert systems as a subsystem of GIS functionality, or as an embedded system, where existing GIS facilities are enhanced with expert system functionality. The second type of tight coupling is 'expert command languages', where expert system reasoning is added to GIS macro or command languages (Zhu and Healey, 1992). Zhu (1997) uses an extra tool in coupling - a hypertext diagramming tool (HARDY) used to represent spatial problems that are translatable into CLIPS, an expert system shell.

Kirkby (1996) reported on the development of interactive land classification methodology that identifies key land areas, then conveys information regarding decision-making process to the user. The "Salt Manager" is an integrated expert system, GIS, remotely sensed information and a relational database management system. Knowledge is in the form of if-then production rules within the expert system and conditions conducive to the development of groundwater discharge and existence of recharge are spatially determined with a GIS. In addition, there is knowledge about climate, soil composition, terrain, general a priori knowledge and remotely sensed images to infer land units suitable for a specific land use. In conclusion, the application suffered from a lack of field data, and the site-specific nature of the rules, but was able to achieve 75% accuracy.

Lastly, Johnsson *et al.* (1993) describe ES and GIS coupling, controlling the GRASS GIS from within an expert system (RESHELL, a Prolog-based expert system shell), for SEIDAM (System of Experts for Intelligent Data Management). At a low level of coupling, the interface parses GRASS commands, executes them, and interprets, then translates GRASS output into a form that other expert systems within SEIDAM can use. At a higher level, expert systems are created that translate user-defined tasks into command sequences, which are executed. For example, there are expert systems for data import, export and DEM processing.

2.5 Environmental Information Systems and the Internet

The availability of more powerful and affordable computers (Openshaw and Abrahart, 1996) leads from the spatial aggregation of systems to system distribution (Fedra, 1996). The important role of the Internet (World Wide Web - WWW) in global communications and dissemination as well as being a huge source of information is commonly known. The Internet works with browsers through a client-server system, where the client makes a request to the server, which, all being well, leads to information delivery from the server to the client (Green and Massie, 1997).

The need to disseminate coastal zone management data, information and knowledge through the Internet is recognised by Agenda 21 (Fedra, 1996) and the EU Demonstration Programme (EC, 1999), recognising that in the past, such resources have not been widely disseminated, leading to avoidable problems on the coast. An ICZM 'observatory' is suggested as a parallel means of dissemination of generic good practice and general knowledge, encouraging public participation in decision making (Davos, 1998). It may also identify necessary pathways for the information from responsible organizations to those that need it. Kay and Christie (2000) state that the Internet is integral to the work of many coastal managers, though still in its infancy. It is predominantly used for information access (e.g. metadata listings) and communication.

As a general example, a prototypical network expert geographic information system for landfill siting has been proposed. It has a forward chaining knowledge base derived from the domain's literature. The actual siting analysis occurs in a GIS and is evaluated by triggered rules from the expert system. The expert system and GIS are combined to give the strengths of both. What is novel about this application is that it can be accessed from the Internet (Figure 2.7), cutting distribution costs and any non-standard software installation or management on the part of the user (Kao *et al.*, 1996).

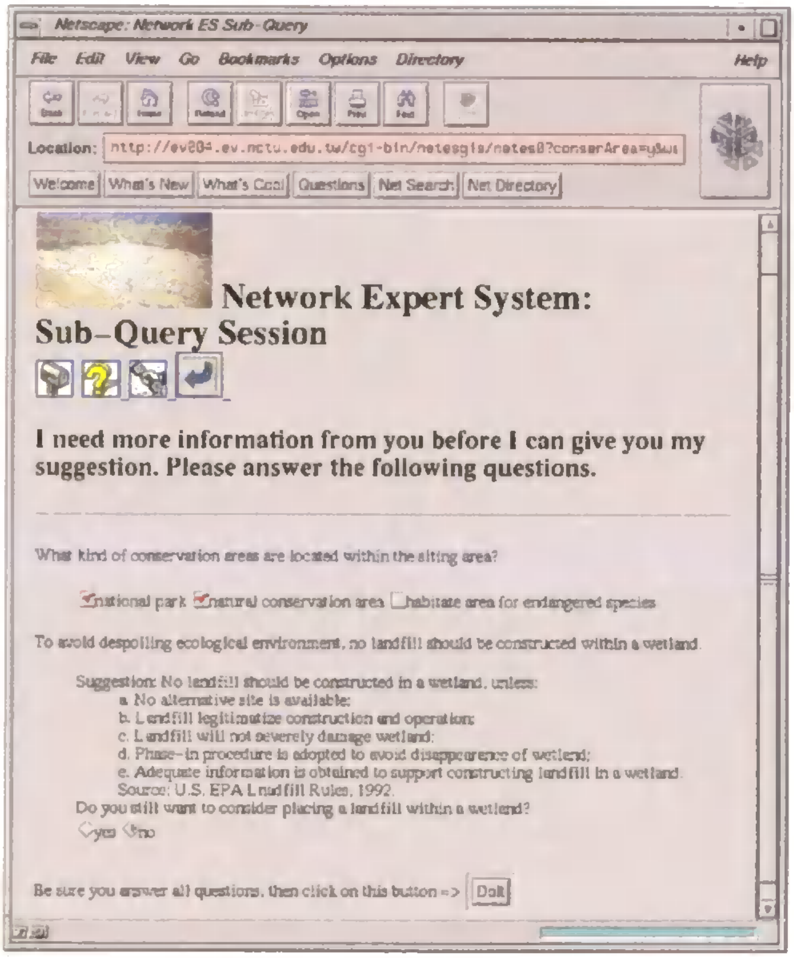


Figure 2.7: An Internet page from the Landfill Siting expert GIS (Kao *et al.*, 1996).

As the content of the Internet is not quality controlled, there is a role in picking out good sites from the cross section that exists. This variability of quality can be seen on list servers (*e.g.* GIS-L, SEA-GIS, NETCOAST), where communications can range from a simple request for information from a student to serious discussions on topics at the forefront of the field.

2.6 Summary

This chapter has formed a philosophical basis for the thesis, as well as an overview of coastal zone management information, expert systems, GIS and DSS applications and the role of the Internet. The rate of growth of data and information for ICZM is large, building on a huge existing base. These bases are essential, mostly the result of scientific investigation, but ways must be found to communicate the information that lies within them. Tools such as GIS and DSS may help with this, but are often too complex for general use. However, both have much analytical capability to offer the coastal zone manager, and have been successfully applied. Once data is in a digestible form, the Internet provides an effective means of dissemination and communication. Current concerns are not with access to data, but knowing where to find the data through metadata, effecting virtual integration.

Expert systems are seen as a major challenge in ICZM, though its application in the discipline has been limited. With major advances in the magnitude and speed of computing resources, there is potential for widespread use of such technology. Moving away from conventional rule-based systems to object-orientation breaks away from the conventional "if-then" structure, allowing the separation of the inference engine and knowledge base to be explored. Finally, error handling is important when dealing with system output.

The next chapter shows how the information covered in Chapter 2 translates into expert system design.

3. METHODOLOGY: PRINCIPLES OF DESIGN

3.1 Introduction

A need for large-scale information management in CZM can be met by the computing resources that we currently have. An expert system is one of those resources. The literature review has both highlighted expert system potential in CZM and described methods through which such an entity can be built in practice. This chapter takes the latter line and outlines the processes and components of COAMES, stressing its unique and novel design as a response to the information needs of the coastal zone manager.

3.2 The Conceptual Design of COAMES

COAMES (Coastal Zone Management Expert System) is an object-oriented expert system (Figure 3.1), consisting of a user interface, a database, an object-oriented knowledge base (incorporating both the expert's factual knowledge and the process knowledge embodied in models) and most importantly an inference engine (Moore *et al.*, 1996). Models are one of four groups of functions, the others being data functions, rule functions and toolbox functions. Within the inference engine are algorithms to calculate belief through the Dempster-Shafer Theory of Evidence.

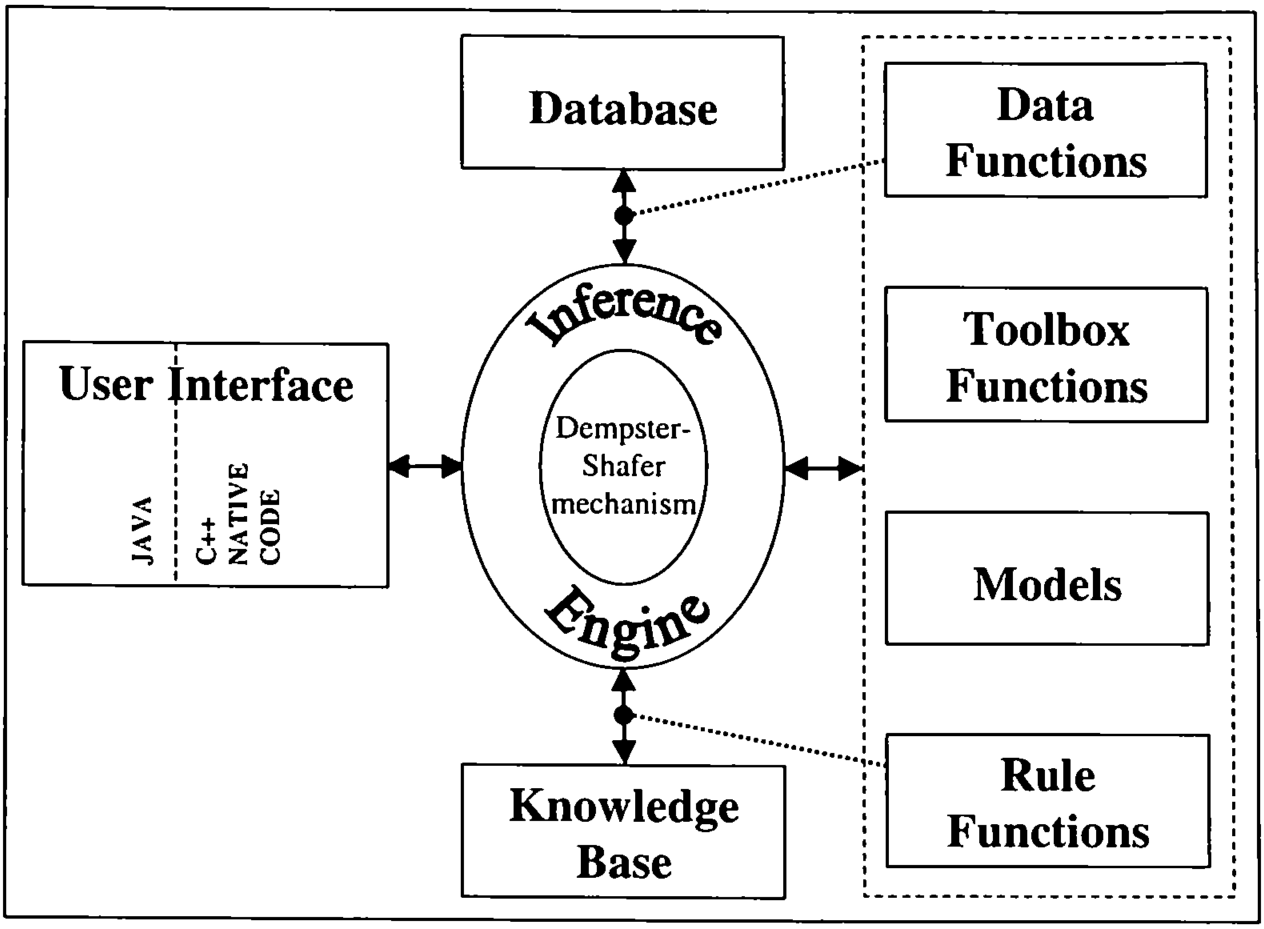


Figure 3.1: The configuration of COAMES containing the major components: user interface, database, functions, knowledge base and inference engine.

The object-oriented paradigm (Section 2.3.5) remedies some of the shortfalls that have been noticed in rule-based knowledge bases. In these cases, the knowledge base and inference engine have been observed as being closely entwined (*i.e.* the action is the task of the inference engine). Openshaw and Openshaw (1997) state that to some extent the use of the words "expert system" to describe the series of IF-THEN statements that occur in this case results from AI hype and exaggeration. However, in COAMES, the knowledge base is not so 'hard-wired' into the system, as it may need to be modified to meet specific demands. This is best done as a separate entity in what is known as a modular approach (Shortliffe, 1976). Rules can be arranged as a hierarchy of objects. The knowledge base is called upon by the inference engine 'Does this rule apply?' 'This one?' etc. until a rule is found that satisfies the operative words and the derived data. This is then repeated for the next tier in the hierarchical object structure. At this stage no action is taken on the rules - appropriate action is implemented by the inference engine once the levels in the hierarchy have been traversed (Moore *et al.*, 1996). This separation and modular approach is used by Davis *et al.* (1989). Rizzoli and Young (1997) advocate a similar method for decision support systems, in the separation of data from models.

3.3 Hardware and Software

For the user interface, the central software should be potentially accessible via the World Wide Web, making full use of this network. This suggests that the ideal language to program in would be the platform-independent Java, which has been the subject of much interest in recent times. Java is an object-oriented language, heavily influenced by C++ and Smalltalk, other object-oriented languages. Through simple modular and maintainable programs, Java has been used in the main to support applications on the World Wide Web, due to its machine independence and tight security (Davis, 1996).

This makes Java the interface language of choice, although in practice no use has been made of platform independence to ensure linkage with the expert system code, for reasons explained in the discussion.

The decision to choose C++ as the programming language for the central expert system was due to the compatibility of its object orientation with the way that humans think, and therefore the way that an expert system works. It was also a decision based on a familiarity with, and speed of the language. The C++ language was developed from C, and first reported in 1986. It was designed to be compatible with C (a backward compatibility) but also allow object-oriented programming, making it a hybrid language (Ammeraal, 1995).

The C++ expert system code is in the form of a Dynamic Link Library (DLL), and is accessed by Java as a native method. A native method is one implemented in another programming language. Reasons for using native code (as opposed to converting any existing code to Java) include already having access to a substantial library or application in another language, and having to use code that takes a lot of time to run. Both of these reasons apply to COAMES – there was legacy C++ expert system code, which would be most effective remaining in the faster C++ form for linkage to the expert system. Through native methods, both the native language side and Java side of an application can create, modify, access and share Java objects. The native language can call Java methods, passing parameters and accepting returned data (Stearns, 2001). This is most important for exchange of dialogue between user and expert system, and passing expert system output for display.

Another choice was whether to program the expert system, or populate an expert system shell with application-specific rules. After experimentation with one such shell, a decision was made to program the expert system, to allow greater flexibility for the applications covered by this thesis. As explained earlier, the inference engine / knowledge base separation approach makes for a modular program, where individual elements such as the inference engine and knowledge base are closely entwined (there is greater discussion of expert system shells in section 6.5.3).

An initial consideration was the use of the UNIX operating system, which has C (a procedural language) as standard. C++ grew out of C, and is closely related, being easily accessible through UNIX workstations. The rationale for initially using UNIX workstations was also one of convenience and speed. However, taking the increase in speed and capacity recently experienced by PCs, and the user-friendly programming environments (e.g. Microsoft Visual C++ 6.0, Sun Java Development Kit 1.3 fronted by a programming editor) into account, the expert system was transferred to a PC environment.

Finally, it is the aim that all rules and data (currently stored in ASCII files) will eventually reside in a relational database (SQL Server, MS Access), accessible through the C++ program.

There is an overriding consideration in the choice of programming language, operating system and hardware. A high processing speed is a must, due to the computationally intensive workings of the inference engine and the large amount of knowledge and data that the expert system may have to handle. The latter in itself is also a pre-requisite for high capacity.

3.4 User Interface

This is the program front-end through which the user can pose a scenario or query. An initial user input is put through a process that extracts words based on comparison with lists of terms (forming the dictionary, or lexicon) contained within classes (see section 3.5) such as 'Landform' (landform-specific terms such as 'cliff', 'beach' etc), 'Action' (action terms such as 'display raster', 'overlay' etc) and category terms (terms linked to categories such as 'physical', 'chemical' etc). In the words of Fischer (1994a), the user interface translates the query from the user into a form that the inference engine can understand.

3.4.1 Non-Graphical User Interface

In the case study of Holderness described in Chapter 4, a query could read "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 (Section 3.5), in this case based on the topology between beach features shown in Figure 4.3. This interaction will develop into the envisaged dialogue between the coastal zone manager and the system. The expert system returns output in the form of data, which can be subsequently manipulated and displayed by the user through the appropriate software.

Should there not be such a key word present in the initial query then the system will prompt the user to provide more information, and so on until a key word has been provided.

The set of rules in the expert system knowledge base relating to the object "ord" have been derived from personal communication (Pringle, pers. comm.), a paper on the subject (Pringle 1985), and a related thesis (Scott, 1976); the rules are set out in a hierarchical fashion, expressing the topology of beach features in a typical ord.

The user interface described above has been superseded by a Java Graphical User Interface (GUI), which can access the data, metadata and knowledge behind the case studies described in both Chapters 4 and 5[1]. The GUI is described in detail in the next section.

3.4.2 Java Graphical User Interface (see Appendix D for code).

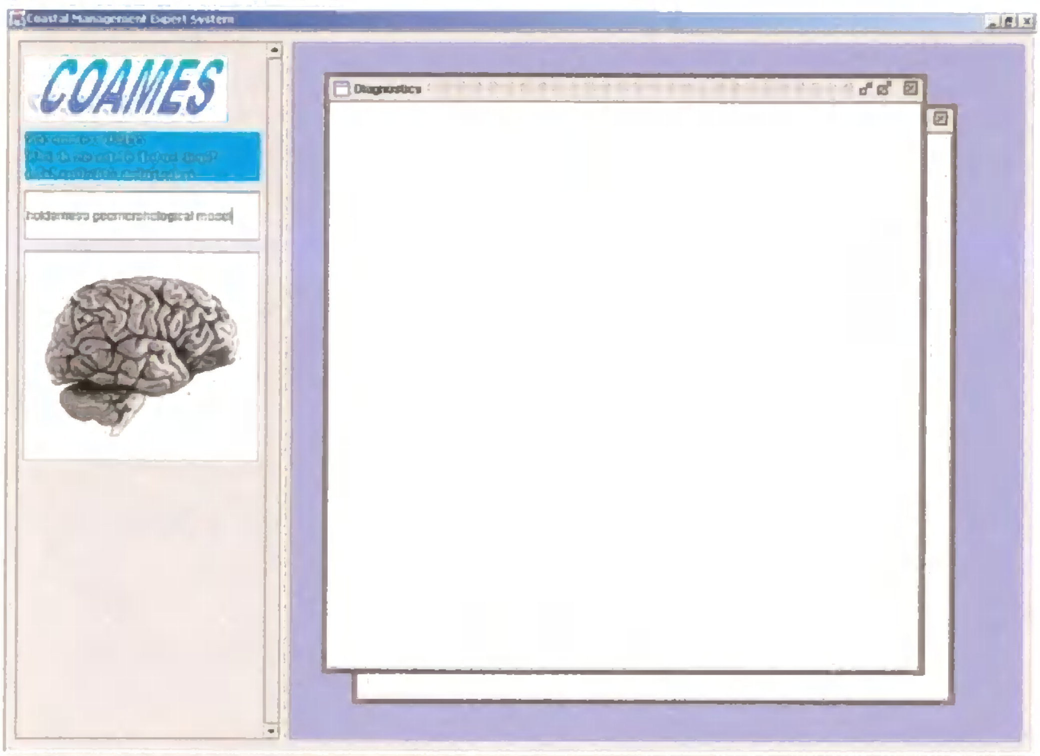


Figure 3.2: The basic GUI with the dialogue partition on the left and the display partition on the right.

[1] Avouris and Finotti (1993) promote a graphical dialogue, especially to deal with spatial concepts.

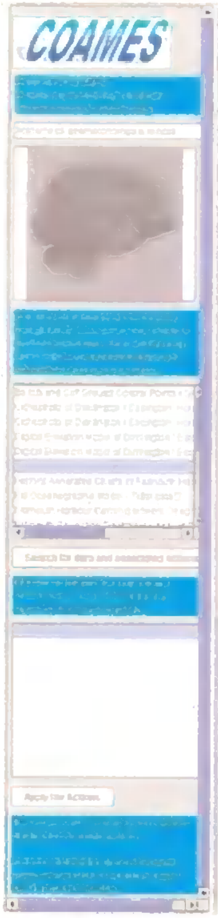
The COAMES user interface in its initial state is shown in Figure 3.2. It has been constructed in the Java programming language (more specifically using the most recent Java GUI classes, called Swing) and accesses the C++ expert system code as a series of native functions.

In multimedia terminology, the GUI is termed an Interactive Multimedia Document (IMD). The IMD comprises actors (objects such as buttons, text, images), events (user interaction primitives that result in a change of state for the actor) and scenario tuples (defines what actions happen, when they happen and in what order) (Vazirgiannis, 1999).

The form of the COAMES interface can be divided into two parts: **dialogue**, through which the user responds to expert system output in the form of written queries and lists, and **display**, where the diagnostic information, metadata and output data are displayed. Given that the focus of the thesis is in the application and expert system workings, the interface is purely functional. However, it does try to capture what is important in the expert system process: adequate explanation to the user and decision support output presented in a useful form.

The Dialogue Interface

The dialogue interface occupies a strip of area on the left-hand side of the application and is scrollable so that successive iterations of dialogue can be shown vertically one after the other (Figure 3.3).



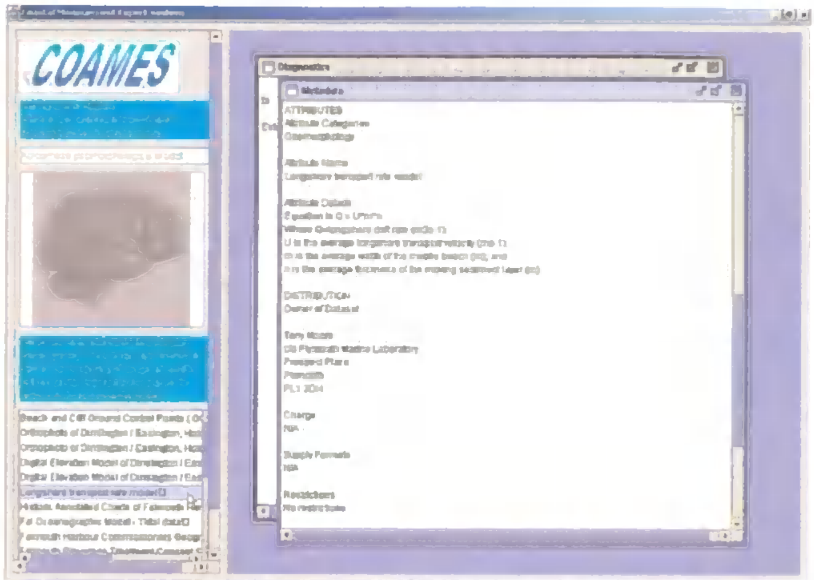


Figure 3.3: The dialogue partition shown in its entirety (left)

Figure 3.4: The metadata for "Longshore Transport Rate Model" is shown as a result of clicking the relevant list entry.

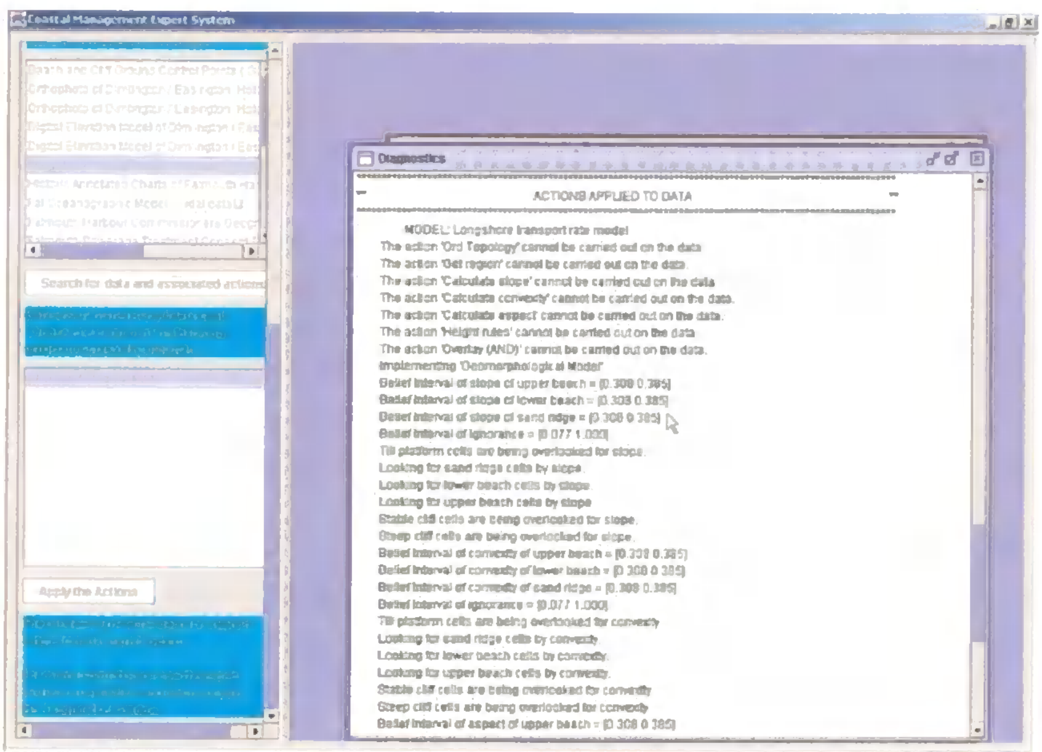


Figure 3.5: The display partition, showing the diagnostics window with details on inferencing through the action rules. The list of possible actions in the dialogue section is shown as a result of selecting the "Longshore Transport Rate Model" entry in the metadata list.

Below some introductory labels, there is a text box into which the user can type a query. Once the query has been worded to the user's satisfaction (the query need only contain the key words), the button is pressed and the query string is passed to the expert system. Once processed, the titles of metadata sets that match or approximate to the query are shown in a scrollable list. The user can click on a list entry to view the metadata in one of the display windows (Figure 3.4). Having perused the metadata, one or more metadata sets of interest can be selected from the list and passed to the expert system for processing. What comes back is a list of possible actions that can be applied to the data stored behind the metadata (if any) – Figure 3.5. The user can select one or more of these actions from the list and send this information to the C++ native code, which will then implement the actions (if possible) and return with the relevant outputs displayed in the other partition.

The Display Interface

The display interface occupies the right-hand side of the application (*e.g.* Figure 3.5). The initial set-up in Figure 3.2 shows two empty windows: a diagnostics window and a metadata window. The diagnostics window is updated with rule and associated belief information on each passing to and from the expert system code (see Figure 3.6 for metadata rule diagnostics). The metadata window is used as described in the previous section (Figure 3.4). In Java Swing terminology they, and any other output window, are internal frames, so they can be minimized, maximised or switched off if desired.

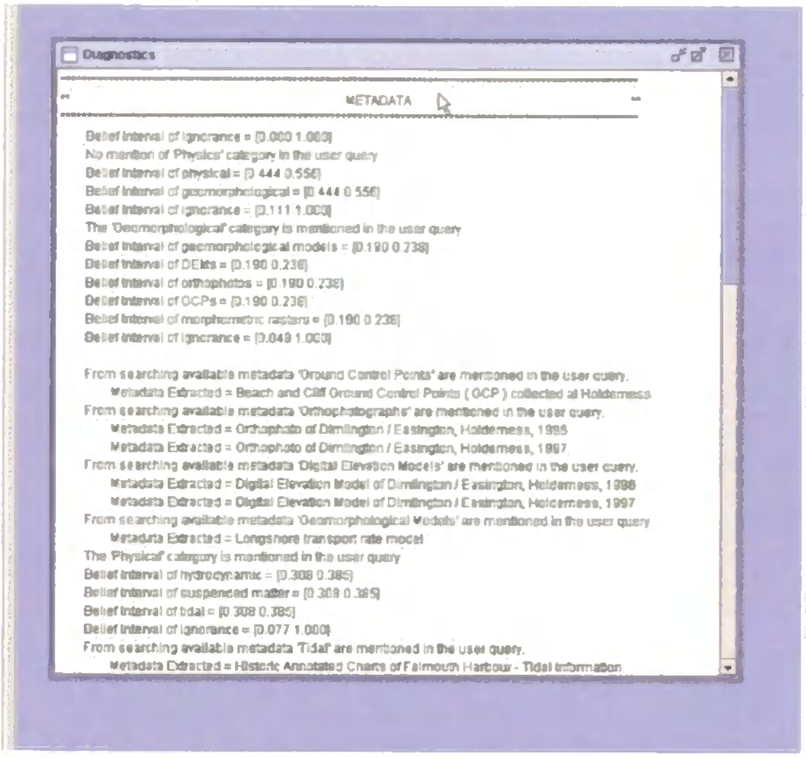


Figure 3.6: Example diagnostics output for metadata.

Any one of four output types may be passed into the interface by the expert system. The first two are output derived from raster data, such as Digital Elevation Models and associated morphometric measures, and background raster output, such as orthophotographs, which provide context. Next, there is vector point data, such as ground control points. Vector and raster data can be displayed on top of a background raster, and a scale bar provides further spatial context for all three types described above. The last type of data output is textual information, such as the Longshore Transport Rate Model result. Visual examples of each data type can be found in section 3.8.

3.5 The Hierarchical Knowledge Structure

COAMES is underlain by an object-oriented knowledge structure (Section 2.3.5), where modelling is performed through the functions and attributes belonging to objects in reality (called classification – Worboys, 1994). For example, objects may contain geomorphological rules and are classified within the prototype domain. Figure 3.7 shows the form of the class structure of the COAMES prototype described in Chapters 4 and 5. For example, 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 broken line reveals another class from which inheritance is derived (multiple inheritance), the raster class. This reflects an inherent 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.

Taking the example further, the rules contained within the object define their interrelationships with other constituents of the ord and their morphometric properties. For instance, in the example outlined in Chapter 4, 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).

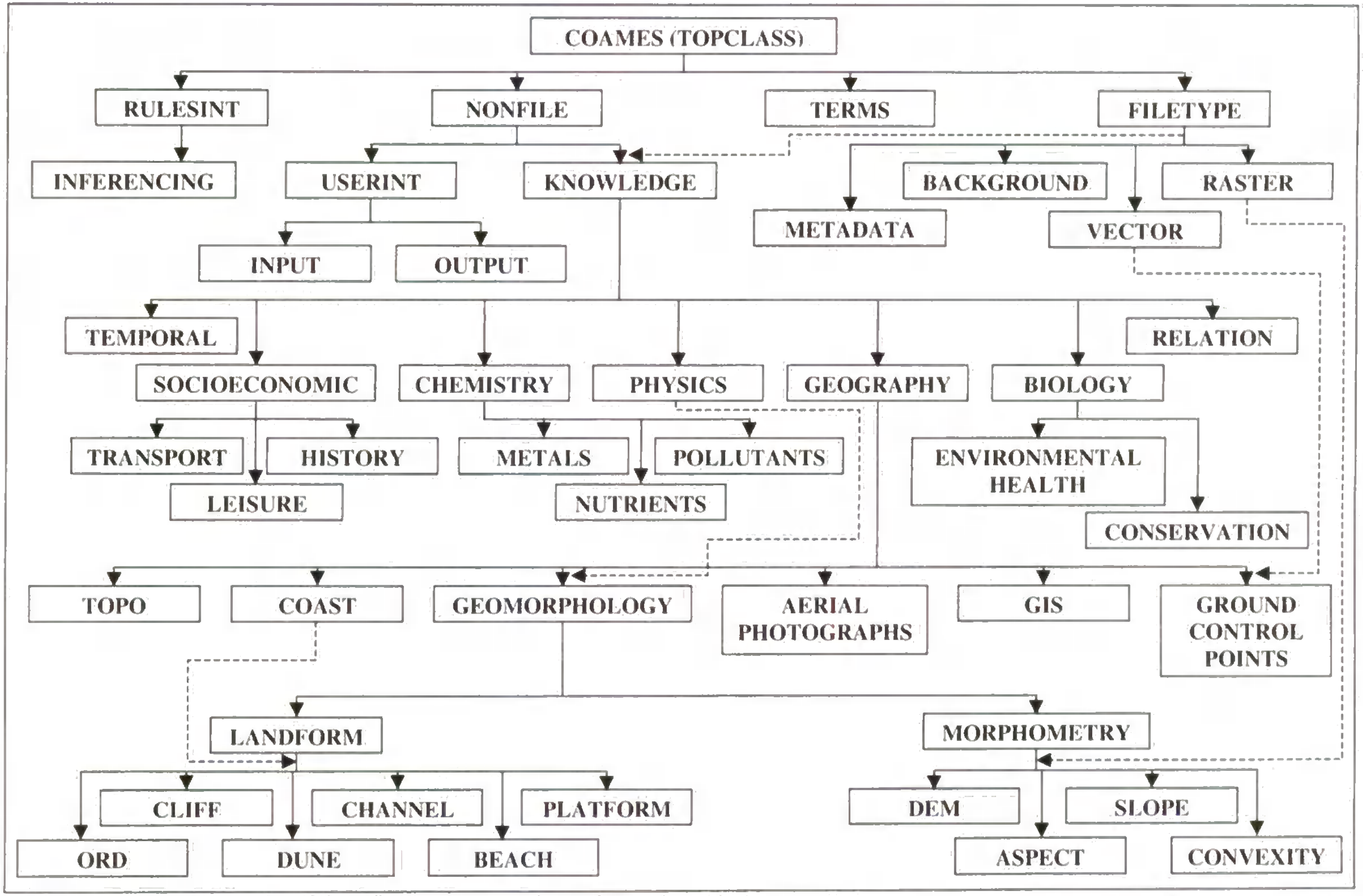


Figure 3.7: The object-oriented hierarchical structure of knowledge and data in the prototype (multiple inheritance links are dashed).

Figure 3.7 represents an overview of all classes in the COAMES system prototype, using a hierarchical notation. However, there are other notations that are much more semantically rich. Such notations should provide unambiguous communication, and should be standardized so that software engineers anywhere will be able to understand it. This would enable the automation of the more tedious tasks in software design and provide more time to work on more advanced problems (Booch, 1994). The most commonly used notation is that put forward by Booch (1994) (see Wachowicz and Healey, 1994; Raper and Livingstone, 1995; Lilburne *et al*, 1996); an example is given in Figure 3.8 using a subset of COAMES' classes. This selective view-based approach is necessary in the Booch notation as there is too much detail in the class members to lay out all classes in their entirety.

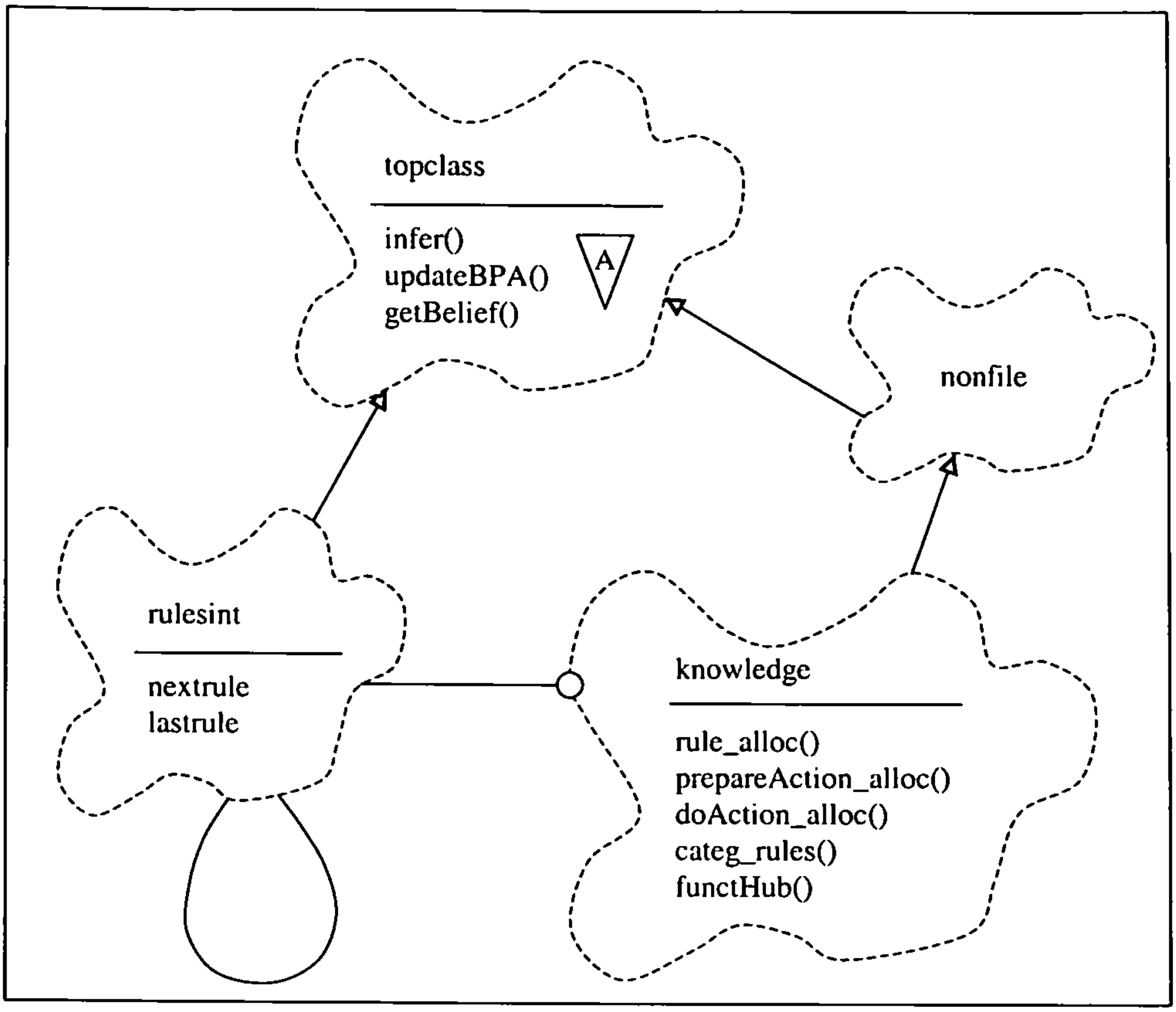


Figure 3.8: A 'view' of some important top-level COAMES classes rendered in Booch notation. See text for explanation. See also Figure 3.15 for the rulesint branch in more detail.

The top level classes shown deal with rules and are central to COAMES' operation. Each class is represented in a Booch "cloud" (with a dashed line; a solid line signifies an object as opposed to a class); the name of the class being separated from the class attributes and operations by a horizontal line. This form of notation only displays important class members, which implies a process of selection (*e.g.* the topclass class actually has eight operations). The inverted triangle indicates that topclass is an abstract class, whose functions can only be accessed by the classes that inherit from it, rulesint and nonfile (inheritance is denoted by the arrows). The class knowledge uses the rulesint class: this is signified by the connecting line with a circle attached to the user class. Finally, the loop attached to rulesint indicates a reflexive association (where a class has an association with itself), pointing to the occurrence of a chain of rule instances, linked together by the attributes nextrule and lastrule.

3.6 Models

Models can be seen as 'engines' for anticipating alternative environmental outcomes. Modelling has formed the core of a great deal of research focusing on inherently geographical aspects of our environment. This is a good reason to link models and GIS (Parks, 1993). Reciprocally, the role of models as 'engines' for anticipating alternate environmental outcomes should not be forgotten. Fedra (1996) regards models as a separate entity in itself - a quantitative engine as opposed to the qualitative expert system.

A significant role of COAMES is to link, via the inference engine, various models - physical (*e.g.* hydrodynamic models and cliff erosion models), biological and chemical. These models themselves can be viewed as a knowledge base of processes as opposed to the largely fact-based object-oriented knowledge base. Within the expert system, geographical algorithms such as defining regions and raster processes (deriving slope, aspect and convexity from a Digital Elevation Model) 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.

Section 4.6.3 gives an account of accessing a Longshore Transport Rate Model through COAMES, making use of available data (DEMs) to calculate one of the input parameters. In addition, Appendix A details the spatial and attribute coupling of two environmental models (an experiment undertaken before the COAMES prototype was built).

3.7 Functions

Models are grouped with other actions to form one of the four categories of function used by COAMES. Referring to Figure 3.1, the other three are data functions, rule functions and toolbox functions. The vast majority of functions are declared as members in classes (termed 'operations' in section 3.5), accessible through a generic function functHub() (to enable access from function information stored within a rule instance – see section 3.10) via the appropriate wrapper. Wrappers are functions that merely serve as a buffer between the function as accessed through functHub and a C++ #define macro that enables the assignation of a pointer (a variable containing the address in computer memory of an item of data) to a class member function without error (see Cline, 2001).

3.7.1 Models and Other Actions

The functions corresponding to models and other actions can be divided on the basis of data type and to a lesser extent type of output. Firstly, there are the models themselves, which do not adhere to any particular data type. However, at the current stage in COAMES' development, models (specifically the Longshore Transport Rate Model) use raster data and only display text output. The second category contains actions on raster data, such as classifying rasters through rules based on ranges of slope, aspect, convexity and height. Overlaying (AND or OR) two or more rasters and displaying rasters are two other actions in this category. Related to raster data actions are actions on background rasters (the third category), of which there is one – display. The final category relates to actions on vectors, including display, calculate Minimum Bounding Rectangle and applying ord topology rules to extract points. (See Appendix C for more information on how actions can be accessed through the system).

3.7.2 Rule, Data and Toolbox Functions

Rule functions relate to operations that allocate memory to rule and Frame of Discernment (FoD – see section 3.9 for definition) structures, read in rule and FoD data from files, then load that data into the appropriate structures. Finally, there are further operations that set up rule chains and recursively pass the current rule to the inference engine.

Data functions include operations that read in dictionary terms, metadata (including vector, raster and background header data), vector data and raster data from the relevant files. Other operations include setting the display mode, initialising global raster threshold values, extracting selected points from a vector dataset and copying selected metadata into a display buffer.

Finally, toolbox functions operate the non-specific low-level tasks such as comparing strings on a non-case sensitive basis, opening files and freeing pointers to memory after use.

3.8 Data and Metadata

In considering data and metadata, it may be useful to observe what kind of role they play within the system (Figure 3.9). COAMES approaches the interplay of data (including actions performed on data), information and knowledge in an integrated manner. Metadata is taken to be a form of information, as it is a resource extracted from raw data; it has meaning in itself and gives meaning to the data. The user engages in dialogue with the system, and the input is processed by the inference engine, using knowledge to derive the relevant metadata.

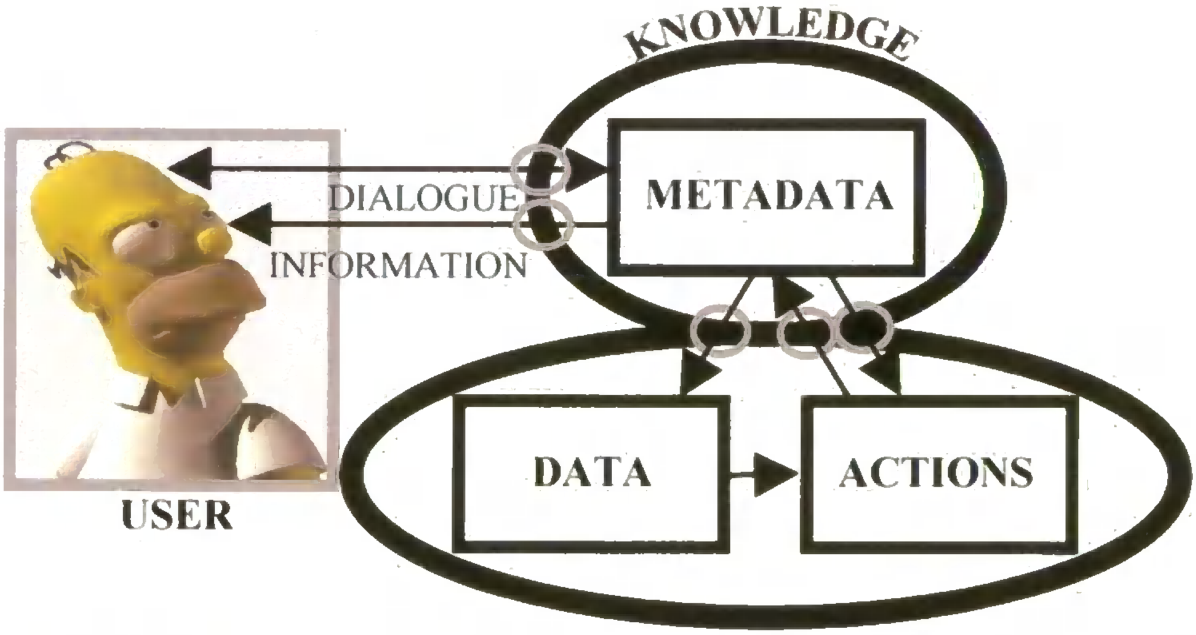


Figure 3.9: The current interplay of knowledge, information (metadata) and data in COAMES. The grey circles emphasize the role of knowledge in the system (ideally there would be use of knowledge between data and the actions applied to that data).

Metadata is seen as holding the key to the data and actions (including models) situated behind it (Ramroop and Pascoe [1999] expand the definition of metadata from "data about data" to "data about processes" [or actions]. The reason why is that with interoperability, data integration and process integration are inseparable). Knowledge is the intermediate step in this case, as well as in providing output to the user. So, knowledge has an all-encompassing role.

Data sets and metadata are and will be stored in ASCII files until such a time as they can be transferred to a relational database. This task was not implemented for the thesis as the research focus is on the inferencing and the application, not the data.

3.8.1 Metadata

Metadata is stored in the fields as set out in Table 5.1 (based on the FGDC standard – see section 2.2.5). Assuming the role as an index to the data and actions, the metadata also serves as a header, containing vector, raster and background raster information in the format field (see section 3.8.2), as well as a list of possible actions that can be performed by the expert system on the data (in the format-function field – section 3.7.1). If there is no header or action information in the metadata entry then there is no data for that entry. The metadata fields 'title', 'attribute category', 'attribute name' and 'attribute details' can be used in place of any dictionary terms (which are also stored as ASCII data) when processing the user query (see section 3.10.2 for the process).

3.8.2 Data

There are four types of data (and corresponding display modes) recognised by COAMES. Vector data are stored on CSV files, with the fields ID, description, x, y and z (see section 4.4.2 for a ground control point example). Additional fields are added upon loading: the number of points in a vector dataset and a flag to mark points selected according to some criteria. A vector display is shown in Figure 3.10.

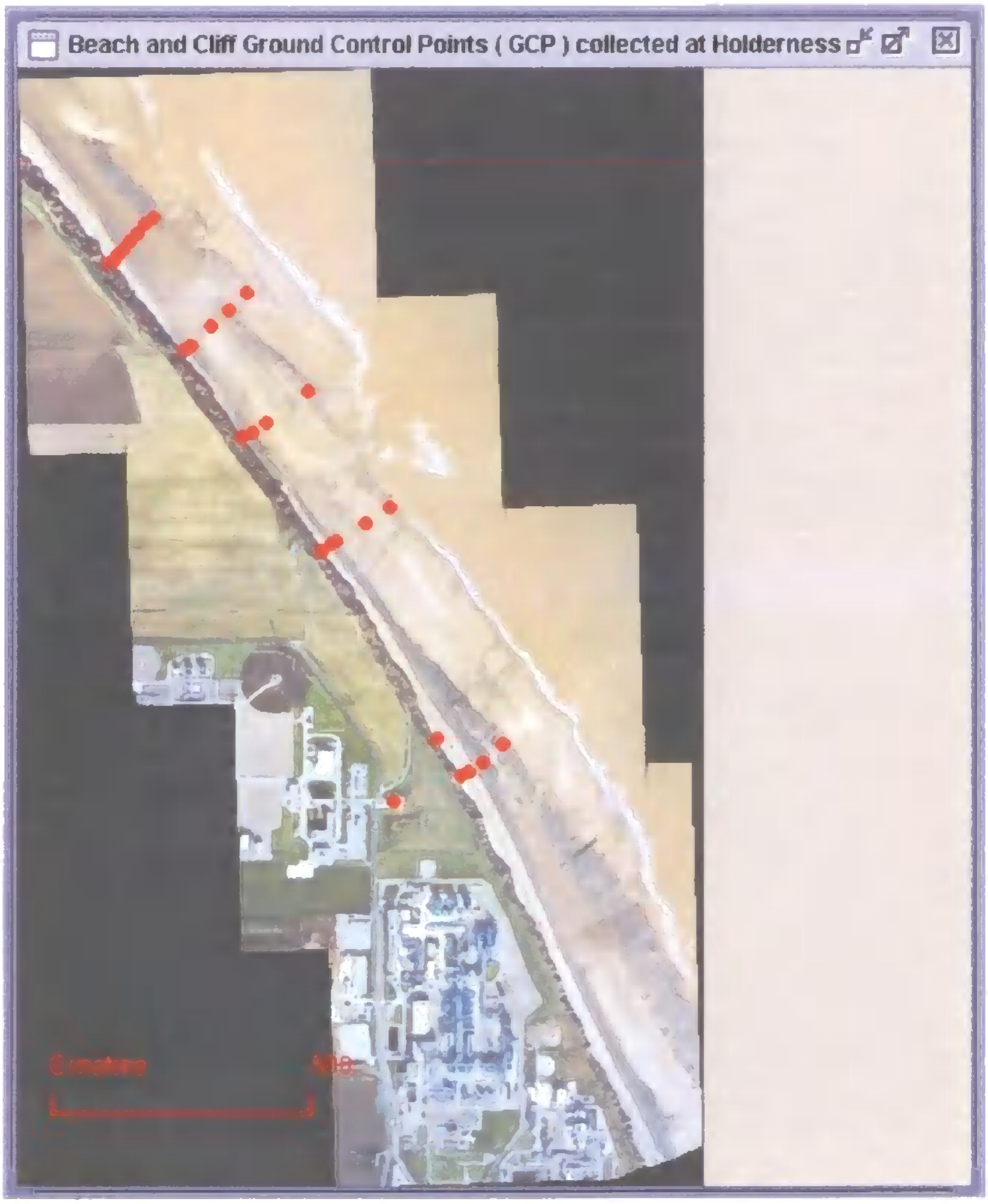


Figure 3.10: Location of Ground Control Points collected at the Holderness Coast. The vector data is superimposed on an orthophotograph.

Raster data are also stored in ASCII files, with each cellvalue separated by a space. The metadata provides essential header information such as the number of rows and columns, the lower left coordinates and the cellsize. These fields are all included in the raster data class. An example of raster data display is shown in Figure 3.11. It shows a Digital Elevation Model – other themes of rasters include derived data, namely slope, aspect and convexity maps.

Figure 3.11: Digital Elevation Model of the Dimlington / Easington region of the Holderness Coast, photogrammetrically derived from photography taken on 26th October, 1996. The raster data is superimposed on an orthophotograph.

Background raster data are stored as bitmaps (JPG format). They form a spatial context for the raster and vector datasets – COAMES uses orthophotographs to relate the stored data to objects on the ground (Figure 3.12). Metadata header information includes the top right and lower left coordinates, and scale. Together with the filename, this provides Java with all the information it needs to display the background with the appropriate dimensions. Incidentally, raster and vector metadata header entries also store filenames to tell COAMES where to retrieve the data.

Figure 3.12: Orthophotograph of the Dimlington / Easington region of the Holderness Coast, that serves as a background raster for raster and vector data. Derived from photography taken on 26th October 1996.

The final recognised data type is model output in textual form. Example output from the Longshore Transport Rate model is shown in Figure 4.13.

3.9 Rules and Inferencing

Before outlining the workings of the inference engine, an understanding of the inferencing mechanism used by COAMES has to be gained. The Dempster-Shafer Theory of Evidence has already been introduced in section 2.3.8. The next subsection presents the specific terminology and calculations used in this method of inferencing, working through an example. Then section 3.9.2 sets out the rule and inferencing (Frame of Discernment – see next for definition) structures, as dictated by the Dempster-Shafer method.

3.9.1 Dempster-Shafer Theory of Evidence

The working area in Dempster-Shafer theory is called the Frame of Discernment (FoD) or Θ. It is equivalent to the sample space in probability terms. The FoD contains a set of possible (mutually exclusive) answers or hypotheses aiming to resolve a question. For example (adapted from Gordon and Shortliffe, 1984), the question could be "What metals are polluting this estuary?". In response, the FoD may be $\Theta = \{iron, nickel, lead, mercury\}$. Furthermore, any subset of this FoD is a hypothesis.

e.g. hypothesis of heavy metals $= \{lead, mercury\}$

hypothesis of ferromagnetic metals $= \{iron, nickel\}$

The set of all hypotheses represented by a FoD is 2^{Θ}. If a FoD has four elements, as above, then the number of hypotheses $= 2^4 = 16$.

The hypotheses are represented in Figure 3.13.

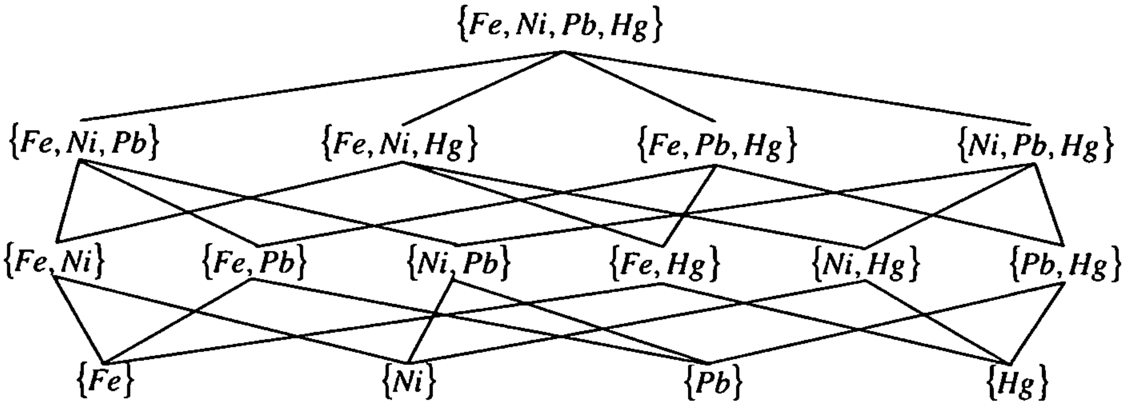


Figure 3.13: The hypotheses used for a four-member frame of discernment, consisting of the metals iron, nickel, lead and mercury.

The sixteenth subset is represented by the empty set $\varnothing$, which corresponds to a hypothesis that is known to be false. Out of these subsets, only some may be important, as shown in Figure 3.14, where metals are classified into ferromagnetic and heavy.

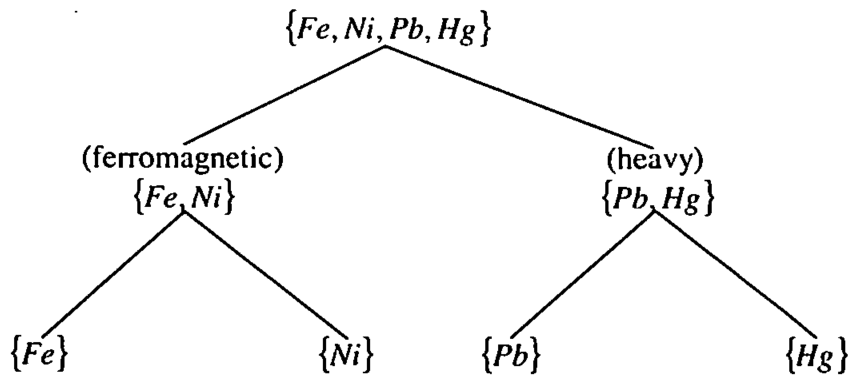


Figure 3.14: A representation of the important subsets in the four-member frame of discernment introduced in Figure 3.13.

A basic probability assignment (BPA) is given to each subset A where the BPA is represented by a mass function m and $0 \leq m \leq 1$. All m values in the FoD will add up to one. In the example above, the following values have been arbitrarily allocated:

$m(\{Fe, Ni\}) = 0.2$
$m(\{Pb, Hg\}) = 0.4$
$m(\{Fe\}) = 0.2$
$m(\{Ni\}) = 0.1$

$m(A) = 0$ for all other subsets

Any probability not assignable to any subset is grouped under $m(\Theta)$ - this is the ignorance and is not used to negate any of the hypotheses, as in probability theory. In this case, $m(\Theta) = 0.1$.

The belief function (denoted Bel) corresponds to a specific BPA, m, and is the sum of the BPAs (or beliefs) committed to a subset A (i.e. including any subsets beneath A in the hierarchy).

e.g. $Bel(\{Fe, Ni\}) = m(\{Fe, Ni\}) + m(\{Fe\}) + m(\{Ni\})$

$= 0.2 + 0.2 + 0.1 = 0.5$

Any observation against a hypothesis is viewed as evidence supporting its negation.

e.g. evidence against hypothesis $\{Fe\} \equiv$ evidence for hypotheses $\{Ni, Pb, Hg\}$

(i.e. Ni OR Pb OR Hg)

Also, $Bel(-\{Fe, Ni\}) = Bel(\{Pb, Hg\})$.

This is analogous to the calculation of posterior probability from prior and conditional probability using Bayes' theorem. Consider two pieces of independent evidence represented by BPAs m_1 and m_2. Their combined probability assignment is $m_1 \oplus m_2$, which is the orthogonal sum of m_1 and m_2, as illustrated in the following calculations. It is based on the assumption that $\sum m_1(X)m_2(Y)$ always sums to 1 (where X and Y run over all subsets of FoD Θ).

For a subset A:

$$m_1 \oplus m_2(A) = \frac{\sum_{X \cap Y = A} m_1(X)m_2(Y)}{1 - \sum_{X \cap Y = \varnothing} m_1(X)m_2(Y)}$$

The best way to effect this calculation is to draw an intersection table. Table 3.1 represents the evidence introduced as an example in the last section (m_1), and m_2 is as follows.

$m_2(\{Fe\}) = 0.8$

$m_2(\Theta) = 0.2$

$m_2(A) = 0$ for all other subsets.

m_1

m_2	$\{Fe\}$ (0.2)	$\{Ni\}$ (0.1)	$\{Fe, Ni\}$ (0.2)	$\{Pb, Hg\}$ (0.4)	Θ (0.1)
$\{Fe\}$ (0.8)	$\{Fe\}$ (0.16)	$\varnothing$ (0.08)	$\{Fe\}$ (0.16)	$\varnothing$ (0.32)	$\{Fe\}$ (0.08)
Θ (0.2)	$\{Fe\}$ (0.04)	$\{Ni\}$ (0.02)	$\{Fe, Ni\}$ (0.04)	$\{Pb, Hg\}$ (0.08)	Θ (0.02)

Table 3.1: An intersection table, combining two groups of evidence.

κ is a normalizing variable and is calculated as the sum of all values assigned to $\varnothing$.

$\kappa = 0.08 + 0.32 = 0.4$

Then the sum of evidence for each subset is divided by $(1 - \kappa)$.

$m_1 \oplus m_2(\{Fe\}) = (0.16 + 0.04 + 0.16 + 0.08)/(1 - 0.4) = 0.733$
$m_1 \oplus m_2(\{Ni\}) = (0.02)/(0.6) = 0.0333$
$m_1 \oplus m_2(\{Fe, Ni\}) = (0.04)/(0.6) = 0.0666$
$m_1 \oplus m_2(\{Pb, Hg\}) = (0.08)/(0.6) = 0.1333$
$m_1 \oplus m_2(\Theta) = (0.02)/(0.6) = 0.0333$

Example of a belief calculation:

$Bel_1 \oplus Bel_2(\{Fe, Ni\}) = m_1 \oplus m_2(\{Fe, Ni\}) + m_1 \oplus m_2(\{Fe\}) + m_1 \oplus m_2(\{Ni\})$
$= 0.733 + 0.0333 + 0.0666 = 0.833$

Belief Intervals

For a subset A, the belief interval is of the form $[Bel(A), Plaus(A)]$.

$Plaus(A)$ is the plausibility of A, where $Plaus(A) = 1 - Bel(-A)$. It is the maximum amount of belief that *could* be committed to A. $Bel(A)$ is the amount of belief *currently* committed to A. The width of this interval is a measure of the belief that neither supports nor refutes A - it is the amount of uncertainty associated with a hypothesis, given some evidence (Gordon and Shortliffe, 1984; Scheerer, 1993). The belief and plausibility have been called the lower and upper probability respectively by Dempster (1967).

3.9.2 Structure of Rules and Frames of Discernment

The structure of the original COAMES rule, as developed for the Chapter 4 case study, was shown in Box 3.1. Also, an outline of how it works in practice will be given in section 3.10.1.

```
justcliff.truerule=(int )steep_ptr; /* Next rule if true */
justcliff.falserule=(int )jcl_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 */
```

Box 3.1: The structure of the original COAMES rule, as developed for the Holderness case study.

The incorporation of the Dempster-Shafer inferencing method (and therefore uncertainty), as outlined in the last section, has meant a radical restructuring of the rule class structure (also a move to file storage), as shown in Figure 3.15. Explanation and dimensionality of the class members for the classes 'rulesint' and 'inferencing' are explained in Figure 3.16. Selected sample rules and Frames of Discernment are annotated in Appendix B for further context.

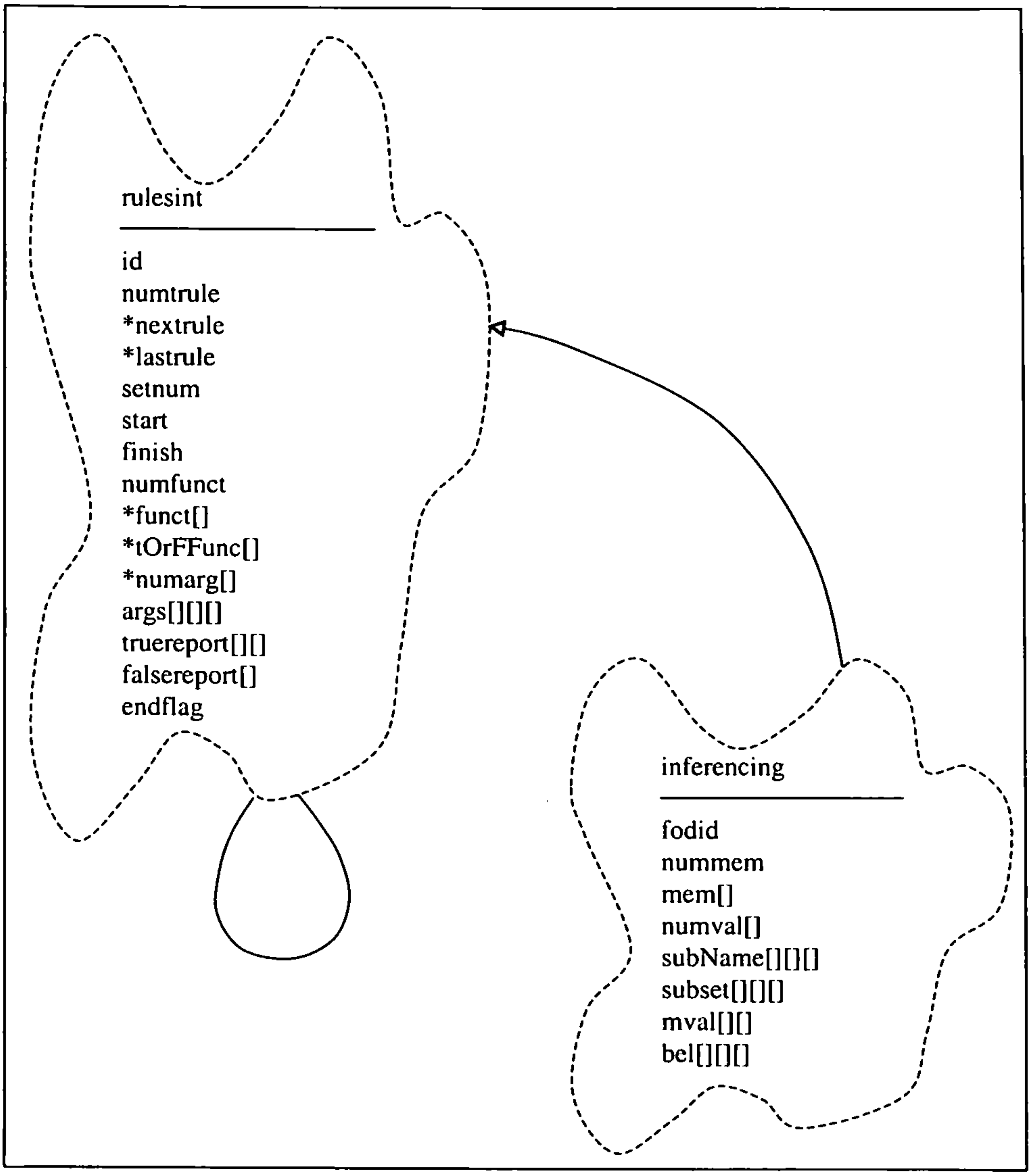


Figure 3.15: Booch-style 'view' of the rulesint and inferencing classes, showing all class members (*i.e.* the structure of the current COAMES rule). The reflexive relationship within rulesint (via nextrule and lastrule – see Figure 3.8) and inferencing inheriting from rulesint are shown. For explanation of the attributes see Figure 3.16 and the text.

ID	Number of true rules	Next rule	Last rule	Set number	Start	Finish	Number of functions	Function codes	Function: True or False	Number of Function Arguments	Function Argument Codes	True Report	False Report	Endflag
a	t	Points to next rule in chain	Points to last rule in chain	When not used as a dictionary address, this member is used to store Frame of Discernment IDs			n	$1 \rightarrow n$ < zero = pre-process; > zero = post-process	$1 \rightarrow n$ 0 =Function started if rule is false; < 0 = true or false; > 0 = true	$m_1 \rightarrow m_n$	$1 \rightarrow n$ $1 \rightarrow m$	$1 \rightarrow t$		0 = normal 1 = end 98 = function 99 = metadata

Frame of Discernment (FoD) ID	Number of members (rules) in FoD	Member Codes	Number of belief values per member	Names of each item for which there is belief	Codes of members constituting belief items	Basic Probability Assignments (BPAs or mvals)	Belief Intervals
b	n	$1 \rightarrow n$	$m_1 \rightarrow m_n$	$1 \rightarrow n$ $1 \rightarrow m$	$1 \rightarrow p$ $1 \rightarrow m$ $1 \rightarrow n$ p = number of members (this dimension is extracted from strings)	$1 \rightarrow n$ $1 \rightarrow m$	$1 \rightarrow q$ $1 \rightarrow m$ $1 \rightarrow n$ Where q = 2 (upper and lower limits)

Figure 3.16: Explanations and dimensionality for each of the class members in the classes (a) 'rulesint' and (b) 'inferencing'.

Tackling the 'rulesint' class first, each rule (which forms part of a rule chain) has a unique identifier ('ID') within their own FoD. The 'number of true rules' (t) really relates to the number of function groups that can be implemented if the rule is proven true. In practice, there is only need for two such groups (*i.e.* t=2) – the second group consists of actions implemented when the action rule hierarchy is descended for the second time (see 3.10.2). The 'next rule' and 'last rule' refer to pointers to the next and previous rules in the rule chain respectively, forming a double-linked list (Oualline, 1992). The 'set number' is used initially as a data file address (to an element within an array of data files), then later on as a store of which FoD ID the rule comes from. The 'start' and 'finish' members refer to the address range within a set of dictionary terms (the code of which is indicated by 'set number').

The 'number of functions' (n) able to be accessed through a rule can be of various kinds. The functions themselves (to be read through the function hub functHub()) are indicated by an array of n codes. If the code is negative, then it is implemented before the evidence gathering takes place; if the code is positive, then the function is started after the evidence has been gathered. In the latter case, the 'Function: true or false' class member must be used. The value stored here will be zero if the function is to be started when the rule is proved false only, less than zero if the rule is implemented in both cases, and a positive number indicated a function that is only started when the rule is proved true. The magnitude of the number in the latter case will be between 1 and t and is used to indicate which group of true functions is to be implemented. For each of the n functions the 'number of arguments' (m) must be set. For example, the value m_1 indicates the number of arguments for the first function, and so on until m_n, the number of arguments for the n^{th} function. The next member is a 2D array consisting of the 'function arguments' themselves, the size of which is delimited by n and m. These arguments may be in number (floating point and integer) and string forms. For each of t groups of 'true' rules there are corresponding 'true reports', information that will be inform the user of expert system progress. The same applies to the 'false report' if the rule is proved false. Finally, the 'endflag' indicates the end of a chain of rules (a value of one). Otherwise, this class member may have a value of zero if the rule employs comparison with dictionary terms, a value of 99 if the comparison is with metadata, or 98 if the rule concerns actions.

The 'inferencing' class has eight members and inherits from the 'rulesint' class (this is not inheritance in the sense of 'inferencing' being able to access all of the 'rulesint' members, but more an indication of structure – in this way the 'rulesint' members could be classified as private). An instance of this class corresponds to a Frame of Discernment (FoD), with a unique identifier ('FoD ID'). Each FoD has a 'number of members', or rules (n), and for each of these there is a 'member code', which corresponds to the rule IDs as introduced in the last paragraph. For each member, there may be a number of member subsets, or groupings for which there is belief. The number values are represented by m_1 for the first member, up to m_n for the n^{th} member. For example, inference of a member searching for evidence of iron may have three belief intervals, one for ignorance, the second for iron alone, and the third for ferromagnetic metals, a grouping of iron and nickel (which must be another FoD member). Each of these subsets are assigned names (*e.g.* "ignorance', "iron" and "ferromagnetic"), which are stored in a 2D n*m array (effectively 3D as the names are stored in 1D string arrays). Alongside the names are their respective codes. In the example, "ignorance" and "iron" will have single member codes, stored as strings.

The grouping of the "iron" and "nickel" members to form "ferromagnetic" is represented as a concatenation of the two member codes. Any two-digit codes have a zero inserted in between the two digits to avoid confusion with single-digit codes. This class member is a 3D array n*m*p, where p is the number of members in a grouping (*e.g.* for "ferromagnetic", p=2). Penultimately, for each grouping, there are Basic Probability Assignments (BPAs – 'm' in Dempster-Shafer terminology), stored in a n*m 2D array. Finally, the belief intervals for each subset of members (grouping) are stored in a 3D n*m*q array, where q is always equal to 2. This corresponds to the upper and lower probability values that form the interval (or belief and plausibility).

An account of how these classes work in practice is given in section 3.10.2.

3.10 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 (Section 2.3.4).

3.10.1 Inferencing for the Holderness Case Study

Referring to the Chapter 4 case study as an example, the structure for the rule 'justcliff' (enquires whether or not the object in question is a cliff in general) is displayed in Box 3.1. 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' 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 'recognise-act cycle' (see Section 2.3.4). 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 is the procedure when comparing groups of text. This process is repeated until the hierarchy has been fully descended (see Figure 3.17).

In the Chapter 4 case study, the trained hierarchy is subsequently descended again (the second part of the 'recognise-act cycle' – section 2.3.4) with the ground control point 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 ground control point in some way defines the feature to be isolated in agreement with the original query, then the associated three-dimensional co-ordinates are recorded and used to define a region. This is facilitated through a function encapsulated in the geography class (see Figure 3.7) as a model. This use of the associated topological information gives the ground control points intelligence (see Figure 3.18 for a pictorial representation of this process).

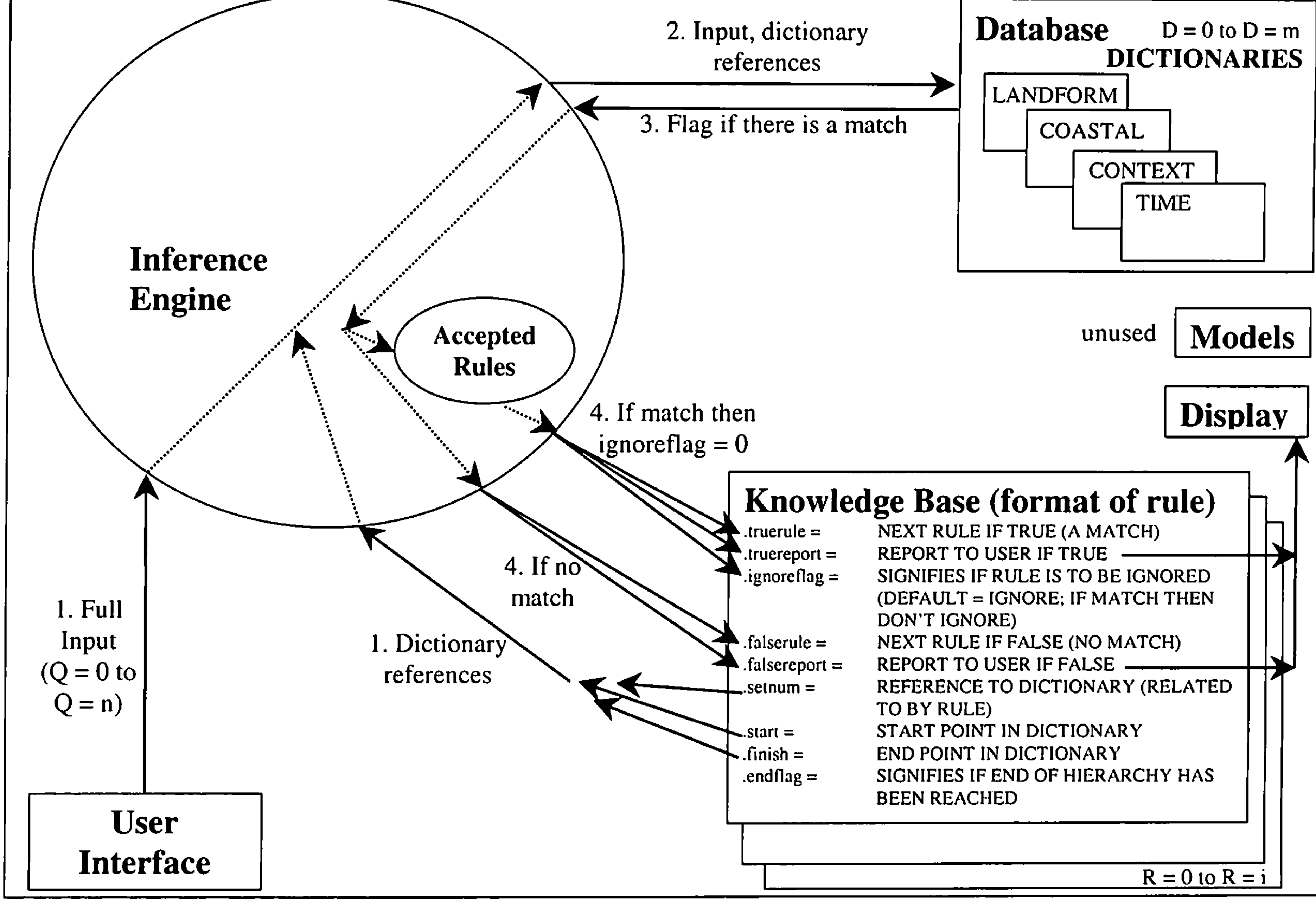


Figure 3.17: A schematic of the first stage of inference - processing the user input. {Q = a word in the input; n = number of words in the input; D = dictionary; m = number of dictionaries; R = a rule in the knowledge base; i = number of rules in the knowledge base} Based on a previous version of Figure 3.1 that separated the Display function from the User Interface.

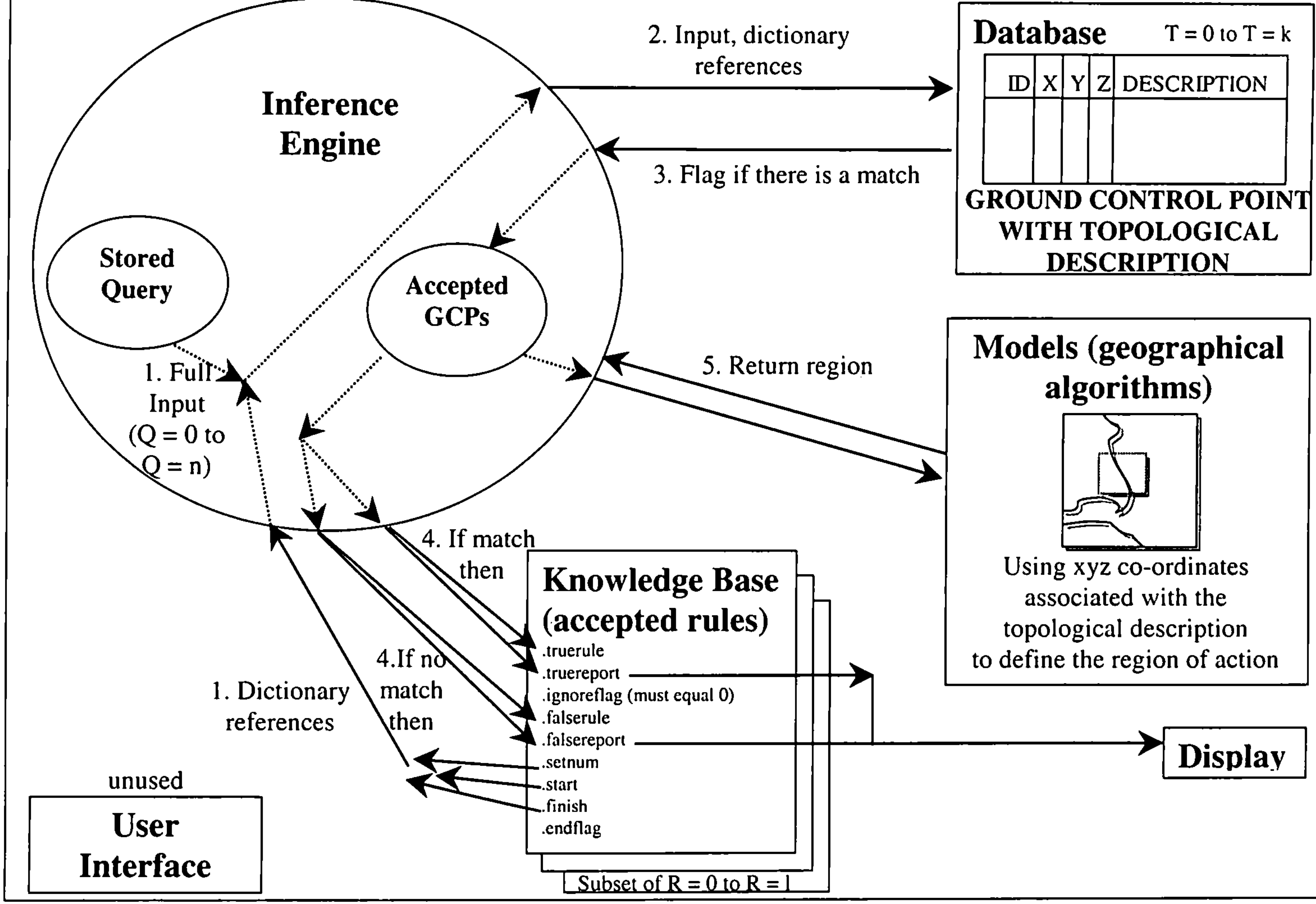


Figure 3.18: A schematic of the second stage of inference - defining the region of interest. {T = an entry in the database; k = number of entries in the database}.

All the while, the inference engine (IE) works separately from the knowledge 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; Wood, 1997) 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, of the same form as the original topological rule hierarchies (refer to Chapter 4 for more details).

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 recognise 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 degrees in terms of slope; these limits are represented in 'start' and 'finish', to be processed by the expert system (see Figure 3.19).

The above describes a single hierarchical branching system. The prototype system should be able to handle multiple branches, so that the inference engine can assess many groups or items of knowledge at the same time. In addition to modelling uncertainty, the Dempster-Shafer process, as implemented here, has the capability to work with various groups (or subsets) of rules. Section 3.10.2 describes the current inference engine process (refer also to Chapter 5).

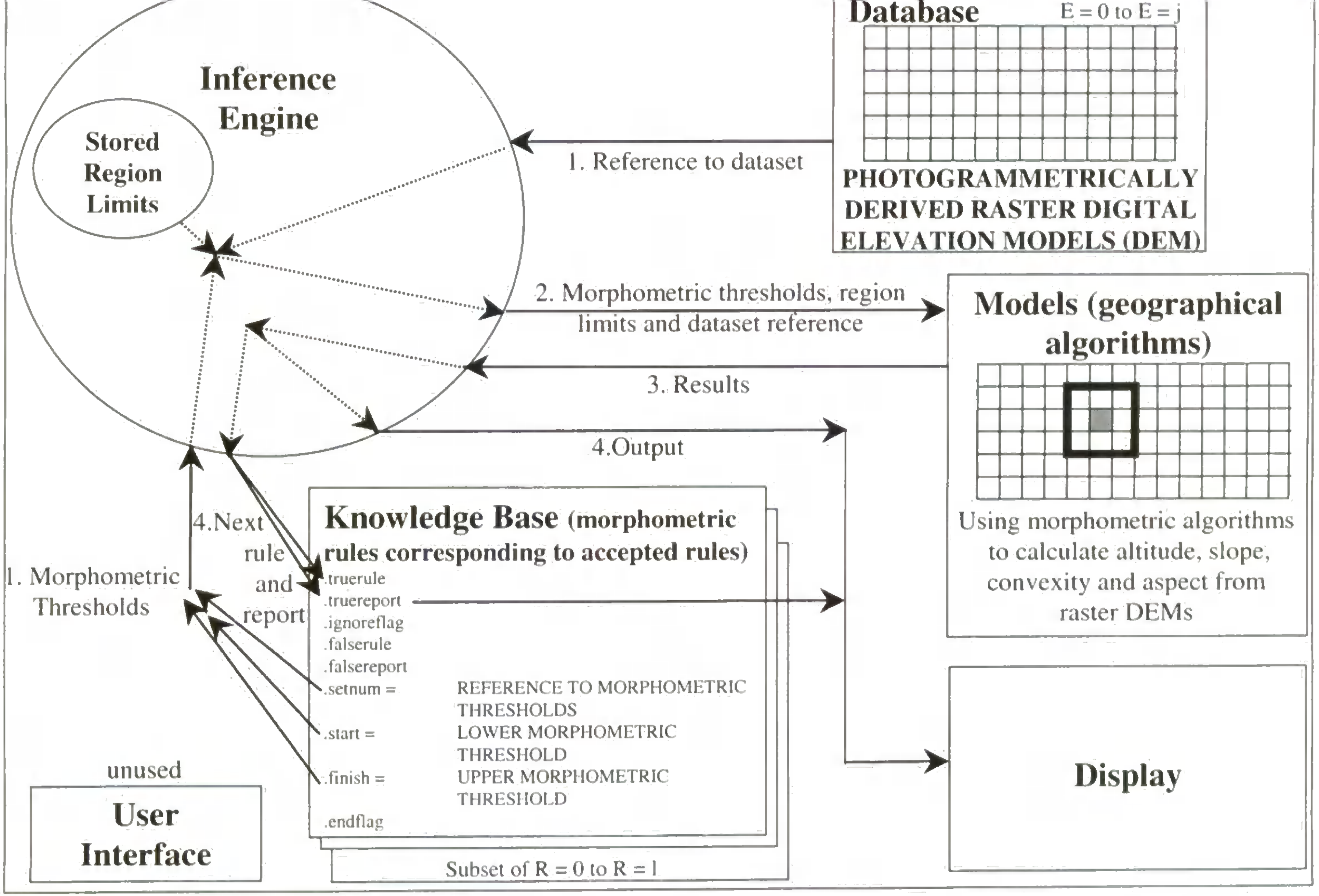


Figure 3.19: A schematic of the third stage of inference - processing for morphometry. {E = a DEM in the database; j = number of DEMs in the database}.

3.10.2 The Current Inference Engine Process

Figure 3.20 shows a graphic version of the following process, implemented for the Chapter 5 case study (though the developments of the Holderness case study can also be accessed in this way). The initial query is passed in from Java to the native (C++) function CoamesMeta (1) and broken up into the constituent words, ready for processing. The rule hierarchy for metadata is then started. The metadata (2), metadata category frames of discernment (FoD - 3) and the rules (4) are loaded into the relevant structures (as defined by classes) from files (the class members are outlined in Section 3.9.2 and Figures 3.15 / 3.16). A note is also made of the current tier in the hierarchy. The rules within the FoDs are set up (5), with a linked list of rules being formed (through the class member nextrule) and the current rule pointer being placed at the first rule in the list, ready to traverse the hierarchy.

The first rule is passed to the inference engine (6), where it enters an evidence-gathering mode. All functions that are to be invoked before the belief calculation (these are coded within the rule), such as loading dictionaries, are run at this stage (7, 8, 9). The evidence gathering itself takes the form of comparison of the user query (10) with a subset of the relevant dictionary terms (indicated by the rule's 'start' and 'finish' class members). The comparison program is accessed through the toolbox functions. If there is a match, then the Basic Probability Assignments (BPAs) for the rule are updated, taking into account any other evidence that has been found (11 - see section 3.9.1 for an in-depth discussion of the process).

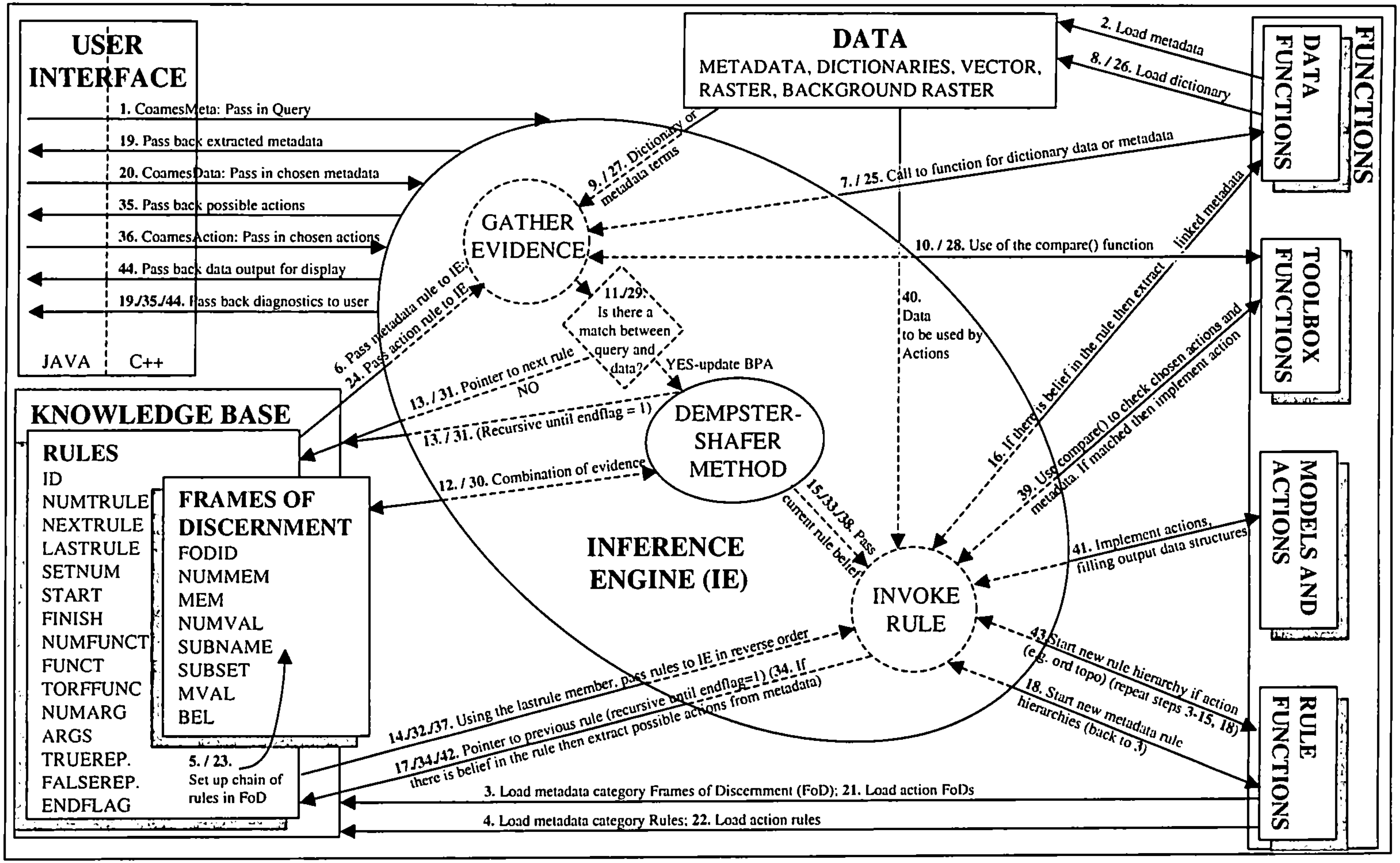


Figure 3.20: The COAMES inference process. Follow the numbered steps and refer to the text for more detail.

In practical terms, this means that two 'inferencing' class structures (*i.e.* the current one, which has accumulated the belief for all evidence found so far, and the new evidence), or more specifically the 'mval' (or BPA) class member, have to be multiplied out into a matrix. This is Dempster's rule of combination, as explained in section 3.9.1 Having derived new BPAs, the belief interval is (re)calculated for each item of evidence (object), by considering if the other items constitute evidence that is for or against the object. The ignorance is also updated through this process (12).

Whether or not there is new evidence to be considered, the inference engine sets the rule pointer to the nextrule class member (13), and therefore the next rule in the chain. The lastrule class member for the new rule is set to the rule just processed (14), indicating which branch of the hierarchy has been traversed. Any belief intervals are also copied into the diagnostics array, ready to be passed to Java when the time comes. This process of evidence gathering continues until the endrule is reached, at which time the chain of rules is traversed again, but from a reverse direction, repeatedly following the lastrule property back up to the first rule. The mode has also changed for this second traverse – all the evidence for the current FoD has been gathered, so each rule is now revisited with a view to implementing actions contained within the rule (15). Like Johnsson *et al* (1993), the expert system can work at a low level to execute single functions for an action, or work at a high level, using sequences of functions to effect an action (see example in Appendix B). The belief for each rule is compared with a threshold belief, and if greater, the functions and reports (copied into the diagnostics array) linked with the 'true' part of the rule are started (e.g. at stage 16, metadata is extracted). If less than the threshold, then their 'false' counterparts are started. Evidence for the current rule may also lie in subsets associated with other rules, so there is a check for this.

To ensure that the inference process ends once the traversal has gone forwards then backwards to the first rule, the lastrule class member for the first rule was pointed to the end rule back when the FoD was initially set up (17). The two traversals are necessary as evidence for one rule may affect another rule, so decisions made on actions to be implemented could only be made once all possible evidence had been combined.

Amongst the functions accessed through the true part of the rule are further rule hierarchies (see Chapter 5 for more details), forming three tiers of metadata themes (stage 18 marks the start of a new rule hierarchy). The first two tiers make the initial comparison between query and dictionary terms; the third tier makes the same comparison but between the query and certain metadata fields (such as title, and attribute category, name and details). If there were a match in this case, the metadata set in question would be copied into an array ready to be passed to Java for display (19).

From the first of the native functions, CoamesMeta, Java is accessed first for passing any diagnostic information, and second for passing the extracted metadata list. The indices for any metadata chosen from that list by the user are passed back into the second native function, CoamesData (20). This function is similar to CoamesMeta in that it uses the same expert system structure to infer action rules instead of metadata rules (21-34). The chosen metadata indices and the associated metadata are put into a global array, and it is the function field of the metadata (in the format category) that initially gets compared with the dictionary terms (as opposed to the user query previously - 28). This function field has a list of possible functions that the expert system can apply to the data described by the metadata. If the aforementioned data is not present the function list would be empty. See section 3.8.1 for more details. Through the two-way process of gathering evidence and implementing functions described above, the actions that are indicated by the metadata are also copied into a list to be passed to Java (35).

The actions that the user has chosen are returned in the last of the native programs, CoamesAction (36). For each of the datasets chosen (raster, background raster, vector, model text output) through a corresponding metadata entry (as described above), the action rule hierarchy is descended again, but only in 'implement function' mode as the evidence has already been gathered in the previous action run (37-43). This time the comparison is between the chosen actions and the relevant dictionary terms, and if there is a match then there is a subsequent comparison between the metadata function field and the relevant dictionary terms. This is to make sure that the action is implemented on the correct data. After the inference process, and the final diagnostics report, the output data derived from the actions are passed one-by-one to Java, where they are displayed (44).

3.11 Summary

This chapter has outlined the design of COAMES, from the inference engine at the heart of the expert system, to the knowledge, data and user input that it processes. Hardware and software specifications have also been examined.

COAMES has been designed as a direct response to the domain of coastal zone management. It is now time to apply the system to a real case study - that of the Holderness coast and the ord landform.

4. CASE STUDY: GEOMORPHOLOGICAL CHARACTERISATION ON THE HOLDERNESS COAST, EAST RIDING OF YORKSHIRE

4.1 Introduction

The first test of COAMES is the development of a prototype covering a narrow domain in coastal expertise. Here, the area of application is coastal geomorphology, specifically to characterise beach morphology on the rapidly eroding Holderness Coast, Eastern England. Multi-temporal aerial photography was photogrammetrically processed to derive Digital Elevation Models (regularly spaced grids of elevations) as input into the system. The constituent features of a composite landform (ord) were elicited and stored as expert knowledge or rules, both in terms of positional relationships and morphometric parameters (slope, aspect and convexity). The ord was chosen due to a correlation between its presence and enhanced cliff erosion, a key factor in the socio-economic environment. These rules were successfully used on consecutive Digital Elevation Models to extract a geomorphological feature and track it through time.

4.2 Geomorphological Background of the Study Area

4.2.1 Cliff Erosion

The area of study (Figure 4.1) is backed by glacial till cliffs, which are subject to a long term and rapid rate of recession estimated at 1.89m/yr (calculated as a 100 year average at Easington - Valentin, 1954). Easington is the specific area of study (Figure 4.2). More recently, Pringle (1985) measured the average seasonal recession rates at points between Easington and Withernsea from April 1979 to April 1983, giving a summer (April to October) average of 0.7m. and a winter (October to April) average of 3.4m.

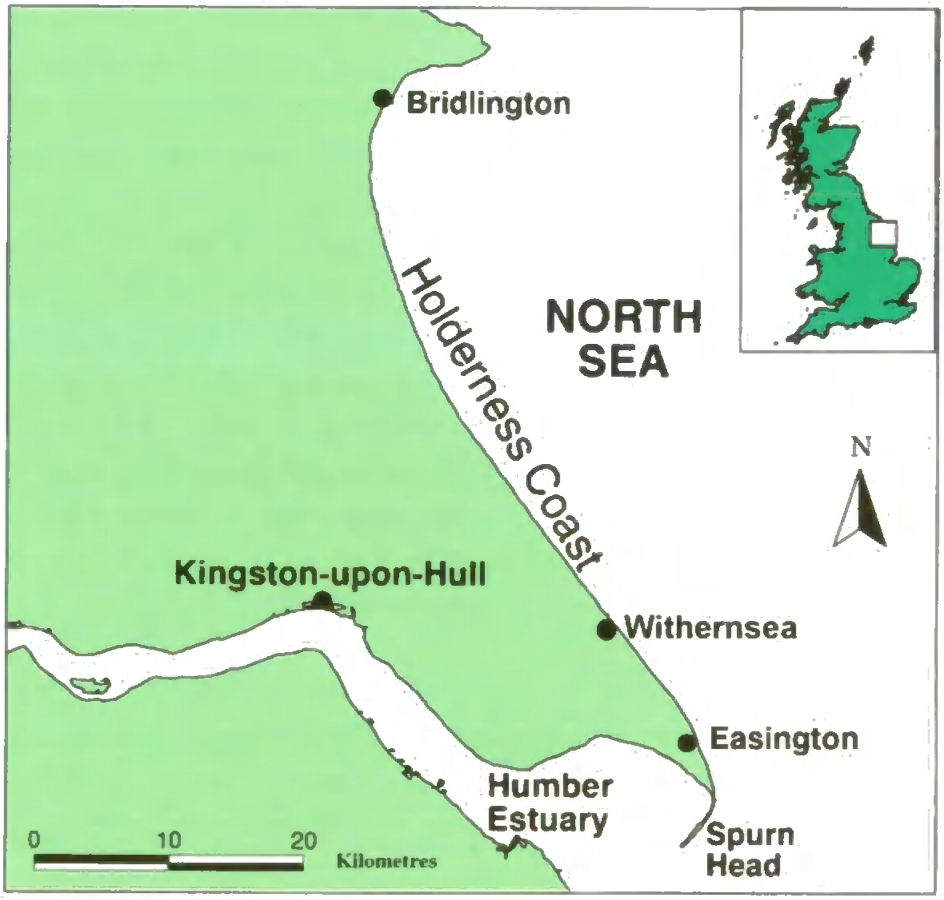


Figure 4.1: Location of the Holderness Coast.

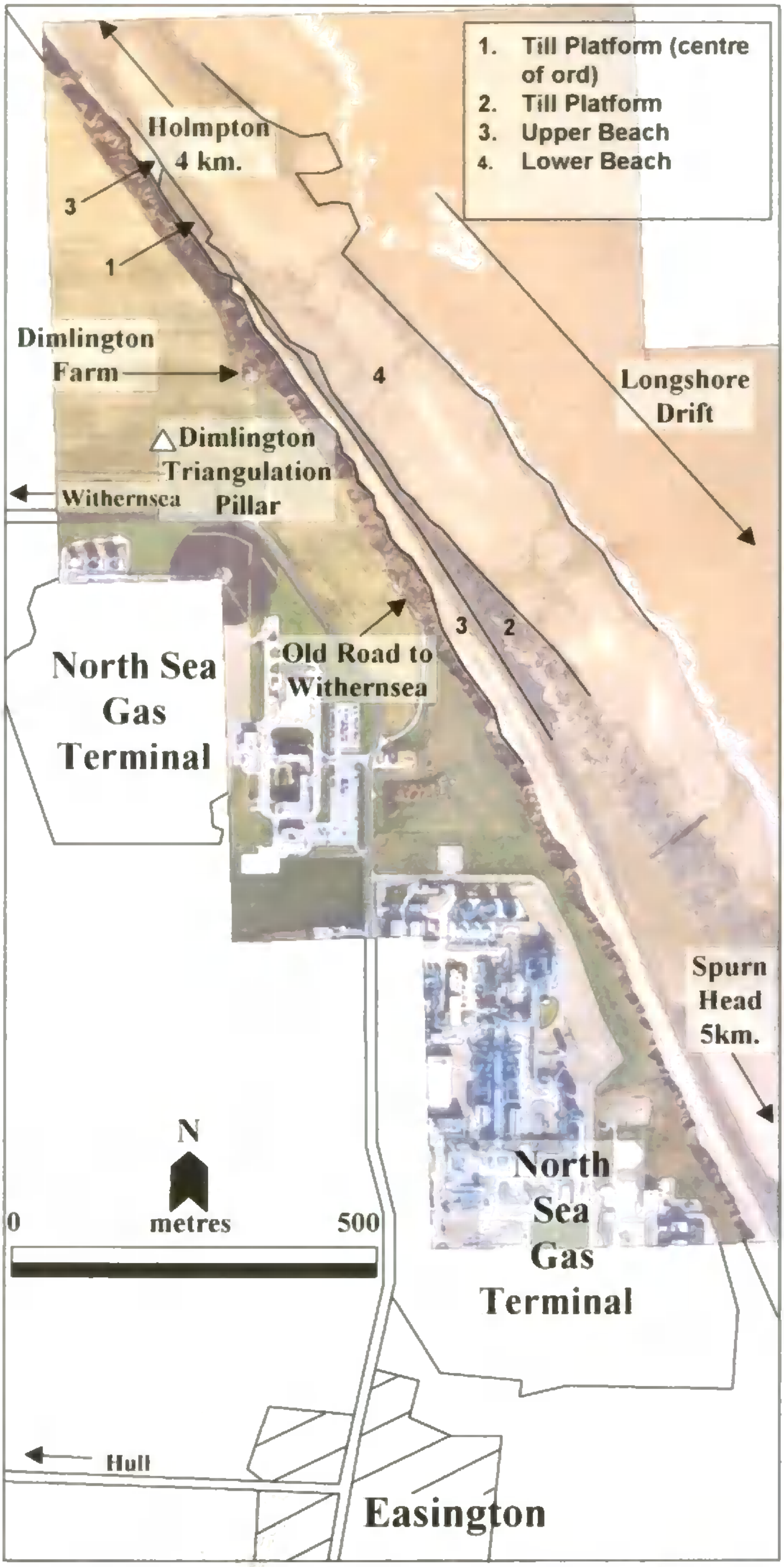


Figure 4.2: Location of the Study Area, based on an orthographic photograph derived from the 26th October 1996 sortie. (Orthographic photographs or 'photo-maps' have all perspective distortion removed so that measurements may be taken from them like a map, and yet retain the terrain detail necessary for photograph interpretation - Lillesand & Kiefer, 1979).

Where does the eroded material go? An ongoing study of Holderness coastal erosion to quantify sediment yield into the North Sea (Balson *et al.*, 1996) has observed that 3.15 – 3.9 x $10^6 m^3$ of sediment (fines) from the entire length of the coast (61.5 km) is discharged into the North Sea every year. Furthermore, this sediment is known to be transported anti-clockwise through the North Sea and possibly accreted on the coasts of Belgium and the Netherlands (Moffat, 1995). On some stretches of coast, such as that adjacent to the Wadden Sea, a rise in sea level is being matched by a rise in the level of offshore areas (de Ronde, 1994).

4.2.2 Beach Morphology and Morphometry

In general, the beach morphology in Holderness can be divided into two parts: the steeper upper beach and the lower beach, which is characterised by a gentle slope. However, there are instances where the upper beach is absent or low, exposing the till platform underneath. These upper beach gaps are at the centre of the **ord** landform (Figure 4.3).

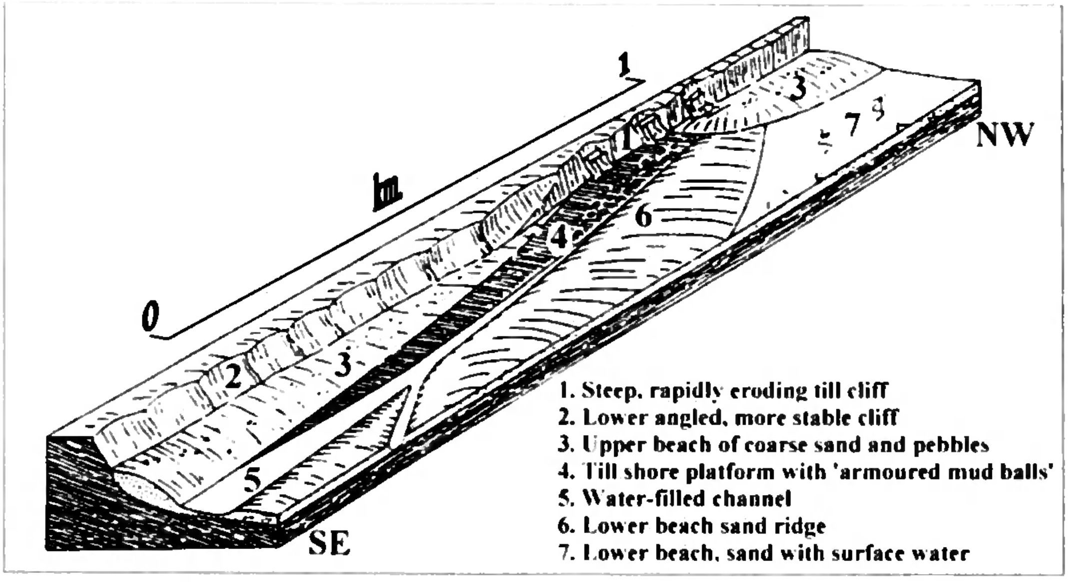


Figure 4.3: The characteristic features of a Holderness ord (from Pringle 1985). This is a composite ridge-type landform, which migrates in the direction of longshore drift. At the centre of the ord, the protective upper beach peters out to expose a lower till platform, facilitating more intensive cliff erosion.

This is a composite feature also consisting of an asymmetrical sand ridge lower beach, with a runnel (trough) separating the lower and upper beach for the most part. In this way the ord exhibits both ridge and trough features (oriented longshore).

These landforms are typically 1 to 2 km in length (Scott, 1976) and migrate in the direction of longshore drift (southeast) at an average rate of approximately 500m/yr (Pringle, 1985). Along the length of the Holderness coast (*i.e.* approximately 61.5 km.) there are usually about ten ords. Mason and Hansom (1988) refute the existence of ords, identifying small and poorly-defined till patches, which were transient on Northern Holderness. These areas of exposed till were not observed to migrate southward, and were purported to be the natural result of restricted sediment supply and prevailing wave conditions.

In terms of beach morphometry, the upper beach adjacent to the cliff foot is usually convex in profile (Pringle 1981), and slopes relatively steeply seaward. Scott's (1976) study of ords in the Holmpton – Easington area, has the upper beach slope ranging from 3.6° – 4.9° to the horizontal (Mason and Hansom [1988] identify a range of 4° - 7°). However, during constructional wave activity (associated with offshore winds), the upper beach might steepen to 10° or more. A steep upper beach may also result from very strong offshore wind conditions during which sand might be blown against the cliff-foot (Ada Pringle, pers. comm.). The lower beach has a more even and gentle overall gradient, with an asymmetric sand ridge having a gentler seaward-facing slope of 0.4° - 3.6° and a steeper landward-facing slope of 4.0° - 4.5°. The gradient of the underlying till platform was measured as 5° – 9° in a 40m-wide strip parallel and adjacent to the cliff foot, and 1° - 1.5° further seaward (Pringle, 1985).

4.2.3 Other Data

Other Holderness geomorphological data exist, but were not included in this test of COAMES. The following overview is from the reviews carried out by Valentin (1971), Pringle (1985) and Balson *et al.* (1996). It is said that reliable measurements for cliff recession date back to 1786 (Reid, 1885). Thompson (1923) carried on the study of recession, concentrating on small, specific sites. There have been numerous estimates of sediment yield, starting with Redman (1869), who estimated approximately 1.73 x $10^6 m^3/yr$ discharge, but did not take subtidal erosion into account. The following studies did include inputs from subtidal erosion and each give a figure of between 3.15 - 3.9 x $10^6 m^3/yr$ (Pickwell, 1878; Reid, 1885; Dossor, 1955; Pethick, 1994). Finally, particle size analysis and differentiation of the Holderness tills have been undertaken by Madgett (1974) - this can be used to assess how far each size fraction and each type of till (also what proportion of the total yield) can be transported and therefore where they will be deposited.

4.2.4 Ord Formation - the Effect of Longshore Drift on Beach Morphology

The process of ord movement begins with rapid longshore drift, produced by obliquely breaking storm waves, forming an oblique tongue-shaped upper beach extension consisting of coarse sand and shingle (Figure 4.4). This feature initially lies at an angle to the main beach, though parallel with the incoming waves. Over a period of a few days or weeks, the tongue moves landward and eventually forms the upper beach at the base of the cliff. At the southern end of the ord, the upper beach diminishes, exposing the till platform anew. Therefore, in this cycle there is a net movement southwards during which the overall form of the ord retains its integrity (Pringle, 1981).

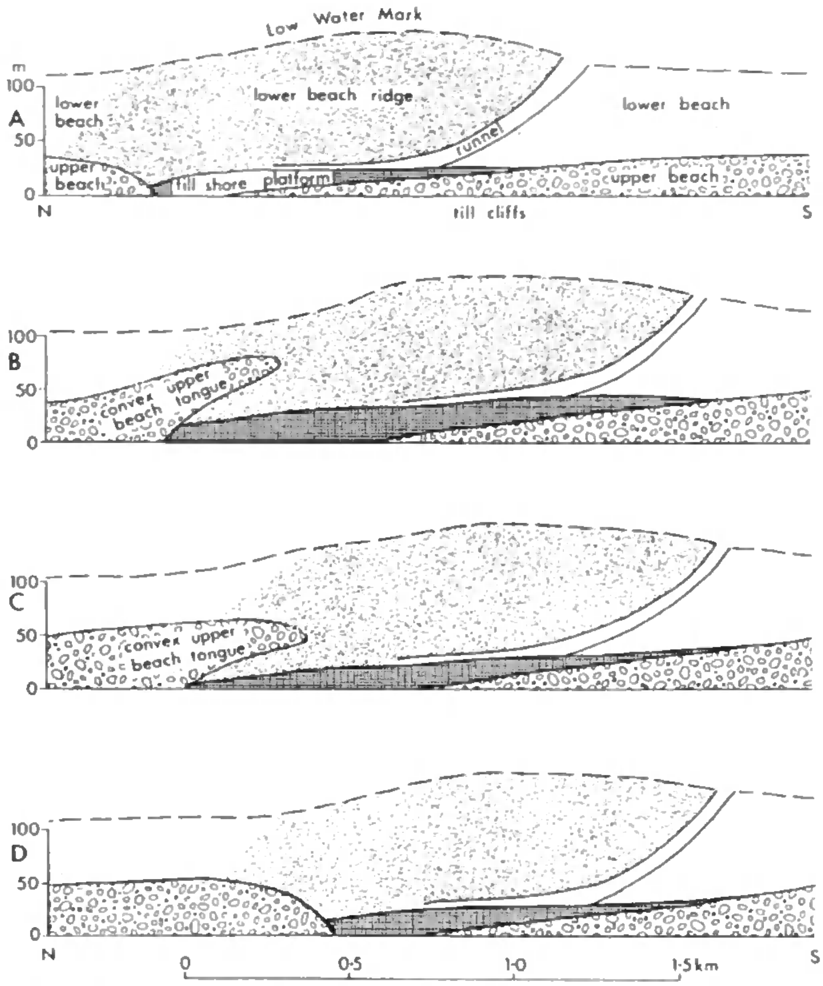


Figure 4.4: Stages in ord movement (from Pringle 1981). The initial tongue of upper beach migrates landward, whilst to the south of the section, upper beach removal leaves the till platform exposed at the foot of the cliff, moving the centre of the ord southwards.

4.2.5 Effect of Beach Morphology on Cliff Erosion

Since the ord landform is explicitly defined by the beach morphology, it is safe to say that changes in one will have a direct effect on the other. There is also a close relationship between beach morphology and cliff erosion 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 (Mason and Hansom, 1988). This is the centre of the ord, 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).

Cliff erosion is caused by a combination of toe retreat and sub-aerial weathering, leading to cliff steepening and the occurrence of numerous small slumps on the scale of tens of metres. The debris is quickly assimilated into the suspended sediment present in the North Sea, to be transported by longshore drift, and deposited further south, either on another section of the coast backed by cliffs, or on Spurn Head, helping build it up (Balson *et al.*, 1996).

It follows that if the movement of the ord can be extrapolated into the future, then the locations and times where the greatest erosion will take place can be predicted (see later discussion on cliff erosion models), with past ord studies indicating likely erosion rates. This 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 evidence of this), despite the short term / small scale variability (Balson *et al.*, 1996).

4.2.6 Effect of Geomorphological Change on the Human Environment

Changes in beach morphology influences cliff erosion. Both increased cliff erosion and changes in beach morphology can be expressed in the human environment in the following ways. The most obvious is cliff erosion and the loss of valuable agricultural, residential and industrial land. The construction of sea defences on dynamic beach topography also poses problems.

The effects of ords on existing sea defences can be evaluated. The centre of the ord is characterised by a depression in the upper beach, and where this feature lies adjacent to sea defences, erosion of their foundations may be expected. Any sea defences constructed on the Holderness coast may result in a reduction of sediment yield, which could starve the adjacent beach of sediment and cut off sediment supply along the shore. An example is the possible erosion of Spurn Head (Figure 4.1), a spit formed at the mouth of the Humber Estuary and a valuable bird breeding ground. Given the anti-clockwise sediment transportation regime in the southern North Sea, any sea defences constructed on the Holderness coast may also result in fine sediment deprivation for certain low-lying coastal areas on the Dutch coast. The potential role of the system in evaluating the possible effects of installing sea defences has long term and large-scale implications. This will be important, especially as the North Sea Gas terminals at Easington have recently constructed defences. This shows how the perceived erosion hazard turns into a socio-economic threat.

This in turn calls for a coastal zone management response. Here, the role of COAMES is to provide decision-support to help formulate this response. The coastal zone sociological framework within which COAMES operates is discussed in more detail in Chapter 6.

4.2.7 Overview

The main aim of this case study was to capture a narrow domain that was important both in the natural and the socio-economic environments. This offered a wide scope for the case study, as land loss is an ongoing physical process that impinges directly on the local population, agriculture, tourism and industry (North Sea Gas Terminals).

Other reasons why Holderness was chosen as an apt test for COAMES include the historical context (the initial development of COAMES was within the Land-Ocean Interaction Study, which used Holderness as one of its main research foci), dynamicism of the coast locally, abundance of data and knowledge, and the complexity of the landform in question. These reasons are detailed in section 1.3.1.

The ord currently adjacent to the Dimlington-Easington stretch of the Holderness coast was chosen for this study, predominantly due to the availability of stereo aerial photography and related ground control points for this area, particularly at the centre of the ord. Recent studies have also revealed this ord to most resemble the archetypal ord, in terms of both form and behaviour (Pringle, personal communication). The two time periods of study were 26th October 1996 and 8th April 1997; this interval covers winter, the time of year when most erosion is expected to take place (Pringle, 1985).

4.3 Using Digital Photogrammetry to Derive the Digital Elevation Model

4.3.1 Photogrammetry

The use of aerial photographs has in the past been invaluable for the geomorphologist. Qualitatively, terrain characteristics such as bedrock type, soil texture and landform can be estimated by earth scientists through air-photo interpretation. Photogrammetry is the derivation of reliable measurements and maps from photographs and describes the quantitative use of aerial photographs. For instance, photogrammetry can be used to gain a value of slope of a feature that could only be guessed at using interpretation (Lillesand & Kiefer, 1979). Photogrammetry is another discipline to reap the benefits of increased computing capability, conventional analogue and analytical methods giving way to widespread digital usage (for an overview of digital photogrammetry see Petrie, 1997).

It is possible to produce Digital Elevation Models by applying photogrammetry to the common area of two overlapping aerial photographs, enabling the subsequent measurement of slope (or some other morphometric measure) of a ground feature. A consecutive aerial photograph pair (taken by a Wild DC-10 camera from a NERC Piper Chieftan Aircraft at 1000m on both dates) was digitised through scanning (to 400 d.p.i and in TIFF format) for each of the time periods so that the derived area of stereo overlap captured the distinct elements of the ord. The photographs are normally taken with a 60% overlap. These scanned photos were imported and used as input into Erdas Imagine's digital photogrammetry module, Orthomax. For an example, Brown and Arbogast (1999) have measured active coastal dunes in Michigan using digital photogrammetry.

4.3.2 Orientation

For any stereo pair, inner orientation establishes the position of each photograph in modelled space through the manual digitisation of each corner of the scanned image; the corners represented by fiducial marks. The user measurements are compared against the original camera dimensions (provided by the manufacturers) to derive an error value (in pixel units). Should the magnitude of this error exceed a predefined threshold, the fiducial marks are remeasured until accuracy is at an acceptable level.

Relative orientation links the two photographs together through the identification and measurement of precise features that can be identified on both. For instance, discernable points (tie points) such as the corners of buildings are used throughout the area of overlap to ensure that each photo is correctly oriented relative to the other. The user may interactively add or remove new tie points until the positional error is at a minimum.

The last stage is absolute orientation, which involves the modelling of the stereo pair to real ground co-ordinates in all three spatial dimensions. A good spread of these co-ordinates (or ground control points, which have to be imported into IMAGINE as a comma separated variable file [CSV] or manually input one by one), either unprojected (latitude-longitude) or projected as the OS National Grid (a form of the Transverse Mercator projection), is advised across the area of stereo overlap for the optimum photogrammetric model. Errors in the orientation occur where there are large areas of overlap devoid of ground control points, through unrealistic demands being placed on interpolation algorithms (Figure 4.5 shows one of the scanned aerial photographs with superimposed ground control points). For the 1996 photogrammetric model of Easington, it was possible to derive root mean square errors (RMSE[1]) of 93cm. in x, 67cm. in y and 46cm. in the vertical dimension (z). The 1997 model was derived with RMSE of 49cm. in x, 70cm. in y and 58cm. in z. All forms of orientation described here are manually operated.

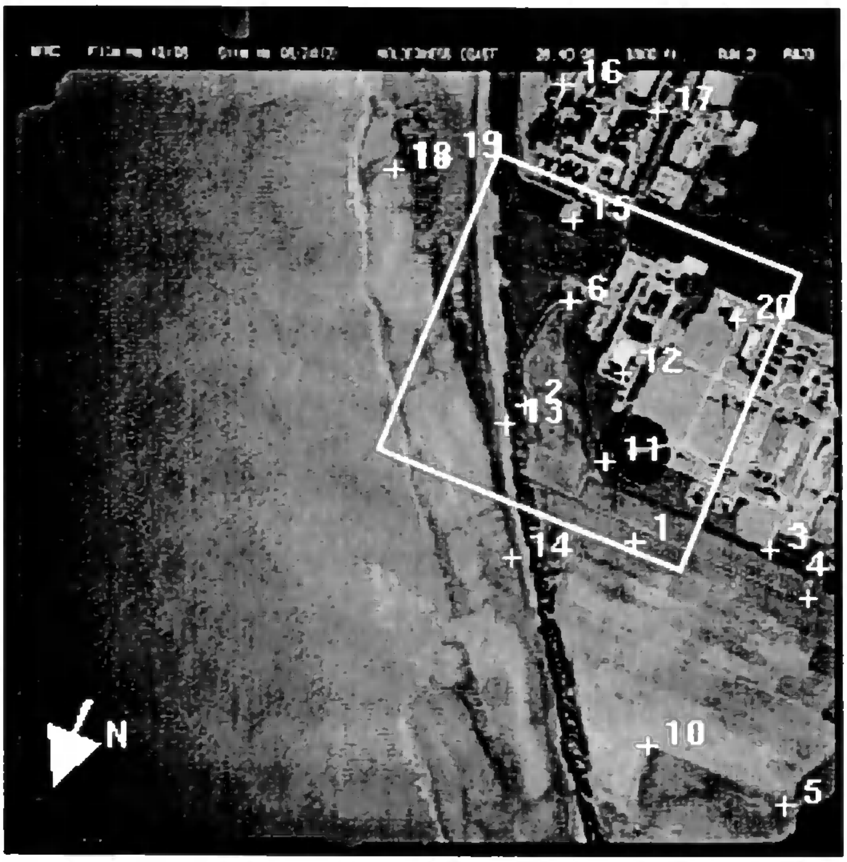


Figure 4.5: Aerial photograph of the Holderness coast near Easington with superimposed ground control points. The extent of the Figure 4.6 DEM is boxed. Taken 26th October 1996.

[1] The RMSE has been a conventionally popular method of calculating error, particularly in the case of DEMs (Gao, 1997), though it has been termed statistically impure (Monckton, 1994).

4.3.3 Ground Control Point Measurement through the Global Positioning System (GPS)

Some Ordnance Survey benchmarks exist which can be used as ground control points, though for a mobile feature such as the beach, where such points are not likely to be found, additional accurate control was needed. This was provided by a Differential Global Positioning System (DGPS) survey undertaken in late October 1996 in conjunction with the aerial photography sorties. According to W.H. Wooden (cited in Hofmann-Wellenhof *et al.*, 1994), the "Global Positioning System (GPS) is an all-weather, space-based navigation system .... to accurately determine .... position, velocity and time in a common reference system, anywhere on or near the Earth on a continuous basis". Two Ashtech Z-12 geodetic GPS receivers were used in a 'differential' mode, where one stayed static, gathering positional information from at least four satellites (to ensure a three-dimensional fix), whilst the other (called a 'rover') collected data from the same satellites and was taken through consecutive points in numerous beach transects. The static receiver was placed at a known point (in this case Dimlington Triangulation Pillar), where it computed the errors of each satellite signal it received, ready to correct the signals received by the rover receiver in post processing (Gilbert, 1994). At each point, a minute sufficed to gather the requisite amount of satellite information relating to xyz position. Combining and comparing (hence 'differential') the two datasets in post processing (using Ashtech Prism software) resulted in a group of potential ground control points of sub-metre accuracy (an accuracy of 10cm. has been achieved). In this way, some twenty points were collected for each day of survey (there are generally three days of survey per GPS trip). Morton *et al.* (1992) outline a use of GPS to monitor beach changes.

4.3.4 Aerial Triangulation and DEM Collection

Through an iterative and automated process of aerial triangulation, the best possible fit for the stereo model and ground control points was derived. It is here that the positional errors of the overall model and each ground control point is revealed. If the overall error is high and one or more ground control points can be seen to be contributing to that error, then they can be removed and the aerial triangulation repeated, to give new error values. The user can experiment with various combinations of ground control points in the quest to minimize the overall error, providing as the minimum number and optimum spread of ground control points is not compromised.

Once the user has specified the area of the prospective DEM (by manually drawing a box on the screen map), an involved stereo matching process contained within the software is used first to automatically detect patterns in the area of overlap so that the same features in each of the photographs are matched. The second task in stereo matching is to automatically measure parallax between the two photos within the stereo overlap area and at a predefined sampling interval of one metre. For the purposes of geomorphological feature extraction, this sampling interval was considered adequate as the landforms to be extracted were significantly larger than this resolution. There may be instances, such as when measuring cliff erosion, where denser sampling strategies are required.

Parallax is "the apparent change in relative positions of stationary objects caused by a change in viewing position." The parallax effect can be seen when looking out of the side of a moving train. Objects in the landscape that are further away, such as distant hills, appear to move slower than closer objects, such as a railway platform (Lillesand & Kiefer, 1979). The same effect can be observed and measured when regarding the difference in viewing position of the aircraft between taking one photograph and the next in a stereopair. The higher the terrain, the closer it is to the aircraft, and the more it will have moved between the two photographs, and vice versa. It is these parallax measurements that constitute the matrix of heights in the Digital Elevation Model (DEM), relative to a Mean Sea Level datum. An example of one such DEM is shown in Figure 4.6. Photogrammetric processing of one stereo photograph pair, from the initial scanning to the production of a DEM, may take as much as a couple of days, depending on how quickly the optimum photogrammetric model can be iteratively attained.

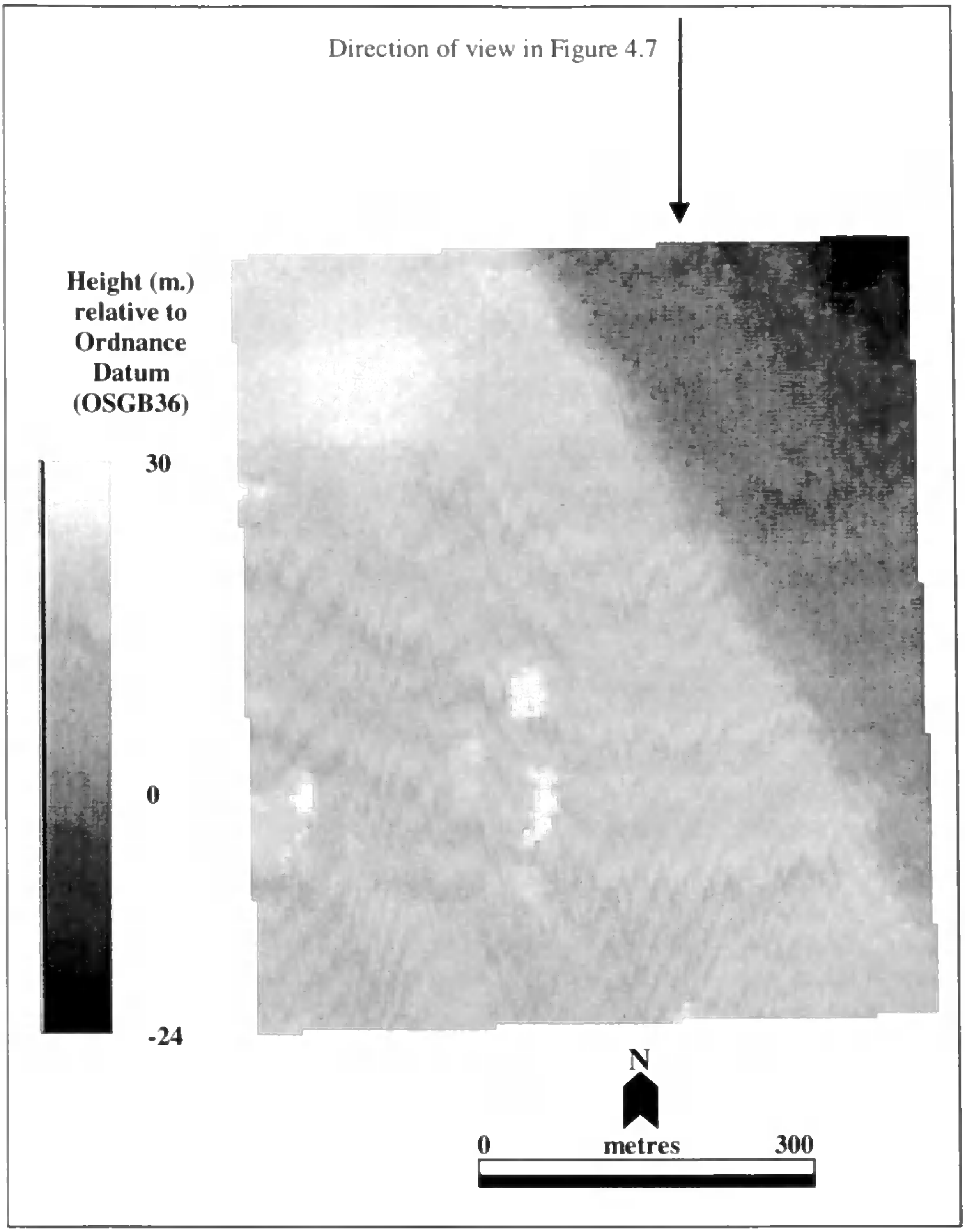


Figure 4.6: Reduced Resolution Digital Elevation Model of Easington, 26th October, 1996 (transformed to Ordnance Survey National Grid; 143 x 124 cells; 5 m. resolution), covering part of Figure 4.5. Note the peaks on land due to the North Sea Gas Terminal buildings, and the troughs in the top right. The latter is an erroneous result produced by attempting to calculate the parallax of the sea (*i.e.* a moving object).

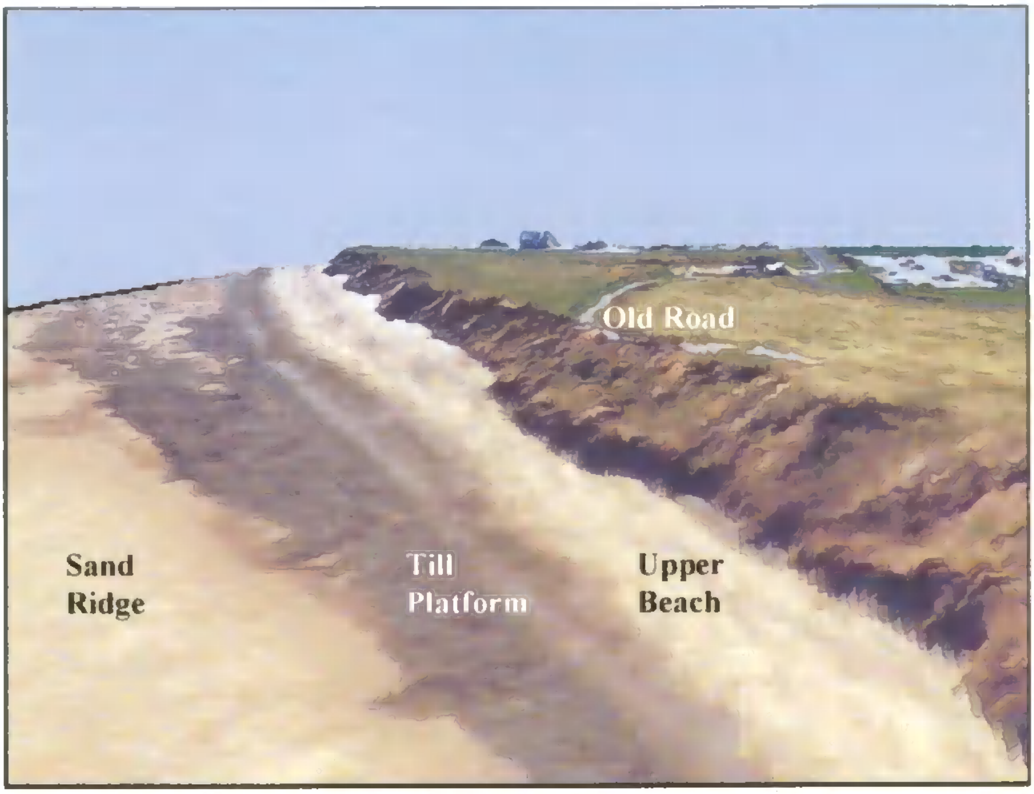


Figure 4.7: Perspective view of a DEM (view looking south), draped with an orthographic photograph. The salient elements of the beach can clearly be seen, from the sand ridge on the left, through the darker till platform to the steeper upper beach banked against the till cliffs.

The ground control points measured at the same time as the photography were accompanied by topological (relative position) descriptions of the constituent features of the ord. It is these descriptions that are used by the expert system to locate salient elements on the beach from the DEM. Figure 4.7 shows a perspective view of the DEM for October 1996 overlain with an orthorectified photograph. This type of photograph (or 'photo-maps') have all the perspective distortion of the original photograph removed, as well as height distortion due to parallax (the DEM is used in the latter distortion removal). Orthophotos have the advantage of enabling direct measurement like a map, and yet retain the terrain detail necessary for photograph interpretation (Lillesand and Kiefer, 1979).

4.4 Use of the Expert System

4.4.1 Rule Overview

Each constituent of the ord landform, such as the upper beach or till platform, is an object with associated rules. The rules may define their interrelationships with other constituents of the ord (Figure 4.8) and their morphometric properties (Figure 4.9). In total there are 45 rules programmed into the expert system (17 defining topological relationships of ord constituents, and 28 defining the morphometric thresholds of each constituent (7 rules for each of height, slope, aspect and convexity).

4.4.2 The Ord Rule Hierarchy

Refer to Figures 3.17 - 3.19 for more detail on the following. The user query (for example "track the movement of upper beach within an ord from time 26/10/96 to 04/04/97 at Easington") was initially compared with the terms in the dictionaries to store the important or operative words that will drive the expert system. These 'trigger' words serve to invoke hierarchical rule structures. For example the word 'ord' triggered the rule structure displayed in Figure 4.8.

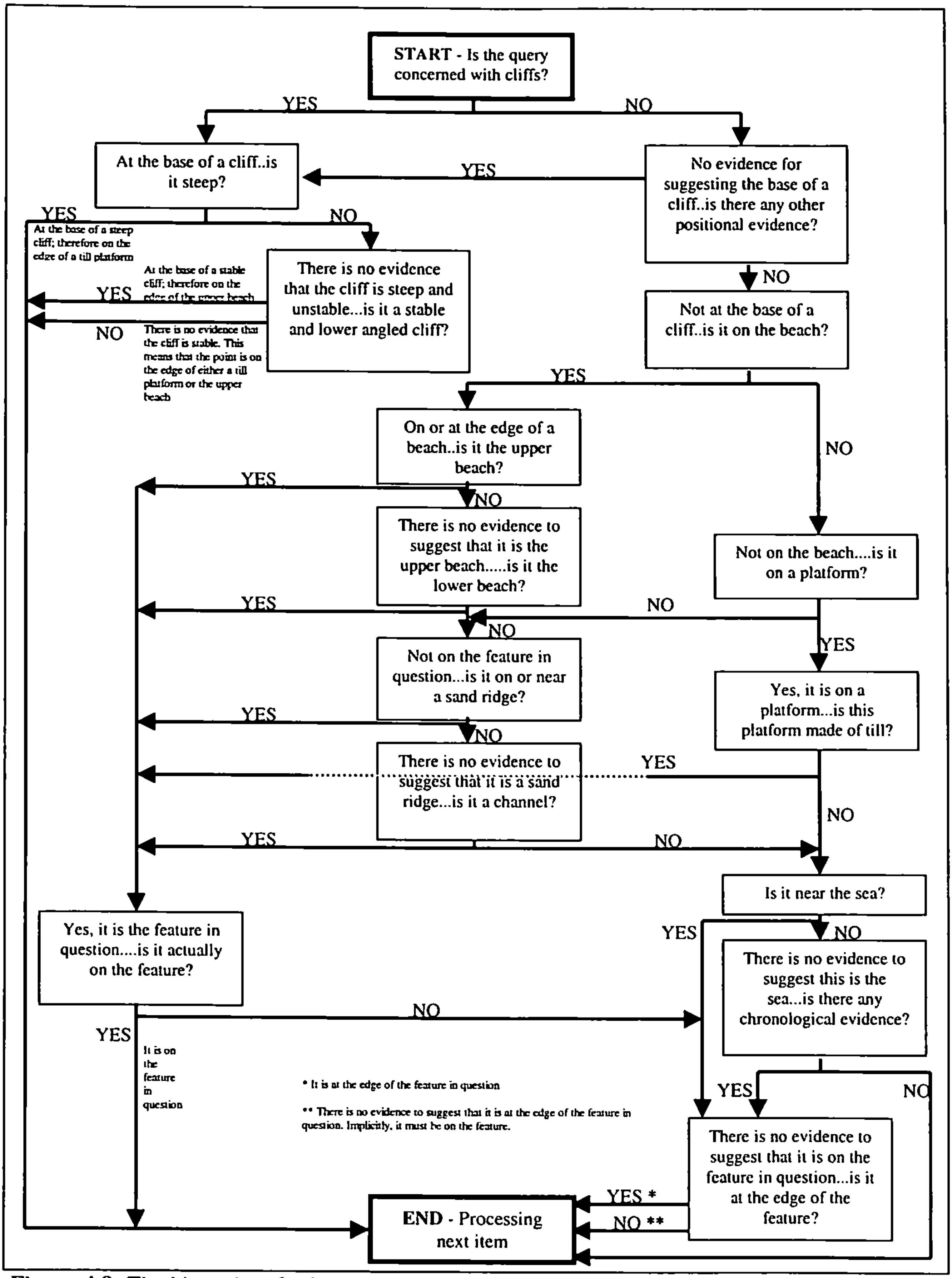


Figure 4.8: The hierarchy of rules used to process the user query and ascertain which portions of knowledge to use. The configuration is derived from the archetypal ord schematic in Figure 4.3. Each of these rules have attributes that link with the relevant dictionary terms (see Figure 3.17 for internal structure of rule). The extracted terms are compared with the user query.

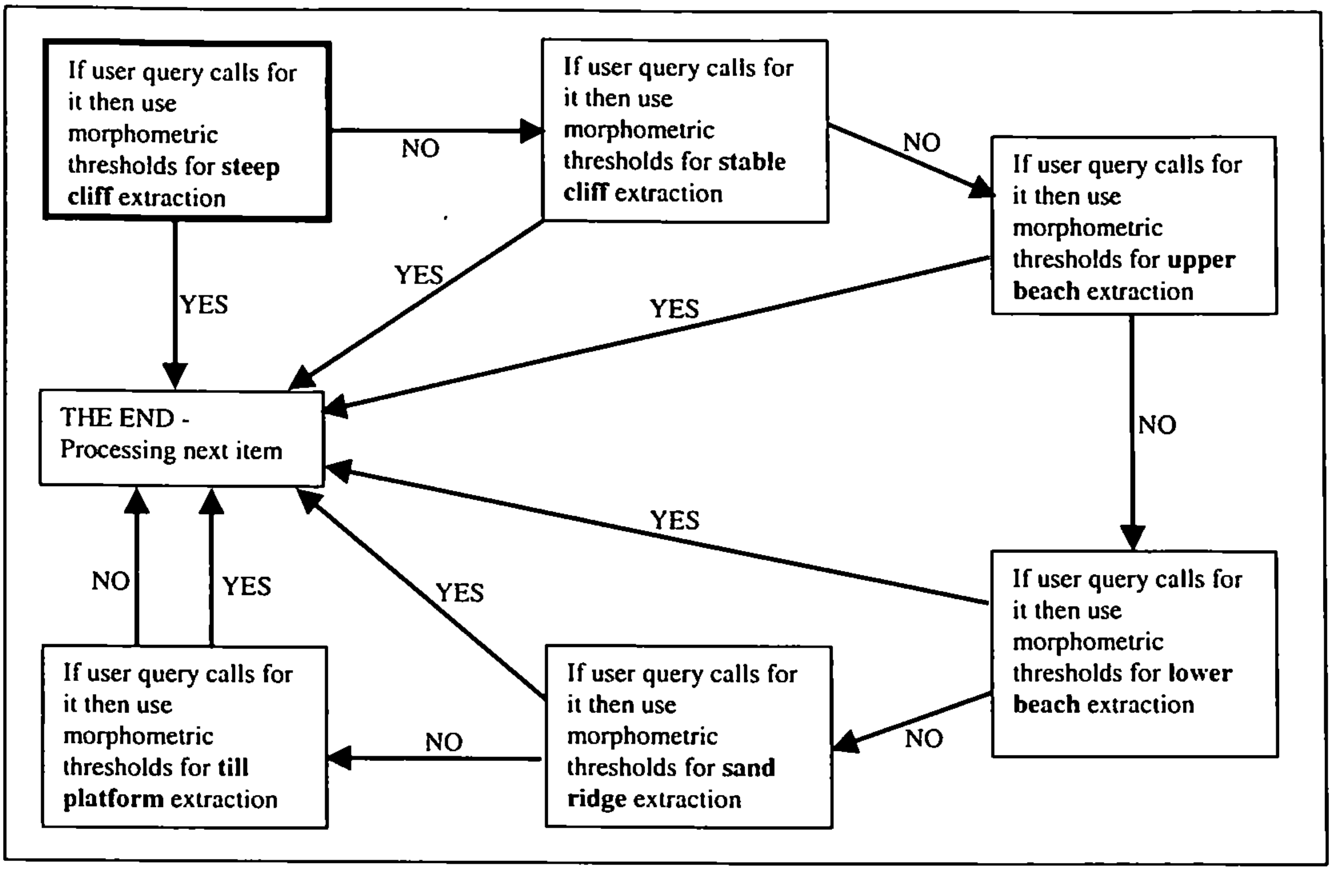


Figure 4.9: The hierarchy of rules used to set parameters for morphometric extraction. There is a set of these rules for each basis of extraction: height, slope, aspect and convexity. Each of these rules have attributes that link with the relevant morphometric thresholds (see Figure 3.19 for internal structure of rule). The extracted thresholds are passed to the relevant morphometric function. The threshold values are derived from the work of Scott (1976) and Pringle (1981, 1985, pers.comm.).

Starting from the initial rule concerning cliffs, attributes exist within the cliff rule (see Figure 3.17 for internal structure of rule) that link with the relevant part of each dictionary. For example, in the case of cliffs, dictionary words include (as well as 'cliff' itself) 'toe' and 'slump' (from the 'coastal' dictionary), and 'base' and 'foot' (from the 'context' dictionary - this is the basis of the second rule asking for positional evidence). 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 4.3. 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 adjacent to an upper beach or till platform, or enabling two or more rules in combination to define a feature. (Edwardson *et al.* [1997] use the dynamic segmentation of coastlines to explore adjacency and topology, identifying three types of relationship: adjoining [end-to-end], across-shore [from backshore to foreshore] and overlapping).

With progress through the hierarchy, the query-highlighted ord rules were flagged (with 'ignoreflag') and subsequently used to extract ground control point (GCP) coordinates on the basis of words in the associated topological descriptions. Referring to the case of the above example query, the flagged rules are highlighted in Figure 4.10. 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

These points were normally collected where two ord constituents meet (section 4.3). It should be noted that datasets such the GCPs above are only chosen if they are present in the system.

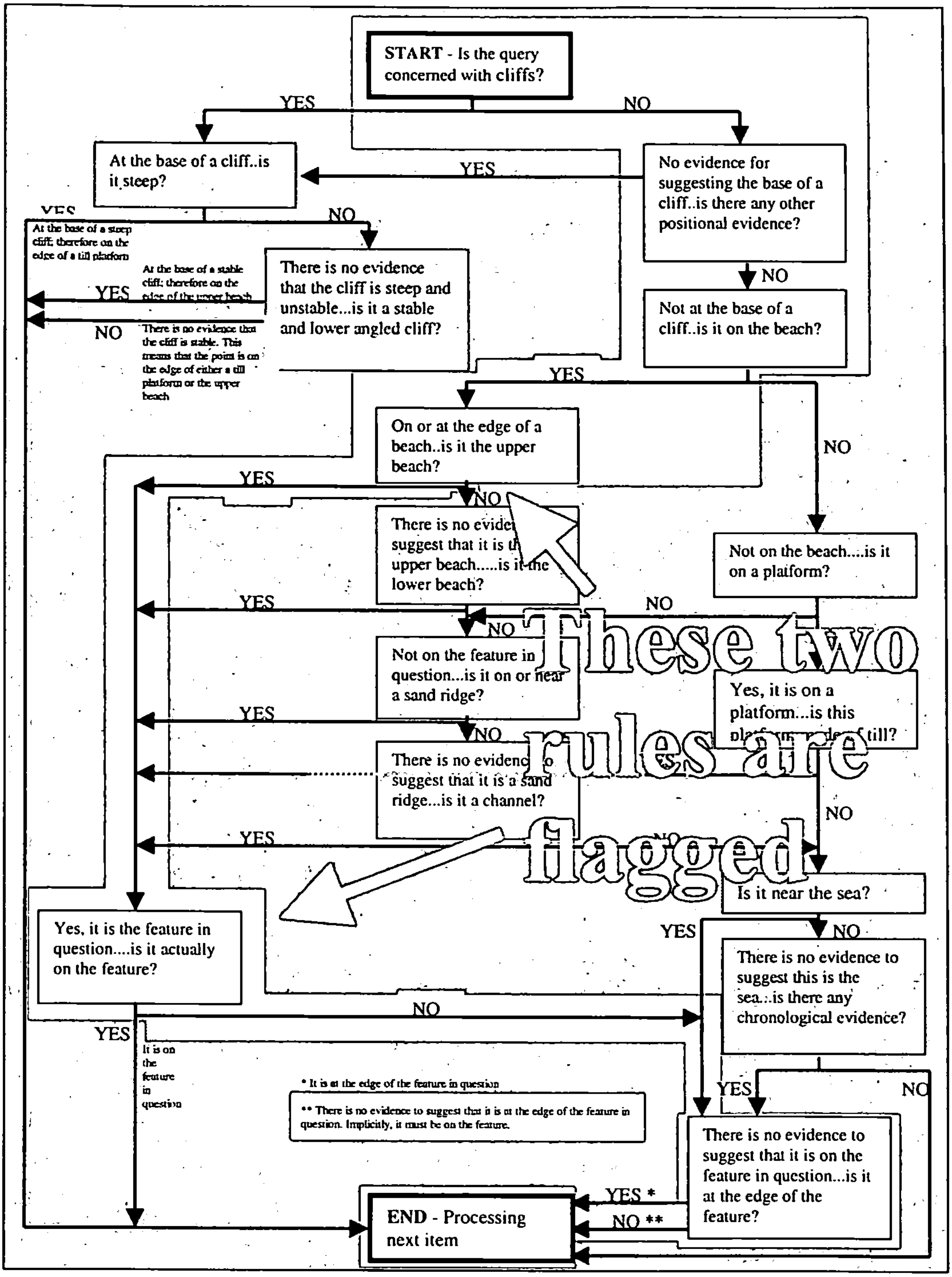


Figure 4.10: An amended version of Figure 4.8 showing the progress through the rule structure on the basis of the query "track the movement of upper beach within an ord from time 26/10/96 to 04/04/97 at Easington". The rules concerning the upper beach are flagged.

4.4.3 The Morphometric Rule Hierarchies

The extracted points were used to define a region within which morphometric extraction would take place. This is a minimum bounding rectangle (MBR) for the chosen points, often used as a pre-process to ease operations on very large datasets (Dawson and Jones, 1995). Then each of the morphometric rule hierarchies (model in Figure 4.9) were descended in turn. For each of height, slope, aspect and 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 (see Figure 3.19 for internal structure of the rule). (The maximum and minimum feature threshold values that were stored as knowledge in the expert system were originally measured by conventional ground survey - Scott, 1976; Pringle, 1981; Pringle, pers. comm.). The extracted 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 or convexity.

For an in-depth explanation of how the expert system works, see section 3.10.1 in particular for details on how the inference engine processes these objects to produce the output presented in the following section.

4.5 Results

Figures 4.11 and 4.12 are decision support output maps resulting from 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 (a simple further test of COAMES may be in developing rule-based automated deduction routines).

Within the expert system, the areas were extracted from the DEM data, using the positional knowledge and ground control point data to zoom in to the appropriate geographical area. The morphometric knowledge was then applied to restrict the area further. The cliff top line for 1996 was digitised from the orthophotograph of 26th 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 extracted landforms.

Figures 4.11 and 4.12 show considerable evidence for ord presence and associated movement in the direction of longshore drift. In October 1996, there was one large area of steep cliff that extended for some 100 metres. By April 1997, the northern end of this steep cliff zone had moved between 75 to 100 metres southwards, whilst the southern end had extended the length of the strip by approximately 250 metres southwards (in this way the steep cliff exhibits longitudinal wave behaviour). This movement and extension of steep cliff correlated spatially and temporally with similar behaviour by thin sections of upper beach. This is borne out, since steeper cliff gradients are indicative of increased erosion where the upper beach has been removed, exposing the lower till platform.

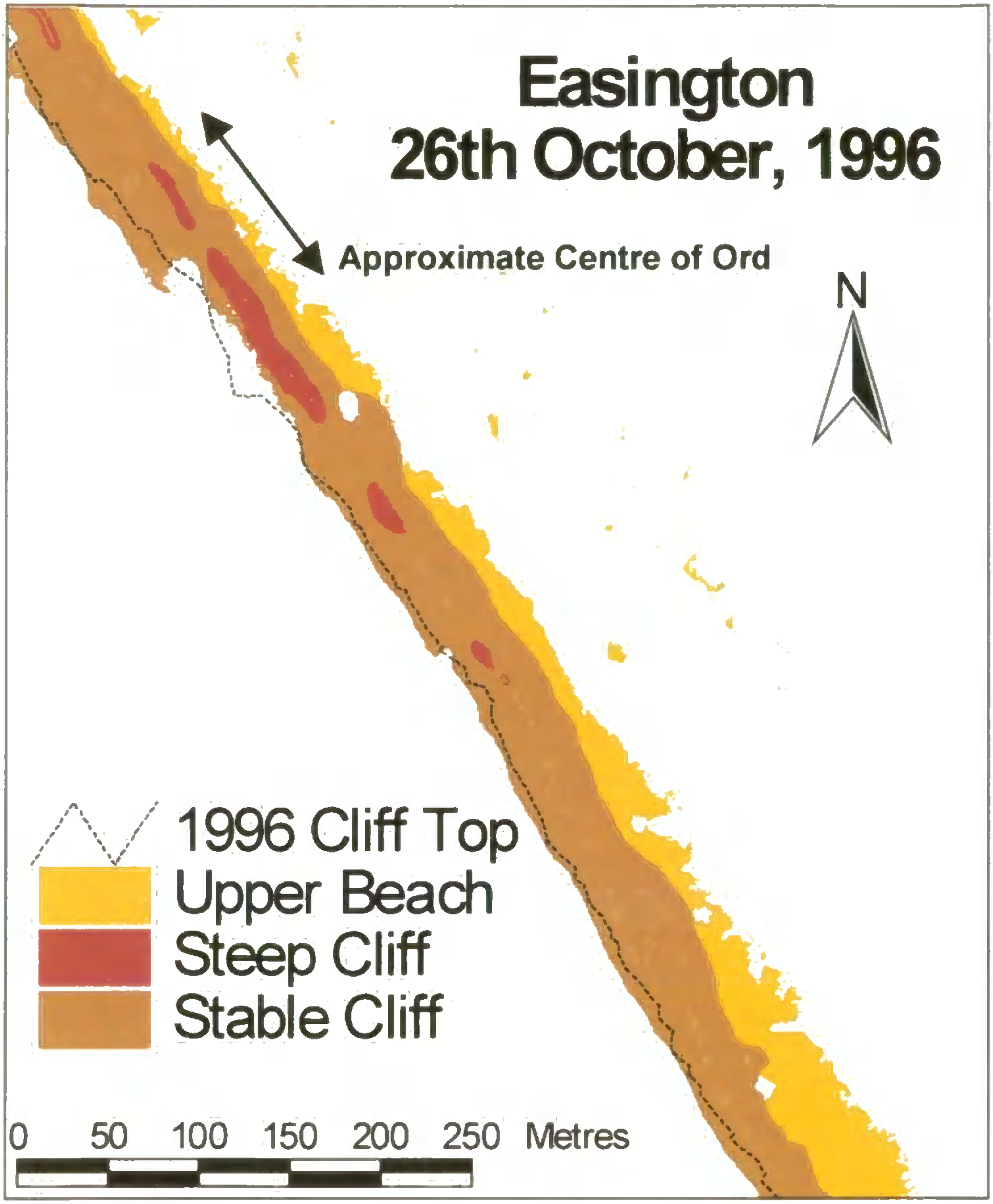


Figure 4.11: The isolation and extraction of steep cliff, stable cliff and upper beach from the study area in October 1996 on the basis of intelligent ground control points and morphometric parameters driven by the COAMES expert system. (Ordnance Survey National Grid). The 1996 cliff top line is included for reference and is derived from manual digitisation of the cliff edge: therefore it may not coincide with the morphometrically-extracted classifications.

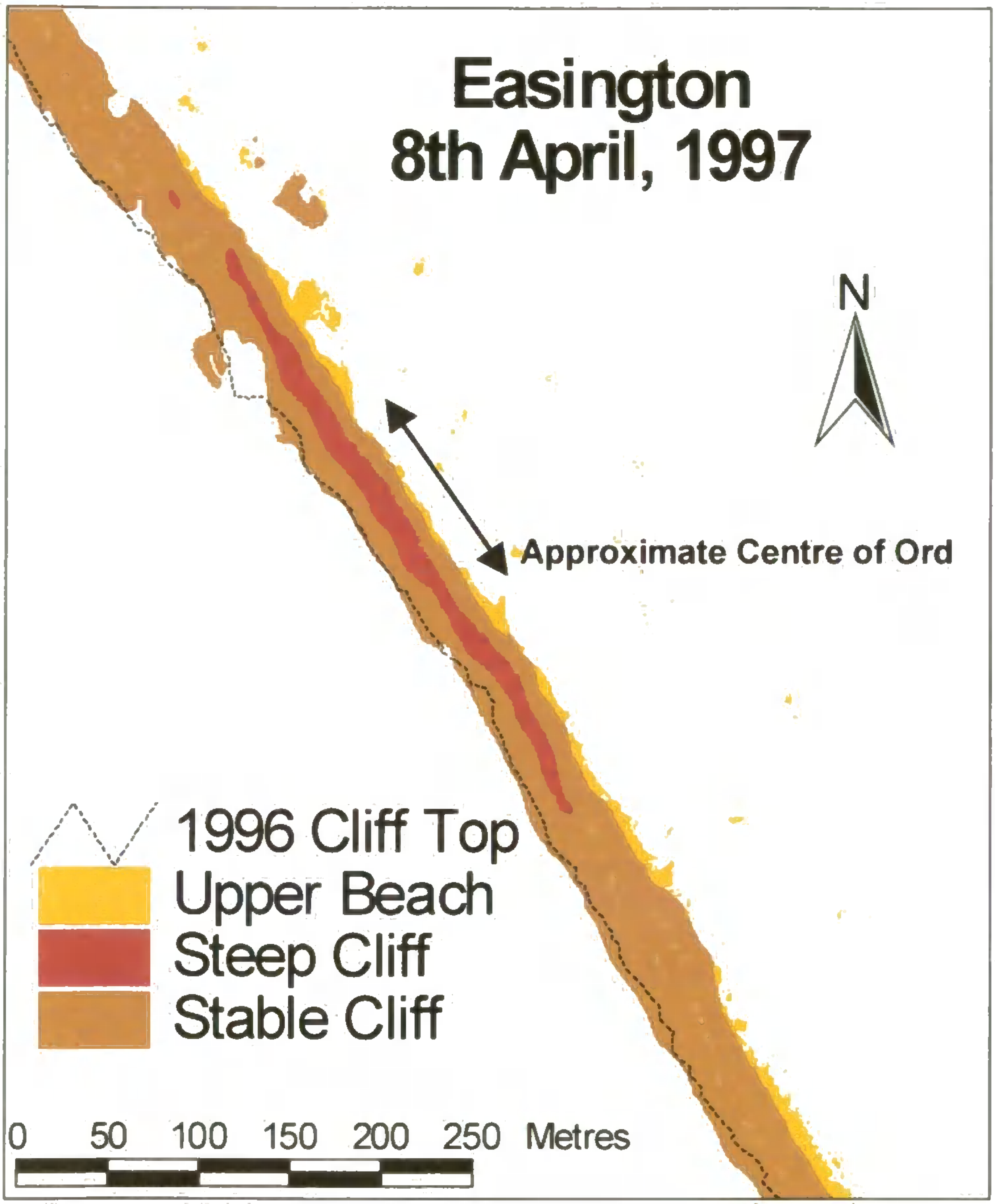


Figure 4.12: The isolation and extraction of steep cliff, stable cliff and upper beach from the study area in April 1997 on the basis of intelligent ground control points and morphometric parameters driven by the COAMES expert system. (Ordnance Survey National Grid). The 1996 cliff top line is included for reference and is derived from manual digitisation of the cliff edge: therefore it may not coincide with the morphometrically-extracted classifications.

Conversely, the extracted stable or lower gradient cliff areas for the same times indicate protection of the cliff by the upper beach (Pringle, 1981). Indeed, as a whole, the more contiguous areas of stable cliff correspond with the broader and higher upper beach. This is notably not the case to the extreme north of the April 1997 map. The presence of a stable cliff 'island' on the beach indicates a misrepresentation in the stereomatching process (measurement of parallax), 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. The reasons for this occurrence of noise, and possible solutions are outlined in section 4.6.

The direction and rate of narrow upper beach movement supports previous observations. Movement of the ord centre has been measured at approximately 500 m/yr in the direction of longshore drift (Pringle, 1985). 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/yr.

4.6 Commentary

4.6.1 The Value of COAMES

These decision support results are corroborated by past measurements, which is an apt indication of COAMES' capabilities and the ability to capture a limited environment in terms of expert rules. 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). All the knowledge (morphometric thresholds, positional relationship of ord constituents) and data (Digital Elevation Model data) are fully integrated and selectively accessed on the basis of user input, then combined by the expert system to produce meaningful and useful results. Therefore, COAMES does not share the inflexibility of the manual process, being able to use whatever the scope of the user input, knowledge base and database allows.

4.6.2 Limitations

The above results demonstrate the power of an expert system to apply knowledge and data for the automation of geomorphological characterisation with reference to a specific feature. For some tasks, such as the extraction of the upper beach, the system has not performed perfectly, classifying isolated clumps of upper beach elsewhere in the intertidal zone. Conversely, an area that can be identified as upper beach from qualitative analysis of the photographs (extreme north of Figure 4.5), has not been extracted (this kind of error also accounts for gaps amidst the stable cliff classifications). This occurrence of noise is bound to happen where morphometric thresholds are defined as explicitly as they are here. One solution is to fuzzify these thresholds (see sections 2.3.8 and 4.6.4). 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. This is an example of an *a priori* means of DEM analysis (Wood, 1997).

4.6.3 Models

The prognostic capabilities of COAMES could be developed by feeding the decision support output analysed earlier into a cliff erosion model (see section 7.2.2 for a discussion of this). Brooks and Anderson (1998) state that GeoComputation has most value for the geomorphologist in modelling long-term landform change, specifically topographic change (for this the DEM would be the major input and output). At a further level of detail, a systems approach to coastal morphology modelling (see Eleveld, 1999) uses a behaviour-oriented method and provides a holistic example. In this project, a 5 to 10 year historical study of coast change formed the basis for prediction over a similar period into the future. This is normal, as upscaling in coastal dynamics is difficult. There is a tendency to overextrapolate, with increasing uncertainty observed the further back or forward modelling occurs at (Brooks and Anderson, 1998). This is the inverse problem, and validation is not possible at these temporal extremes.

Some factors to consider when modelling the coastal zone have been outlined above. Martinez and Harbaugh (1993) detail the simulation of nearshore environments and associated deposition processes. As an example, a featured model SEDSIM is used to simulate longshore transport on deltas. SEDSIM has since been adapted to model the development of spits (Livingstone and Raper, 1999).

The coupling of a Longshore Transport Rate Model with COAMES

A Longshore Transport Rate Model (Lee *et al.*, 2000) has been coupled with the current version of COAMES, and is accessible through the relevant action rule (typical content of a rule is outlined in Appendix B).

The equation for the model is

$$Q = \bar{U} * m * n$$

Where Q = longshore drift rate (in metres cubed per second);

$\bar{U}$ = average longshore transport velocity (in metres per second);

m = average width of the mobile beach (in metres), and;

n = average thickness of the moving sediment layer (in metres).

These parameters may also be stored with the rule, though in the absence of *a priori* values, certain parameters can be calculated from available data. For Holderness, the $\bar{U}$ value is approximately 500 metres per year (or 0.00001585489599 ms^{-1}), as established by Pringle (1985) based on the evidence of ord movement.

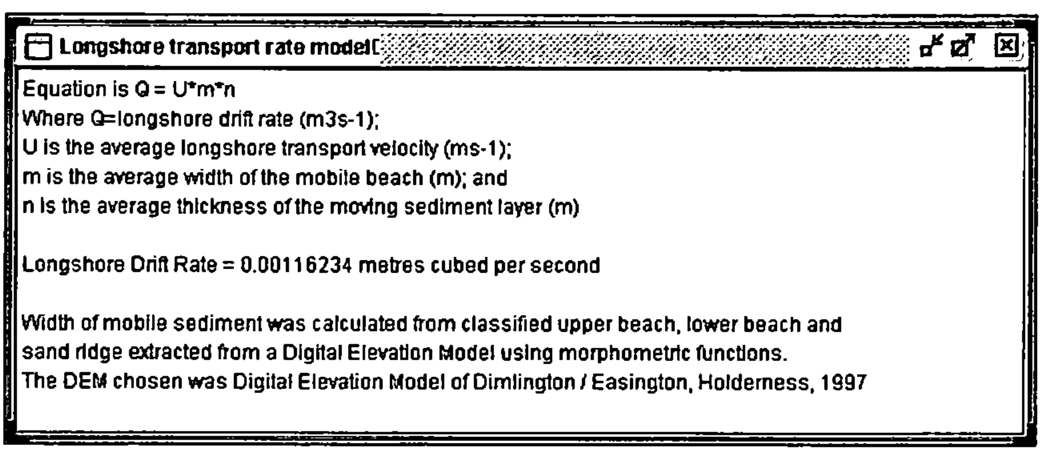


Figure 4.13: Output (through COAMES) from the Longshore Transport Rate Model of Lee *et al.* (2000).

An approximate value for m can be established from available DEM data and the feature extraction capabilities of COAMES. Taking mobile sediment as an aggregation of the upper beach, lower beach and sand ridge areas, a query stating those three features was automatically put through the expert system, where the classification mechanism described in this chapter extracted cells on a morphometric basis (an implicit Overlay [OR] operation ensured that the results for the three features were merged). A heuristic was then applied to the chosen cells to establish the longest axis passing through them, with an assumption that these landforms run parallel with the coastline. Starting at a random point on an extracted cell, a line to the furthest extracted cell was established. That cell then became the cell of focus, and a line was drawn to the furthest cell from that. This process continued until there was no change in line length. The area of classified cells was divided by the length of the line to give the average width of mobile beach.

At this stage, the thickness of the mobile layer (n) has been given a nominal value of one metre, though a way of deriving a value from DEM data has been suggested. The method uses the expert system to classify the immobile sediment (*i.e.* cliff and till platform), then interpolate a surface to form a base level beneath the mobile sediment. For each grid cell, the vertical distance between the immobile sediment surface and the mobile sediment surface was calculated and averaged to give the average thickness of the mobile layer.

/

Some sample output from the model is shown in Figure 4.13. As well as the coarse assumptions made for the model, the output figure was derived from a DEM covering only a small area. For the result to have more validity at the Holderness scale, figures calculated from cotemporal DEMs of other stretches of coast would have to be used. However, a generic, holistic approach has been demonstrated with this coupling of a simple model, not only in the use of the same rule structure as for metadata, but in employing other actions (morphometric classification and extraction) in its methodology.

4.6.4 Error

Where model output involves the coupling of two or more models, the propagation of error must be considered. Indeed, output that is derived from imprecise or uncertain data and knowledge (the latter of which is characteristically imprecise, anyway) would be useless to the coastal zone manager unless linked to some estimate of error to indicate reliability of the output. Applied to COAMES, the Digital Elevation Models used in this prototype conventionally use RMSE estimates and this information can be included for any DEM object. Ways of modelling uncertainty include fuzzy logic, an alternative to the "yes or no" absoluteness of conventional data analysis. For example, there is a great deal of uncertainty in defining morphometric thresholds, which are incorporated into the expert system rule. Although defining an upper beach to have a slope of between 3 and 15 degrees could be true, it is not exclusive, and there will be examples that fall outside this. Exploring the use of fuzzy logic for "non-crisp" terms (as in Brimicombe, 1996) would have beneficial implications, due to the potential confusion arising out of processing user queries and the rendering of terms such as 'steep' and 'stable' cliff into quantifiable terms. Reasoning with uncertainty is developed and tested in the Chapter 5 case study, using the Dempster-Shafer theory of evidence.

4.7 Summary

In this chapter, 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 extraction of landforms 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 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 exists - it needs the analytical capabilities of the expert system to handle these challenges effectively.

Adding elements such as ancillary data and models will be a viable test of COAMES, as an important theme in the philosophy of COAMES is the ease with which additional groups of data and knowledge can be incorporated into the framework. Accordingly, this prototype study provides a foundation block that will be added to. The greatest value will lie in the integration of existing environmental data and knowledge with demographic, sociological and legislative knowledge at a range of different spatial and temporal scales. This forms the basis of the next case study, metadata provision on the Fal Estuary, Cornwall.

5: CASE STUDY: TOWARDS HOLISM - INTELLIGENT METADATA EXTRACTION IN THE FAL ESTUARY

5.1 Introduction

The second test of COAMES is the expansion of the prototype outlined in Chapter 4 to process digital resources of wider scope, in terms of discipline and institution, spatial and temporal scale, and, for the first time, uncertainty (using the Dempster-Shafer theory of evidence – section 3.9.1). The area of application has also expanded to encompass integrated coastal zone management (ICZM), specifically to intelligently extract metadata of the Fal Estuary, south-west Cornwall. Five tests were used on the metadataset (originally collected as part of the Atlantic Living Coastlines project – Moore, 2001) to successfully choose and display the correct metadata. During this process, tools such as *ignorance* and methods of integration were used to intelligently work within the holism paradigm.

5.2 Coastal Zone Management Background

5.2.1 The Fal Estuary

The Fal Estuary, situated on the south coast of Cornwall, UK (Figure 5.1), is a prime candidate for Integrated Coastal Zone Management, as it is an area where many different coastal interests meet.

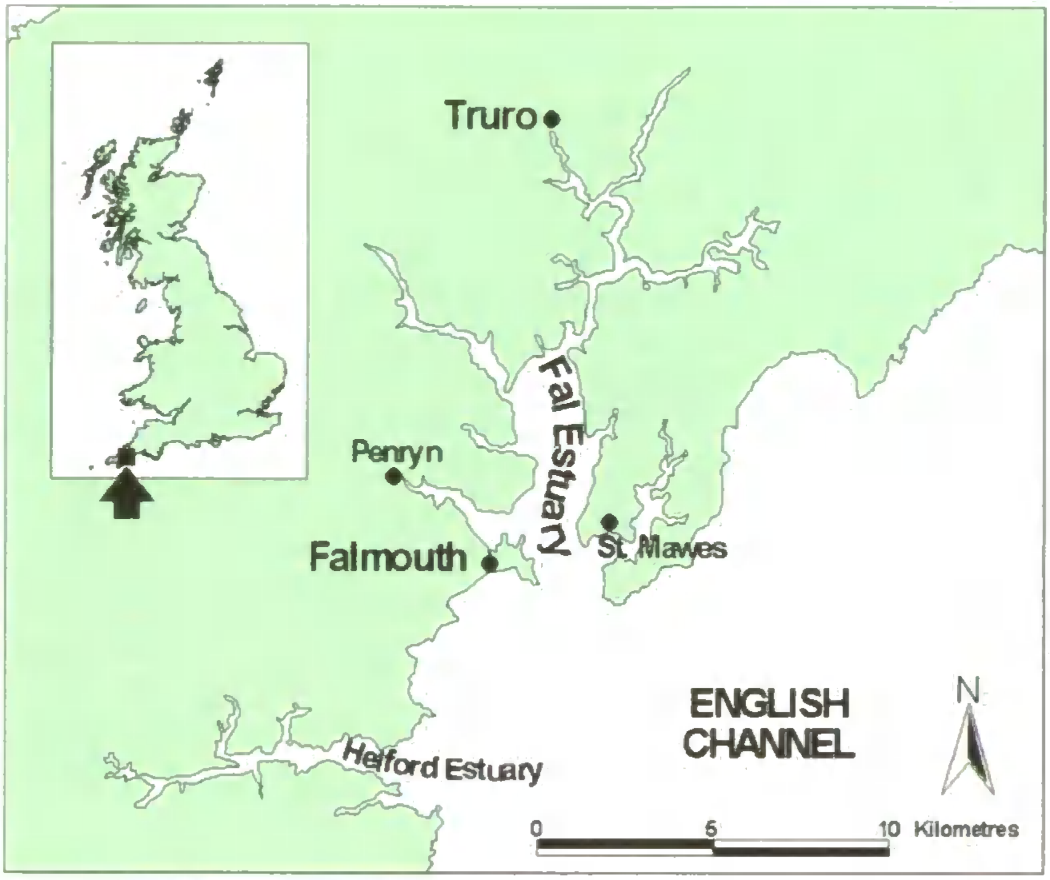


Figure 5.1: Location of the Fal Estuary, UK.

The estuary is a drowned river valley (or ria), containing two major centres of commerce and population: Falmouth and Truro. Both settlements have ports able to accommodate freight (Truro less so) and recreational boating. Falmouth in particular is one of the largest ports in South West England, as well as being a major centre for tourism. A large proportion of tourism revenue for Falmouth derives from recreational boating. Outside the major settlements, the Fal and Helford Estuaries form a candidate Special Area of Conservation (cSAC), due to habitats such as subtidal sandbanks, intertidal sand / mudflats, saltmarsh and shallow inlets / bays (Bayliss and Moore, 2000).

5.2.2 Holism and Coastal Zone Management

As shown in Section 2.2, within Coastal Zone Management there are widespread calls for an integrated approach. To enable participatory decision making in coastal zone management, Deakin (1994) called for a 'rigorous framework' to oversee interpretation of data, dependent on quality and suitability for use. This is a holistic view, which Doody (1996) and the EC (1999) advocate as a solution to integrate fragmented and undocumented data. Kucera (1995) supports this but acknowledges that to adopt a holistic view of coastal environmental management would be a challenge, due to the diversity of the coast and feature interactions. Also, data relating to the coastal zone can confuse through its sheer quantity and variety, requiring a method of 'navigation', and an overall framework (Riddell, 1992).

It has been noted that land or water resources management are different from coastal resources management, in that a unified approach is essential for the latter (Clark, 1998). The alternative is a piecemeal approach, which has historically led to unsatisfactory results (i.e. one problem alone is addressed, causing other problems in turn). For example, in coastal defence measures undertaken at one site may exacerbate erosion further along the coast (French, 2001).

Integrated Coastal Zone Management (ICZM) is sustainable management of the coast, integrating the concerns of all stakeholders (in various activities and sectors) in relation to all goals (from local to international scale) (Clark, 1998; Scholten *et al.*, 1999). ICZM employs a holistic approach, and really came to the fore through Agenda 21 of the Rio de Janeiro Earth Summit (Cicin-Sain *et al.*, 1995, Drummond, 1998). Agenda 21 was an influence on the European Union's Demonstration Programme on Integrated Coastal Zone Management (see EC, 1999). The Atlantic Living Coastlines Project was a component of the Demonstration Programme, being the source of the data to be used in this case study, as will be explained in the next section. The Demonstration Programme was completed in 2000, and was followed by 'A strategy for Europe', a number of recommendations for ICZM, which has been taken up by a number of European nation states (EC, 2000).

5.2.3 Integrated Coastal Zone Management in Devon and Cornwall: The Atlantic Living Coastlines Project

The Atlantic Living Coastlines Project (ALC) was one of the European Union Demonstration Projects. The main aim of the ALC was to develop an integrated coastal zone strategy for the counties of Devon and Cornwall, practising Integrated Coastal Zone Management (ICZM). The Demonstration Programme came about when the EU realised that it must take some of the responsibility for sustainable coastal zone management. The ALC project was one of 35 such projects covering the full range and diversity of the European coastline. In particular, the ALC project was part of a subgroup of six (the Coast*Link* network) with each group learning from the other's experiences of ICZM (Bayliss and Moore, 2000).

An initial step in this is to assess the degree of integration between existing plans. These include Shoreline Management Plans (SMPs), which, despite being sectoral, aim to give a holistic view of environmental management by referring to other plans. The SMP that refers to the study area is the Rame Head to Lizard Point SMP. One of its four volumes is a 'Studies and Reports' section (Halcrow, 1999) containing an information database. Some of the entries in this database were used as part of the metadatabase to be accessed by COAMES in this case study. Another plan relevant to the study area was the Strategic Guidelines produced by the Fal Bay and Estuaries Initiative (FBEI). The role of the FBEI is to help coastal management by building on the strengths of previous initiatives. Although plans such as these had been locally successful in meeting their objectives, a major role of the ALC project was to bring these plans into an integrated regional context (Bayliss and Moore, 2000).

The Coastal Information Focus Group (CIFG)

The Coastal Information Focus Group was one of four subgroups feeding into the overall ALC project. Its role was to identify and review the then current coastal information resource status of Devon and Cornwall, and to recommend a coastal zone management information strategy for those counties. These activities were supported by a demonstration metadata access system, produced by the author.

This was achieved through a three-stage process. Firstly, an audit of available coastal data and information in the ALC area was undertaken (see section 5.3). The findings of this audit were used to develop three software templates demonstrating methods of access to coastal information (Moore *et al.*, 2000). This marked the start of an evolutionary prototyping process, where the projected users of a software system were actively involved in its development (Kay, 1999). Explicitly, this was enabled through a consultative seminar (stage two), where the templates along with the results of the audit were presented to assorted coastal zone managers. The feedback received was used to build a set of recommendations and the final demonstration system (stage three).

Figure 5.2 shows the ALC demonstration metadata access system (ALC, 2001). The system gives a choice of query modes: map (as shown), dialogue and list, each of which correspond to the mode of access demonstrated by the original templates. As a result of the query, the list of available metadatasets (on the right) is modified and available to be displayed - most of the buttons along the top represent a category of metadata (these categories are detailed in section 5.3) (Moore *et al.*, 2000).

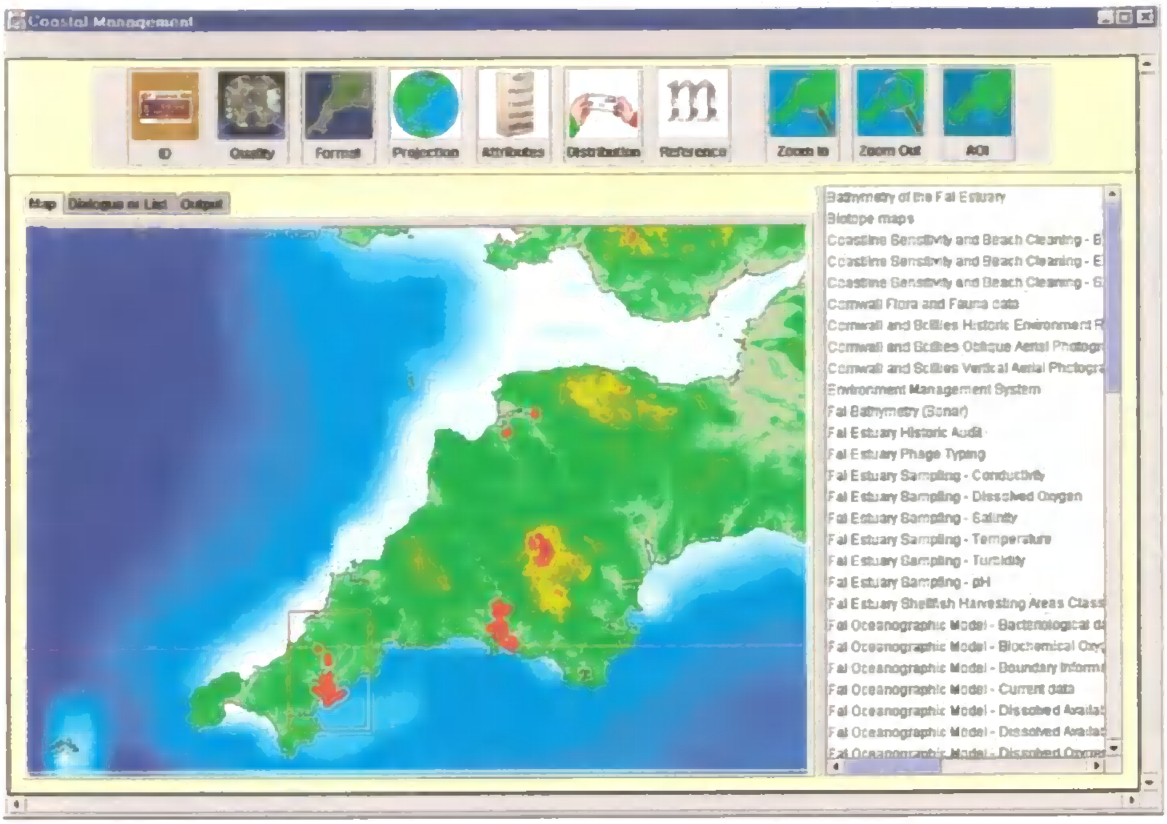


Figure 5.2: The Atlantic Living Coastlines Metadata Access System. The list of available metadatasets is on the right, ready to be accessed through the map query mode.

5.2.4 Overview

This chapter describes a use of the COAMES expert system through the holistic paradigm. Such an approach was not evident in the Holderness case study discussed in Chapter 4. Though the previous case study has shown what can be achieved through use of rules, it does not depict the full picture. It does not try to attain a holistic approach, one of the main aims of the thesis. Although the Holderness example uses a number of technology types (demonstrating a type of holism), it is location-specific, and concerned solely with natural environmental data, information and knowledge. Therefore, the technology used therein was not easily portable. It is proposed here that metadata can enable this portability, as a way of navigating the huge amount of fragmented coastal data, information and knowledge that exist.

To prove the power of metadata, COAMES will be tested on a coastal metadataset describing the Fal Estuary data encompassing both natural environmental and socio-economic themes, and at a variety of spatial and temporal scales. Part of the reason for choosing the Fal Estuary as a case study area is historical, as this area was one of the case study areas for the ALC project. Other factors (most of which influenced the Fal's selection in its original ALC context) include an abundance of multidisciplinary data of different temporal and spatial magnitudes, applicability to the coastal zone manager and portability. Metadata itself is also prevalent in CZM information management across the globe, so it is relevant. These reasons are detailed in section 1.3.2.

Five tests were set to prove the efficacy of expert system (and by extension its inferencing mechanism, the Dempster-Shafer [D-S] theory of evidence), in terms of value for the coastal zone manager and capturing the essence of holism. The first investigates straightforward belief in a rule - if evidence supports the rule then the belief is updated (see section 3.9.1 for explanations of these D-S terms). With the second test, conflicting belief in another, independent, rule is introduced, allowing a critique of linkages within the expert system. Furthermore, the new evidence is weighted with a large ignorance value (i.e. there is not much confidence in this rule), inviting pathways to holism (ignorance measures what is *not* known, an appreciable part of the whole picture). The third test adds further support for the weaker rule. The next test again assesses the effectiveness of links within the expert system, but in a hierarchical fashion. It assesses the effectiveness of a superset (consisting of two or more amalgamated rules to create another rule with its own belief) on its subsets, and vice versa. Finally, the explicit use of belief against a rule will be assessed, giving an idea of how links can be suppressed.

5.3 Metadata

5.3.1 Definitions

Metadata is 'designed for description of the contents of a data set' (Goodchild, 1998) or put simply, it is 'data about data'. As such, it gives a general overview of the dataset it describes, and is therefore ideally placed to be the mode of linkage (in conjunction with stored knowledge) to provide a holistic capability to COAMES. Indeed, it is a way of bringing data together without physically integrating them (Moore *et al.*, 2000). Metadata is universally accepted as being essential in data management, to make data useful through the description (Busby, 2000) and to aid data discovery (Payne, 2000). Medyckyj-Scott *et al.* (1996) added data transfer and data management to comprise the four functions of metadata. An indication of this importance is the repackaging of ESRI ARC/INFO in v.8 (1999), which includes metadata as a key component in its data management program, ArcCatalog (ESRI, 2001).

5.3.2 Metadata Collection

The metadataset used was originally collected for the Atlantic Living Coastlines project by the author, then working as the project information officer. A short questionnaire was sent to a large number of coastal zone managers in Devon and Cornwall (working in local authorities, fisheries, leisure, local wildlife trusts, national environmental institutions, as well as academics, estuary managers and harbour masters). The questionnaire responses were augmented by a series of meetings with the data holders, where data and information bases were described in further detail to fill in various categories of metadata (see section 5.3.3).

The metadatabase was supplemented by the information database in the Rame Head to Lizard Point Shoreline Management Plan (Halcrow, 1999). The subject of the information described therein was on a broad range of coast-related topics, particularly if it was relevant to coastal defence planning. The fields in the database are similar to those in the metadata standard described in the next section: Title / Subject of data, Date, Area (in terms of sediment subcells - e.g. Fal Estuary = 6D-4), Format, Topic, Content, Author, Source, Availability.

5.3.3 Metadata Standards

An overview of selected metadata standards is given in section 2.2.5. The standard used by the ALC project for their metadata was that of the Federal Geographic Data

Committee (FGDC, 2001). It is perceived to be normal for organisations to continue to establish their own standards, while aligning themselves in principal to the seven broad categories shown in Table 5.1 (adapted for ALC metadata). An example of a metadataset is shown in Box 5.1.

Category		Field 1	Field 2	Field 3	Field 4	Field 5
Identification Information	Field	Title	Geographical Coverage	Time Period	Level of Access	
	Details	Title of the dataset being described	The dataset's geographical extent (placename)	The period of time for which the data was collected	Level of access to the data for outside enquirers	
Quality Information	Field	Temporal Quality	Spatial Quality	Attribute Quality		
	Details	Frequency with which data is collected	Spatial accuracy of the data	Accuracy of the attribute being measured (function of the measuring instrument)		
Format Information	Field	Data Format	Functions			
	Details	About the data format, analogue or digital. If digital - GIS (raster / vector), spreadsheet, database etc.	If there is data behind the metadata, this field lists the functions that can be applied to the data.			
Geographical Projection	Field	Projection				
	Details	About the geographical projection				
Attribute Information	Field	Category	Attribute Name	Attribute Details		
	Details	The discipline group to which the attribute belongs	The attribute name	Any details about the attribute (e.g. units of measurement)		
Distribution Information	Field	Owner of Dataset	Charges	Supply Format	Restrictions	Originator of Dataset
	Details	Current person with the dataset	Any charges to be paid when acquiring the dataset	Range of supply formats	Any restrictions on the dataset's use	The person who originally created the dataset
Metadata Reference	Field	Logger	Last Update			
	Details	Person who collated and logged the metadata	Date on which the metadata was last updated			

Table 5.1: Metadata categories, fields and details, based on the FGDC standard (2001).

IDENTIFICATION

Title: Metals in Water, Sediments and Biota - Arsenic
Geographical Coverage: Fal Estuary and Restronguet Creek
Time Period: 1/1/1992 - 1/1/1999
Level of Access: Highly restricted unless already published

QUALITY

Temporal Quality: Sporadic - ranging from 4 times in 2 months (high tide and low tide at springs and neaps) to annual data collection
Spatial Quality: +/- 1km. (based on Ordnance Survey six figure grid reference)
Attribute Quality: +/- 20% [measured with Atomic Absorption Spectrometer]

FORMAT

Geographical Format: Vector - Fixed vertical point / Transects up and down estuary
Data Format: Mostly Microsoft Excel spreadsheets, and notebooks

GEOGRAPHICAL PROJECTION

Projection: Ordnance Survey - Transverse Mercator

ATTRIBUTE INFORMATION

Category: Metals
Attribute Name: Arsenic
Attribute Details: Parts Per Billion

DISTRIBUTION INFORMATION

Owner of Dataset:
Dr.Bill Langston
Metals Ecotoxicologist
Plymouth Marine Laboratory
Citadel Hill
Plymouth
Devon
PL1 2PB

Charges: None
Supply Format: Published Papers
Restrictions: As the data is a part on ongoing work, access is highly restricted unless already published

Originator of Dataset:
Dr.Bill Langston
Metals Ecotoxicologist
Plymouth Marine Laboratory
Citadel Hill
Plymouth
Devon
PL1 2PB

METADATA INFORMATION

Logger: Tony Moore
Last Update: 28/4/1999

Box 5.1: An example metadataset: Metals in Water, Sediments and Biota – Arsenic.

How much a standard is adhered to may be a function of a cost-benefit evaluation (Hootsmans *et al.*, 1992). Certainly, in the case of the ALC project, the resources available dictated that only a selection of fields was used. All metadatasets are stored in ASCII files.

5.3.4 Metadata Groupings

Once collected, the metadata was grouped by theme or discipline into five major thematic groups that feed into coastal zone management - metadata describing chemical data, biological data, physical data, socio-economic data, and data with an explicitly geographical content such as coastlines or topographic maps. These five thematic categories were subdivided into more specific subcategories. The identity of these subcategories was limited to the scope of the collected metadata. For instance, the chemical thematic category was subdivided into nutrients, metals, pollutants and chemistry (i.e. pH, alkalinity). Within these subcategories, there are further divisions. For instance, the metals group is divided into specific metals such as copper and zinc. Again these are limited to the scope of the collected metadata. The full breakdown of the metadata categorisation is shown in Figure 5.3.

The Θ at the top of the diagram reflects terminology used by the Dempster-Shafer theory of belief, which is the inferencing method employed by COAMES (see section 3.9.1). It represents the frame of discernment (a set of objects) that takes all the metadata categories into account. There will be more on Dempster-Shafer in the next section.

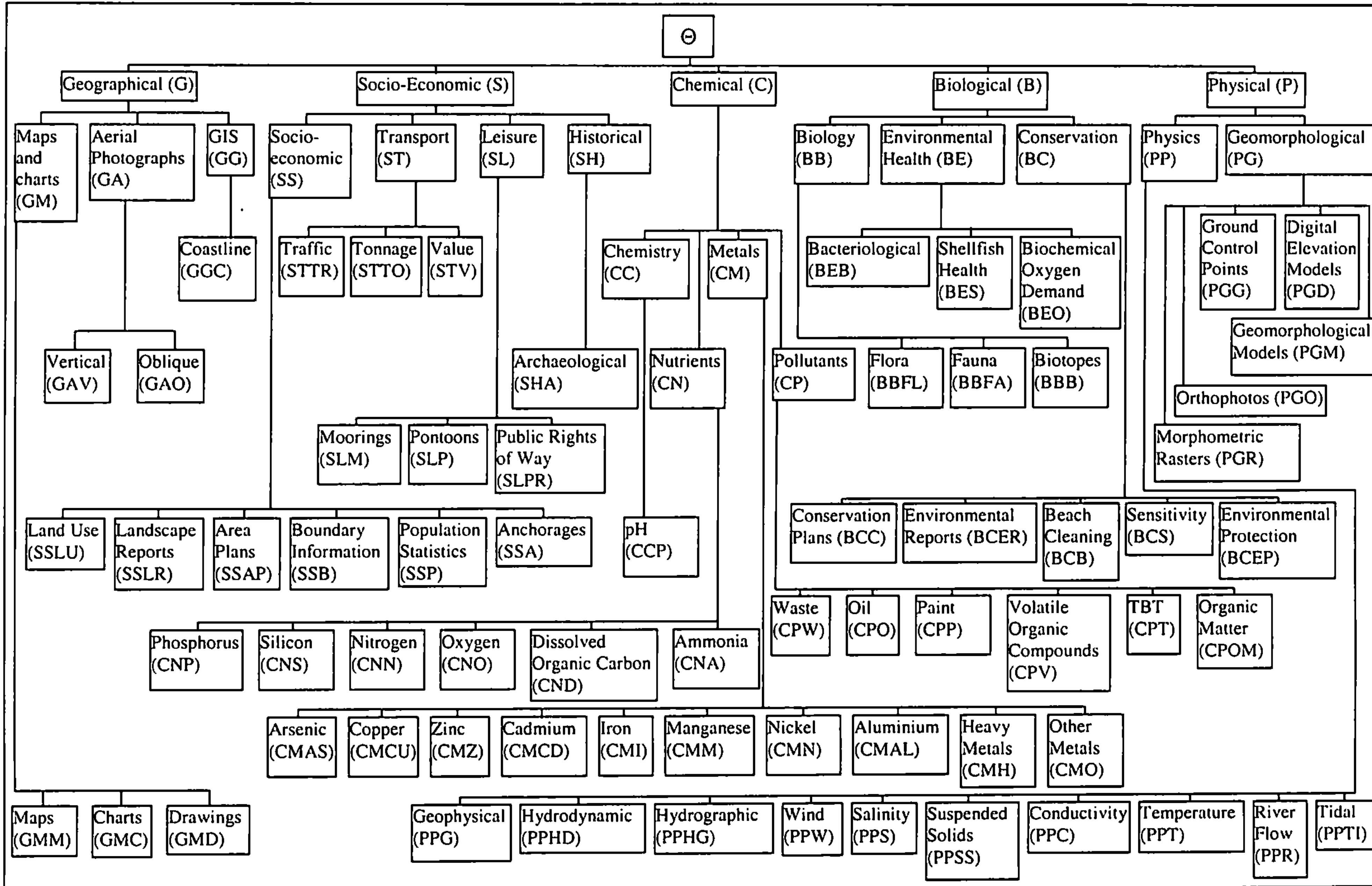


Figure 5.3: The full breakdown of metadata categories. Thematically, parts of this hierarchy are an extension of the object-oriented hierarchy shown in Figure 3.7.

5.4 Use of the Expert System

5.4.1 Rule and Frame of Discernment Overview

Each element of the hierarchy shown in Figure 5.3, such as 'biological', 'metals' and 'vertical aerial photography' is an object with associated rules. The rules are used to process user input to extract the correct metadata from the metadatabase. This process normally occurs as a prelude to the rule-led data and model processing described in Chapter 4. In all, there are five top-level rules, 16 middle-level rules and 68 bottom-level rules (Figure 5.4).

The hierarchy in Figure 5.3 was also split into frames of discernment (see section 3.9.1 for definition), within which groups of rules process user input through inferencing with uncertainty (using the Dempster-Shafer theory of belief). The frames of discernment (FoD) are represented in Figure 5.4. In all there is one top-level FoD, five middle-level FoDs and 16 bottom-level FoDs.

5.4.2 The Rule Hierarchy

Refer to Figure 3.20 for more detail on the following. The user query (for example "I am interested in metals, particularly arsenic") was initially compared with the terms in the dictionaries to identify and extract important words (i.e. words of relevance to the content of the knowledge base).

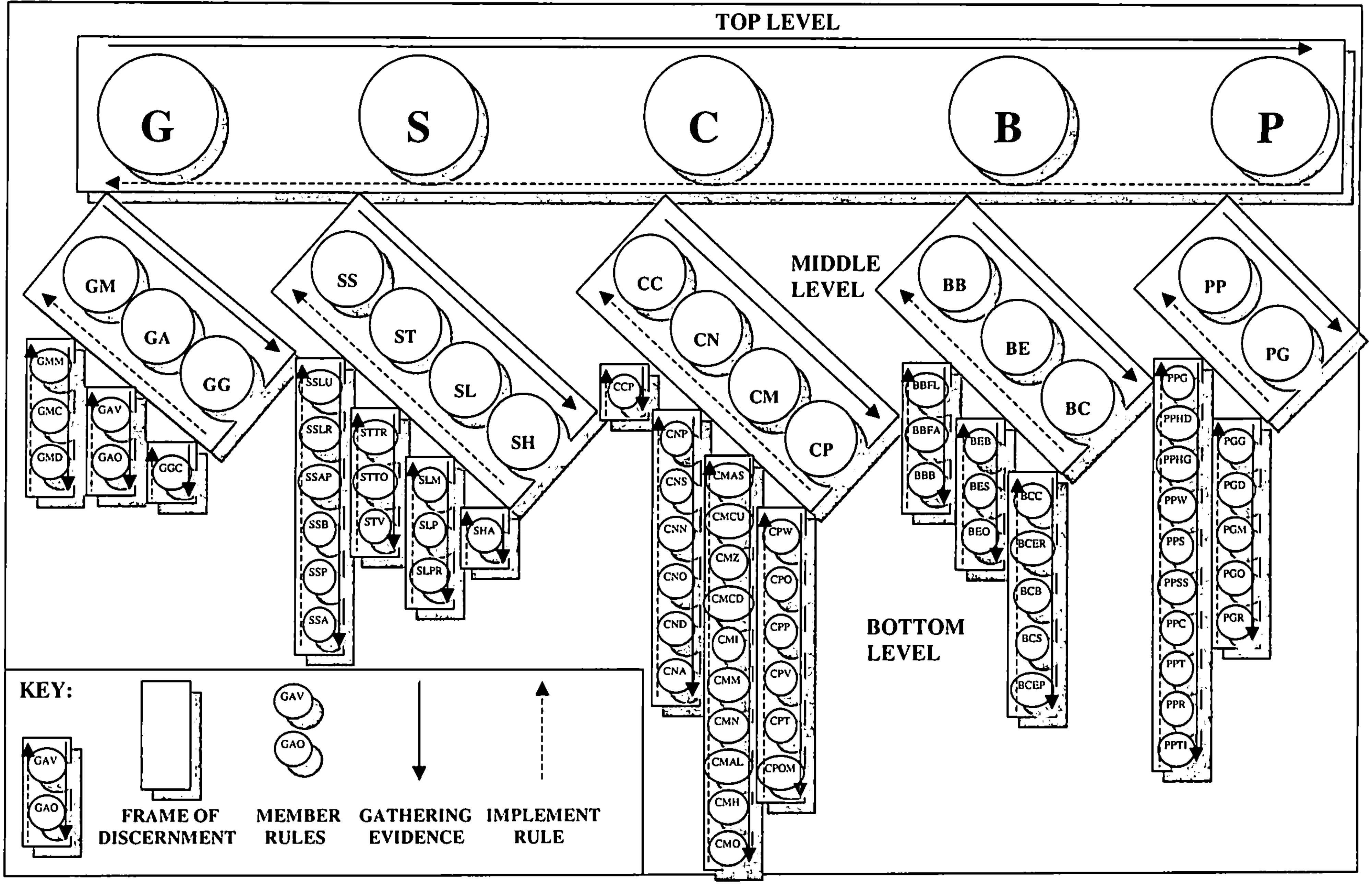


Figure 5.4: The arrangement of frames of discernment and rules, based on the hierarchy in Figure 5.3. This figure does not include endrules. For a guide to the codes see Figure 5.3.

There was a dictionary corresponding to each of the rules on the top two tiers in Figure 5.4 (there was also a corresponding class definition). The link between dictionary and rule was stored as an attribute within the rule itself (see Figures 3.15 and 3.16 for the internal structure of a rule).

The first frame of discernment was set, that containing the geographical, socio-economic, chemical, biological and physical themes. The FoD was traversed in that order - this is the evidence gathering phase. If there was a match between an item in the user query and a particular dictionary term, then the belief in that rule was updated. For example, in the case of the geographical theme, dictionary terms included 'geography' and 'spatial'. Belief in the geographical theme was zero (i.e. $Bel(\{geographical\}) = 0$), though the basic probability assignment (BPA) was $m(\{geographical\}) = 0.8; m(\Theta) = 0.2$. Should there have been evidence supporting the geographical theme, the belief would have been updated with the BPA (see section 3.9.1 for example calculation).

Once the 'end' rule was reached, the FoD was traversed in the opposite direction, back towards the geographical theme. The belief in each rule was assessed, and, if sufficient (*e.g.* greater than the threshold value if used), the tier below was accessed. From the physical theme rule, a new FoD was set up, consisting of physics and geomorphological rules. The evidence gathering was started again, this time with the new rules. This process was repeated until the geographical theme rule was returned to.

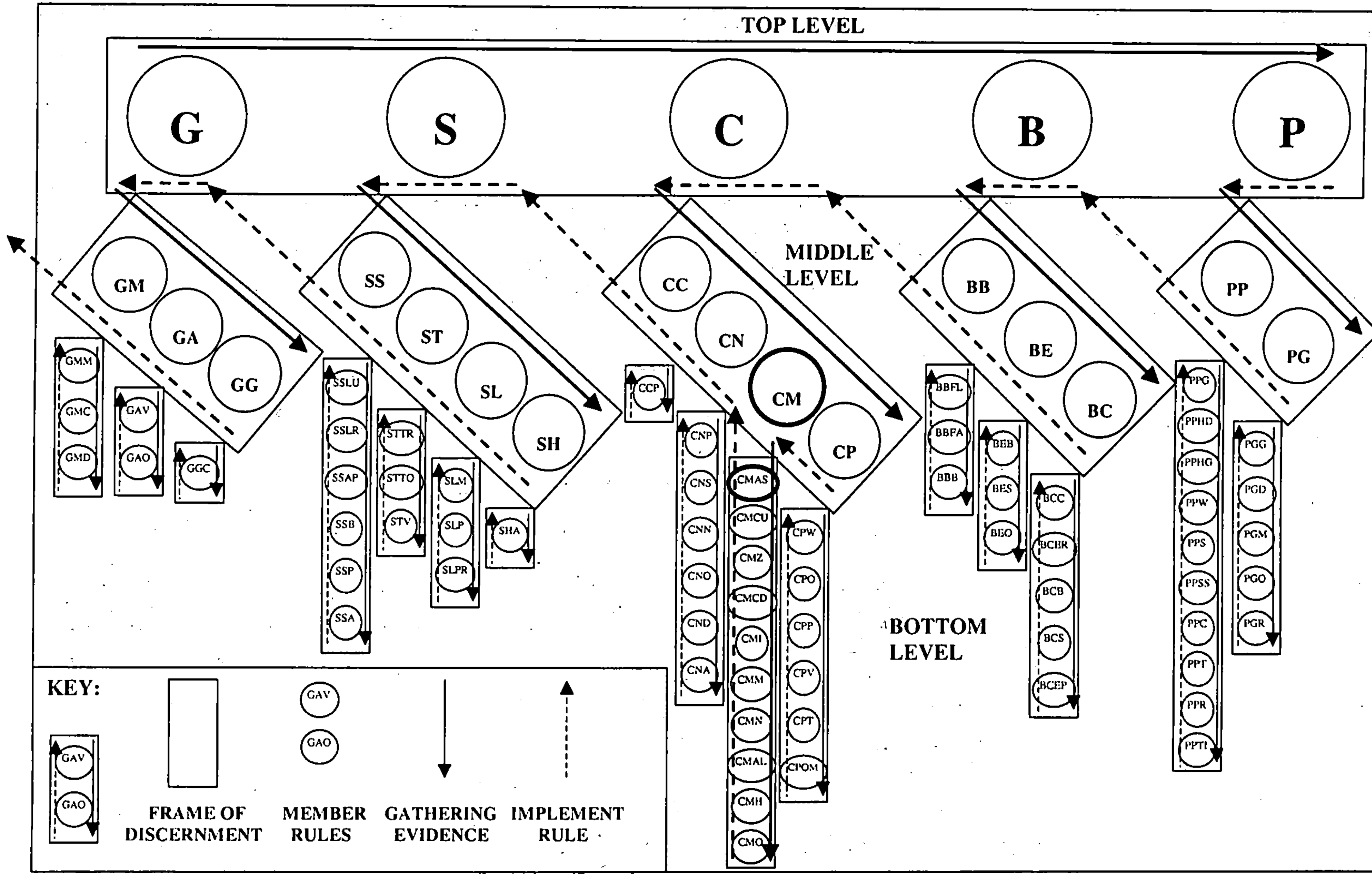


Figure 5.5: Passage through the hierarchy, based on a query concerning metals (CM) and arsenic (CMAS). The relevant rules have been fired.

Figure 5.5 shows the results of the featured query. It shows that belief was sufficient to fire rules where the important words in the user query (i.e. 'metals' and 'arsenic') matched the relevant dictionary terms. Attributes within the fired rules were subsequently used to extract metadata relevant to the original query.

5.5 Results

As specified in section 5.2.4, five progressively more challenging tests were put to COAMES. These tests are represented in Figure 5.6. They explored the use of the Dempster-Shafer inferencing mechanism for combining evidence provided from a user query, using the result to optimally and intelligently select coastal metadata related to the query. The following account does not go into mathematical detail - section 3.9.1 has a simple worked example and definitions of the basic terms. For the five tests, the 'metals' frame of discernment (FoD) will be used. There is a threshold belief that applies to all rules (*e.g.* arbitrarily set to 0.25 in this case) - this has to be exceeded for a rule to fire. The threshold can be raised or lowered, depending on how tight or loose the user wants the metadata search to be.

Metadata selection based on straightforward belief

This scenario uses a single rule based on a simple query. The members of the FoD are rules concerning the selection of arsenic, copper, zinc, cadmium, iron, manganese, nickel, aluminium, heavy metals and other metals. Each has a basic probability assignment (BPA) of $m(\{X\}) = 0.8$ (where X is any FoD member) and $m(\Theta) = 0.2$ (Θ is ignorance).

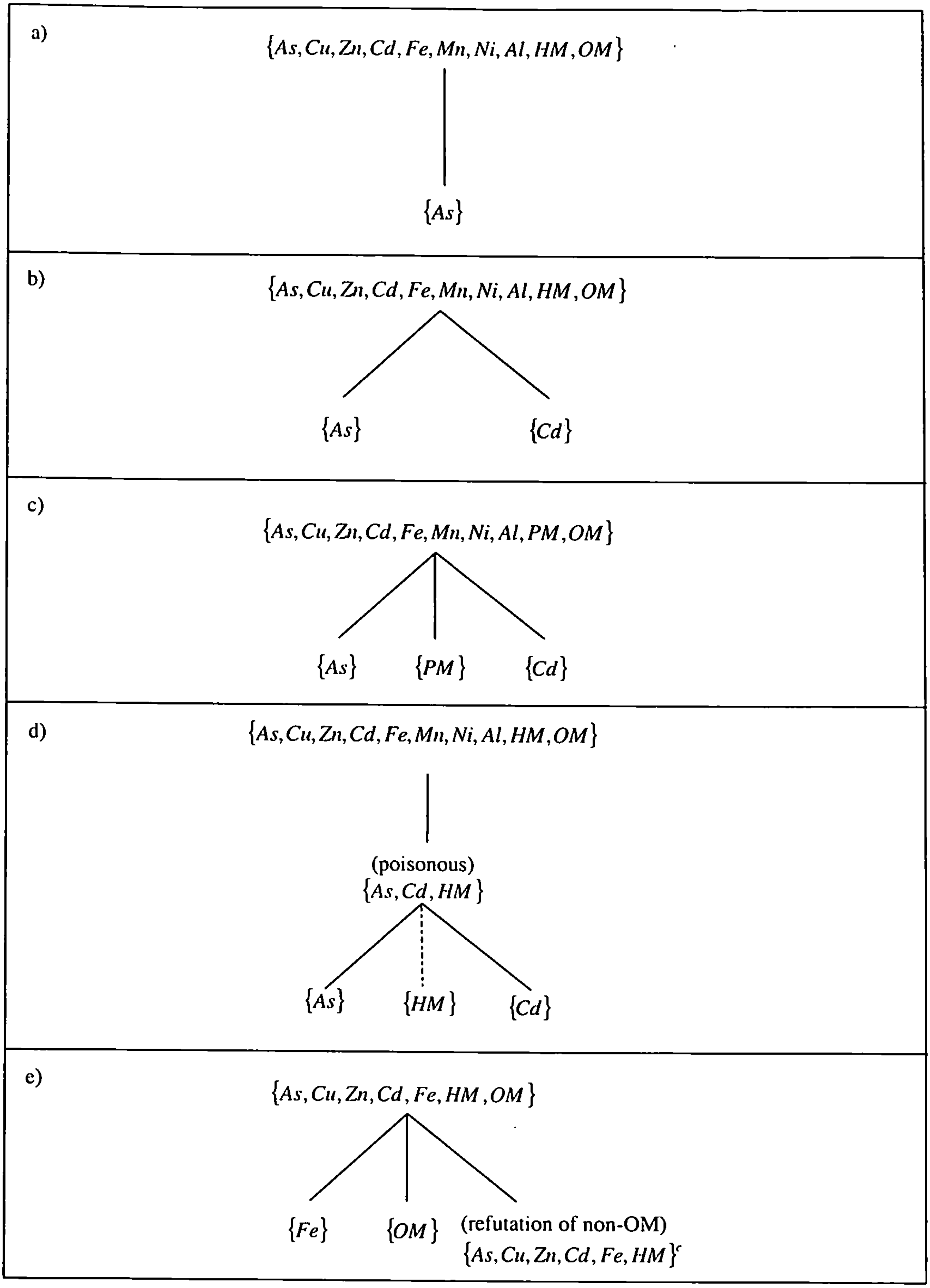


Figure 5.6: Arrangement of rules for which there is belief in the five tests. (a) straightforward belief; (b) competing rules; (c) competing rules (with further support for the weaker rule); (d) the influence of supersets; (e) belief against a rule (refutation). See section 3.9.1 for more details on calculation. (As = Arsenic; Cu = Copper; Zn = Zinc; Cd = Cadmium; Fe = Iron; Mn = Manganese; Ni = Nickel; Al = Aluminium; HM = Heavy Metals; OM = Other Metals; PM = Poisonous Metals).

Therefore, if the user query includes 'arsenic' in its terms then the BPA $m(\{arsenic\}) = 0.8; m(\{\Theta\}) = 0.2$. Since there is no other evidence to add, the calculation of the belief is straightforward - the belief interval of arsenic is [0.8 1.0]. The second number is the upper probability, which reduces as evidence against 'arsenic' mounts up. This is investigated in the next scenario. A full printout of the expert system explanation is shown in Box 5.2. Having exceeded the threshold belief, the arsenic metadata was extracted.

```
Belief Interval of ignorance = [0.000 1.000]
No mention of 'Physics' category in the user query.
Belief Interval of ignorance = [0.000 1.000]
No mention of 'Geomorphological' category in the user query.
No mention of 'Physical' category in the user query.
No mention of 'Biology' category in the user query.
Belief Interval of ignorance = [0.000 1.000]
No mention of 'Conservation' category in the user query.
No mention of 'Environmental Health' category in the user query.
No mention of 'Biological' category in the user query.
No mention of 'Chemistry' category in the user query.
Belief Interval of metals = [0.800 1.000]
Belief Interval of ignorance = [0.200 1.000]
No mention of 'Pollutants' category in the user query.
The 'Metals' category is mentioned in the user query.
Belief Interval of arsenic = [0.800 1.000]
Belief Interval of ignorance = [0.200 1.000]
No mention of 'Other Metals' in the user query.
No mention of 'Heavy Metals' in the user query.
No mention of 'Aluminium' in the user query.
No mention of 'Nickel' in the user query.
No mention of 'Manganese' in the user query.
No mention of 'Iron' in the user query.
No mention of 'Cadmium' in the user query.
No mention of 'Zinc' in the user query.
No mention of 'Copper' in the user query.
From searching available metadata 'Arsenic' are mentioned in the user query.
Metadata Extracted = Metals in Water, Sediments and Biota - Arsenic
No mention of 'Nutrients' category in the user query.
No mention of 'Chemical' category in the user query.
No mention of 'Socio-Economic' category in the user query.
Belief Interval of ignorance = [0.000 1.000]
No mention of 'Historical' category in the user query.
No mention of 'Leisure' category in the user query.
No mention of 'Transport' category in the user query.
No mention of 'Socio-Economic' category in the user query.
No mention of 'Geography' category in the user query.
Belief Interval of ignorance = [0.000 1.000]
No mention of 'GIS data' category in the user query.
No mention of 'Aerial Photography' category in the user query.
No mention of 'Maps and Charts' category in the user query.
```

Box 5.2: Expert system output for straightforward belief.

This scenario uses two rules, one with a high BPA (as in the last scenario), and one with a low BPA (and correspondingly a large component of ignorance). This arrangement can be used to represent metadata that respectively have high and low confidence levels. The members of the FoD are the same as the last test. The BPAs are also the same, except for that of arsenic, which has been reduced to $m(\{arsenic\}) = 0.25; m(\{\Theta\}) = 0.75$ to indicate dataset(s) of poor quality. The BPAs of two different rules (the other is for cadmium metadata) now have to be combined, with resulting belief intervals of [0.063 0.250] for arsenic and [0.750 0.938] for cadmium, as well as an ignorance value of 0.188. The shortened printout for this scenario in Box 5.3 shows that metadata was only extracted for cadmium because of the poor belief in arsenic. The upper probability (also called the plausibility) for arsenic is also low due to the correspondingly high belief in cadmium, which in Dempster-Shafer terms is used as evidence to refute arsenic. The uncertainty in belief (the difference between the belief and plausibility) for the two rules is the same.

```
No mention of 'Biological' category in the user query.
No mention of 'Chemistry' category in the user query.
Belief Interval of metals = [0.800 1.000]
Belief Interval of ignorance = [0.200 1.000]
No mention of 'Pollutants' category in the user query.
The 'Metals' category is mentioned in the user query.
Belief Interval of arsenic = [0.063 0.250]
Belief Interval of cadmium = [0.750 0.938]
Belief Interval of ignorance = [0.188 1.000]
No mention of 'Other Metals' in the user query.
No mention of 'Heavy Metals' in the user query.
No mention of 'Aluminium' in the user query.
No mention of 'Nickel' in the user query.
No mention of 'Manganese' in the user query.
No mention of 'Iron' in the user query.
From searching available metadata 'Cadmium' are mentioned in the user query.
Metadata Extracted = Metals in Water, Sediments and Biota - Cadmium
No mention of 'Zinc' in the user query.
No mention of 'Copper' in the user query.
No mention of 'Arsenic' in the user query.
No mention of 'Nutrients' category in the user query.
No mention of 'Chemical' category in the user query.
No mention of 'Socio-Economic' category in the user query.
```

Box 5.3: Expert system output for competing rules.

Metadata Selection with competing rules (with further support for the weaker rule)

A third rule is added to the previous scenario; this rule has an equivalent BPA to that of arsenic. The members of the FoD are the same as previously except for the 'heavy metals' rule, the scope of which has been expanded so that it now encompasses all 'poisonous metals' (which becomes the rule's new name). For this rule, there is a single BPA supporting arsenic to the same weak magnitude as in the last scenario (*i.e.* $m(\{arsenic\}) = 0.25; m(\{\Theta\}) = 0.75$). The aim is to see if the new evidence significantly increases the belief in arsenic. The results in Box 5.4 show that arsenic now has a belief of [0.135 0.308]. While this increase in belief (also plausibility) is not enough to select arsenic metadata when compared against the current threshold value, yet further evidence for arsenic may render the rule important enough to fire. Though still high, there is a corresponding drop in the level of belief in cadmium to [0.692 0.865]. The ignorance and uncertainty have also been reduced slightly by the introduction of the fresh evidence.

```
No mention of 'Biological' category in the user query.
No mention of 'Chemistry' category in the user query.
Belief Interval of metals = [0.800 1.000]
Belief Interval of ignorance = [0.200 1.000]
No mention of 'Pollutants' category in the user query.
The 'Metals' category is mentioned in the user query.
Belief Interval of arsenic = [0.135 0.308]
Belief Interval of cadmium = [0.692 0.865]
Belief Interval of ignorance = [0.173 1.000]
No mention of 'Other Metals' in the user query.
No mention of 'Poisonous Metals' in the user query.
No mention of 'Aluminium' in the user query.
No mention of 'Nickel' in the user query.
No mention of 'Manganese' in the user query.
No mention of 'Iron' in the user query.
From searching available metadata 'Cadmium' are mentioned in the user
query.
Metadata Extracted = Metals in Water, Sediments and Biota - Cadmium
No mention of 'Zinc' in the user query.
No mention of 'Copper' in the user query.
No mention of 'Arsenic' in the user query.
No mention of 'Nutrients' category in the user query.
No mention of 'Chemical' category in the user query.
No mention of 'Socio-Economic' category in the user query.
```

Box 5.4: Expert system output for competing rules (with further support for the weaker rule).

In Dempster-Shafer theory, groups of FoD members can be formed (supersets) to create a new hypothesis with corresponding BPA / belief. The FoD in this scenario is the same as for scenarios 1 and 2 (*i.e.* the 'heavy metals' member has been reinstated). However, in taking the 'poisonous metals' entity further, a new superset with that name has been formed, consisting of the 'arsenic', 'cadmium' and 'heavy metals' members. The BPAs assigned to arsenic are as follows:

$m(\{arsenic\}) = 0.5; m(\{poisonous = arsenic, cadmium, HeavyMetals\}) = 0.4; m(\Theta) = 0.1$

The assignments for cadmium and heavy metals are the same as this, except for the first BPA, which relates specifically to either cadmium or heavy metals. The user query relates to both arsenic and cadmium, with an overall scenario aim of seeing whether or not the poisonous metals assignment linked with each will lead to the selection of heavy metals metadata. Box 5.5 displays the results of this scenario - both arsenic and cadmium have a belief interval of [0.333 0.667]. The 'poisonous metals' superset has a belief interval of [0.987 1.000], which is enough to extract metadata for all its members, including 'heavy metals'. The high belief and plausibility is because both arsenic and cadmium are subsets of poisonous metals and are therefore added onto the belief of that group. For the same reason they do not refute 'poisonous metals', leaving the plausibility at one. Note also that the belief from the superset does not get added onto the belief of each subset.

```
No mention of 'Biological' category in the user query.
No mention of 'Chemistry' category in the user query.
Belief Interval of metals = [0.800 1.000]
Belief Interval of ignorance = [0.200 1.000]
No mention of 'Pollutants' category in the user query.
The 'Metals' category is mentioned in the user query.
Belief Interval of arsenic = [0.333 0.667]
Belief Interval of cadmium = [0.333 0.667]
Belief Interval of arsenic or cadmium or heavy metals = poisonous = [0.987 1.000]
Belief Interval of ignorance = [0.013 1.000]
No mention of 'Other Metals' in the user query.
From searching available metadata 'Heavy Metals' are mentioned in the user query.
Metadata Extracted = Falmouth Inner Harbour Environmental Data - Heavy Metals
No mention of 'Aluminium' in the user query.
No mention of 'Nickel' in the user query.
No mention of 'Manganese' in the user query.
No mention of 'Iron' in the user query.
From searching available metadata 'Cadmium' are mentioned in the user query.
Metadata Extracted = Metals in Water, Sediments and Biota - Cadmium
No mention of 'Zinc' in the user query.
No mention of 'Copper' in the user query.
From searching available metadata 'Arsenic' are mentioned in the user query.
Metadata Extracted = Metals in Water, Sediments and Biota - Arsenic
No mention of 'Nutrients' category in the user query.
No mention of 'Chemical' category in the user query.
No mention of 'Socio-Economic' category in the user query.
```

Box 5.5: Expert system output showing the effect of supersets.

Metadata Selection using belief against a rule

It has already been seen that, in D-S theory, members that are not in common (e.g. {arsenic} and {cadmium}; {iron} and {arsenic,cadmium}) are used to refute one another. The last scenario deals with this refutation explicitly. The FoD in this scenario is the same as for scenarios 1 and 2, except that the manganese, nickel and aluminium members have been absorbed into 'other metals'. The aim is to show what happens when a member (*i.e.* other metals) is chosen to the exclusion of all others. This is based on the premise that evidence for 'other metals' negates belief in any other member in the FoD. The BPAs for 'other metals' are as follows: $m(\{OtherMetals\}) = 0.5; m(\{arsenic, copper, zinc, cadmium, iron, HeavyMetals\})^c = 0.4$ (NOT arsenic or copper or zinc or cadmium or iron or heavy metals); and $m(\Theta) = 0.1$.

In addition we have a competing BPA for the iron member: $m(\{iron\}) = 0.6; m(\Theta) = 0.4$. Box 5.6 shows the results of the user query (concerning iron and manganese as an example of 'Other Metals'). Iron has been suppressed effectively with a belief interval of [0.130 0.217], whilst the relatively high 'other metals' member ([0.435 0.870]) has a further influence by feeding into the 'NOT As/Cu/Zn/Cd/Fe/heavy metals' superset to give [0.783 0.870].

```
No mention of 'Biological' category in the user query.
No mention of 'Chemistry' category in the user query.
Belief Interval of metals = [0.800 1.000]
Belief Interval of ignorance = [0.200 1.000]
No mention of 'Pollutants' category in the user query.
The 'Metals' category is mentioned in the user query.
Belief Interval of iron = [0.130 0.217]
Belief Interval of other metals = [0.435 0.870]
Belief Interval of NOT arsenic or copper or zinc or cadmium or iron or
heavy metals = NOT As/Cu/Zn/Cd/Fe/heavy metals = [0.783 0.870]
Belief Interval of ignorance = [0.087 1.000]
From searching available metadata 'Other Metals' are mentioned in the
user query.
Metadata Extracted = Metals in Water, Sediments and Biota - Manganese
No mention of 'Heavy Metals' in the user query.
No mention of 'Iron' in the user query.
No mention of 'Cadmium' in the user query.
No mention of 'Zinc' in the user query.
No mention of 'Copper' in the user query.
No mention of 'Arsenic' in the user query.
No mention of 'Nutrients' category in the user query.
No mention of 'Chemical' category in the user query.
No mention of 'Socio-Economic' category in the user query.
```

Box 5.6: Expert system output showing the effect of refutation.

5.6 Commentary

5.6.1 Results

The first test really does little more than if there was no method used to inference with uncertainty. What is important here is the introduction of *ignorance*, as it is stated in the Dempster-Shafer theory of belief. It is a truth that holism is an unattainable goal, since anyone modelling a domain cannot hope to totally represent that domain in all its complexity. Holism can be represented as a target, and the aim is to get as close as possible to that ideal. This, along with identifying pathways towards holism is one of the aims of COAMES.

What ignorance does is to introduce a means by which the unknown can be quantified, effectively providing one such pathway to holism. What the expert perceives is missing from the expert system rules and the metadata behind them can be represented by a proportion (a number between 0 and 1). The methods by which this figure is actually reached is another matter.

Another important facet of holism is integration. The way that Dempster-Shafer theory links different rules (via its combination method and hierarchy of supersets) satisfactorily attains this integration. Especially important in ICZM are causal relationships - the methods available here can effectively model these. For example, tests two and three have shown what happens when two rules of differing belief magnitude are combined. As expected, the weaker rule does not fire, even when further evidence is introduced. Eventually, with evidence mounting, the rule will be deemed important enough to fire, conforming to the deductive process.

Test four examines the other method of linkage, where specific rule members are grouped together to produce a new rule hypothesis. Returning to the original definition of holism (section 2.1.1), this grouping method demonstrates that two or more specific rule members considered alone cannot predict the properties of a grouping of those rule members. To exemplify, Simmons and Cox (1985) use the properties of hydrogen and oxygen versus the liquid properties of water, which is a grouping of those two gases. Although the BPAs assigned to the 'poisonous metals' superset and its subsets are probably too high (more testing is needed here), it shows clearly how effective this hierarchical link is. The firing of the 'poisonous metals' rule resulted in the firing of the 'heavy metals' rule beneath it in the hierarchy. This downward expression of belief is another step towards the hierarchical passing of belief demonstrated by Shafer and Logan (1987). However, until full hierarchical capabilities are reached, inferencing will always be limited by the members of the FoD (*i.e.* a 'metals' member cannot directly be compared with a 'nutrients' member). This arrangement is a barrier to achieving full integration, and therefore a hindrance to the system being useful in aiding ICZM. A way round this could be to put every single rule in the same FoD, but this would be cumbersome if the number of rules rose above a certain amount, not to mention being computationally inefficient. The hierarchy is an efficient structure because it cuts time by omitting searches of whole chains if there is not enough evidence to support it.

The fifth test covers explicit refutation of a rule (refutation of rules has already occurred in tests 2-4 simply by there being two or more opposing rules present). Although the example given is highly unlikely, it would be easy to see where the power to refute would be useful in ICZM. With two rules concerning an increase in algae presence and fish productivity, for instance (or relating to the example in Chapter 4; the topological relationship of the upper beach and the sea at low tide), a belief in the first would negate the other. Test five demonstrates this effectively.

The uncertainty element of D-S (i.e. the difference between the belief and plausibility) has been underplayed throughout this chapter, as belief in the rules is not sufficiently complex for uncertainty to differ from rule to rule (*i.e.* in the featured tests it is normally equivalent to the ignorance). Uncertainty would come to the fore when using more FoD members in a variety of groupings to produce a range of supersets.

The setting of a threshold value is in this case quite arbitrary, but with increasing use of the system it can be tweaked with some accuracy to give a group of results that exactly meet the query, to a larger group of results that includes the previous group along with looser matches. It is up to the user to define this threshold level, which can change with the unique circumstances surrounding each query. In this way it is a very useful ability to have.

5.6.2 How COAMES Faces the Challenges of Being Holistic

The following acknowledges four major ways in which COAMES approaches holism:

- scale
- disciplines and institutions
- data, information and knowledge
- technology

The ways that are of relevance to Chapter 5 will be discussed here. Technology, in particular, will be discussed in section 6.5.

Along with uncertainty, which has been discussed in detail in section 5.6.1, scale is one of the greatest challenges to adopting a holistic approach, according to the list provided by Bartlett *et al.* (1992) and Kucera (1995). Overcoming both these challenges is central to COAMES.

What we have seen in the case study is that the system can operate at a variety of spatial and temporal scales, but without explicitly addressing the question of scale (the theme of the metadata has been the search criteria). Comparison of placenames in a user query with those that may lie in the metadata will link the user and selected metadata on a common scale level (*i.e.* the placename itself is an indication of scale), but it is not intelligent and not in keeping with the principles of COAMES. It is suggested here that a further ruleset can be easily created (see Figure 5.7), using a hierarchy of spatial scales, and using the 'Geographical Extent' field of the metadata as a point of comparison. Taken to its most extreme level, the 'world' is the group of all members within this 'spatial scale' frame of discernment, subdividing into various subsets (or supersets of the individual elements). For example, specific members may include 'Falmouth' or 'Truro' whilst the superset 'Fal Estuary' may include these members and more. The number of members need only be as large as the metadata allows. In the same way, a hierarchy of temporal scales can be built (with the 'Period' field of the metadata as a point of comparison), ranging from the geological (*i.e.* millions of years) to fractions of a second.

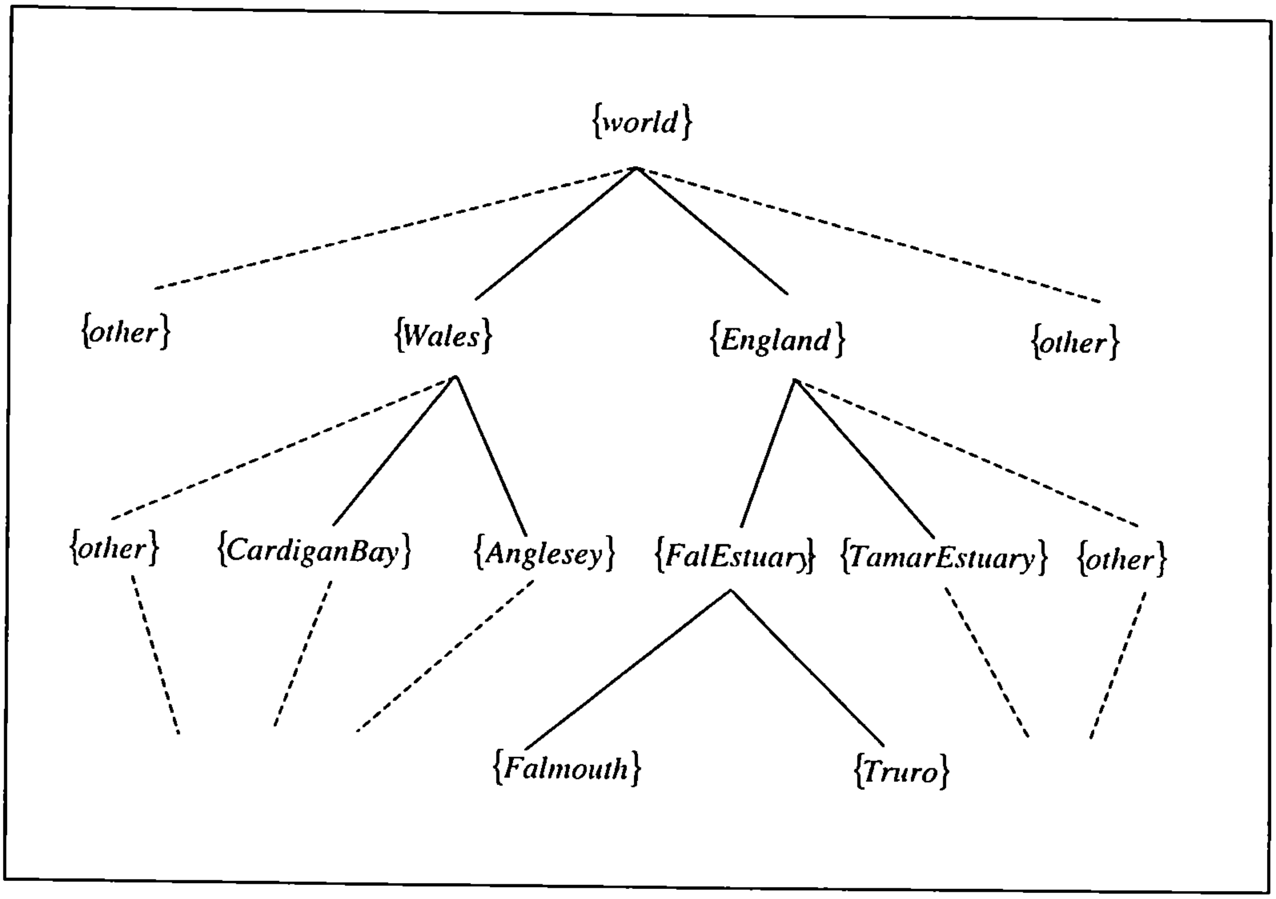


Figure 5.7: How a spatial scale based hierarchy may look. Additional tiers could be added at the continent and county scales.

COAMES approaches the interplay of data, information and knowledge in an integrated manner, as Figure 3.9 has shown. As described in section 3.8, metadata is taken to be a form of information, holding the key to the data and models situated behind it. Knowledge is the interim step, also providing output to the user, and therefore is prevalent in the vast majority of expert system operations. The case studies (particularly Chapter 4, which actually uses the data behind the metadata) has shown that this arrangement works well. A great part of COAMES' approach to holism is using the same rule structure to handle the Holderness data / knowledge and metadata.

The Fal Estuary case study, in particular, was chosen to demonstrate holism across disciplines and institutions, not forgetting integration across the land-sea interface, which is central to ICZM. The treatment of holism in this case is an extension of the ALC metadata access system mechanism, but with added knowledge usage. So again, metadata is the key, and has been shown to succeed in this case study (section 5.6.1 details the evidence).

Other suggestions for pathways from the system to holism include enabling the inference engine to sift through metadata and identifying holes where data should be (this would be represented by the figure given for belief in ignorance). Also, quality assessments should be made on all existing system data and combinations of the same. This would feed through to an overall 'significance' value for each expert system output.

The evidence outlined in this section would suggest that COAMES addresses holism well, and therefore it has relevance to managers practising ICZM. In the past, systems have promised much but delivered little. Taking the example of SPITSIM (King and McCullagh, 1971), a program to simulate spit growth (based on Hurst Castle Spit, Hampshire), limited initial scope, artefact generation in the results and unrealistic future scenarios have reduced the value of the model. What COAMES does to avoid this is to add intelligence to the modelling process - if the system is not performing as it should, then add rules to account for the inconsistency. This would mean more time in system development, but ultimately the manager would have a system that may at least be useful in ICZM. This would be particularly true if the system development went the way of evolutionary prototyping.

5.7 Summary

COAMES, backed up by the Dempster-Shafer inferencing mechanism, has proved adept at intelligently extracting metadata from the Fal Estuary metadataset. Regarding uncertainty and holism, the concept of ignorance is crucial as a pathway to holism. Also important to holism is integration, effected here by methods of rule combination and supersets, demonstrating the properties of the group as opposed to the properties of each of its constituents. The capability of explicitly refuting a rule has also been proved. The Fal Estuary case study effectively demonstrates integration across disciplinary and institutional boundaries, as well as holism in terms of a parsimonious data-information-knowledge structure and use of various technologies. This underlines COAMES' potential value to coastal zone managers, superseding past systems that have lacked the intelligence to give meaningful answers when put into practice.

By way of limitations, the limited belief passing between tiers in the rule hierarchy is a severe handicap to the system's ability to handle holism. A simple solution would be to do away with the hierarchy altogether, which, although achievable with the limited number of rules presently in the system, would not be viable in the long term as the rule base grows and the inferencing process correspondingly becomes more inefficient. The current treatment of spatial and temporal scale, although adequate, is not intelligent and therefore not in keeping with the aims of the thesis. However, simple methods have been suggested that can address this issue.

What we have seen in this chapter is a top-down approach (*i.e.* holistic) to coastal data and information management, as opposed to the bottom-up approach demonstrated in the previous case study. The next chapter combines and assesses all the findings of the two case studies, relating them to the aims and objectives of the thesis, as specified in the introduction.

6: DISCUSSION AND CONCLUSIONS

6.1 Introduction

This chapter draws together the findings of the two case studies and gives a critique of the thesis, assessing how successfully the thesis, and COAMES, has fulfilled the original aims.

6.2 Meeting the Need for Data, Information and Knowledge Management in ICZM

The thesis explores the holism approach to Integrated Coastal Zone Management (ICZM). This paradigm already underlies ICZM in practice, but what is novel is a computer-based approach attuned to this aspect of ICZM (in GeoComputation, Longley [1998] advocates matching technology with the application). COAMES is the digital embodiment of the ideas presented in this thesis.

While ICZM deals with coastal zone management practices and strategies in a holistic fashion, COAMES uses the same approach to address their data, information and knowledge counterparts (this is tested in the case study presented in Chapter 5).

6.2.1 The Operational Context for a Coastal Management Expert System

Parallels apart, the operational context into which a coastal management expert system could be placed is shown in Figure 6.1. The coastal zone manager would liaise with the coastal zone stakeholders via a decision support forum. They would be a source of coastal information, which could be incorporated in the expert system as knowledge, possibly via the Internet (see section 6.3). The decision support forum would have, as its input, products from the system, with associated errors and uncertainties clearly indicated. These could be either scenarios fed in by the manager via dialogue, or, in a future arrangement, from real time output from the system. This may be based on real time data telemetered from the environment as part of a monitoring action cycle. As a result of this process, any incident such as an oil spill or metal discharge could be identified and quantified, with causality established. Evaluation would follow and ameliorative action such as use of booms or chemical dispersion, advocated.

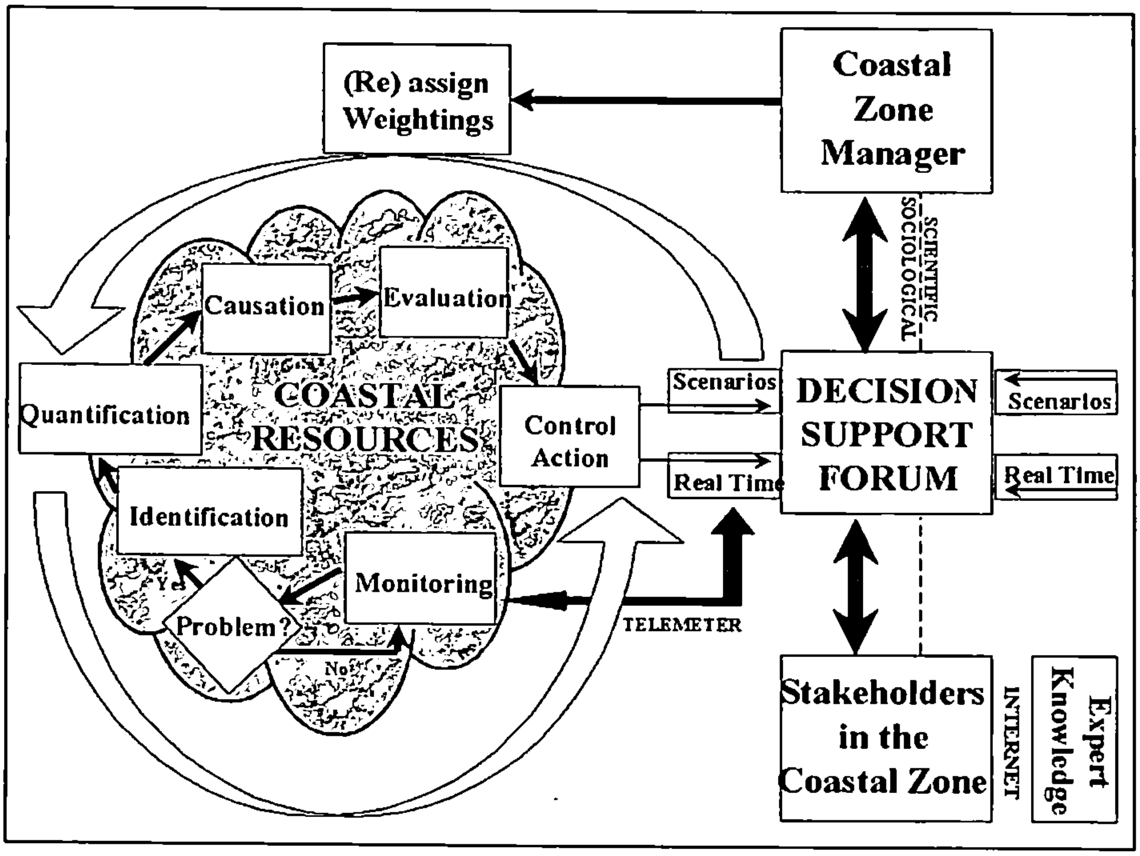


Figure 6.1: An operational view of coastal zone management. The Coastal Zone Manager discusses the scenario to be evaluated with the coastal zone users, aided by decision support output from the system. When action is taken, cyclical monitoring of the environment takes place, with further identification, quantification, causation and evaluation being made whenever a problem arises (elements of figure derived from GESAMP, 1995; Abel, 1996; Agenda 21 leaflet).

Scenario exploration is a valuable activity for the coastal manager. It is useful in forecasting future trends (*e.g.* impact of sea level rise), in playing out conflicts between coastal users, in assessing planning consent applications from those users, and in gauging the future effects of proposed legislation. In all these cases, the coastal zone manager would assign parameters and weightings to represent the scenario. The effects of these would be quantified and some control action recommended. The manager then has the option of either accepting the scenario simulation or adjusting the weightings in preparation for another iterative cycle.

6.2.2 Implications of Coastal Data Management

The role played by data and information is not shown in the above schematic. The massive scale and international priority of this resource has already been acknowledged. COAMES purports to offer management solutions for this resource – how far is this true? What has been shown through the two case studies is that COAMES, through knowledge, can adeptly manage coastal data, using metadata (a form of information) as an entry-level reference layer (with data and associated actions occupying the level below – see Figure 3.9). That COAMES manages data is not out of the ordinary, but when the mode of management, coupled with the unique properties of coastal data (multiple disciplines, formats and locations etc.) is considered, the challenges represented become clear.

The size of the resource accessed by the system is relatively small; the next test would be to attempt management of a larger dataset. This could be all the data unearthed by a Shoreline Management Plan survey (example size is 271 datasets, derived from the Rame Head to Lizard Point scoping study). Even the metadataset from which the Fal Estuary metadata was derived, that of the Atlantic Living Coastlines project, had only about 100 entries, none of which had data behind them. This is due to an overriding problem of access to data and associated issues of copyright and sensitivity, which in this case resulted in metadata collection only (Moore and Moore, 1999). Assuming that a large coastal dataset can be amassed, challenges arising from multi-origin data need to be overcome (this is addressed in section 6.4).

An important issue to be addressed with such a scenario is one of data storage. Current methods of storage employed (ASCII files) are fine for the limited group of data used for this thesis, but will render the expert system process impossibly slow with the larger volumes considered in future growth. This is especially true of data and metadata, which will predictably grow proportionally to the size of the resource. However, the knowledge required to manage the database and metadatabase will not grow in kind – this happens as new items of knowledge are only required when new thematic data groups are introduced (i.e. knowledge is at a level of abstraction above data and metadata).

Once read into the expert system, data and metadata are stored in an object-oriented class structure, so broadly speaking they are stored in an object-oriented (OO) database at run time. Approaches to management of large coastal datasets, metadatasets and the rules or Frames of Discernment (FoDs) that comprise knowledge include the use of an off-the-shelf OO database program (effecting faster retrieval) to be accessed by the expert system at run time (*i.e.* storage in the same structure right up to the point in the program run when a piece of knowledge or metadata or data is needed, as opposed to the current loading from an ASCII file into an OO structure at run time).

An alternative method would be use of a relational database, which would be beneficial for long-term management of large datasets, but is not in keeping with the OO ethos of COAMES. However, in the time frame of the thesis, the use of such off-the-shelf databases was not deemed to be an issue of concern, hence the storage and retrieval method currently employed by COAMES. Finally, the Geography Markup Language (GML) presents another way of disseminating and storing geographical information (OGC, 2001). It has been developed by the OpenGIS Consortium and has recently been adopted by the Ordnance Survey (OS, 2001).

The types of data that the system is expected to handle would expand from the present point vector, raster, background raster and text to include line and polygon vector and perhaps multimedia such as video. Contextual data sets might include coastline (low and high water), land-use, infrastructure, elevation and bathymetry, remotely sensed imagery (aircraft, satellite and video / digital photos) and real-time data such as moorings. As a specific example, Raper *et al.* (1997) used terrain data, descriptions of sedimentary materials, wave height and period data, and tidal stage and flow data in a study of Scolt Head Spit, North Norfolk. The majority of the data will be geospatially referenced and in the case of real-time data a temporal component will also be provided. All such spatio-temporal data will need at least three variables (x,y and t) and frequently four (with the addition of the z dimension).

Data integration will be facilitated by conforming to established standards (e.g. BS7666 - Spatial datasets for geographical referencing: NLPG, 2001). Where possible, each dataset will preferably have an associated error value (Root Mean Square Error, Standard Deviation). RMSE has been provided for the DEM data. Examples of error in a raster image would include spatial (error in xyz) and attribute error (*e.g.* SPM - in remotely sensed imagery this would be related to spectral error), although in some cases (including this thesis) this error information would be included in the metadata. Associated with data integration is the propagation of these error values.

An important capability is to enable easy navigation through the mass of data, information and knowledge, removing the uncertainty or confusion for the decision-maker associated with traversing such a large and diverse resource (Sims, 1998). That way, the science behind the data can be better communicated, and be of real use in the Coastal Zone Management process – this is the subject of the next section.

6.3 Dissemination of Scientific Knowledge

An important aim of COAMES is to make coastal science easily accessible to coastal zone managers. Access to the relevant knowledge allows the manager to adopt the proactive approach postulated by Cooper and Harlow (1998) when taking on the challenges that arise from ICZM.

6.3.1 Using Knowledge for Coastal Data Dissemination

It has been said, "Data does not equal information; information does not equal knowledge; and, most importantly of all, knowledge does not equal wisdom. We have oceans of data, rivers of information, puddles of knowledge and the odd drop of wisdom." (Nix, 1990). The data accessed by COAMES alone is of limited use; it needs the metadata (or information) before it can be put into a geographical, temporal and thematic context. Then the coastal zone manager is able to make an initial decision on whether the dataset being described is useful in tackling a particular problem. Looking at a higher level of description, the information alone is unstructured – a structure is needed to navigate even the small amount of datasets and metadatasets focussed on here. That structure is provided by knowledge in the form of rule hierarchies. These are intelligent ways to enable swift access to the correct metadata for use in ICZM.

Process knowledge is accessed through a combination of metadata and rule-based knowledge. Stored as actions, or functions, processes can be regarded as operating at the same hierarchical level as the data they operate on, since they are both accessed through metadata.

Another view on the same configuration sees two levels of knowledge: these are rule-based, which work with metadata to operate process knowledge. This has been exemplified in Chapter 5, where rules were used to intelligently extract metadata, and Chapter 4, where geomorphological process knowledge was used to classify coastal DEMs. The integrated use of knowledge and metadata to access both data and associated actions has also been applied to the Chapter 4 case study (see section 3.8 and Figure 3.9).

The two types of knowledge can be likened on another level. From Davis *et al.* (1989), models are quantitative mathematical engines, whilst the knowledge base works with the inference engine to form a model of another kind – a logical and qualitative one of the coastal zone management domain. The Chapter 4 case study has already demonstrated the successful parameterisation and implementation of a quantitative model (of Longshore Transport Rate) accessed through logical knowledge (see section 4.6.3). Most importantly, the Holderness case study has also shown how rule-based knowledge (topology, morphometry) has combined with process knowledge (the quantitative morphometric functions) to classify landforms from DEM data. Section 7.2.2 extends the case study by suggesting the addition of a prognostic cliff erosion model, then considers COAMES as an agent for loose coupling as further models are introduced. The process of loose coupling is already present, in effect, through COAMES' rule-driven management of the various actions that can be applied to data (see section 6.4).

The knowledge that COAMES imparts to the user can be adopted or ignored (see Figure 6.1 for context) as part of the decision-support process operating outside of the digital system. The coastal zone manager can choose to add the proffered knowledge to knowledge already possessed, and use the combined resource to reach a decision. Returning to the quote at the beginning of this section, any wisdom is an attribute of the user only – this entity is probably a long way off for any digital construction.

6.3.2 Technological Issues and Dissemination

A major barrier to overcome in disseminating data and information is any that may be caused by use of the system itself. This is mainly to do with the user interface - Avouris and Finotti (1993) single out interaction as the main expert system challenge, which weights importance towards the user interface. Chapter 3 introduced the form and function of the COAMES user interface – since it is not explicitly involved in the main aims of the thesis, it has not been a developmental focus. Before leaving the subject of interfaces (there is more discussion on interfaces in sections 6.4 and 7.2.1) the essence of communication (a vital expert system asset) in COAMES is through the two-way dialogue and one-way display from the expert system. This two-part arrangement is as simple as possible for the non-specialist user, in particular employing transparency (ensuring that the user is informed of everything the ES does to reach a conclusion and getting away from the historical black box approach).

Although designed with the potential users in mind, there was no actual contact with users in the design process of COAMES (although the ALC metadata access system did go through a user consultation phase). This step is part of the evolutionary prototyping process, which actively involves the user in system design, making for a program that will be widely used in practice, and less likely to fail (Moore, 2001). For example, a coastal zone manager may identify the importance of a rule input mechanism to supersede the current arduous ASCII file edit method (see examples of rule and FoD storage in Appendix B).

Still on the subject of the user, the amount of formal knowledge acquisition has been minimal in the generation of COAMES rules, mostly drawing from papers and indirectly from interviews undertaken for the Atlantic Living Coastlines project. As a result, there has been no scope to explore the well-documented knowledge acquisition bottleneck. However, it is likely that, in coastal zone management, the bottleneck phenomenon would be exacerbated by the climate of data protection owing to copyright and sensitivity (Moore and Moore, 1999).

The major influence on coastal data and information dissemination has to be the ultimate dissemination mechanism: the Internet. Moore (2001) reports on a Web-based metadata access system (a Java applet) developed for the Atlantic Living Coastlines project. Mounting COAMES as a web page in a similar way would be ideal for dissemination (see Figure 6.2) but there are practical barriers to this.

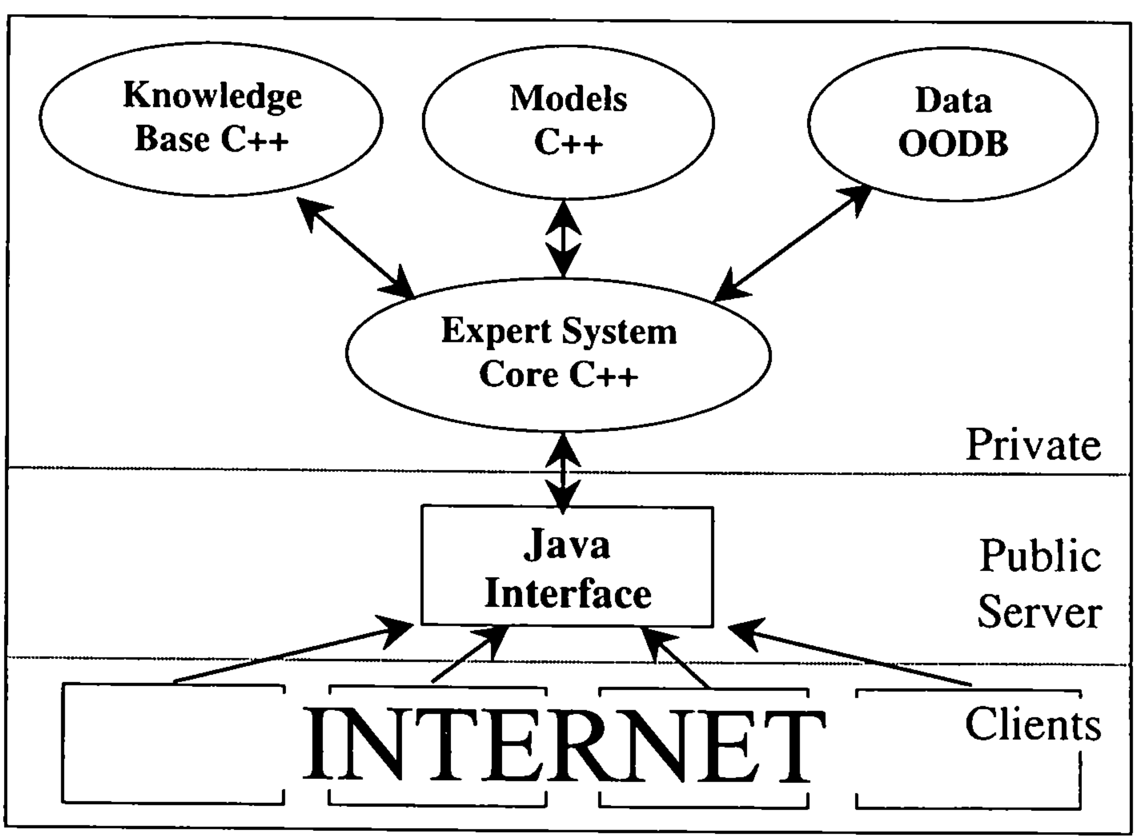


Figure 6.2: An operational scenario for an Internet-based expert system.

COAMES uses native C++ code and accesses data, information and knowledge from files; both effectively render the Java code platform dependent, so the system cannot be accessed remotely (except through security bypasses with client consent – Mark George, pers. comm.).

The next section explores data, information and knowledge, but from an alternative viewpoint, that of holism. The holistic approach will also be discussed in the context of multiple disciplines, technology, and various spatial and temporal scales.

6.4 Demonstrating the Holistic Paradigm

Taking the assumption that COAMES is the physical component that exemplifies the main findings of this thesis, the system's claims of a holistic approach (and resulting generics) will be discussed in this section.

Holism means an appreciation that, whatever we know, it is but a subset of the sum total of potential knowledge. For the purposes of the thesis, this is an acknowledgement that coastal data, information and knowledge exists, is possessed by some body and is waiting to be unearthed. What should not be forgotten in the case of knowledge is the Socratic truth that we "know nothing" and the unknown is ready to be discovered at the frontiers of knowledge.

6.4.1 The Value of Evidence Theory

A compelling tool to model what is not known lies within the Dempster-Shafer method of inferencing with uncertainty. This is the inference method used by COAMES, and unlike other such techniques (*e.g.* Bayes), it quantifies the unknown with an ignorance value. Given the demand for holism within ICZM and the acknowledged gaps in coastal data and information, this is an extremely powerful capability.

The ignorance value used in evidence theory can be used to suggest where thematic (and, with implementation of the relevant rule hierarchies, spatial and temporal) gaps exist. This disclosure can be used to plan and prioritise collection of future coastal data. When any new coastal data augments the current database it should be the job of the expert system (armed with ignorance values) to suggest under which thematic category that data is best placed or even suggest a new category. Sections 6.5 and 7.3.2 suggest a learning strategy that forms a starting point for practical implementation. The use of ignorance may start to address one of the weaknesses of expert systems, as identified by Openshaw and Openshaw (1997), that they are no good at recognising when they fail, or if no answer exists or if the user query is outside of the stored expertise. An and Moon (1993) have already used evidence theory for similar purposes, to search for mineral deposits in unexplored areas where there have been no known mineral occurrences.

The Dempster-Shafer theory also provides a practical means to integrate belief placed in groups of knowledge, which has been discussed in the context of properties of a grouping not being predictable from the individual properties of its constituents. This ability makes the theory valuable, particularly given the importance attached to integration in ICZM. (The worth of ignorance and integration is also discussed in section 5.6.1).

6.4.2 Holism and Data, Information and Knowledge

The challenges facing the system largely result from the nature of Coastal Zone Management itself. In terms of discipline it represents a mix of natural science, social science and humanities that demands an integrated approach. It is this assortment that translates into a wide range of data themes. Added to this are characteristics that are possessed by most data sets: fragmentation (though Wright *et al.* (1998) say that coastal data is more prone to this than land-based data), many formats (resulting from data held in many institutions, again indicating many disciplines) and lack of documentation.

This last factor has only recently been addressed through the widespread construction of metadata and the associated adoption of standards (though the notion of metadata has been around for a long time, it is only recently that it has come to such prominence in geospatial research – as an example of the status of metadata, the ISO standard on geospatial metadata is expected in early 2002 (ISO, 2001). The idea of standards underlies a need to integrate. Therefore metadata conforming to one standard can itself (in conjunction with knowledge) be used to integrate, to be the agent of holism.

The way that data, metadata (information) and knowledge interplay has been represented in Figure 3.9 and discussed in sections 3.8 and 5.6.2. The link from metadata to the data it describes and the actions that can be performed on that data is within the metadata itself (this also forms a type of header to the data, removing the need for explicit header information, which normally precedes the data it describes), ready to be utilised by the knowledge stored within the system. However, the link between data and associated actions is currently indirect (through the metadata) and lacks intelligence (i.e. the system relies on the predetermined order of actions, which uses no knowledge).

In this situation, the onus is on the user to sift through the list of actions and associated beliefs in the diagnostics display before making a decision on what combinations of actions are actually used. This user interaction reinforces the "computer output as decision support, not as the final word" view expounded in section 6.2. The setting of the lower threshold belief could be made available to the user, should an automatic purging of smaller belief values be desired.

The desired arrangement of data, information and knowledge is indicated by Figure 6.3, a 'clover' schematic that introduces knowledge between data and action. In practice, this may take the form of a further rule hierarchy explicitly linking data and action. The use of rule hierarchies to govern spatial, temporal and semantic relational operators in user input is a good example, in particular to solve the current lazy method of implementing the Overlay (OR) action. In the geomorphological classification case study (Chapter 4), the query could specify two or more landforms and the expert system would automatically aggregate them together without consideration of their actual interrelationships.

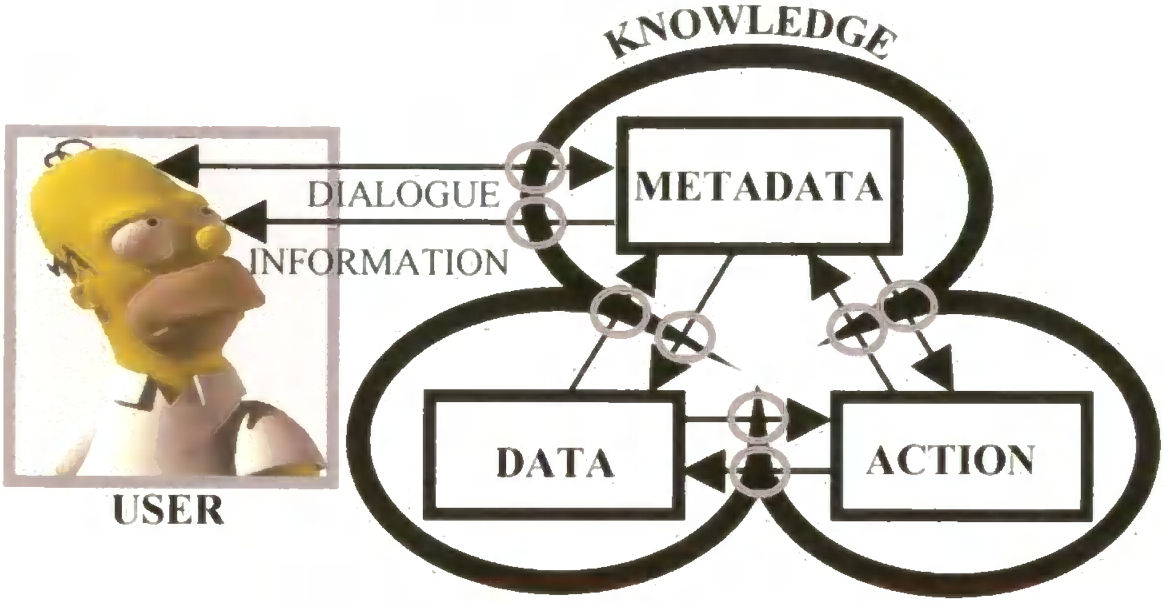


Figure 6.3: A future scenario for the interplay of knowledge, information (metadata) and data in COAMES (clover diagram). The major additions to the related diagram in Figure 3.9 is the introduction of Knowledge between Data and Actions, and the notion that Data could use Knowledge to update Metadata.

Alternatively, the hierarchical passing of belief discussed in Chapter 5 could be used to link the current action hierarchy with a new data type hierarchy. The tiered structure in Figure 5.4 indicates how COAMES goes some way towards a future capability to reason across the breadth and depth of the hierarchy.

Another capability indicated by Figure 6.3 is the use of data and knowledge to update metadata if the data changes. This would apply if any statistical measures were present in the metadata categories, where parameters such as mean or standard deviation would have to be recalculated.

Like actions, data retrieval in COAMES relies on the order in which data is indexed in the metadata and subsequently loaded into the system: this is unintelligent. The latest dataset to be loaded is the dataset on which the rules and actions are implemented (i.e. there is no way to address a specific dataset). By way of remedy, a pointer to the dataset currently being processed could be stored within a rule or rule hierarchy (i.e. Frame of Discernment), and be passed through the inference engine along with knowledge.

The two case studies employed a number of digital processes that operated outside of the expert system workings. Some, such as the processes used to create the photogrammetric models from which the DEM data was collected (see section 4.3), are not central to the thesis aims and are not likely to feature in the aims of future incarnations of COAMES, due to their specialization and overall irrelevance to ICZM. However, cartographic support through the expert system is an integral part of human-computer communication, and therefore the effectiveness of the system. The current sparse title and scale bar accommodation would be augmented with legends, annotation and orientation, either by extending the Java interface display (an important component of this is adjusting the program to enable display of decision support output or multiple spatial scales) or linking to an existing GIS such as ArcGIS (there is more on GIS coupling in section 6.5.3).

By way of summing up the holistic paradigm and how it relates to data / information / knowledge, there will be brief mention of the two case study results. The Holderness case study has demonstrated the use of rules to govern actions (processes) and data; the Fal Estuary has demonstrated that the same rule structure can be used to navigate a varied metadataset (and metadata was subsequently applied to the Holderness case study). This demonstrates the success of one angle on holism – the alternative slant of spatial and temporal scale will be discussed next.

6.4.3 Holism and Scale

The way that COAMES deals with spatial and temporal scale has been proved with the results of the two case studies. The case studies were chosen for the different scales at which they operate - Holderness coast at the local scale (less than 2km) and the Fal Estuary at the regional scale (of the order of 20km and upward). The Fal Estuary case study actually operates at a variety of scales, reflected by the spatial extent of the metadata. Temporally, the Holderness coast case study covers about six months (defined by available data), whilst the Fal Estuary has metadata with a time range of at least 30 years. Again, metadata is the key to identifying scale and the corresponding scope of operation, linking to scale-specific functions.

The discussion in section 5.6.2 acknowledges the successful handling of scale, but comments on the unintelligent way this was effected. Practical solutions were supplied there to introduce knowledge into spatial and temporal scale processing (along the lines of the solutions suggested to effect intelligent management of data and actions).

6.4.4 Other Views on Holism

The value of holism to the various disciplines and institutions involved in the coastal zone management process has already been proved in the way that COAMES effectively navigates the metadata that reflects this diversity. The arguments are outlined in the Chapter 5 case study, which was designed to correct the lack of disciplinary and institutional diversity in the Chapter 4 case study.

The final view on holism to be discussed, that of technology, is the subject of the next section, along with other technological issues such as inference engine and knowledge base separation.

6.5 A Critique of Technology

6.5.1 Holism and Technology

If the Fal case study set out to prove holism in relation to various disciplines and institutions, then the Holderness case study tries to do the same with various types of technology. In the past, many technologies used for ICZM have received the integrated approach, a development flagged by O'Regan (1996). In developing an integrated environmental coastal zone management system for assessing coastal change and scenario evaluation, van Zuidam *et al.* (1998) have a GIS working platform that integrates remotely sensed data, physical / morphodynamic and ecological / hydrological modelling, and a decision support system. These technologies, in their present form, were not being fully exploited. Welch *et al.* (1992) use remote sensing, GIS and GPS in combination to monitor Sapelo Island off the Georgia coast, USA.

COAMES achieves technological holism, as it brings together expert systems and GIS, as well as remotely sensed data and GPS measurements. It has already been said that tools such as ES and GIS, and the knowledge that the ES rely on, are essential to a computer-based holistic approach to coastal zone management (Davis *et al.*, 1989; Ricketts *et al.*, 1989; Riddell, 1992). Since expert systems store knowledge, they are useful in this case and also have the potential to place information into the hands of decision-makers in a useable form.

6.5.2 The Value of Object-Orientation

It can be argued that COAMES qualifies as an object-oriented expert system. The evidence lies in the OO Java interface, the OO C++ language used to program the ES, and the conceptual design outlined in section 3.2 (though there is no OODB).

The use of the object-oriented paradigm is vital for the integrated approach demonstrated by COAMES. Firstly, it enables the separation of the inference engine and knowledge base, overcoming past ES problems that have arisen from the two entities being closely entwined (mainly difficulty of modification). The IE-KB separation facilitates the addition of further knowledge classes to represent new groups of knowledge as they are found. Such modification has been made easier with the move from a hard-coded knowledge structure (for the Chapter 4 case study) to knowledge being stored in files (importantly these have the advantage of being accessible to the user).

Object-oriented classification imposes a logical structure to knowledge, more so than other paradigms. It has often been said that the OO approach is the way that humans perceive reality, making it an elegant and natural solution to knowledge representation. Duff and Carlson (1991) predict that OO will be ever-growing as it is "easily understood". This was found to be the case with COAMES. Other OO innovations include associations through the hierarchy, effected by inheritance (e.g. subclasses of "knowledge" being able to use "knowledge" class members, avoiding replication). Even where there is not a regular class behaviour to conceptualise, special cases can be accommodated through use of multiple inheritance (*e.g.* making the morphometric measures inherit the characteristics of the raster data structure).

6.5.3 Technological Possibilities for COAMES

By analysis of its parts and function, COAMES is a DSS; it satisfies this definition by providing decision support output (albeit in simple form). The expert system is but a component of this, lying in the interaction of the IE and KB. Another component of this DSS is a display-only GIS enabling decision support output visualization. This configuration can be amended by coupling a commercial GIS, bringing a suite of spatial operations to COAMES, though it may be preferable to let the expert system operate these. Another option is to build the DSS as a pre-existing expert system, either a shell filled with rules, or with declarative languages such as Prolog and Lisp. These options were considered at the start of the thesis, but rejected as ideas emerging from the thesis would be better demonstrated by an expert system built from scratch (though Leung and Leung [1993] suggest using a shell to save time). Added to this are drawbacks associated with ES shells, which would need considerable reprogramming to be used in practice (Davis *et al.*, 1989). Whigham *et al.* (1990) add incompatibility with representation and reasoning for natural resource management, difficulty in combining the mathematical and the logical (*e.g.* Johnsson and Kanonier [1991] use the Nexpert Object shell, which has no facilities for modelling uncertainty), and difficulty in displaying any results of inference with a spatial content.

All this evidence points to a successful expert system project, which is possible if the ES does not claim superhuman performance, one of Openshaw's (1995) main arguments. That, and the arguments supporting CZM as a uniquely suitable application (Ripple and Ulshoefer, 1987; Miller, 1994b) justify the ideas in this thesis. The lack of CZM expert systems is not due to an incompatibility of approach, more that only recently has technology made such a prospect viable. Successful expert system applications in the past have focussed on narrow domains such as geological prospecting or diagnosing specific medical conditions. CZM by comparison is a multifaceted prospect, demanding a complex and computer-intensive approach if successful expert system application is to take place. This challenges one of Openshaw and Openshaw's (1997) criticisms of expert systems, that they are "brittle" due to sole success with narrowly defined problems.

Although by definition COAMES does not claim superhuman performance, in a practical sense the system represents a saving on time and resources:

- time taken gathering the datasets together
- time taken to arrange them in a logical structure
- processing time - it is implemented as a batch job rather than a series of individual commands

- time taken to interpret data with knowledge

There is more discussion on this in the Chapter 4 case study.

Having established an application of technology that matches the complexity of the domain (according to Longley [1998] part of the "spirit of geocomputation" is "matching technology with environment"), there is a lot that can be done to build on the foundations of this thesis. Extensions to COAMES' capabilities can be made with attributes commonly associated with expert systems such as learning and natural language. Added to this are alternative prospects for intelligent research in the ICZM domain – simulating using cellular automata for example. These and other technological innovations will feed into further research, along with projections of the other ideas put forward in this chapter. Such future prospects are described in the next chapter.

6.6 Summary

The thesis (and the software counterpart, COAMES) has achieved the aims, as set out in the introduction:

- COAMES meets a need for data, information and knowledge handling in ICZM
  - Knowledge successfully uses metadata to navigate the data resource
  - Although the test knowledge base, datasets and metadataset are too small to be an optimal test of the vast overall resource, alternative data storage mechanisms, data types and incorporation of data error are considered
- COAMES can effectively disseminate coastal data, information and knowledge
  - Both rule-based and process knowledge (models and actions) are integral in disseminating the correct data and information to the user
  - The interface facilitates dissemination through transparency, although the decision support output needs further attention to achieve full potential
  - The role of the user has been underplayed both in the system design process and knowledge acquisition
  - The Internet represents the ultimate dissemination means and COAMES goes some way towards being web-based
- COAMES accomplishes a holistic approach, as is fitting for the application, Integrated Coastal Zone Management
  - The inferencing mechanism, the Dempster-Shafer theory of evidence, provides two tools that make this possible: ignorance and integration
  - The holism works in various ways
    - In integrating data, information (metadata) and knowledge
    - In integrating a variety of spatial and temporal scales

- In integrating a variety of disciplines and institutions
- In integrating a variety of technologies (see next main point)

- However, knowledge could do more in intelligently processing scale and linking data to actions (and vice versa)

- COAMES uses the most suitable available technological innovations for addressing the coastal zone management domain
  - Matching a complex domain with a complex solution without making claims to superhuman performance
  - Knowledge is utilized to classify landforms from DEM data
  - The successful application of object orientation:
    - Enables a modular approach, embodied in the inference engine and knowledge base separation (therefore it is easy to add or take away rules)
    - Provides a logical but natural structure to knowledge (a function of object-oriented properties such as classification and inheritance), making it easily decipherable by the user
  - On a practical level, COAMES represents a saving in time and resources
  - Other technological possibilities are considered along with further research (in Chapter 7).

7: FURTHER RESEARCH

7.1 Introduction

The following ideas for further research build on the foundation provided by this thesis, and COAMES. This chapter will be divided into two sections; one extrapolating thesis research themes, and the other exploring alternative technological approaches.

7.2 Extrapolating Thesis Research Themes

7.2.1 Involving the User and the Internet

The primary importance of further research is to establish where this thesis and COAMES stand in relation to operational Coastal Zone Management. Section 6.2.1 and Figure 6.1 discuss the system and human-computer interaction through a decision support forum. This arrangement can enable the coastal zone manager (*i.e.* the user) to become actively involved in the system design process (through evolutionary prototyping) and knowledge acquisition, both of which are areas marked for future attention in section 6.3.2.

Evolutionary prototyping can be used to ascertain just how important the Internet is for dissemination in coastal zone management. A survey of coastal zone managers in Devon and Cornwall in 1998/9 (Moore and Moore, 1999) revealed that only 12% had access to the Internet, but this figure is sure to have increased (see Kay and Christie, 2000). If implemented, the Internet would make COAMES the focus for a virtual decision support forum, with coastal zone experts able to remotely give feedback on system performance and introduce new rules, as well as the currently implemented dialogue and display modes.

However, scoping a move of COAMES to a web-based Java applet would itself be a subject of further research. It would mean either requiring security bypasses from the client end (an unrealistic prospect although possible: Mark George, pers. comm.) or moving the C++ native code to Java (resulting in a loss of speed, coupled with prohibited file usage due to security). Realistically, the latter would render COAMES without any large datasets to access (*i.e.* metadata and knowledge only), though rules and FoDs could be stored in a mark-up language.

The metadata used was derived from the Atlantic Living Coastlines project that, while active represented a forum of coastal zone managers in Devon and Cornwall (Bayliss and Moore, 2000). Although this forum was concerned with regional innovative approaches to ICZM, and not with a specific coastal zone problem, a similar grouping is envisaged for the decision support forum introduced in section 6.2. They would act as a focus for the collection of a more comprehensive and therefore larger metadataset (the original was based only on three local study areas), which would provide a resource for a more representative test to COAMES, more indicative of the huge resource that exists. More effort would also be made to collate and provide access to the data behind the metadata.

The increase in resource would necessitate the testing of more efficient data structures, introduction of further data types and systematic measurement of data error to assure data quality. Finally, improved methods to address specific datasets (*e.g.* pointer stored as a rule attribute) will be investigated (see section 6.4.2). New datasets might include ancillary data such as airborne remote sensing data classified for beach and cliff landforms, which would have reduced some of the noise in the expert system landform classification (Chapter 4).

7.2.2 Modelling Possibilities

An extension of the system would be incorporation of, or linkage to modelling. Thus, a further move for the Chapter 4 case study would be to input the results into a cliff erosion model (see also section 4.6.3). Given the link between the centre of the ord and increased coastal erosion (Pringle, 1981, 1985; Richards, 1997), data on the movement of the ord would be valuable. The derivation of movement data would require a rule-driven routine that measured spatio-temporal change between two or more maps of the same phenomenon at the same location. In this way, forecasts of erosion could be made, aided by the identification of areas where the till platform is directly adjacent to a steeply eroding cliff. The cliff erosion model will be encapsulated within the system in the same way as the geographical algorithms described in section 3.6 and the Longshore Transport Rate Model (LTRM) described in section 4.6.3 Further work on the LTRM entails the development of an algorithm that measures the depth of mobile sediment from cell to cell. Such a method has been described in section 4.6.3.

The presence of more than one model opens the possibility of model coupling. It is proposed here that COAMES would facilitate a loose coupling between two or more models (for an account of an early loose coupling experiment and an indication of the role that COAMES could play between models see Appendix A). Coupling need not be confined to models; the idea of coupling a GIS to COAMES has already been put forward in sections 6.4.2 and 6.5.3. This is to rectify the current minimal decision support output (*i.e.* using GIS functionality for map design and adding features such as legends and orientation symbols), which needs to be improved if effective communication, and therefore dissemination is to take place. Another modelling-related matter, cellular automata, is discussed in section 7.3.6.

7.2.3 Knowledge and Validation

Much work needs to be done on knowledge and how it is used within COAMES. Evidence from the findings of this thesis suggests that the decision to build a knowledge-based system from nothing was correct. Even so, there is the need for validation, which would involve trying to populate existing expert system shells with the rules used in this thesis and comparing results. The same activity could be applied to an expert system constructed using the Prolog and Lisp declarative languages. Similarly, to validate the Dempster-Shafer inferencing method, an investigation of Bayes, fuzzy logic and certainty factors would be in order to provide a point of comparison.

The forms of expert system validation outlined above are a step on from conventional validation, which involves comparing test case results with known results or expert opinion, and is the method used in this thesis. Validation is just one part of the evaluation process; other parts include exhibiting acceptable performance levels, and assessing useability, efficiency and cost-effectiveness (O'Keefe *et al.*, 1988).

Currently, knowledge is used to drive the dialogue process, combine with metadata to manage data and actions (reciprocally, actions can use knowledge to manage metadata), and return decision support output to the user (Figure 3.9). Future research would explore the role of knowledge between data and actions (through adding a relational rule hierarchy and / or enabling the hierarchical passing of belief), and investigate how data can be used to update metadata (see section 6.4.2 and Figure 6.3). Addition of extra rule hierarchies can also be inserted to intelligently process metadata on the basis of spatial and temporal scale. See section 5.6.2 for further details.

7.3 Supplementary Approaches

COAMES ignores some of the features commonly associated with expert systems, which in practice are infrequently implemented for a variety of reasons. These are natural language, learning and use of metaknowledge. In addition to these are approaches external to the expert system, such as distributed expert systems, agents and cellular automata.

7.3.1 Natural Language

Natural language processing could enable suitable dialogue between the user and the expert system. Although Davis *et al.* (1989) have stated that natural language is not common in ES applications, Shortliffe (1976) has flagged the ability to understand and respond to simple questions as an integral ES quality, and Mark and Egenhofer (1994) regard natural language as normal in problem solving and spatial reasoning. This would be posed in the form of spatial relations such as *X is [on, next to, near] Y* (see also Dawson and Jones, 1995). An alternative is the object-attribute-value (O-A-V) triplet (Morris, 1995); for example "cliff slope ≥50°" can be used to retrieve any cliff object with a slope attribute that has a value greater than or equal to 50 degrees. More sophisticated natural language algorithms can parse grammar, from the simple parse tree structure of Forsyth and Naylor (1985), which is described in Appendix A as a first step in COAMES' natural language development (the parse tree lends itself nicely to COAMES' rule hierarchies), to the complex but popular Generalised Phrase Structure Grammars (GPSG) of A J Fisher (1989, 1991).

7.3.2 Learning

Another property commonly associated with expert systems is learning. This ES capability has not been implemented extensively, and yet the value of learning to a system that strives to emulate humans cannot be denied. A simple learning algorithm from Naylor (1983) has been included in Appendix A as an example. The addition of a rule input module to the COAMES user interface has already been mentioned; once the rule has been input, the learning algorithm can iteratively converge (through dialogue with the user) on the most suitable node in the knowledge structure at which to store that rule. This has been flagged as a challenge, for as Navinchandra (1993) puts it, as the knowledge base increases in size, such (semi-) automated rule placement gets more difficult.

Eklund *et al.* (1998) classify learning strategies into three categories, all of which are COAMES development paths. Firstly, there are inductive learning techniques, used by Eklund *et al.* (1998) as a data mining tool to restructure a rule base. This method was also used by Smith *et al.* (1987) in their KBGIS-II application. Within COAMES, induction would be used in a data-mining context, to generate new rules from patterns of data and metadata. Secondly, there is backpropagation, which is central to neural networks research. Lastly, there is Instance-Based Learning, which is linked to Case-Based Reasoning (see CBR notes in Appendix A).

7.3.3 Metaknowledge

The next innovation is metaknowledge, or "knowledge about knowledge". According to Davis and Buchanan (1984) this can come in four forms – knowledge about contents of rules in the knowledge base, knowledge about the representation of objects, knowledge of predicate functions and knowledge about how best to use other knowledge (metarules). Rizzoli and Young (1997) use metaknowledge to make the expert system capable of understanding which problems it can solve. In the case of COAMES, metarules indicate top-level linkages (see Section 5.4) and may in future point to ancillary knowledge to take into account during the main knowledge processing. This would have great potential in linking rules and associated beliefs in diverse rule hierarchies. For example the Chapter 4 case study indicates that while an upper beach may be the user's focus, metarules may point to the features that fringe the upper beach, such as a till platform, making that object available in the main round of processing (morphometry).

7.3.4 Distributed Expert Systems

In keeping with holism is the arrangement of several inferencing processes working in parallel to achieve one goal. In the coastal geomorphology example, this is exemplified by parallel processing of the salient elements of an ord, where ultimately for this prototype, the consideration of the ord landform as a whole is an issue, as a means of testing the expert system's ability to prove or disprove the original theory (Chapter 4). Referring to the class hierarchy diagram (Figure 3.7), classes such as cliff, beach and platform have been defined, and also declared as class members of the landform they constitute – the ord. This is an initial step towards research in this area. This idea of distributed expert systems is nothing new – Sharma (1994) sees them exhibiting synergy and being able to tackle problems of greater scope. Kim (1987) uses a similar set-up to recognize man-made objects embedded in natural scenes.

7.3.5 Agents

Emerging from distributed systems research is the concept of hardware and / or software agents (Rodrigues and Raper, 1999). Agents are self-contained problem solving entities, which should be autonomous, are able to interact, are responsive to changes in their environment and are proactive (the last two properties in particular imply some ability at learning). It is proposed here that each landform constituent (see Figure 4.3) can work as a hybrid software agent, reasoning according to a symbolic model of the world (as a deliberative agent) and reacting to external changes (as a reactive agent). The external stimulus would either be similar landform agents or human intervention. Other types of agent exist – Rodrigues and Raper (1999) explore issues involved with the use of a mobile agent to locate and retrieve spatial information on the Internet, which would clearly be of benefit to the metadata extraction case study in Chapter 5.

7.3.6 Cellular Automata

Cellular Automata (CA) are "computable objects existing in time and space whose characteristics, usually called states, change discretely and uniformally as a function of the states of neighbouring objects" (Batty, 2000). From this definition, the parallels with agents are clear. Cells (commonly the objects in the above definition), like agents, change state according to their environment. From these local changes, a global pattern emerges, which is the goal state (Rodrigues and Raper, 1999; Batty, 2000). An example of possible CA use for COAMES is comparing COAMES output, CA output and expert opinion on the drift of the protective upper beach in the Chapter 4 case study. In CA terms, directional drift could be enabled by an asymmetric neighbourhood (Batty, 2000), which would make behaviour trend in a certain direction. The application of CA to geomorphology is not new. Smith (1991) used CA to model landform erosion. Working on a raster profile, 'exposed' cells were made more susceptible to erosion, and the surface was maintained by simulating gravity. If there was an empty neighbouring cell below the object cell (which was filled), then there was a downward shift of the filled property to the empty cell. Briefly, CA is driven by rules that operate on cells, making it similar to the application of rules to rasters demonstrated in Chapter 4. The main difference is the scale at which the rules operate: in CA rules operate at a local scale whereas in the Holderness case study rules are implemented globally.

7.4 Summary

The following areas flagged for future research build on the findings of this thesis:

- Establish COAMES in the real world of coastal zone management using a decision support forum as focus
  - Get the users (coastal zone managers) active
    - in future system design (evolutionary prototyping)
    - in knowledge acquisition
  - Move the system to a web-based existence to facilitate use of COAMES by the coastal zone managers.

- Collect a larger coastal metadataset and dataset – this would involve research into suitable data structures, types, error measurements and addressing methods in COAMES. Alternatively, find a collaborating body which has a large amount of data.

- Expand modelling capability in COAMES
  - Develop cliff erosion model which processes coastal change data to provide spatial and temporal erosion forecasts
  - Develop Longshore Transport Rate Model to fruition
  - Use COAMES to facilitate model coupling
- Research knowledge representation and inferencing methods
  - Validate COAMES' knowledge structure through comparison with expert system shells and declarative languages
  - Validate Dempster-Shafer inferencing method through comparison with Bayes, fuzzy logic and certainty factors
  - Expand the role of knowledge to intelligently manage data in relation to actions, and spatial and temporal scale
- Add capabilities to the internal workings of COAMES
  - Use natural language processing to enable true human-computer dialogue
  - Enable learning to automatically place newly inputted rules in optimum place in the knowledge hierarchy, and create rules from patterns observed in the data and metadata
  - Use metaknowledge as a way of spanning diverse rule hierarchies
- Add innovations external to COAMES

- Use distributed expert systems: several instances of COAMES working in parallel to achieve one goal
- Build a hybrid software agent to simulate landform behaviour, and investigate use of a mobile agent to navigate the huge coastal data resource on the Internet
- Use cellular automata to simulate and investigate landform behaviour

The final chapter draws together the findings of the thesis and related suggestions for further research.

8: FINAL REMARKS

Coastal data and information comprise a massive coastal resource, with characteristics such as fragmentation, various formats and properties unique to coastal data. This resource requires a tool that is a match in terms of complexity, yet does not try to do too much. The domain that makes most use of the resource, Integrated Coastal Zone Management (ICZM), is just as complex but uses the holistic paradigm to deal with the sophistication. Consequently, a tool that employs holism to manage and make optimal use of the resource would be of value to ICZM.

An object-oriented expert system, COAMES, has been constructed to prove this concept. With the recent explosion of computing power, the choice of potential available tools has become immense. However, the application of expert systems to CZM in particular has been flagged as a viable challenge and yet very few have taken it up. COAMES uses the Dempster-Shafer theory of evidence to reason with uncertainty and importantly introduces the power of ignorance and integration to model the holistic approach. Object-orientation forms a natural structure for knowledge and enables a modular approach, embodied in the inference engine-knowledge base separation.

Having established grounds for a holistic tool, two case studies were designed that tested COAMES' effectiveness in this area. Knowledge has been successfully used to drive data and actions using metadata, thus a holism of data, information and knowledge has been proved. The Holderness case study has utilized the same knowledge structure to classify landforms from DEM data, demonstrating a technological holism. The Fal Estuary case study has employed knowledge to intelligently manage metadata, proving that a holism across disciplines and CZM institutions exists. Finally the differing spatial and temporal scales that the two case studies operate at implicitly demonstrates holism of scale.

All this is meaningless if the coastal resource, and the science behind it, is not disseminated to the coastal zone managers. The knowledge, metadata and data are easily accessible through the system, and some of these can be combined through inference (this process is also transparent to the user) to produce a higher order resource. In this sense, COAMES is an effective disseminator, but only scratches the surface of what can be done. The use of the Internet has been discussed as an obvious next step, perhaps in conjunction with mobile agents. The presentation of the decision support output could be improved by coupling a GIS to COAMES.

These are modifications that could have been given priority at any time during the course of study, but were not deemed to be of sufficient importance for the scope of this thesis. This choice was made independently of the potential users, who have been underused during this study. Valuable feedback on the issues above and system design (*e.g.* maybe highlighting the value of natural language) will be provided in a process of evolutionary prototyping. This would happen in the real-world context of a decision support forum, which would also act as a focus for knowledge acquisition, coupled with metadata collection and data collation to build a test resource more representative of the global resource. Associated with this are research issues on data structure, type, error and addressing methods.

Knowledge is the subject of much potential research; there is a need for validation, effected through performance comparison with ES built from shells and declarative languages. Inferencing is set to go through a similar process, with Bayes, fuzzy logic and certainty factors being the main rivals to evidence theory. Extensions to current rule-based knowledge processing include intelligent data-action and scale management, inductive learning (data-mining) to extract data and metadata patterns, learning for automatic rule placement, and spanning diverse rule hierarchies with metaknowledge. Work on process-base knowledge would build on the Holderness case study and include finishing the Longshore Transport Rate Model and introducing a cliff erosion prognostic model. Related innovations stem from the proposed distributed and parallel operation of several COAMES to achieve one overall goal. Similar proposals entail experimentation with hybrid software agents (thus achieving a state of learning) and cellular automata.

Clearly, the thesis aims have been satisfied, but the research contained therein is only a small part of the whole picture. In this way it is much like holism itself.

APPENDIX A: ANCILLARY INFORMATION

A1 Learning

A1.1 Learning with MYCIN

The learning strategy used with MYCIN is enabled when experts input new knowledge to the system. The method of rule acquisition entails the expert to type in the new rule in English (in the syntax of the other rules in the knowledge base). The system then translates the rule into the LISP language and back into English for assessment by the expert (*i.e.* to check if the system has it right), who subsequently assigns a certainty value to the rule (Shortliffe, 1976). The following algorithm from Naylor (1983) follows much the same lines (Figure A1).

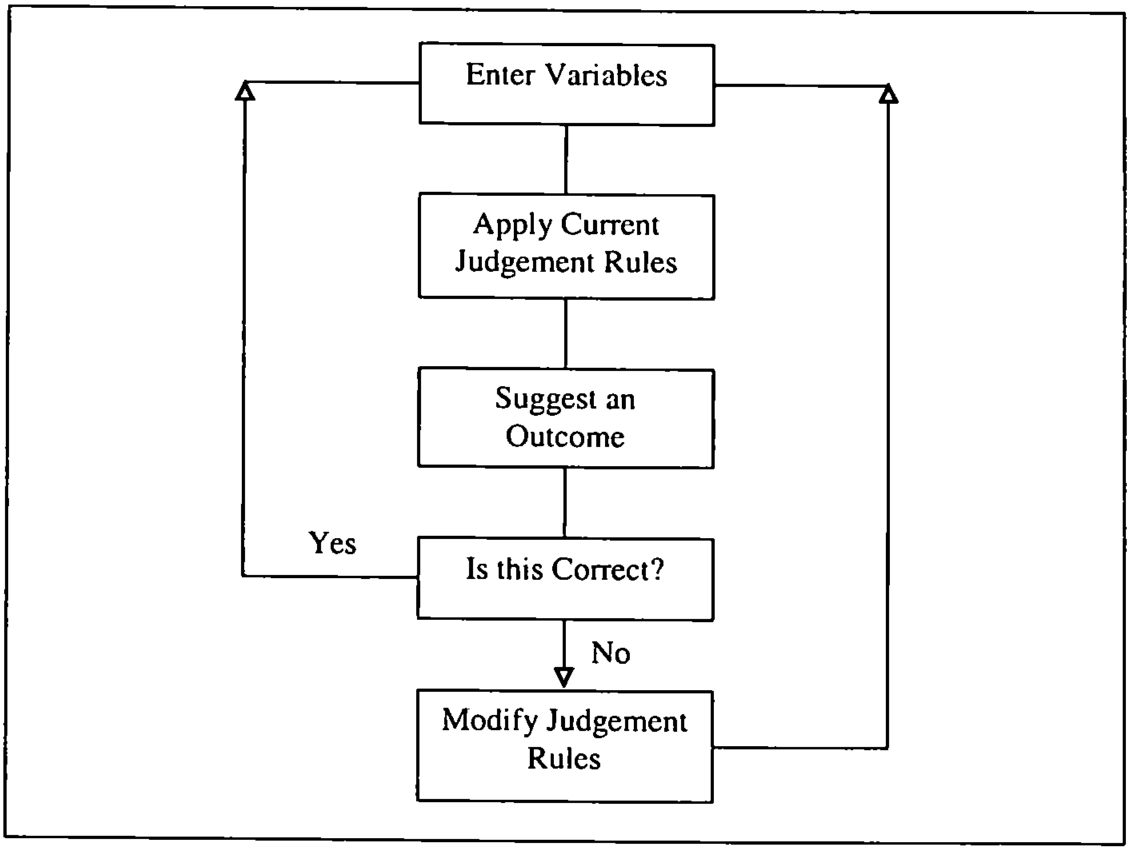


Figure A1: A learning process for developing a set of judgement rules (from Naylor, 1983).

A1.2 Case-Based Reasoning (CBR)

Holt and Benwell (1999) propose high level processing through case-based reasoning (CBR) or memory-based reasoning (MBR: Openshaw and Openshaw, 1997), giving the ability to reason (compute and learn). They contend that most AI techniques used for spatial problem solving have been in low level processing, for instance in image classification and noisy data eradication.

Case-based reasoning is a framework for reasoning from experience, providing a memory model (representation, index and organisation of past cases) and a process model (retrieval and modification of old cases; assimilation of new cases). The case itself is organised into three: the state before the solution, the solution itself and the state after the solution is decided.

Figure A2 shows the CBR cycle, a process whereby the most similar cases are retrieved, information and knowledge in those cases are reused to solve the problem, the proposed solution is revised, and the useful parts of solution are retained for future use (Holt and Benwell, 1999). CBR has been extremely effective in complex cases (Turban, 1995).

An important distinction between this method and the rule-based method is that rules have to match the input exactly to be retrieved; a case only has to be partially matched (through putting case constituents and associated weights into a similarity algorithm) to be retrieved.

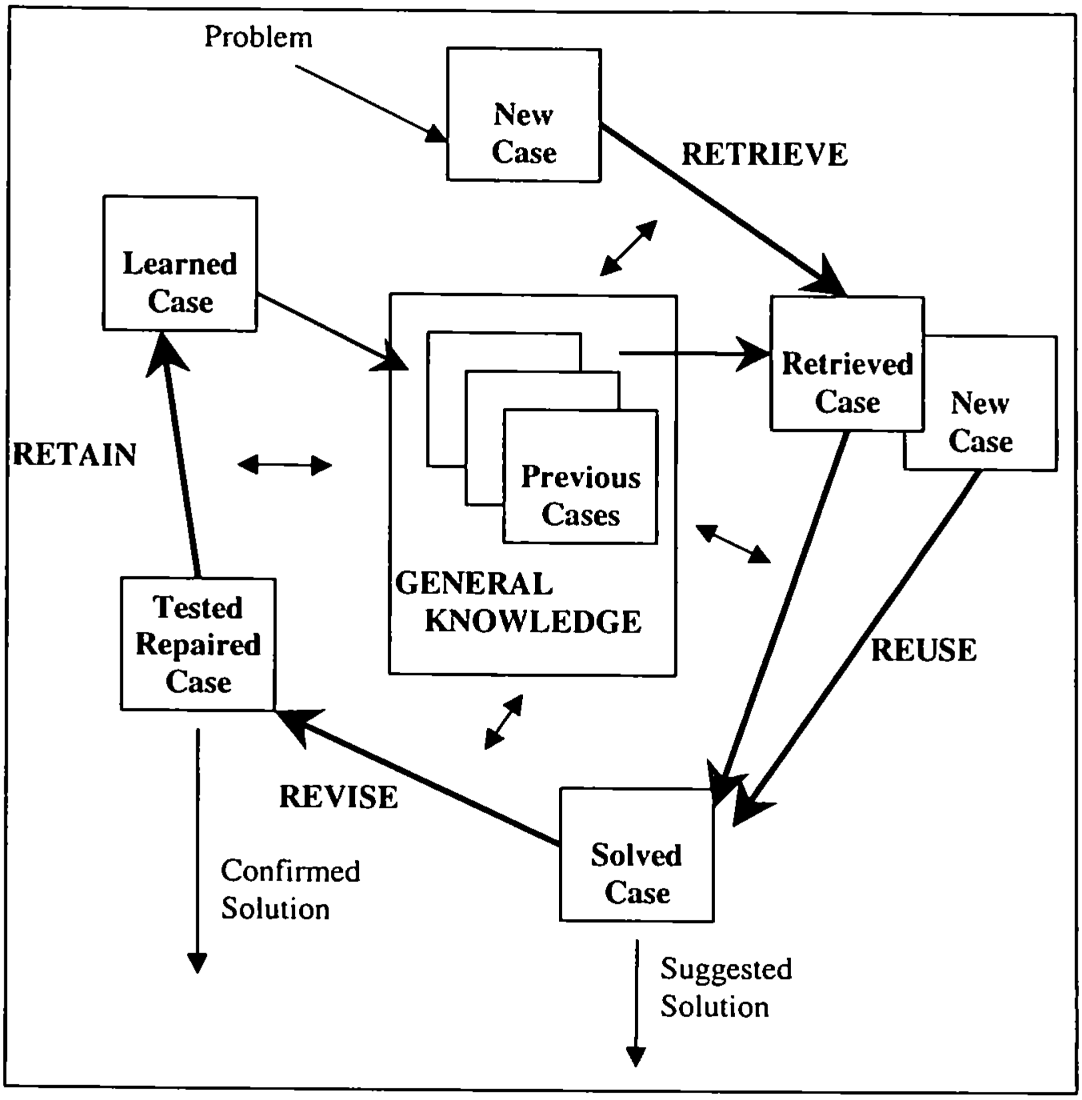


Figure A2: The Aamodt and Plaza CBR cycle (from Holt and Benwell, 1999).

A2 Hierarchical Calculation of Dempster-Shafer Theory

Consider a simple hierarchy (Figure A3).

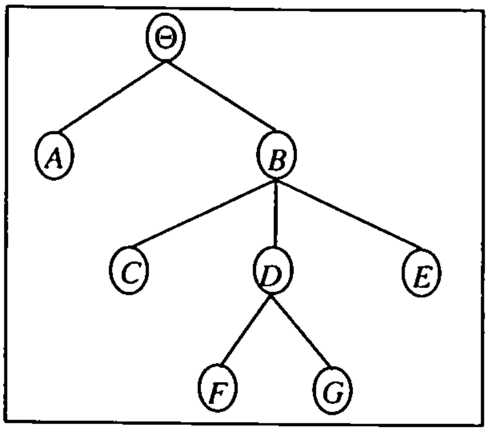


Figure A3: A simple Dempster-Shafer hierarchy.

Starting from the terminal nodes F and G, calculate the belief of D. Then ignoring F and G use C, D and E to calculate the belief of B. Then in the same way, use A and B to get the belief of Θ.

In the next stage, calculate $\underline{Bel}_\Theta$ for the nodes immediately below Θ and their complements (i.e. nodes A and B; also $\neg A$ and $\neg B$),

where, for B, $\underline{Bel}_\Theta = \underline{Bel}_B \oplus Bel_B \oplus Bel_X$

where $\underline{Bel}_B$ = orthogonal sum of all child nodes

(i.e. $Bel_C \oplus Bel_D \oplus Bel_E \oplus Bel_F \oplus Bel_G$)

and Bel_X = orthogonal sum of all nodes that are not equal to or below B in the hierarchy (*i.e.* Bel_A).

Finally, calculate Bel_Θ for all nodes in the next level in the hierarchy C, D, E. Repeat this until the terminal nodes F and G are reached (Shafer and Logan, 1987; Srinivasan and Richards, 1990).

A3 Natural Language

The following notes are from Forsyth and Naylor (1985). They describe a simple parse tree (Figure A4) that can parse a simple sentence. The tree lends itself well to the Dempster-Shafer hierarchies postulated in the thesis with, for example, sufficient belief for a verb able to be passed up to 'Verb Phrase', and so on.

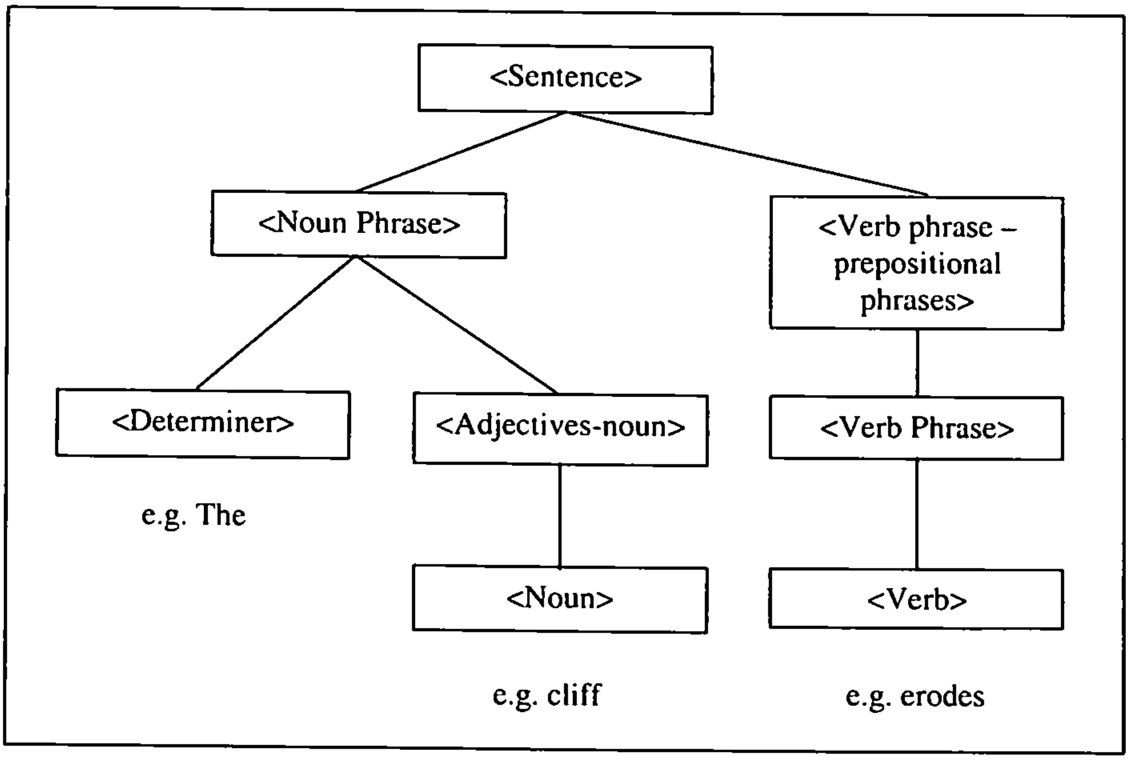


Figure A4: A simple parse tree derived from Forsyth and Naylor (1985).

The algorithm works as follows (a depth-first exhaustive search).

- Input sentence
- First word extracted and compared against right hand side of grammar rules
  - E.g. <VERB.PHRASE> = <VERB>
  - <DETERMINER> = A, THE
- If there is a match then replace the word with the left hand side of grammar rule
- Repeat for all words until only one grammatical unit remains
- If this is not possible then search for and apply alternative rules until one grammatical unit has been achieved or no rules remain
  - Example of alternative rule is:

    <VERB.PHRASE> = <VERB> <NOUN.PHRASE>

A4 The coupling of two environmental models

Environmental models can be coupled to GIS using approaches similar to those identified for expert systems, loose or tight coupling. However, where more than one environmental model is to be employed, then there may be additional considerations, as will now be shown.

Moore *et al.* (1996) report on the coupling of two environmental models in development within the Land-Ocean Interaction Study (LOIS) - ECoS (Estuarine Contaminant Simulator) and ERSEM (The European Regional Seas Ecosystem Model). ECoS employs a 2D model of the Humber Estuary, UK, that simulates discrete transfer and exchange systems (*e.g.* physico-chemical and biological transformations) in the context of advection-dispersion transport (Harris *et al.*, 1993). ERSEM is a generic model which dynamically describes the biogeochemical seasonal cycling of carbon and associated (re)cycling of macro nutrients, nitrogen, phosphorus and silicon, whilst being forced by physical irradiance, temperature and transport processes. The model is unique in that it fully couples the pelagic and benthic components of the North Sea to describe the complete ecosystem (Baretta *et al.*, 1995).

The two models were coupled so that a transfer of nutrients from an estuarine environment (represented by ECoS) across the coastal zone into a marine environment (represented by the ERSEM North Sea model) was modelled. A hypothetical scenario was arranged so that ECoS was used to output selected variables at the mouth of the Humber after a theoretical and arbitrarily high leakage of nitrate adjacent to the port of Hull. These values were then converted and used as inputs to the ERSEM model.

The values show a marked increase in nitrate due to the theoretical discharge. Figure A5a illustrates a graph of nitrate levels throughout the simulated year in the cell adjacent to the Humber Estuary (Box 72). This surplus diminishes markedly with distance from the Humber mouth, as the nitrate is increasingly absorbed due to fixing by organisms. This depletion of the surplus is shown in the graphs for boxes 73 (Figure A5b), 74 (Figure A5c) and 80 (Figure A5d).

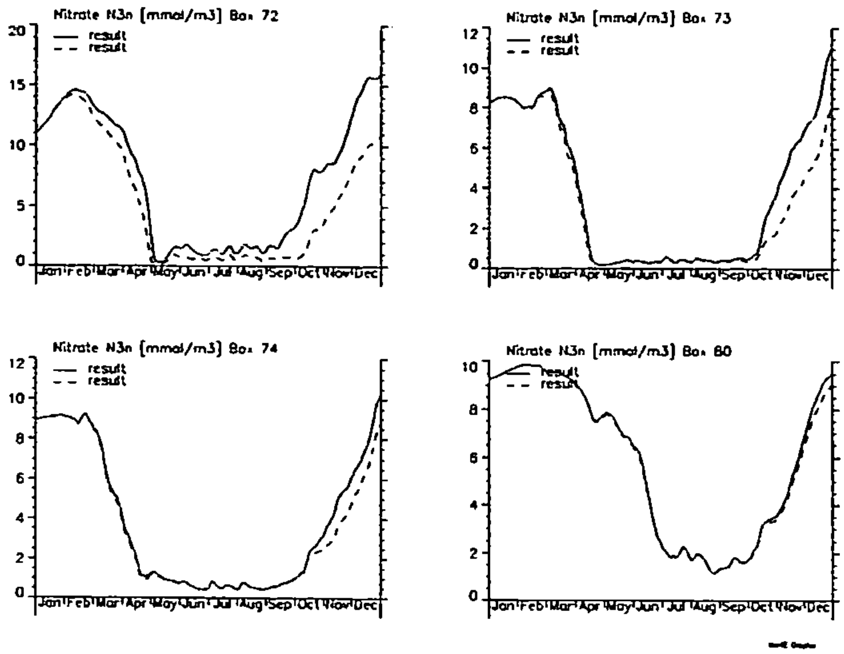


Figure A5a-d: Output of ERSEM North Sea model for boxes 72, 73, 74 and 80 showing levels of nitrate with (solid line) and without (broken line) theoretical discharge of nitrate.

Limitations to this approach included differences in approach of the two models. Whilst ECoS is a shell and operates on a small scale, ERSEM is comprehensive and employs a larger scale (also crude in resolution). Biological and physical processes were ignored in this approach (ECoS does not model biology; no account of the turbidity maximum was taken).

APPENDIX B: RULES AND FRAMES OF DISCERNMENT

B1 A Guide to Rules

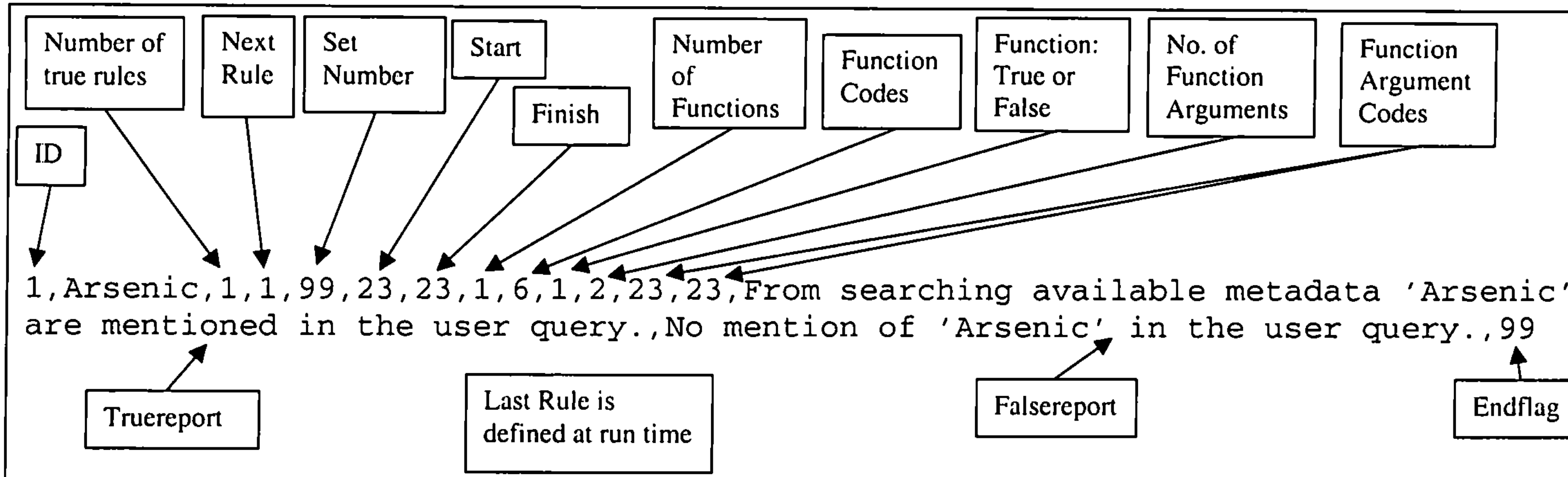
Box B1 outlines the rules used to demonstrate the power of Dempster-Shafer supersets in Chapter 5 (the fourth test in section 5.5). The corresponding frame of discernment is described in section B2.

Box B2 outlines the rules used to invoke the actions employed in Chapter 4. The corresponding frame of discernment is described in section B2.

B2 A Guide to Frames of Discernment

Box B3 outlines the frame of discernment used to demonstrate the power of Dempster-Shafer supersets in Chapter 5 (the fourth test in section 5.5).

Box B4 outlines the frame of discernment used to invoke the actions employed in Chapter 4.




```
2,Copper,1,1,99,24,24,1,6,1,2,24,24,From searching available metadata 'Copper' are mentioned in the user query.,No mention of 'Copper' in the user query.,99
3,Zinc,1,1,99,25,25,1,6,1,2,25,25,From searching available metadata 'Zinc' are mentioned in the user query.,No mention of 'Zinc' in the user query.,99
4,Cadmium,1,1,26,26,47,1,6,1,2,26,26,From searching available metadata 'Cadmium' are mentioned in the user query.,No mention of 'Cadmium' in the user query.,99
5,Iron,1,1,99,27,27,1,6,1,2,27,27,From searching available metadata 'Iron' are mentioned in the user query.,No mention of 'Iron' in the user query.,99
6,Manganese,1,1,99,28,28,1,6,1,2,28,28,From searching available metadata 'Manganese' are mentioned in the user query.,No mention of 'Manganese' in the user query.,99
7,Nickel,1,1,99,89,89,0,From searching available metadata 'Nickel' are mentioned in the user query.,No mention of 'Nickel' in the user query.,99
8,Aluminium,1,1,99,89,89,0,From searching available metadata 'Aluminium' are mentioned in the user query.,No mention of 'Aluminium' in the user query.,99
9,Heavy Metals,1,1,99,29,29,1,6,1,2,29,29,From searching available metadata 'Heavy Metals' are mentioned in the user query.,No mention of 'Heavy Metals' in the user query.,99
10,Other Metals,1,1,99,89,89,0,From searching available metadata 'Other Metals' are mentioned in the user query.,No mention of 'Other Metals' in the user query.,99
11,endrule,1,1,99,89,89,0,Now leaving metal rules.,Now leaving metal rules.,1
```

Box B1: The metals ruleset, with the arsenic rule described.

```
1,ord topology,2,1,1,0,0,2,22,40,2,2,2,2,rules\\toporules.csv,fods\\topoinf.csv,0,1,The action 'Ord Topology' can be carried out on the data.,Implementing 'Ord Topology',The action 'Ord Topology' cannot be carried out on the data.,98
2,get region,2,1,2,1,1,1,47,2,0,The action 'Get region' can be carried out on the data.,Implementing 'Get region',The action 'Get region' cannot be carried out on the data.,98
3,calculate slope,2,1,3,2,2,3,42,43,48,2,2,2,2,2,2,2,rules\\morphrules.csv,fods\\morphinf.csv,0,2,1,0,The action 'Calculate slope' can be carried out on the data.,Implementing 'Calculate slope',The action 'Calculate slope' cannot be carried out on the data.,98
4,calculate convexity,2,1,4,3,3,2,43,48,2,2,2,2,2,0,4,3,0,The action 'Calculate convexity' can be carried out on the data.,Implementing 'Calculate convexity',The action 'Calculate convexity' cannot be carried out on the data.,98
5,calculate aspect,2,1,5,4,4,2,43,48,2,2,2,2,2,0,3,2,0,The action 'Calculate aspect' can be carried out on the data.,Implementing 'Calculate aspect',The action 'Calculate aspect' cannot be carried out on the data.,98
6,height rules,2,1,6,5,5,2,43,48,2,2,2,2,2,0,1,4,0,The action 'Height rules' can be carried out on the data.,Implementing 'Height rules',The action 'Height rules' cannot be carried out on the data.,98
7,overlay (and),2,1,7,6,6,1,48,2,2,5,0,The action 'Overlay (AND)' can be carried out on the data.,Implementing 'Overlay (AND)',The action 'Overlay (AND)' cannot be carried out on the data.,98
```

ID | Number of true rules | Next Rule | Set Number | Start | Finish | Number of Functions | Function Codes

Last Rule is defined at run time

8,geomorphological model,2,1,8,7,7,12,52,42,43,48,43,48,43,48,43,48,48,53,

Function: True or False | No. of Function Arguments

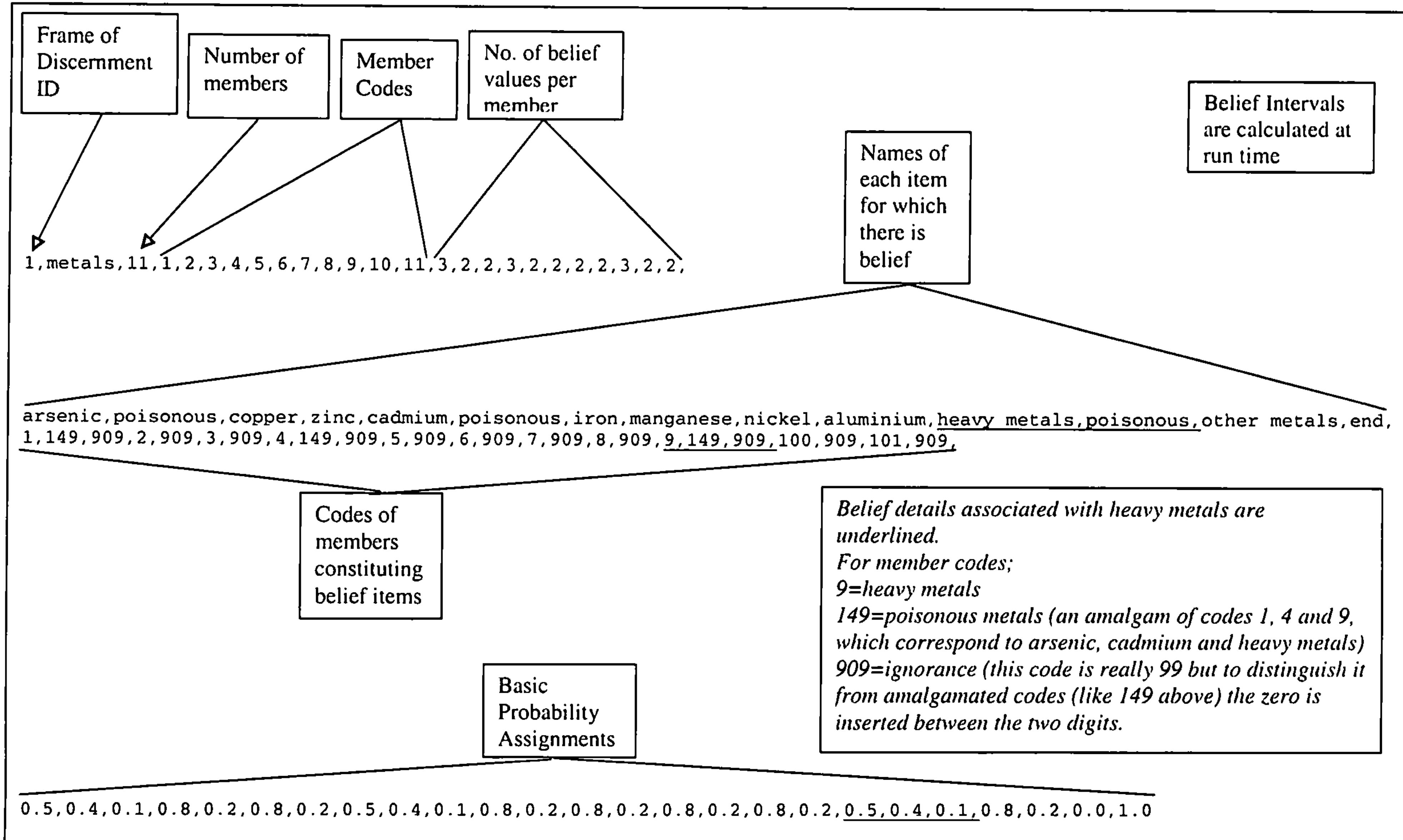
2,2,2,2,2,2,2,2,2,2,2,2,2,2,2,2,2,2,2,2,2,2,2,3,
upper lower ridge,3,rules\\morphrules.csv,fods\\morphinf.csv,0,2,1,0,0,4,3,0,0,3,2,0,0,1,4,0,5,0,
0.00001585489599,-999.0,-999.0,The action 'Geomorphological Model' can be carried out on the data.,Implementing

Function Argument Codes | Truereport 2 | Truereport 1 | Falsereport | Endflag

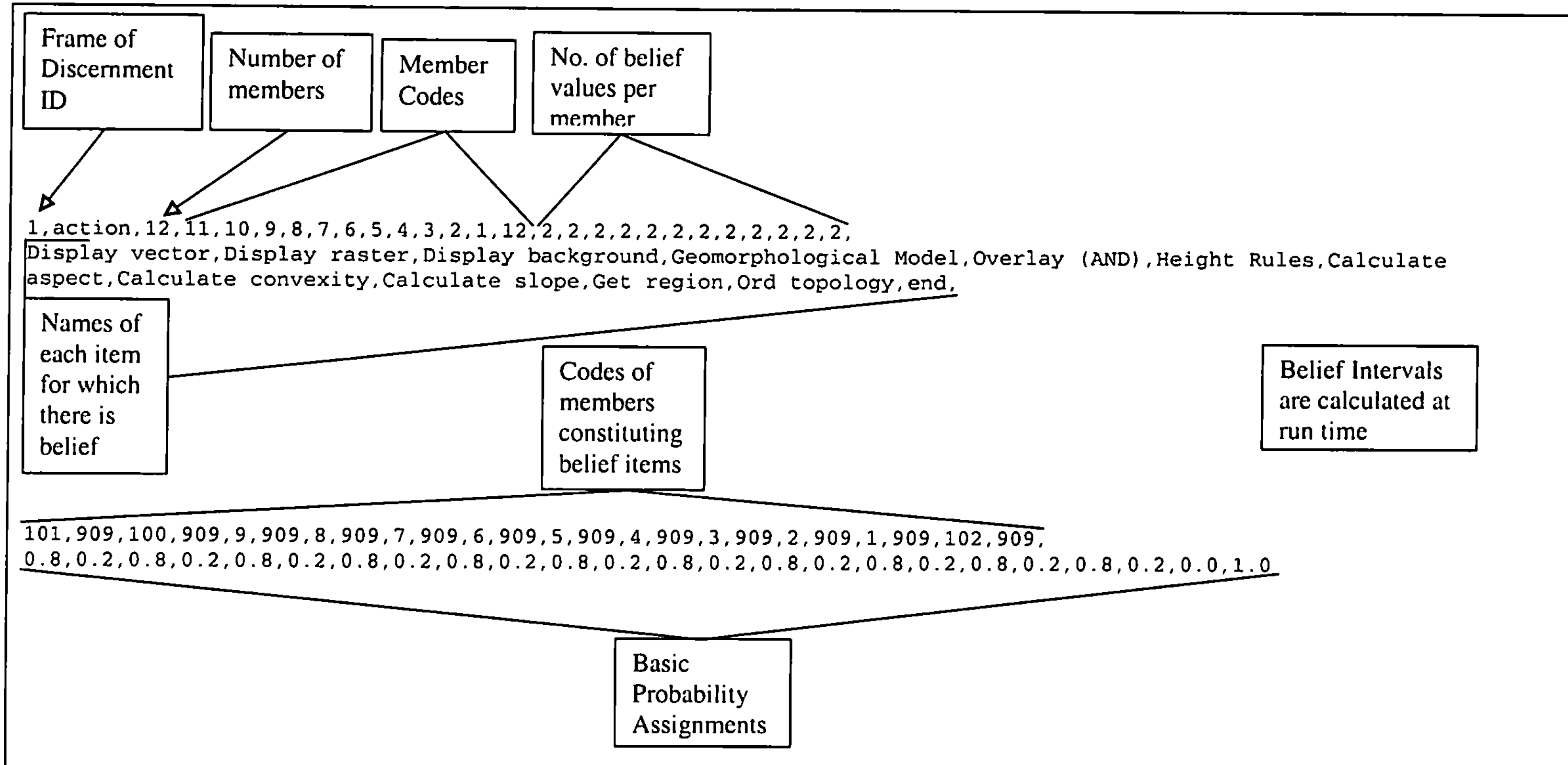
'Geomorphological Model',The action 'Geomorphological Model' cannot be carried out on the data.,98

```
9,display background,2,1,9,8,8,1,51,2,1,2,The action 'Display background' can be carried out on the data.,Implementing 'Display background',The action 'Display background' cannot be carried out on the data.,98
10,display raster,2,1,10,9,9,1,51,2,1,0,The action 'Display raster' can be carried out on the data.,Implementing 'Display raster',The action 'Display raster' cannot be carried out on the data.,98
11,display vector (CURRENTLY FIRST),2,1,11,10,10,3,-1,-3,51,-1,-1,2,1,0,1,lexicon\\actioncat.txt,1,The action 'Display vector' can be carried out on the data.,Implementing 'Display vector',The action 'Display vector' cannot be carried out on the data.,98
12,endrule,1,1,12,-1,-1,0,Now leaving action rules,Have found no actions in metadata.,1
```

Box B2: The actions ruleset, with the 'geomorphological model' rule described.



Box B3: The metals frame of discernment.



Box B4: The actions frame of discernment.

APPENDIX C: GUIDE TO CD-ROM AND INSTRUCTION MANUAL

C1 Guide to CD-ROM directory structure

N.B. The CD-ROM is Appendix D (inside back cover).

Figure C1 shows the CD-ROM directory structure. The program code is to be found in 'C++ Native Code' (expert system) and 'Java Code' (interface). The system itself can be run from the 'coames' directory by double-clicking 'coames.bat'.

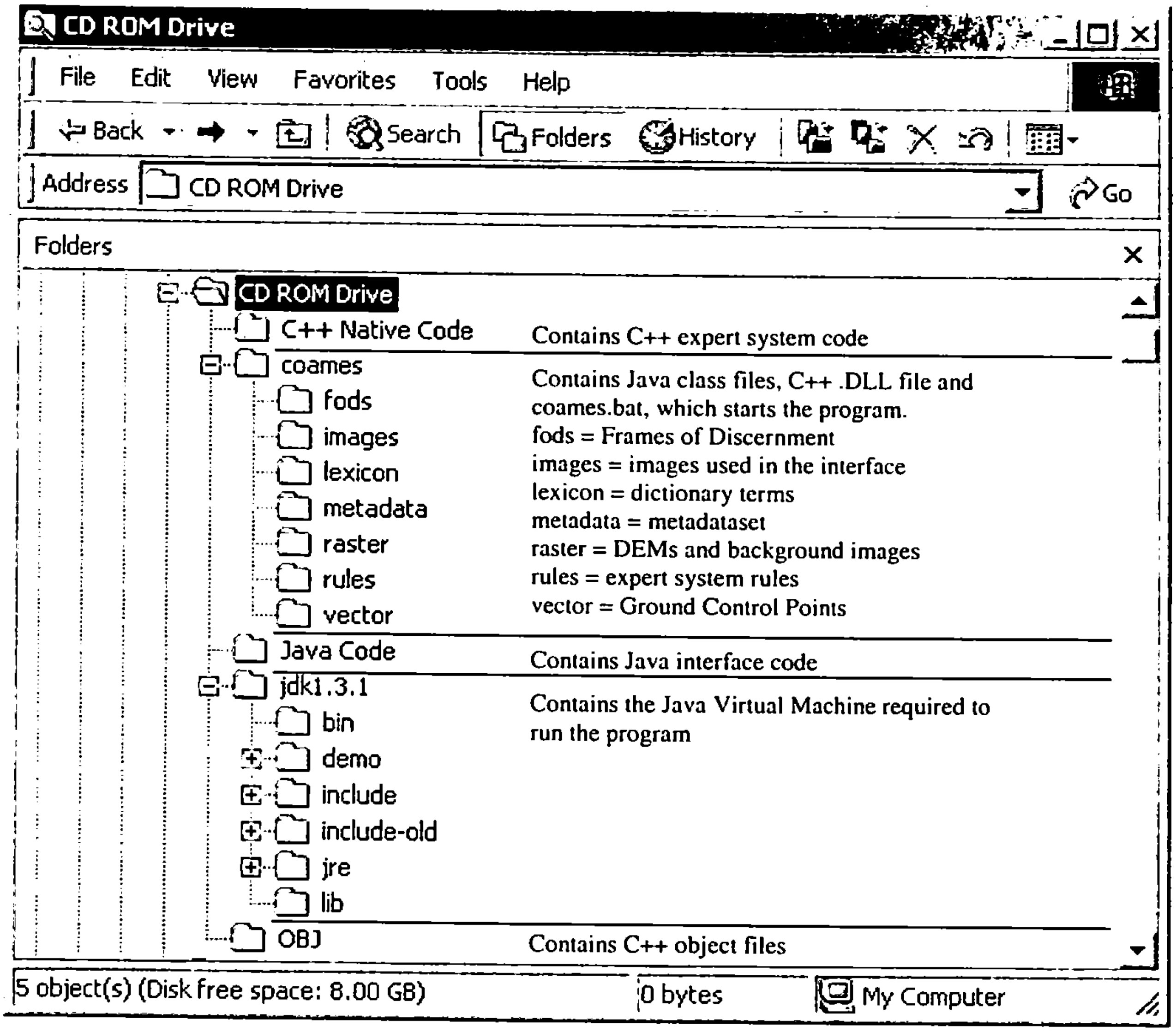


Figure C1: The annotated directory structure of the CD-ROM.

Also contained in this directory are subdirectories containing Frames of Discernment, images, dictionary terms, metadata, raster data, rules and vector data. Finally, Java class files and the C++ native code Dynamic Link Library (DLL) are stored here. The program uses the Java Virtual Machine (stored under 'jdk1.3.1') to run. The C++ object files have also been provided (under 'OBJ').

This software has been developed using a 930 MHz Pentium 3 machine with 256 Mb RAM and a Windows 2000 Professional operating system – the instruction manual in the next section assumes these specifications. The virtual memory settings may also have to be changed – the settings used were Initial Size (MB) = 384; Maximum Size (MB) = 768. From the Start menu in Windows 2000 follow Settings – Control Panel – System – Advanced tab - Performance – Virtual Memory panel and change the settings if necessary (in Windows NT 4 the trail is the same, except there is no Advanced tab).

The software was tested on a 233 MHz Pentium 2, 128 Mb RAM, Windows NT 4 Service Pack 5. After increasing the virtual memory settings to the levels above, the example detailed in section C2 (i.e. using a medium resolution DEM) was processed in about 15 minutes (the same operation takes just under four minutes on the 930 MHz machine).

C2 Instruction Manual

In this section, normal text describes the operational procedure, italicised text outlines a worked example stage by stage, and boxed text displays useful hints and tips.

C2.1 Starting the program

Double click on 'coames.bat' in the 'coames' directory.

C2.2 The user interface

The user interface is split in two parts. The left-hand side is for user-computer **dialogue**, while the right-hand side is for **display** purposes.

C2.3 The query

Upon entering the program, a welcome message is shown above a text box, into which the user types a query.

One has been provided: "holderness landform steep", which should eventually (if the correct options are chosen later in the dialogue) lead to a classification of Holderness DEMs, extracting steep cliffs.

Other queries could be "Holderness landform upper" for a similar upper beach extraction, "Holderness geomorphological model" to invoke the Longshore Transport Rate Model or "Fal Estuary arsenic" to search for metadata on arsenic measured in the Fal Estuary.

Once the query has been formulated, click on the brain.

C2.4 Exploring and choosing metadata

The system will now return a list of metadata titles that match or approximately match your query. To investigate the metadata, click on a title and the relevant metadata will appear in the Metadata window within the display partition.

Although it is not possible to save or print the metadata, the user can copy and paste to a text editor (*i.e.* select the text and press Ctrl and C simultaneously).

You may also notice that the Diagnostics display window shows the expert system workings (with Dempster-Shafer belief values) in reasoning whether any metadata entry matched the query.

Once you have decided which metadata sets you are interested in, click on all the desired entries (use of left-hand mouse click and the Ctrl key) and press the "Search for data and associated actions" button (in the case of the Holderness case study; the Fal Estuary case study involves metadata extraction only).

For example, to continue with the intent of classifying DEMs for steep cliffs, select an orthophotograph and DEM of a particular time period (1996 or 1997). Optionally, add Ground Control Points to limit the classification spatially (through Minimum Bounding Rectangles delineated by any 'cliff' descriptions in the Ground Control Points). See also the advice box on the next page.

Here are some words of advice and caution about the selection metadatasets, since the entries form a direct link to any data that may be behind it.

- High resolution DEMs will not display – use medium resolution instead
- Low resolution DEMs give poor classification results – the medium resolution DEM is therefore optimal
- Orthophotographs form a spatial context for any selected vector and raster data
- Choose a DEM when intending to run the Longshore Transport Rate model – this will give a more accurate figure for 'width of mobile sediment'
- Due to scale-based problems with Java, COAMES does not support the simultaneous display of data from two different time periods. It is allowed, but all data will be displayed with the transformation parameters of the last dataset shown.

C2.5 Choosing actions

Once the button is pressed, the Metadata window will disappear.

The Diagnostics window will be added to, this time showing the expert system results of the search for any stored data behind the metadata entry.

Associated with any dataset are actions that could be applied to the dataset. Based on user selection of metadata, a list of actions is displayed in the dialogue partition. Select combinations of actions to get the desired result.

For classifying DEMs to extract steep cliff (or any other landform), *select ALL the listed actions.*

Having chosen one or more actions, click on the "Apply the Actions" button, and the data will be displayed (if requested).

Here is a list of actions:

- Ord Topology – parses the query in terms of the ord landform configuration
- Get region – calculates MBR window on raster, based on GCP descriptions that match the user query, and their associated vector coordinates
- Calculate slope – classify a landform on basis of slope
- Calculate convexity – classify a landform on basis of convexity
- Calculate aspect – classify a landform on basis of aspect
- Calculate height – classify a landform on basis of height
- Overlay (AND) – combines derived rasters, in this case to identify location of a landform that fulfils certain morphometric characteristics (i.e. combining height, aspect, convexity and slope rasters)
- Display background – to display orthophoto bitmap to give vector and raster data a spatial context
- Display raster – to display DEMs and any rasters derived from them
- Display vector – to display Ground Control Points
- Model – invokes Longshore Transport Rate Model

If performing morphometric operations on a medium resolution DEM, allow at least three minutes for processing, especially if the 'Get region' (*i.e.* MBR calculation) has not been selected to reduce computing time.

For the steep cliff example thread in this manual, seven windows should be displayed: Display vector (GCPs), Display raster (DEMs, classified height, aspect, convexity, slope, and Overlay).

If matched entries were found in the GCPs, then an eighth window would be displayed: Extracted GCPs.

With the amount of windows described here, lack of computer memory renders the program fairly slow (*e.g.* in moving and clicking between windows). The program speeds up considerably once unwanted windows are minimized or closed

Having displayed any data, the Diagnostics window is added to for the last time, to show the expert system reasoning in invoking the actions.

C2.6 Ending the program

To end the program, click the top-right Close button.

APPENDIX D: CD-ROM CONTAINING COAMES AND PROGRAM CODE

The CD-ROM is enclosed inside the back cover.

Conditions of Use

Copies can be made of this software, provided it is for non-commercial use (i.e. for personal, teaching or research use). Accordingly, COAMES must not be sold or a price charged for the use of COAMES.

Disclaimer

This software is provided on an "as is" basis, without warranty. The author does not accept any liability to any person for any direct, indirect, incidental, consequential, special or any exemplary damages resulting from the use of the metadata and data that is provided through this software and from use of the software itself. The metadata and data on the CD-ROM are not to be used for navigational purposes. The author cannot make any assurances about the currency and completeness of the metadataset as a whole, and the quality of the data represented by the metadata, either contained on the CD-ROM or elsewhere. Where data associated with a metadata entry is not held on the CD-ROM, all issues of copyright, sensitivity and confidentiality are to be handled by the third party and the data holders (contact details are stored in metadata).

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An Expert System for Integrated Coastal Zone Management: A Geomorphological Case Study

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This paper outlines the development of the COAstal Management Expert System (COAMES) within LOIS. Recently, there has been an exponential increase in environmental documentation and legislation, matched by an ever-increasing computational capability. The current state of high-performance computing means that for the first time a range of novel techniques can be effectively used to aid the coastal zone manager in addressing an information overload problem. The expert system is a tool within this range that applies expert knowledge to help solve real-world problems.

A prototype of the system has been applied to characterize beach morphology on the rapidly-eroding Holderness Coast, Eastern England. Multi-temporal aerial photography was photogrammetrically processed to derive Digital Elevation Models (a regularly spaced grid of elevations) as input into the system. The constituent features of a composite ridge-type landform (ord) were elicited and stored as expert knowledge or rules, both in terms of positional relationships and morphometric parameters (slope, aspect and convexity). These rules were successfully used on consecutive digital elevation models to extract a geomorphological feature and track it through time. For coastal zone managers, we expect this capability will prove useful for monitoring and managing coasts with long-term erosion problems. COAMES also provides an example of the kind of systems now being developed to aid decision making in coastal regions. © 1999 Elsevier Science Ltd. All rights reserved

Introduction

Management of the coastal zone is now recognized as an issue of importance due to the growing social and demographic pressures that threaten its sustainability. More than half the world's population lives within 60 km of the coastline and it is anticipated that this will rise to 75% by the year 2020 (UNEP, 1995). Furthermore, the number of environmental treaties has been growing steadily since 1950, establishing an exponential growth from the 1970s onward (French, 1995). Traditionally, coastal zone management has relied on manual and paper-based methods. The increased pressure on coastal zone managers has meant that their tasks are becoming more difficult to rationalize. Advances in the methodologies of both coastal zone management and computing serve to significantly aid the manager in this increasingly complex environmental and economic structure.

Early progress in coastal zone management through independent sectoral policies failed to appreciate the overall complexity of the coastal zone, due to their narrow scope of operation (UNEP, 1995). In recent times, Integrated Coastal Zone Management (ICZM) has been evolving rapidly (Jordão *et al.*, 1996), being a flexible form of resource management for sustainable development in the coastal zone (UNEP, 1995). It brings together the tasks facing the coastal zone manager. These include resolving user conflicts, considering planning applications, evaluating possible scenarios, observing legislation, responses to emergencies and other tasks, in both the natural and socio-economic environments, onshore and offshore. The need for integrated coastal zone management can be seen in many processes that cross coastal regions. For example, the relationship between saline and fresh water in estuaries is strong, whilst pollution from onshore to offshore or ports requiring navigational channels offshore require holistic management strategies (DoE, 1996).

There is a requirement for high-performance computing in ICZM, in helping to identify relevant issues, in indicating expected impacts of alternative actions, and fundamentally in the integration of environmental and socio-economic data and knowledge for effective coastal management (UNEP, 1995; Laydner, 1996). Recently, a marked increase in the size, speed and economics of

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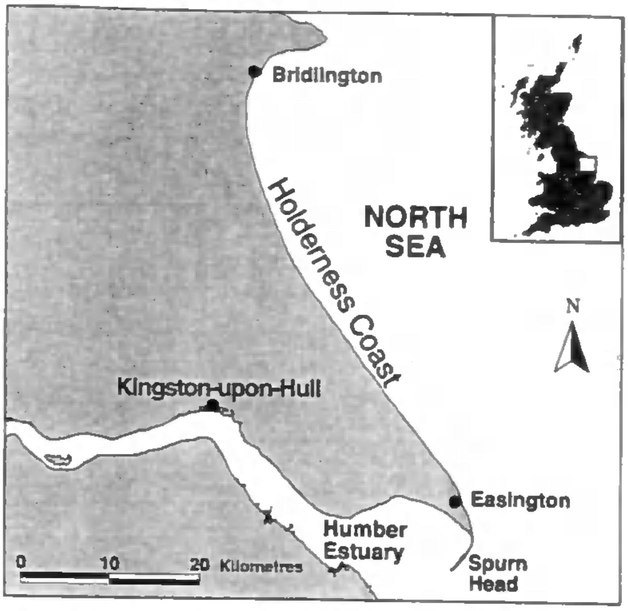

Fig. 2 Location map of the Holderness Coast.

perceive reality – the object-oriented paradigm. Fig. 1 shows the socio-economic and natural scientific domains in which the system would be used, enabling socio-economic and environmental data, related simulation models and contextual information to be integrated. This in turn allows the manager's tasks to be performed more centrally and consistently, optionally using output from the system as a decision support tool and exploring management options and subsequent lines of query in an interactive manner (Moore *et al.*, 1997).

The initial efforts to construct COAMES have been devoted to developing a prototype covering a narrow domain in coastal expertise. Here, the area of application is coastal geomorphology, specifically to characterize beach landforms on a rapidly eroding coast in the LOIS study area (Holderness). Rapid development of a prototype is recommended where there is a high degree of uncertainty in the specification (Fedra and Jamieson, 1996).

Case Study: Geomorphological Characterization of the Holderness Coast

The aim of this case study to test and demonstrate COAMES is to capture a narrow geomorphological domain in terms of expert rules, that is important both in the natural and the socio-economic environments. There is a close relationship between beach morphology and cliff erosion on the Holderness Coast, eastern England. This offered a wide scope for the case study, as land loss is an ongoing physical process that impinges directly on the local population, agriculture, tourism and industry (North Sea Gas Terminals).

Geomorphological background of the study area

The area of study (Fig. 2) is backed by glacial till cliffs which are subject to a long term and rapid rate of recession estimated at 1.89 m/yr (calculated as a 100 yr average at Easington, the area of study – Valentin, 1954). 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. These features are associated with the occurrences of longshore beach troughs called ords (Pringle, 1981). The structure of a typical ord is shown in Fig. 3 (Pringle, 1985). These landforms are typically 1 to 2 km in length (Scott, 1976) and migrate in the direction of longshore drift (south-east) at an average rate of approximately 500 m/yr (Pringle, 1985).

The process of ord movement begins with rapid longshore drift, produced by obliquely breaking storm waves, forming an oblique tongue-shaped upper beach

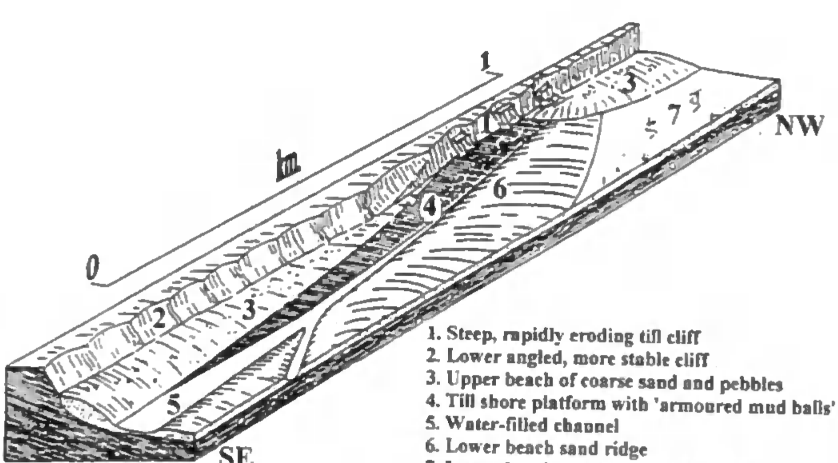

Fig. 3 The characteristic features of a Holderness ord (from Pringle, 1985). This is a composite ridge-type landform, which migrates in the direction of longshore drift. At the centre of the ord, the protective upper beach peters out to expose a lower till platform, facilitating more intensive cliff erosion.

time of year when most cliff erosion is expected to take place.

Using digital photogrammetry to derive the digital elevation model

Photogrammetry is the derivation of reliable measurements and maps from photographs (Lillesand and Kiefer, 1979). It is possible to produce Digital Elevation Models by applying photogrammetry to the common area of two overlapping aerial photographs, enabling the subsequent measurement of slope of a ground feature. For the digital photogrammetry methods used here, an aerial photograph pair for both of the time periods was scanned. The area of stereo overlap was chosen so as to capture the distinct elements of the ord. For any stereo pair, the camera geometry had to be recreated at the time that the photographs were taken. The two photographs were then linked together through the precise measurement of easily identifiable features visible on both, such as the corners of buildings. A photogrammetric model was built by fitting real world co-ordinates, called ground control points, to the area of stereo overlap (Fig. 5 shows one of the scanned aerial photographs with superimposed ground control points). They were measured accurately using Differential Global Positioning System (DGPS) receivers. For the 1996 photogrammetric model of Easington, it was possible to derive root mean square errors (RMSE) of 93 cm in x, 67 cm in y and 46 cm in the vertical dimension (z). The 1997 model was derived with RMSE of 49 cm in x, 70 cm. in y and 58 cm in z.

Within the stereo overlap, and at a predefined sampling interval of 1 m, the parallax between the two photographs was calculated. Parallax is 'the apparent change in relative positions of stationary objects caused by a change in viewing position' (Lillesand and Kiefer, 1979). The same effect can be observed and measured when regarding the difference in viewing position of the aircraft between taking one photograph and the next in a stereopair. The higher the terrain, the closer it is to the aircraft, and the more it will have moved between the two photographs, and vice versa. It is these parallax measurements that constitute the matrix of heights in the Digital Elevation Model (DEM).

For the purposes of geomorphological feature extraction, the chosen sampling interval was considered adequate as the landforms to be extracted were significantly larger than this resolution. There may be instances, such as when measuring cliff erosion, where denser sampling strategies may be required.

The ground control points measured at the same time as the photography were accompanied by topological (relative position) descriptions of the constituent features of the ord. It is this that is used by the expert system to locate salient elements on the beach from the DEM. Fig. 6 shows the DEM for October 1996 overlain with an orthorectified photograph (adjusted to ground co-ordinates).

The Expert System

COAMES is underlain by an object-oriented knowledge structure. Object orientation involves the modelling of data and knowledge as objects, much in the way that we regard the world. Each constituent of the ord landform, such as the upper beach or till platform, is an object (see Fig. 3). Similarly, for other instances of an ord, additional objects of the same type (or class) would be used to model the constituents. Each of these objects has rules, defining their interrelationships with other constituents of the ord and their morphometric properties. Rules are items of knowledge that delimit how an object behaves. 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).

Additional objects within the system are data sets, including the DEMs and GPS positional data collected where two ord constituents meet. For example, surveyed points may locate the junction of upper beach and till platform. This descriptive information is included with the data.

Objects can be used just as easily to model other facets of the coastal environment, from representing knowledge in the form of legislation, to animated output depicting the modelled behaviour of a coastal zone process. It is this ability to integrate disparate data and knowledge in a modular fashion to give powerful decision support output that makes the expert system methodology employed by COAMES so powerful.

Results

Figs. 7(a) and (b) are decision support output maps resulting from queries requesting the location of steep cliffs, stable cliffs and the upper beach at the two acquisition dates. Within the expert system, the areas were extracted from the DEM data, using the positional knowledge and ground control point data to zoom in to the appropriate geographical area. The morphometric knowledge was then applied to restrict the area further. We have represented this interplay of input, data, knowledge and decision support output schematically in Fig. 1.

Figs. 7(a) and (b) show considerable evidence for ord presence and associated movement in the direction of longshore drift. In October 1996, there was one large contiguous section of steep cliff that extended for some 100 m. By April 1997, the northward end of this steep cliff zone had moved between 75 and 100 m southwards, whilst the southern end had extended the length of the strip by approximately 250 m southwards. This movement and extension of steep cliff correlated spatially and temporally with similar behaviour by thin sections of

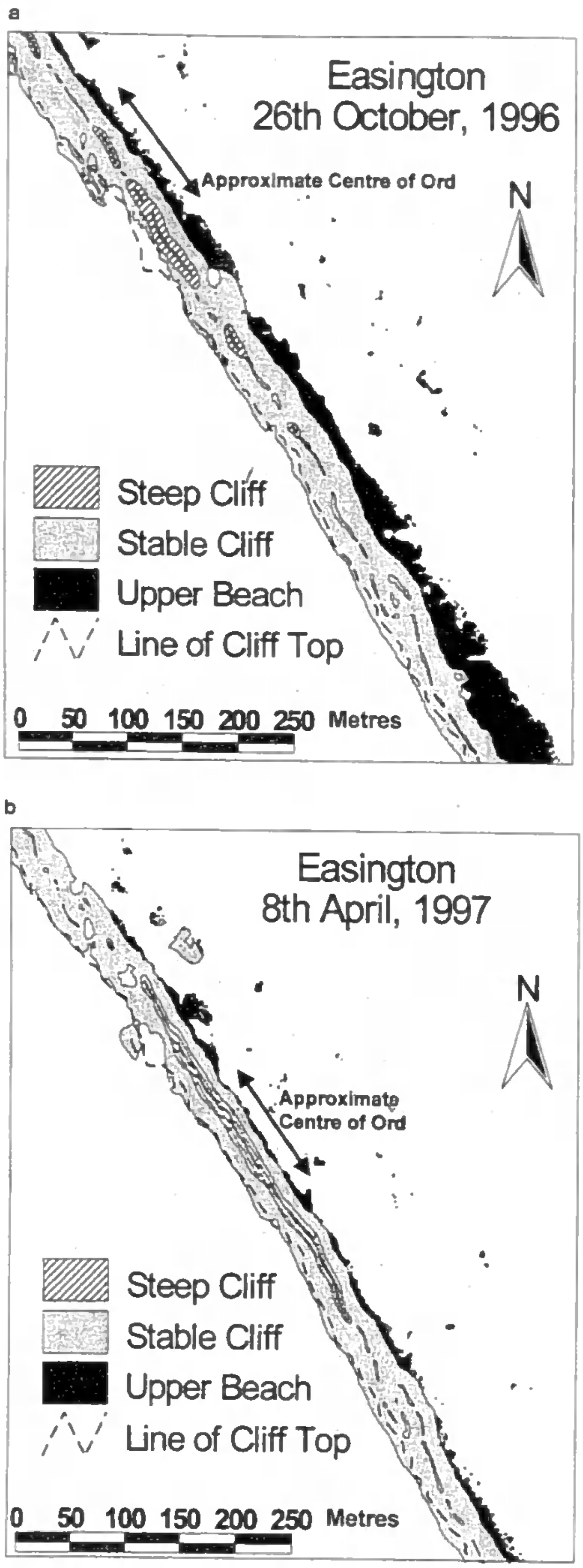

Fig. 7 The isolation and extraction of steep cliff, stable cliff and upper beach from the study area on the basis of intelligent ground control points and morphometric parameters driven by the COAMES expert system. (a) October 1996, (b) April 1997.

upper beach. This is borne out, since steeper cliff gradients are indicative of increased erosion where the upper beach has been removed, exposing the lower till platform. Conversely, the extracted stable or lower gradient cliff areas for the same times indicate protection of the cliff by the upper beach (Pringle, 1981). Indeed, as a whole, the more contiguous areas of stable cliff correspond with the broader and higher upper beach. This is notably not the case to the extreme north of the April 1997 map. The presence of a stable cliff 'island' on the beach indicates a misrepresentation in the stereo-matching process (measurement of parallax), probably caused by surface water on the beach.

The direction and rate of narrow upper beach movement supports previous observations. Movement of the ord centre has been measured at approximately 500 m/yr in the direction of longshore drift (Pringle, 1985). This average figure masks much forward and backward variation of movement throughout the year. A more recent study (Richards, 1997) has recorded movement southward between 130 and 800 m/yr.

These decision support results are corroborated by past measurements, which is an apt indication of COAMES' capabilities and the ability to capture a limited environment in terms of expert rules. 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). All the knowledge (morphometric thresholds, positional relationship of ord constituents) and data (Digital Elevation Model data) are fully integrated and selectively accessed on the basis of user input, then combined by the expert system to produce meaningful and useful results. Therefore, COAMES does not share the inflexibility of the manual process, being able to use whatever the scope of the user input, knowledge base and database allows. Practically, the system also represents a saving on time and resources.

Discussion

The above results demonstrate the power of an expert system to apply knowledge and data for the automation of geomorphological characterization with reference to a specific feature. For some tasks, such as the extraction of the upper beach, the system has not performed perfectly, classifying isolated clumps of upper beach elsewhere in the intertidal zone. Conversely, an area that can be identified as upper beach from qualitative analysis of the photographs (extreme north of Fig. 7(b)), has not been extracted. This merely emphasizes a need for more knowledge, such as a spectral image of the beach of error to indicate reliability of the output. Applied to COAMES, the Digital Elevation Models used in this prototype conventionally use RMSE estimates and this information can be included for any DEM object. Ways of modelling uncertainty include fuzzy logic, an alternative to the "yes or no" absoluteness of conventional data analysis. For example, there is a great deal of uncertainty in defining morphometric thresholds, which are incorporated into the expert system rule. Although defining an upper beach to have a slope of between 3 and 6 degrees could be true, it is not exclusive, and there will be examples that fall outside this. Exploring the use of fuzzy logic for "non-crisp" terms (as in Brimicombe, 1996) would have beneficial implications, due to the potential confusion arising out of processing user queries and the rendering of terms such as 'steep' and 'stable' cliff into quantifiable terms.

Fitting COAMES into an operational context

The operational context into which a coastal management expert system could be placed is schematically displayed in Fig. 8. In future developments of COAMES, the coastal manager would liaise with the stakeholders via a decision support forum. They themselves would be a source of coastal information, which could be incorporated in the expert system as knowledge, possibly via the Internet. The decision support forum has, as its input, products from the system, with associated errors and uncertainty clearly indicated. These can be either scenarios fed in by the manager via dialogue, or from real time output from the system. This is based on real time data telemetered from the environment as part of a monitoring action cycle. As a result of this process, any incident such as an oil spill, for instance, can be identified, quantified, causality established, evaluated and ameliorative action such as use of booms or chemical dispersion, advocated.

Scenario exploration is a valuable activity for the coastal manager in many ways. It is useful in forecasting future trends (e.g. sea level rise), in playing out conflicts between coastal users, in assessing planning consent applications from those users, and in gauging the future effects of proposed legislation. In all these cases, the coastal zone manager would assign parameters and weightings to accurately represent the scenario. The effects of these would be quantified and some control action recommended. The manager then has the option of either accepting the scenario simulation or adjusting the weightings in preparation for another iterative cycle.

Conclusion

This paper brings together two powerful evolving disciplines. Integrated Coastal Zone Management, when coupled with radical advances in high performance computing, has positive implications for coastal zone management. Effective coastal zone management is impossible without a rich yet accessible structure capable of containing and manipulating both data and knowledge, due to the size and complexity of the environment that is the domain of the coastal zone manager. A prototype version of COAMES has been described, which represents a fresh application of expert systems to coastal zone management. A geomorphological case study has demonstrated the capabilities of this parsimonious 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 extraction of landforms through use of this expert knowledge and data. In the case of the ord this technique can be used in the short term to identify areas of increased erosion, which will have a direct affect on social and economic activities. For the coastal manager, the system provides a flexible means of accessing, then combining data and knowledge stored in an integrated fashion without the need for expert guidance with complex computer operations.

An important theme in the philosophy of COAMES is the ease with which additional groups of data and knowledge can be incorporated into the framework. Accordingly, this prototype study provides a foundation block that will be added to. Immediate development will be with the spatio-temporal change of ord landforms, drawing from ancillary data (e.g. wave data, suspended sediment data etc.) and work with different spatial and temporal scales. Incorporation of the ability to estimate error and uncertainty will form an important component of future work, though the greatest value will lie in the integration of existing environmental data and knowledge with demographic, sociological and legislative knowledge. This system fulfils a basic need for effective Integrated Coastal Zone Management.

Nomenclature

Class – a conceptual grouping arising out of the categorization of knowledge or data, based on some criteria. For example, if knowledge or data are grouped by science, then biology, chemistry and physics classes may be formed.

Decision Support System – interactive computer-based systems, which help decision makers utilize data and models to solve relevant problems.

Expert or Knowledge-Based System – helps solve real-world problems using a computer model of expert human reasoning, reaching the same conclusion as a human expert facing a similar problem.

Facts – describes single values such as basic information or events.

Fuzzy Logic – a way by which imprecise or uncertain data can be modelled, where instead of absolutes such as "no" and "yes" (crisp logic), there is a gradual scale from 0 denoting "no" to 1 denoting "yes".

Chapter 6

Geospatial expert systems

Tony Moore

6.1 Introduction

The division of computational science that has come to be known as expert systems (ES) has its origins in the broader discipline of artificial intelligence (AI), where it still resides. Put very simply, the broad aim of artificial intelligence is to simulate human reasoning (Laurini and Thompson, 1992). Expert systems are the most mature products to emerge from this field (Raggad, 1996), dating back to the mid-1960s. Since that time, when researchers at Stanford University developed a program that used chemical expert knowledge to automatically deduce molecular structure (Durkin, 1996), a plethora of definitions for the emergent technology have been put forward. The following gives an indication of how the use of expert systems has expanded to encompass nearly every scientific discipline in that time (Cress and Diesler, 1990):

> '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)

In the literature, expert systems are also known as knowledge-based systems (Skidmore *et al.*, 1996), reflecting the physical computer manifestation of what the expert knows rather than what is actually known by the expert: '. . . developed for representing "knowledge" about some domain and for supporting procedures for deriving inferences about the domain from some knowledge base.' (Smith and Jiang, 1991). The knowledge base can also be called a logistical base and comprises rules governed by the inference engine (an integral part of an expert system), which is a set of procedures for undertaking some kind of reasoning (Laurini and Thompson, 1992).

In addition, Robinson and Frank (1987) have said that expert systems should: interact with humans in natural language; function despite some

In general, this chapter reviews and assesses the application of expert systems to the geospatial disciplines. It aims to be a picture of the status of expert systems in geography. Firstly, the history of expert systems is outlined, before exploring the differences between expert systems and conventional systems. Then aspects relating to the physical form of the expert system are outlined and their coupling to GIS explained. Next there is a review of the current status of expert systems related to geography. Topical issues such as knowledge acquisition are examined, before a final consideration of the practical aspects of building expert systems. This is followed by an examination of further opportunities for expert systems in the geospatial sciences. Finally, selected examples illustrating the elements, processes (building, coupling), tasks (knowledge representation) and structure (object orientation) of the expert system are summarized. There is also a further reading section, structured by application.

6.2 Historical review

6.2.1 History and origins of artificial intelligence and expert systems

Experiments in artificial intelligence began in the late 1950s, but initially concentrated on games playing and solving puzzles. A subsequent shift in emphasis, with the knowledge stored being the subject, resulted in more useful and powerful applications being developed (Dantzler and Scheerer, 1993). Out of this change of approach the birth of expert systems came about. The first expert system can be traced back to the mid-1960s at Stanford University. A group of researchers there were developing a computer program with a chemical application that could deduce the structure of complex molecules from mass spectrograms at a performance level rivalling that of human experts. It was called DENDRAL. Knowledge from an expert chemist was encoded and used as the driving force of the program.

During the 1960s and 1970s, expert systems were developed by researchers looking for ways to better represent knowledge. The number of such developments was small, but their contribution was valuable. The noted expert systems MYCIN and PROSPECTOR were built in this phase. Based upon these successes, more money was put into the technology in the 1980s, leading to growth. This was helped when there was a shift in emphasis from overstretching the technology (by purporting to develop the definitive expert system that could solve problems even the experts could not) to developing expert systems for narrow domains and mundane tasks in the mid-1980s (Dantzler and Scheerer, 1993; Fischer, 1994; Durkin, 1996).

In terms of hardware and software, the 1970s heralded expert system development on powerful workstations with declarative languages such as Prolog and Lisp. Because of this exclusivity, only a select few scientists were rules (Smith and Jiang, 1991) and can support recursive queries (Naqvi, 1986). Data does not have these characteristics. Finally. Smith and Jiang (1991) have noted the inability of relational databases to effectively handle deductive and incomplete information. Alternatives include the object-oriented approach or logic-based approaches, which are covered later on. These approaches can store and manipulate deductive rules of reasoning and data, and can answer queries based on logical derivation coupled with some means of handling incomplete data.

6.2.3 Building expert systems

Once a problem has been defined, the first step in developing a knowledge base is the construction of a conceptual model of the problem domain (Hayes-Roth *et al.*, 1983). Conceptual modelling is an analysis of knowledge acquired from human experts (Chan and Johnston, 1996). Historically, the construction of expert systems has mostly been concerned with logic-based approaches in terms of a declarative language with rules, an example of which is PROLOG (Smith and Jiang, 1991). More will be said about this in the section on knowledge representation.

More recently, knowledge-based techniques have typically taken the form of expert system shells (Fischer, 1994). The expert system shell or 'skeleton' allows the specialist to focus on the knowledge base rather than the workings, which it already provides, e.g. EMYCIN and KAS (Knowledge Acquisition system) are the shells for MYCIN and PROSPECTOR respectively (these two are elaborated upon in the examples section), but with all domain-specific knowledge removed. Shells provide the builder with a number of tools for effective use of the inference engine. They are editing, debugging, consult-the-user and explanation (help) functions (Robinson *et al.*, 1986).

6.2.4 Elements and processes of an expert system

6.2.4.1. Elements

It has been noted that ordinary computer programs organize knowledge on two levels: data and program. Most expert systems organize knowledge on three levels: facts, rules and inferences (Robinson and Frank, 1987). These three levels correspond to two independent core parts of the expert system according to Robinson *et al.* (1986). These are a domain independent inference engine and a domain specific knowledge base (covering both facts and rules).

Expert 'rules' model behaviour of, and functions relating to, a theme. 'Facts' describe single values, such as basic information or events. Other than the core elements of the expert system, there are two other basic parts, a module for knowledge acquisition and a module for interfacing with the user (Laurini and Thompson, 1992).

the reasons behind a situation. In short, if B is true and the rule A → B applies, then by abduction A is also true. There are two other less advertised processes. Induction occurs when two facts are always concomitant and it would be reasonable to assume that there is a rule expressing a relationship between them. In formal terms, if A is true and B is also true then the rule A → B applies. Finally, transitivity involves the interplay of two rules. If A → B and B → C we conclude that A → C is true (Laurini and Thompson, 1992).

6.2.4.2 Control and search

The terms forward and backward chaining are also used in connection with search strategies used to traverse the rule base, or state-space. In state-space search, operators can search in a forward direction from a given initial state to a goal state (also called data-driven search) (Robinson *et al.*, 1986). This implies that there is no knowledge of the goal in the system (Fisher, 1990). Alternatively, the search can occur in a backward direction from a given goal to initial state (also called goal-driven search) (Robinson *et al.*, 1986). This implies that there is some knowledge about the goal in the system (Fisher, 1990). The appropriateness of either method depends upon the nature of state-space and the particular problem involved (Robinson *et al.*, 1986).

Searches in state-space are conducted with the root node as the starting point, from which progress to child nodes (one of which is the goal) is the next stage. There are several types of search: depth-first search, breadth-first search and any number of heuristic ('rule-of-thumb') search methods. The latter is the most popular method of search used, as an applicable heuristic can be chosen for the specific problem addressed. As an example, two best first algorithms (the simplest of heuristic search methods) are outlined here. In 'costed search', the lowest cost child node is removed, then the children of that investigated, and so on, until the goal is reached, or there are no more child nodes to investigate. In 'branch-and-bound search', the lowest cost child node is expanded. This continues until all links are exhausted and the cheapest path to the goal chosen (Fisher, 1990).

6.2.5 Knowledge representation

According to Kartikeyan *et al.* (1995) there are three conceptual models to represent knowledge: rule-based (Wharton, 1987); frame-based (McKeown, 1987); and blackboard architecture (Hayes-Roth *et al.*, 1983). The choice of method is dictated by the nature of the problem concerned.

The rule base contains procedural knowledge and therefore can be programmed using conventional languages. There are several ways in which domain-dependent knowledge can be encoded, which incorporates searching of many paths in the knowledge-base, not all of which lead to solutions.

base and inference engine have been observed as being closely entwined (i.e. the action is the task of the inference engine). The knowledge base should not be so 'hard-wired' into the system, as it may need to be modified to meet specific demands. It is best kept as a separate entity from the inference engine. Alternatively, rules can be arranged as a hierarchy of objects. The knowledge base is called upon by the inference engine 'Does this rule apply?' 'This one?', etc., until a rule is found that satisfies the operative words and the derived data. This is then repeated for the next tier in the hierarchical object structure. At this stage no action is taken on the rules. Appropriate action is implemented by the inference engine once the levels in the hierarchy have been traversed (Moore *et al.*, 1996).

It is also important for an object-oriented system to be able to intelligently process some semantically imprecise spatial operators, e.g. 'close to', 'between', 'adjacent to'. To process such imprecise queries, knowledge about contexts (or user perspectives) can be introduced to the system (e.g. Subramanian and Adam, 1993; Pissinou *et al.*, 1993). There will be more about handling imprecision later in this chapter.

A further method of building object-oriented systems is the responsibility-driven approach, or client-server model (Subramanian and Adam, 1993; Lilburne *et al.*, 1996). For example, in the case of a spatial expert system shell, the ES shell could be the client and the GIS the server, or vice versa.

6.2.6 Knowledge engineering

Knowledge engineering is a term reputed to have been first coined by Ed Feigenbaum, one of the original pioneers of expert systems in the mid-1960s (Dantzler and Scheerer, 1993). It is one of the greatest challenges in building expert systems (Scott *et al.*, 1991), indeed Fisher *et al.* (1988) go as far as to say '. . . perhaps the major effort in developing an expert system'. The predominant process in knowledge engineering, knowledge acquisition, has been defined as the transfer and transformation of problem-solving expertise from some knowledge source to a computer program (Buchanan *et al.*, 1983). Sources for such problem-solving expertise include human experts, textbooks and scientific journals (Robinson *et al.*, 1986).

Knowledge engineering in general involves the codifying of human knowledge, a method by which the expert's knowledge and ways of reasoning can be understood (Laurini and Thompson, 1992). The knowledge engineer chooses a specific paradigm, within which facts and rules can be elicited. There is a parallel between this and software development but for expert systems the choice of paradigm is not obvious, dependent on the application (Robinson *et al.*, 1986). When new knowledge becomes available, it has to be confirmed as consistent with existing knowledge (Laurini and Thompson, 1992).

theory parlance). The Dempster–Schafer theory generalizes the Bayesian approach by replacing single-point probabilities with belief intervals (Scheerer, 1993). The two methods are both accurate and effective if used correctly (Moon and So, 1995).

6.2.9 Expert systems and GIS

It has been stated that the application of expert systems to GIS has been well established. Historically, the problem domains for expert systems in GIS have been automated map design and generalization, terrain and feature extraction, geographical digital databases/user interfaces, and geographic decision support (Robinson *et al.*, 1986).

This section deals with the methods by which expert systems and GIS can be linked or coupled. It should be noted that those striving to integrate expert systems and GIS (for the benefits that they would both give each other) have not done as well as hoped due to exaggerated claims when such initiatives were first mooted (Lilburne *et al.*, 1996).

Referring to Figure 6.2, the first of the linking methods is loose coupling, where expert systems and GIS are 'loosely' integrated by communication links, a communication channel that transfers data from GIS to the expert system. This is called a 'loosely coupled standalone system'. It is also possible

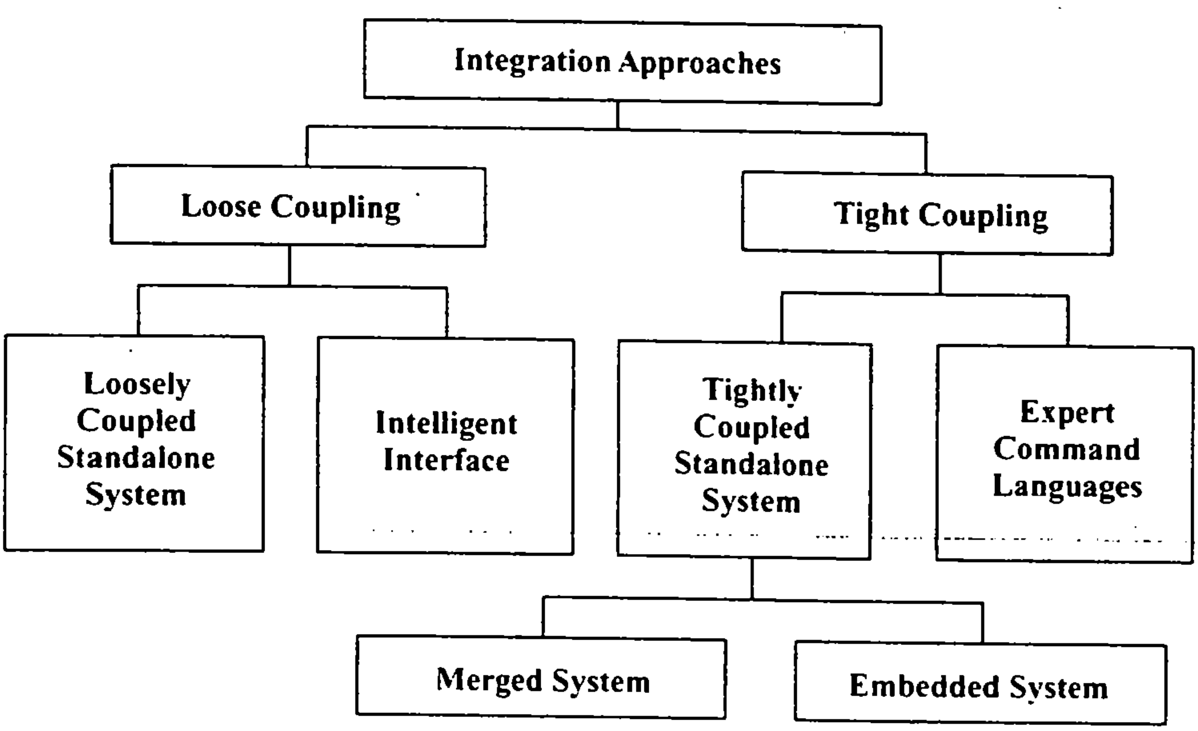

Figure 6.2 A classification of GIS and expert system integration methods (reproduced with permission, the American Society for Photogrammetry and Remote Sensing. Zhu and Healey, 'Towards intelligent spatial decision support', 2, pp. 877–886.)

6.3.2 Where expert systems in GIS are lacking

Expert systems are regarded as the traditional view of AI in geography (Openshaw, 1995). Fischer and Nijkamp (1992) noted a lack of analytical modelling functionality in expert systems. They also found a low level of intelligence in terms of knowledge representation and processing. This is a major hampering factor of current systems. Fischer (1994) has commented on the analytical modelling shortfall – it is not well defined or easily represented in a rules context.

Despite initial attractive designs, most expert systems do not exist in their fully realized and finalized form. This is a comment which can be backed up by the cross-section of applications contained in the examples section of this chapter. The reasons why relate to the open-ended nature of many applications, and the difficulties encountered in gaining pertinent expert knowledge – an often quoted problem.

The trouble is that knowledge acquisition is lengthy, requiring patience on the part of the expert and the knowledge engineer. It is a very poorly understood aspect of the expert system development process (Robinson *et al.*, 1986). Knowledge acquisition is regarded as the most serious barrier to efficient expert system development though expert systems for narrow domains of knowledge are easier to develop than those that need creative or common-sense answers (Yazdani, 1984). Possible strategies to ease this difficult process could include a move to reduce dependency on experts as much as possible. Methods such as model-based reasoning, case-based reasoning and exploration-based learning have been exploited for this purpose (Fischer, 1994).

6.3.3 Should expert systems be used in geography?

There have been suggestions that expert systems are obsolete in geography (Openshaw, 1995), the main arguments being that, by design, expert systems cannot perform better than human experts. Furthermore, no human experts are good enough. Openshaw asserted that the way forward lies in developing systems at superhuman levels, through an expert system that encompasses the knowledge provided by several expert sources and goes beyond the capability of any one human. Also, the trend of expert systems being applied to mundane tasks, as observed by Durkin (1996), would leave the expert more time to work on issues that mattered.

One major academic advantage of expert systems development is that it is essential to fully specify the knowledge of any subject at a number of different levels. It puts the knowledge of one or more experts at the disposal of users and enables the efficient dissemination of that knowledge. Furthermore, preparation of the rule base provides insights into a domain and

Finally, and more generally, it should be noted that use of terms such as artificial intelligence and expert systems may have fallen out of vogue but in fact are being described in subtle terms, e.g. 'intelligent application tools'. The irony is that the AI capability is still there but under a different label (Durkin, 1996).

6.4 Further opportunities and expectations

This section takes a look at current expert systems research as a whole and from the findings identifies future opportunities for the spatial sciences. As quoted by Robinson *et al.* (1986), expert systems development is most likely to follow those already emerging. Of course, there is no harm in suggesting initiatives that have lain dormant for a while.

6.4.1 Getting round the knowledge acquisition problem

Much has been said about the problem of knowledge acquisition. A way has been suggested to overcome this lack of understanding via direct interaction between the domain expert and the program, thus bypassing the knowledge engineer. This is facilitated by having the program 'taught' by the expert by feeding it problems and seeing how it reacts, making amendments and adding knowledge as appropriate (Davis and Lenat, 1982). Alternatively, the discourse characteristic of knowledge acquisition could be expanded to encompass the conceptual modelling stage of system design. This acquisition is no longer seen as expertise transfer, but a co-operative and communicative process between the knowledge engineer and expert (Chan and Johnston, 1996).

Knowledge acquisition can be observed as a 'bottleneck' in developing knowledge-based systems. The manual approach to this suffers from experts unable to articulate their reasoning rules. On the other hand, the automated approach (which induces rules from a set of training cases) suffers from a lack of training cases. Jeng *et al.* (1996) have put forward an integrated approach that uses the strengths of both, in having human experts responsible for solving problems, and utilizing an inductive learning algorithm for reasoning and consistency checking.

The last suggestion in this section concerns an efficient knowledge-acquisition support method which is required for the improvement and maintenance of the knowledge base in durability evaluation of a ship bridge deck. A method to automatically acquire fuzzy production rules is proposed. It makes joint use of a neural network as a subsystem. The evaluation function of genetic algorithms can be provided with the weights from the neural network. In this way it is possible to acquire new knowledge where knowledge is difficult to acquire in the field (Furuta *et al.*, 1996). How well this works is a matter for further research.

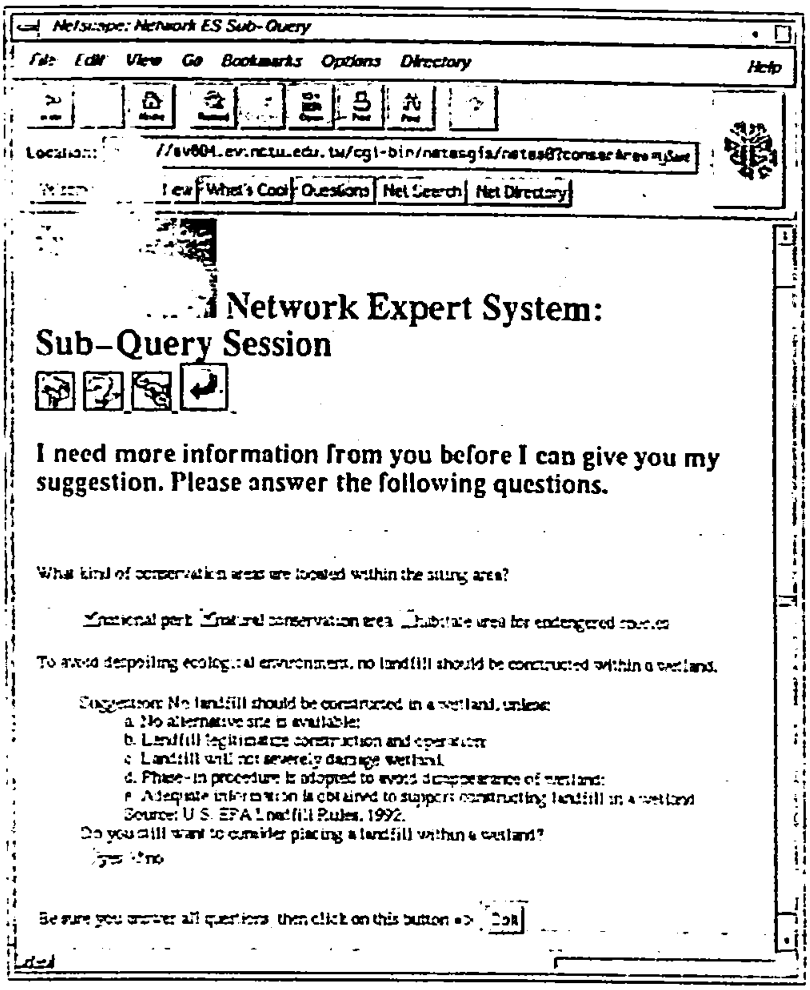

Figure 6.3 An Internet page from the landfill siting expert GIS (Kao *et al.*, 1996).

with some of the benefits to be gained from implementing expert systems on the Internet.

A prototypical network expert geographic information system for landfill siting has been proposed. It has a forward chaining knowledge base derived from the domain's literature. The actual siting analysis occurs in a GIS and is evaluated by triggered rules from the expert system. The expert system and GIS are combined to give the strengths of both. What is novel about this application is that it can be accessed from the Internet (Figure 6.3). cutting distribution and any installation or management on the part of the user (Kao *et al.*, 1996).

A different approach is that of Hardisty (1996). Hardisty described EPISys. an expert system that models hydrodynamic characteristics in the River Humber using equilibrium theory. The results were 96 hour forecast matrices issued in real time, which were found to compare favourably with real observations. Making full use of the WWW, these forecast matrices were updated twice a week for the benefit of all.

6.5 Illustrative examples

6.5.1 *Early geographic expert systems*

One of the most noted expert systems with an earth sciences application has been PROSPECTOR, which was developed to assist field geologists (Alty and Coombs, 1984). The original system was designed to provide three major types of advice: the assessment of sites for the existence of certain deposits; the evaluation of geological resources in a region; and the identification of the most favourable drilling sites. It should be noted that Katz (1991) has remarked that despite initial success in discovering a mineral deposit, none have since been found using PROSPECTOR.

One key feature of geological expert knowledge is that it is incomplete and uncertain. This uncertainty may rest both with the knowledge underlying problem-solving and with the evidence available to the user upon which a conclusion is to be reached. Because of this uncertainty the system needs to use a form of non-definitive reasoning, manifested in this case by the use of conditional probabilities and Bayes' theorem.

The structure of the PROSPECTOR model can be described as spaces connected by rules. A space may be some observable evidence or a hypothesis; each space has a probability value indicating how true it is. Rules have the role of specifying how a change in the probability of one space can be propagated to another. A model is built up by connecting spaces with rules in the form of a network (Robinson *et al.*, 1986).

GEOMYCIN (Davis and Nanninga, 1985) has been developed from EMYCIN, which is itself an 'empty' (i.e. devoid of context-specific rules) version of MYCIN, an expert system used for the diagnosis of infectious blood diseases. GEOMYCIN incorporates geographically equivalenced parameters, geographic data files, and rules that are geospatially specific. These capabilities have been utilized to build a realistic demonstration expert system for fire behaviour in a major Australian national park.

Another case in point involves the use of metadata as knowledge being used in content-based search. This has been used to create a knowledge-based GIS (KBGIS). KBGIS-II handles complex spatial objects by dynamic optimization. The KBGIS-II conceptual design is based on fulfilling five requirements. Firstly, to handle large, multilayered, heterogeneous databases of spatially-indexed data, which was achieved. In addition to this, the ability to query such databases about the existence, location and properties of a wide range of spatial objects was planned. Finally, such a system was designed to be interactive, have flexibility and have a learning capability (Smith *et al.*, 1987). An application of KBGIS-II concerned with the design and implementation of a declarative GIS query processor was detailed by Menon and Smith (1989).

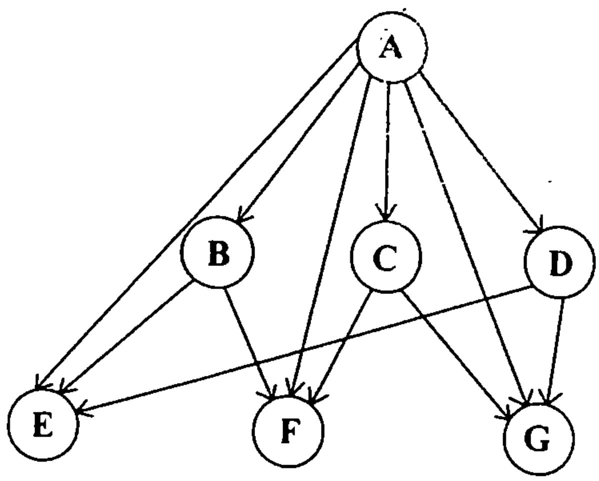

Figure 6.4 An example knowledge representation schematic (from Kartikeyan *et al.*, 1995). (Copyright 1995 IEEE.)

the human expert's interaction in remotely sensed image classification is still in its 'adolescence'. Kartikeyan *et al.* (1995) detail a simple model for spectral knowledge representation. They also outline a method of quantifying knowledge through an evidential approach as well as an automatic knowledge extraction technique for training samples. These methods were used to facilitate land cover analysis on two datasets. The inference engine offered hypotheses (which can be true or false) to test. For instance, observe this knowledge representation schematic (Figure 6.4).

There are three base land cover classes: water (E), vegetation (F) and non-vegetation (G). There are also superclasses such as B, which is a subset of water and vegetation. Based on this test, a given pixel will have an appropriate value or set of values. An iterative process is implemented that ends when one class is decided upon, or no new state is reached after an iteration. All the while, hypotheses are used to decide the next state. These hypotheses are tested through a rule-based approach. There are three possible results of the test: no rules pass; all passed rules correspond to the same hypothesis: and a set of passed rules corresponds to more than one hypothesis. The results were compared with contemporary digital techniques. It was found that commission errors were avoided, and non-spectral and collateral knowledge could be incorporated. The accuracy derived using only spectral knowledge was comparable with standard digital methods. Further investigations may include the extraction and representation of non-spectral knowledge, and also the use of geographic or other ancillary information to minimize efforts in ground truth collection.

A second example is the work of Cress and Diesler (1990), which illustrates the need for a more efficient and knowledgeable production of geological engineering maps (GEM). GEMs should portray objective information in order to best evaluate the engineering involved in regional planning. In this example, GEM production is automated by using a KBGIS approach. It

6.5.6 Efficiency measures

Tanic (1986) detailed URBYS, a tool that was intended to assist urban planners and local decision makers in the form of an expert system computer-based implementation of their own urban rules. The system analyses an urban area and advises on what action should be taken. A measure of efficiency is the use of meta-knowledge rules, by which a specific group of tools can be grouped for a specific kind of urban analysis. The rule interpreter works by either forward chaining or backward chaining. URBYS itself consists of an urban database, an expert system and an interface. It helps in urban planning by adopting the following approaches. Firstly, methods should be natural and close to that of the expert. Secondly, the system's knowledge should be easily accessible and changeable enough not to affect the system's integrity. Finally, the database should account for empirical observations.

6.5.7 Error modelling

Skidmore *et al.* (1996) have outlined the Land Classification and Mapping Expert System (LCMES) (Figure 6.5). The objectives of the study were to construct an intuitive user interface for commercial GIS to make it open to all, to rigorously test the accuracy of expert system output by comparing statistical output with conventional output, and to evaluate if expert system output was of an accuracy that would be considered operational. The methodology incorporates Bayes' theorem, in which knowledge about the likelihood of a hypothesis occurring, given a piece of evidence, is represented as a conditional probability. Two methods exist for linking evidence with the hypothesis: forward chaining (inference works forward from the data or evidence to the hypothesis), and backward chaining (inference flows from the hypothesis to the data).

The successful integration of a Bayesian expert system with a commercially available GIS for mapping forest soils has been facilitated. In this application there were five target soil landscape classes utilizing a digital terrain model, a vegetation map and the soil scientist's knowledge incorporated in the process. It was found that the map drawn by the expert system was as accurate as the map drawn by the soil scientist, statistically, with a 95% confidence interval. Having said this, there were disparities in the visual attributes of the resultant maps.

For some applications, the methodology adopted by conventional remote sensing classification techniques is insufficient or not accurate enough. Kontoes *et al.* (1993) have explored the incorporation of geographical context information from a GIS and how it can be used to remedy these disparities to some degree. In this case, soil maps and buffered road networks have been used as additional data layers to classify SPOT images for estimates of crop acreage. Also, a knowledge base containing both image context rules the result of the integration of a rule-based expert system with a commercial GIS through the use of a relational database management system (CLIPS [an expert system shell developed by NASA], Arc/Info and Oracle). Heuristic rule-bases are selected and applied to pertinent data layers, based on an initial query in the GIS. Any results from the rule base are then stored in the database. Resource managers and specialists are not necessarily conversant with computer technology, so a consistent, friendly and unified user interface was deemed essential for data sharing and a common framework for problem solving. The database also stored metadata, which described the data's availability and location. This allowed for management and use of different rule bases and models to do different tasks. The rule-base design consisted of heuristic knowledge rules (derived from a number of knowledge engineering sessions with experts), computational rules (IF–THEN rules with numerical weights ranging from −1 to +1) and I/O protocol rules (all data tasks are performed by these rules). The expert system module itself does not maintain a separate database. Through the interface between the rule base manager and database manager it communicates with the RDBMS.

According to Varghese and O'Connor (1995) (see also Evans *et al.*, 1993) an expert geographic information system is a tool that integrates the functions of an expert system (Nexpert Object) and a geographic information system (Arc/Info). Two ways were suggested to enable this in a route planning context. Firstly, by allowing one to have the control of the other, the transfer of data can be facilitated. In this case, the expert system shell's C interface and Arc/Info macro language were used to build the interface between the two. In this way, dual control is also enabled, so that Arc/Info controls Nexpert if the emphasis is on intensive spatial analysis, and Nexpert controls Arc/Info if the converse applies. Secondly, coupling can be effected by establishing a data link between the two, for example a common format. Despite certain software-related limitations, this was generally a successful attempt in automating tedious and repetitive route-planning tasks.

As an example of use of expert systems within a decision support environment, WaterWare (Fedra and Jamieson, 1996) has been put forward as a decision support system for river-basin planning. It has been designed to integrate the capabilities of GIS, database management systems, modelling techniques, optimization procedures and most relevantly, expert systems (in the context of handling some of the more complex queries in a problem-specific manner). Furthermore, it is a completely open, modular system with different degrees and mechanisms of coupling at various levels of integration, presenting the user with a common logical structure for hands-on analysis and information retrieval.

6.6 Summary

This chapter has provided a broad overview of the expert systems field and, in particular, its application to geography, i.e. geoexpert or spatial expert

Miller (1994) – coupling knowledge-based systems and GIS, model of vegetation change.

Miller and Morrice (1991); Miller (1994) – predicting changes in upland vegetation of Scotland using expert systems and GIS.

Hydrological

Merchant (1994) – DRASTIC model for groundwater capability.

Smith, Zhan and Gao (1990) – extracting channel networks from noisy DEM data.

Tim (1996) – hydrological/water quality expert systems.

Soil mapping

Skidmore *et al.* (1991) – use of expert systems and ancillary data to map forest soils.

Zhu *et al.* (1996) – infer and represent information on the spatial distribution of soil.

Socio-economic

Barath and Futo (1984) – geographic decision support systems (socio-economic).

Heikkila (1990) – Modelling fiscal impacts using expert GIS: theory and strategy.

Sarasua and Jia (1995) – integration of a GIS and KBES for pavement management.

Engineering

Evans, Djokic and Maidment (1993) – investigation of expert systems and GIS in civil engineering.

Spring and Hummer (1995) – use of engineering knowledge regarding accident causation to identify hazardous locations.

Land use

Chandra and Goran (1986) – GEODEX – evaluating site suitability for specific land use activities.

Goldberg, Alvo and Karani (1984) – FES – Forestry Expert System – landcover change.

Mackay, Robinson and Band (1992) – KBLIMS (Knowledge Based Land Information Manager and Simulator).

Wei, Jianbang and Tianhe (1992) – land use suitability.

Cartography

Freeman and Ahn (1984) – AUTONAP – cartographic name placement.

Robinson and Jackson (1985) – MAP-AID for map design.

Yue *et al.* (1991) – a statistical cartographic expert system for China.

Remote sensing

Goodenough *et al.* (1995a) – an intelligent system (SEIDAM – System of Experts for Intelligent Data Management) for calibrating AVIRIS spectrometer data.

Goodenough *et al.* (1995b) – Methodology for creating sequence of intelligent expert systems (SEIDAM).

Morris (1991) – extraction of 3D structural parameters from remotely sensed imagery and DEMs.

Srinivasan and Richards (1993) – analysis of mixed data types for photo-interpretation.

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Using geomorphological rules to classify photogrammetrically-derived digital elevation models

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Abstract
An object-oriented 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 (Pringle, 1985) 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). Geo-hazard 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 geomorphologic database and the work on sediment budgets for the coastline of Central

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Southern England by Bray *et al.* (1995). However, what is of interest here are the tools used to get the most out of that data. Some geomorphological examples include classification of rocky coasts using airborne multispectral scanning (Wadge and Quarmby 1988), use of Geographical Information Systems (GIS) to estimate coastline change from digitised 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 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).

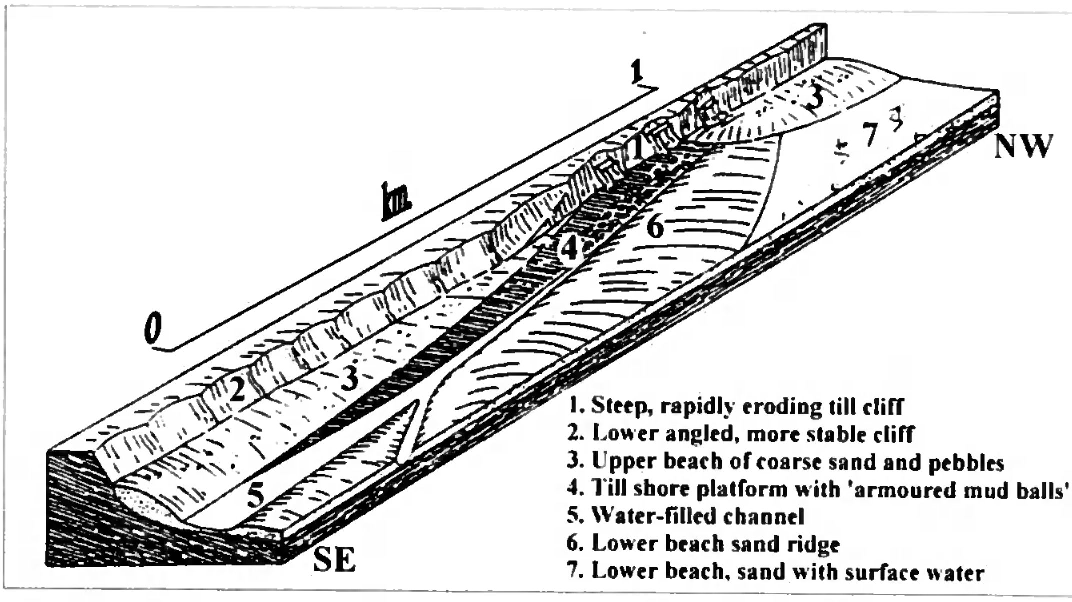


Figure 1: The characteristic features of a Holderness ord (from Pringle 1985). Increased erosion occurs where the upper beach is absent from the foot of the cliff, exposing the underlying till platform.

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 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-1960's (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-oriented expert system, consisting of the core elements as defined above (the object-oriented 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-oriented 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 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).

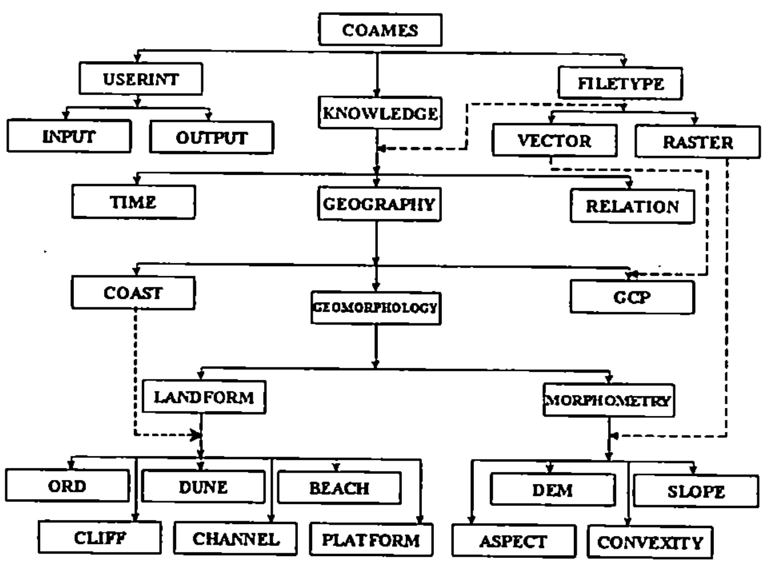


Figure 2: The object-oriented hierarchical structure of knowledge and data in the prototype (multiple inheritance links are dashed).

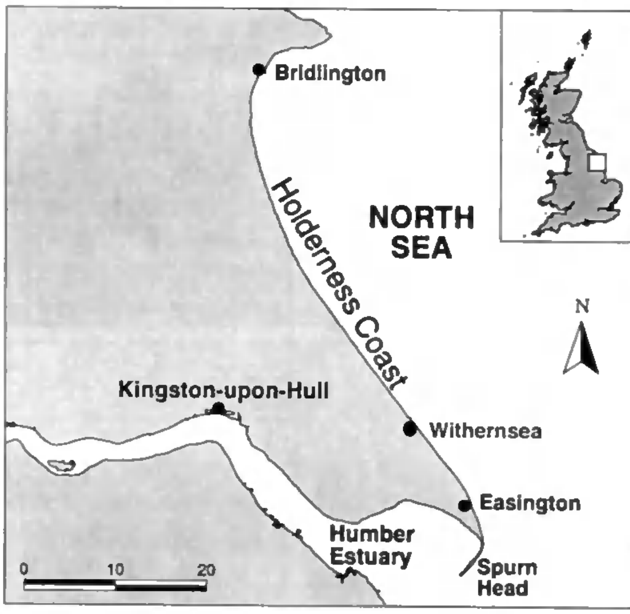
The object-oriented design of COAMES has been established above. The interface and main workings of the expert system are programmed in C++, an object-oriented language (the interface is also Java-based). While COAMES is not presently linked to an object-oriented database, it is conceptually and functionally a true object-oriented 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 2m/yr (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 length (Scott 1976). The ord migrates in the direction of longshore drift (south-east) at an average rate of approximately 500m/yr (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/yr. The ord currently adjacent to the Dimlington-Easington stretch of the Holderness coast was chosen for this study (Figure 3b). 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 (Pringle, personal communication).



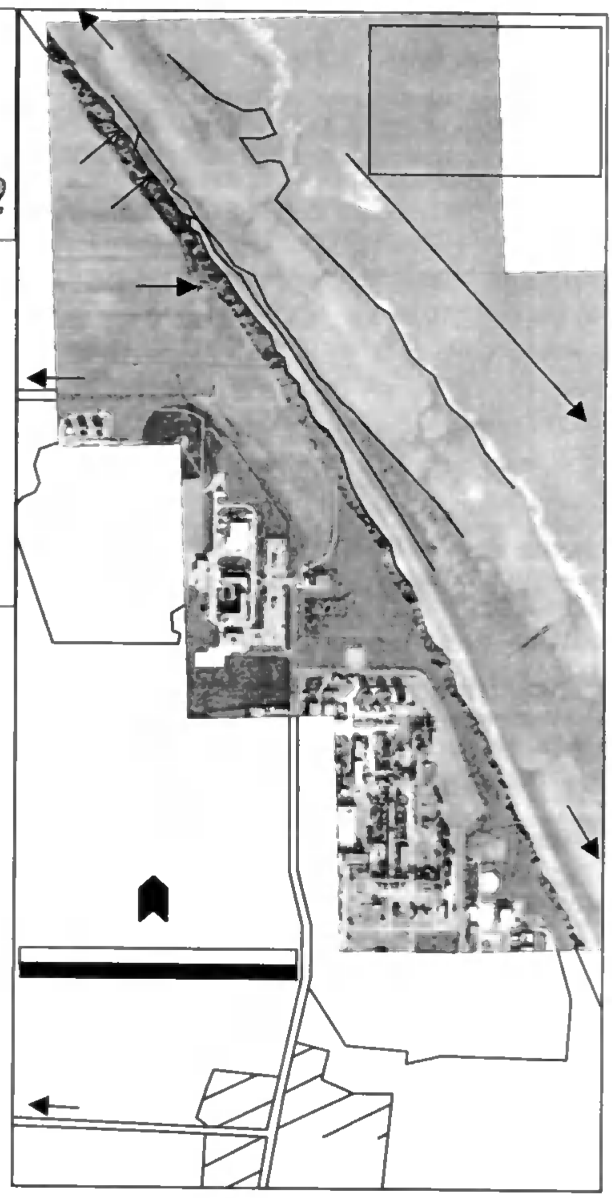


Figure 3a: Location map of the Holderness Coast

Figure 3b: Location Map of the Study Area, based on an orthographic photograph derived from the 26th October 1996 sortie.

The beach (ord) morphometry can be summarised 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 40m-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 Chieftan Aircraft at 1000m. Photographs for two specific dates (26th October 1996 and 8th 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 Digital Elevation Models (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 Digital Elevation Model) 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*

Data sets 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). Box 1 contains the structure for the rule 'justcliff' (enquires whether or not the object in question is a cliff in general).

```
justcliff.truerule=(int )steep_ptr;                        /* Next rule if true */
justcliff.falserule=(int )jcl_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 */
```

Box 1

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' 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 recognise only those rules that are relevant. This is the first stage in what Fisher *et al.* (1988) call a 'recognise-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 4).

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.

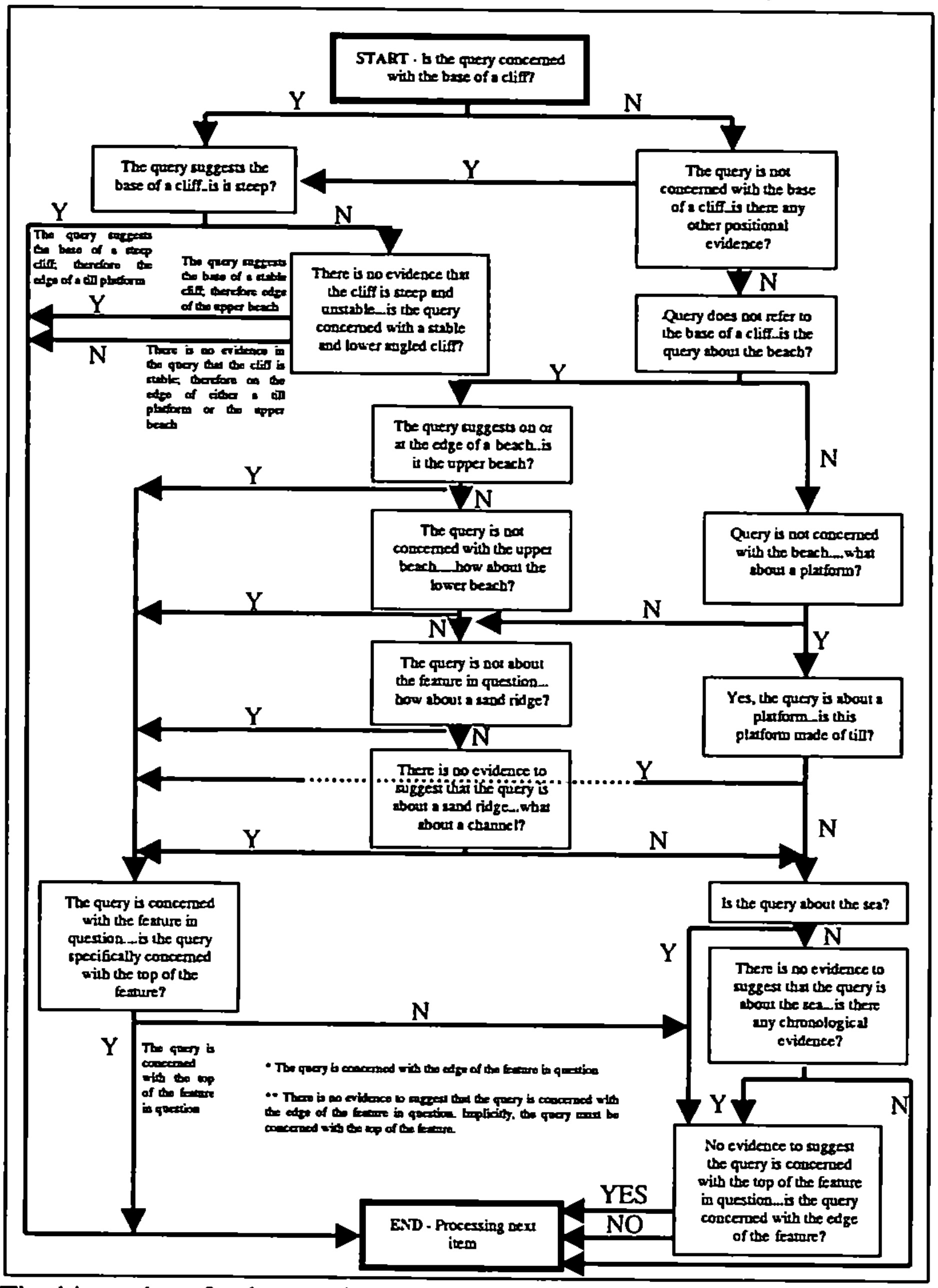


Figure 4: The hierarchy of rules used to process the user query and ascertain which portions of knowledge to use. The configuration is derived from the archetypal ord schematic in Figure 1. Each of these rules have attributes that link with the relevant dictionary terms. The extracted terms are compared with the user query.

The trained hierarchy is subsequently descended again (the second part of the 'recognise-act cycle') with the ground control point 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 ground control point in some way defines the feature to be isolated in agreement with the original query, then the associated three-dimensional co-ordinates 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 ground control points 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 and data base. 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.

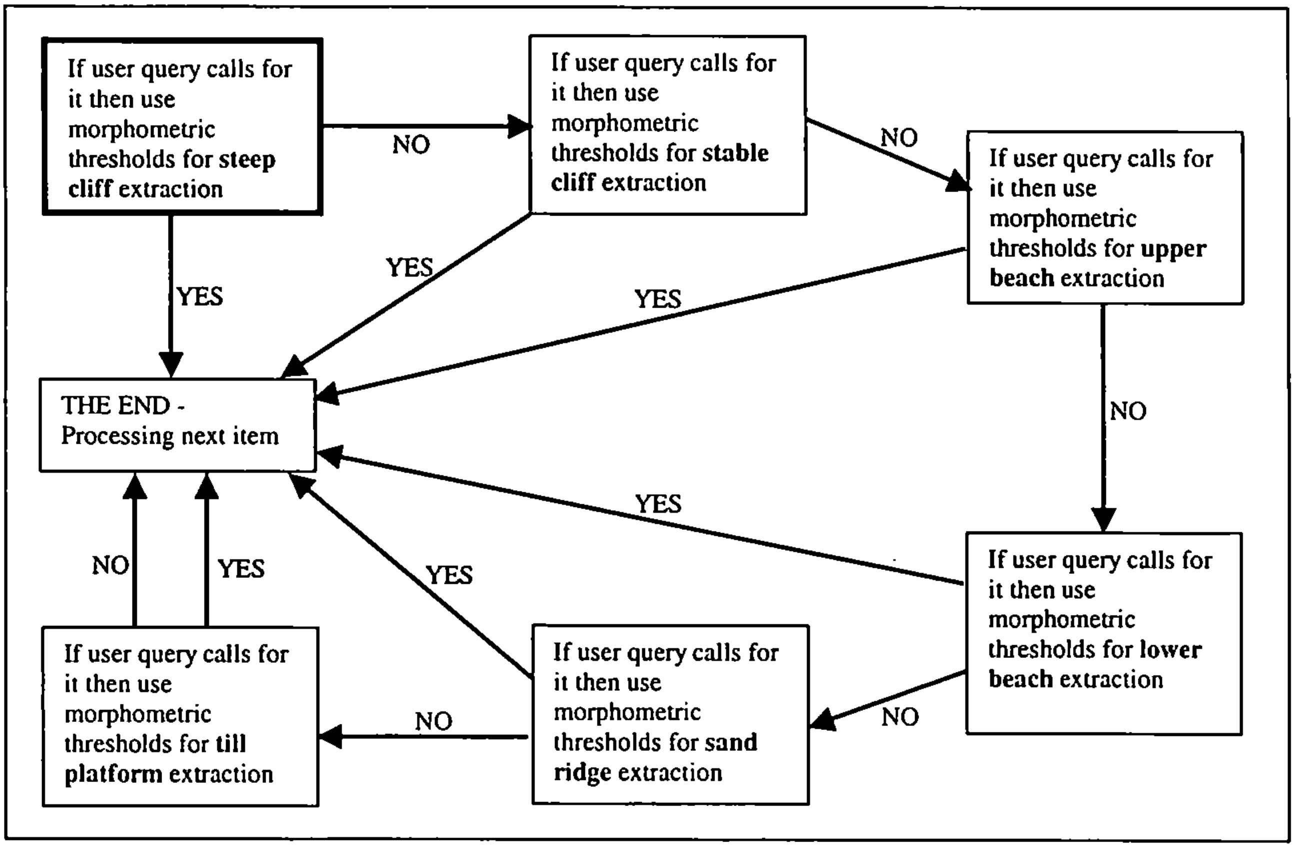


Figure 5: The hierarchy of rules used to set parameters for morphometric extraction. There is a set of these rules for each basis of extraction: height, slope, aspect and convexity. Each of these rules have attributes that link with the relevant morphometric thresholds. The extracted thresholds are passed to the relevant morphometric function.

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 5), which were descended in turn. For each of height, slope, aspect and 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 recognise 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 degrees 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 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 6a and b are decision support output maps intelligently derived from digital elevation models 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 digitised from the orthophotograph of 26th 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 longshore drift. In the time period from October 1996 to April 1997, the southern end of the steep cliff zone (about 100 metres long at first) had been extended by approximately 250 metres southward in the direction of longshore drift, while the northern end migrated some 75 to 100 metres southward. In the past, movement of the ord centre has been estimated at approximately 500 m/yr 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 3b).

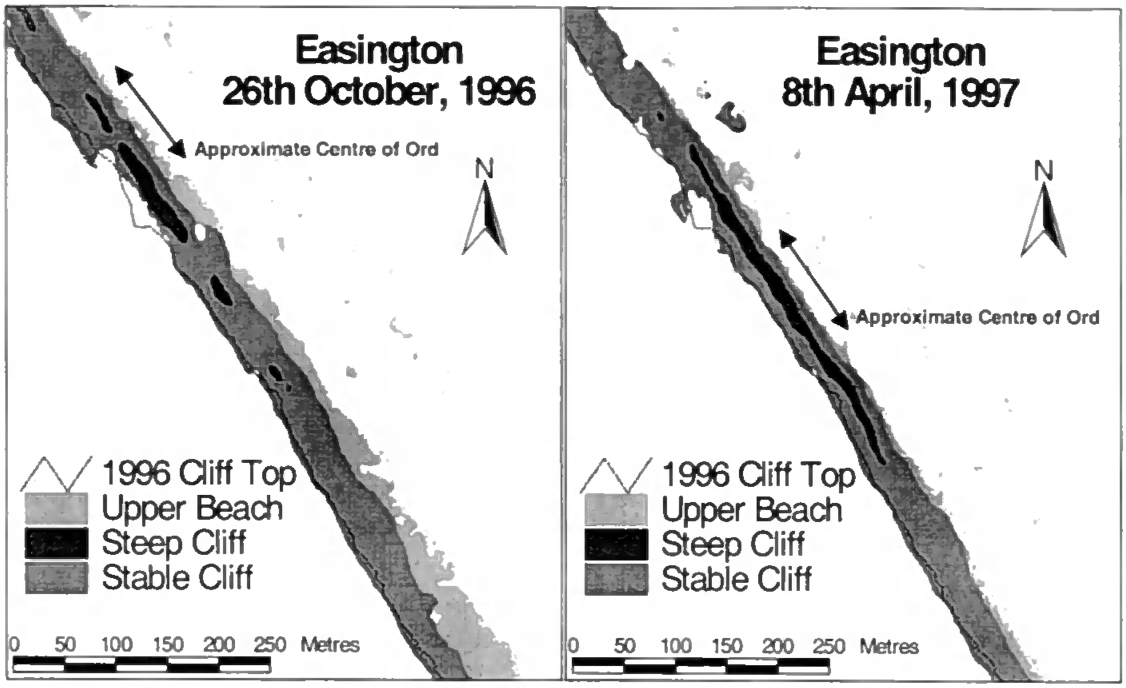


Figure 6: The identification of steep cliff, stable cliff and upper beach from digital elevation models of the study area at two dates, using topological and morphometric rules accessed by the COAMES expert system. (Ordnance Survey National Grid). (a) October 1996. (b) April 1997.

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 exists - it needs the analytical capabilities of the expert system to handle these challenges effectively.

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